INTERNATIONAL DECADE OF OCEAN EXPLORATION

METALLOGENESIS, HYDROCARBONS AND TECTONIC PATTERNS IN EASTERN ASIA

A Programme of Research

Report of the IDOE Workshop on Tectonic Patterns and
Metallogenesis in East and Southeast Asia,
Bangkok, Thailand, 24 - 29 September 1973

COMMITTEE FOR CO-ORDINATION OF JOINT PROSPECTING FOR MINERAL RESOURCES IN ASIAN OFFSHORE AREAS (CCOP)

INTERGOVERNMENTAL OCEANOGRAPHIC COMMISSION, UNESCO (IOC)

1974

Issued by the Office of the Project Manager/Co-ordinator,
UNDP Technical Support for Regional Offshore Prospecting in East Asia
(UNDP/CCOP)

The front cover shows part of an Earth Resources Technology Satellite (ERTS) image of the island of Sumbawa, eastern Indonesia, with the caldera of Tambora showing in the northern peninsula. Other volcanic peaks can be seen in the picture. The Java Trench subduction zone is located south of the island and the volcanicity is associated with the northward underthrusting of the Indo-Australian Plate. The products of the northern volcanoes on the island are alkaline, while those of the southern ones are calc-alkaline, which is a good example of the increase in K_2O content of andesitic volcanoes away from the subduction zone as envisaged by the plate tectonic model. The area covered by the image is about 160 km by 120 km. False-colour reproduction shows forested areas in red.

For citation purposes, this publication should be referred to as:

CCOP-IOC, 1974, Metallogenesis, Hydrocarbons and Tectonic Patterns in Eastern Asia: United Nations Development Programme (CCOP), Bangkok, 158 p.

PREFACE

The Workshop on Metallogenesis and Tectonic Patterns in East and Southeast Asia, organized as part of the programme of the International Decade of Ocean Exploration (IDOE), was held 24-29 September 1973 in Bangkok, Thailand, under the sponsorship of the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP) and the Intergovernmental Oceanographic Commission (IOC).

Initial moves for the organization of the Workshop were made in November 1972 when a proposal for research entitled "Tectonic Development of East and Southeast Asia and its Relation to Metalliferous Ore and Hydrocarbon Genesis" was prepared and submitted to the Office of IDOE, National Science Foundation of the United States of America. The proposal had been formulated by a group of scientists from countries in the region and several developed countries, who had convened a working group during the 1972 (ninth) session of CCOP held in Bandung, Indonesia. CCOP, an intergovernmental body established within the United Nations Economic Commission for Asia and the Far East (ECAFE), is concerned with co-ordination of mineral prospecting in the offshore areas of seven of its member countries, and consequently has a strong economic bias; but it nevertheless recognized that scientific research conducted within the context of IDOE could potentially provide results of great significance to the understanding of mineral distributions in a region of complex crustal interactions. From the outset the link with economic mineral resources, metallic, non-metallic and hydrocarbon, was acknowledged as the pivot of the whole programme, and this emphasis was maintained throughout subsequent developments culminating in the Workshop.

The original proposal contained the following main objectives:

1. To determine the location, characteristics and significance of the principal tectonic features of the continental margins and associated structural elements of east and southeast Asia.
2. To relate metalliferous ore deposits to the major tectonic features and plate boundaries, particularly convergence and shear boundaries.
3. To analyse the characteristics of various types of sedimentary basins and their hydrocarbon habitat in terms of their position relative to plate margins and tectonic features, and to study the geological, geochemical and geothermal history factors governing the transformation of organic matter into hydrocarbons in small oceanic basins.

Copies of the proposal were sent to IOC and the Scientific Committee on Oceanic Research (SCOR), and an enthusiastic response was received from these and other organizations. As a result, a planning session was held in

Tokyo, 12-17 April 1973, to decide on CCOP's participation in the IDOE programme. At this meeting, agreement was reached to sponsor a workshop to formulate proposals for a research programme; a steering committee was appointed, and a list of participants to be invited to serve on the subject panels was drawn up. Date, place and sponsorship of the meeting were decided subsequently.

Of the ninety participants who attended the Workshop, 50 per cent were from governmental organizations, equally divided between developing and developed countries. Universities and research institutions had a 29 per cent representation, and industry 20 per cent: these were predominantly from developed countries. The widely international character of the contributions to discussions and project proposals was a major feature of the Workshop, with over twelve countries and three United Nations organizations participating.

Grateful thanks are extended to the National Research Council of Thailand, which acted as host to the Workshop; to the Office of IDOE, National Science Foundation of the United States of America, for assistance in organizing the meeting; and to the Office of the Project Manager, United Nations Development Programme project on Regional Offshore Prospecting in East Asia (UNDP/CCOP) for secretariat facilities and for final preparation and editing of the report, for which help is also acknowledged from the UNDP Geological Survey and Exploration Project, Burma, BP Petroleum Development of Thailand and the South East Asia Division of Esso Exploration, Inc. The Office of IDOE, IOC, and the project office of UNDP/CCOP jointly financed the participation of a number of international experts, as well as national scientists from CCOP countries.

J.A. Katili

Chairman,

IDOE Workshop on Metallogenesis and Tectonic Patterns in East and Southeast Asia.

METALLOGENESIS, HYDROCARBONS AND TECTONIC PATTERNS IN EASTERN ASIA:

A Programme of Research

CONTENTS

I. INTRODUCTION

The continental margins, small ocean basins and island arc systems of eastern Asia, from the Sunda Arc to the Japanese islands, and from the stable shelf of the Gulf of Thailand to the stable shelf bordering northern Australia, provide one of the most significant regions of the earth's surface for the study of present-day tectonic processes and of their effects in the relatively recent past. Its complexity might be counted a drawback in terms of deriving simple solutions from complicated and inter-related systems, but on the other hand the variety of plate interactions, including triple-plate junctions, offer scientific as well as economic rewards for investigations not found in any comparable area elsewhere. Additionally, the fact that much of the region now lies under water prevents extensive land studies of the plate boundaries, and multiplies the cost of field work; yet the presence of numerous islands, surrounded by depths of water varying from shallow to the deepest known, provide many opportunities for relating marine seismic profiling results to land geological work.

The significance of the area was recognized several decades ago by a number of earth scientists, working in a theoretical context much more barren than at the present time, and with instrumentation and resources far less than are available today. Nevertheless, this region provided evidence upon which Vening Meinesz developed theories of mountain building from gravity studies, and the concept of Benioff zones was developed from Benioff's studies of the seismicity of the Pacific margins. Subsequent work by earth scientists in the region, both indigenous and in other countries, notably that of seismologists in Japan, has advanced scientific knowledge on a global basis, and the search is continuing for fundamental information on crustal activity.

However, the majority of the geological and geophysical work in the region has been and will continue to be undertaken in the search for mineral resources; government agencies in the densely populated developing countries have little time or funds to devote to fundamental research on their own account. In collaboration with scientists from developed countries, however, much useful work has been undertaken, and the link between fundamental scientific research and exploration for mineral deposits is being increasingly recognized. The region has the world's largest production of tin; and copper and other base metal deposits are being developed. Many of these deposits are intimately associated with tectonic activity, past and present. Related basinal areas have contributed to growing petroleum production in the region, and an understanding of the nature of these basins is implicit in any study of tectonic processes in these areas. It was this relationship between tectonism and mineral deposits, together with the need to promote economic development based on exploitation of natural resources, that promoted the concept of a major research effort linking the tectonic structure and history of the region with metalliferous ore and hydrocarbon genesis; this was first outlined at the Bandung meeting in 1972 referred to in the Preface.

The eastern Asian region is considered on present theories to be an area where three gigantic lithospheric plates interact, offering a unique opportunity for regional geological and geophysical investigation of plate tectonics. Within a relatively small area of the globe, all the important processes of plate-boundary tectonics can be examined within a region characterized by relatively high sedimentation rates. It is also a region where there is a gap in presently-organized programmes of marine geological and geophysical investigations, but with the increasing exploration effort for mineral resources in many parts of the region, it is rapidly changing from one of the least explored to one of the more extensively investigated parts of the world. The IDOE Workshop has as its main focus the need to develop a strategy and programme for the effective and efficient use of scientific resources to this end.

The solution of certain problems is basic to any understanding of the geology and mineral distribution in eastern Asia, and these problems were summarized at the commencement of the Workshop as follows:

1. What is the relationship between the processes of mineralization and
   (a) zones of crustal subduction where both oceanic and continental elements are involved in the deformation;
   (b) areas of high heat flow such as inter-arc and back-arc (foreland) basins; and
   (c) small spreading centres within major plates?
2. How does southeast Asia fit into the pattern of continental drift? The literature contains a number of conflicting reconstructions of the spatial relations of individual crustal elements at various geological times: these are all serious hypotheses but they cannot all be true, and more data are urgently needed before such conflicts can be resolved.
3. How can the discontinuities of the zonal distribution of minerals be explained? There are numerous examples such as the lack of porphyry copper deposits in Japan, in spite of discoveries in the Philippines and the island arcs extending to the south, or the abrupt termination east of Belitung of the tin-tungsten belt which runs from Burma to the Indonesian tin islands.
4. Are tin-tungsten concentrations confined to a Cordilleran-type of orogeny within a continent, in which the continent is pushing forward and the oceanic plate is passive? What metals are characteristic of island arcs lying off a continent, in which the continental plate is passive and the oceanic plate advancing?

5. What proportion of sediments on a subducting plate is carried down to the subduction zone to be metamorphosed or consumed, and what proportion is scraped off and uplifted to be added to the outer arc islands such as those of the Indonesian archipelago (Mentawai Islands, Timor, etc.)? Geologically this is an important question, which also has significant economic implications for both metalliferous ore and/or hydrocarbon accumulation.
6. Why do some uplifted arc areas, such as the eastern arm of Sulawesi, contain ophiolites derived from the oceanic-type crust, with possible nickel, chromite and copper deposits, while other arc segments such as Timor and Seram are composed of sedimentary sequences with hydrocarbon shows?
7. Are hydrocarbons more likely to be found in back-arc (foreland) basins, formed inward of the volcanic/plutonic arcs, or are the marginal semi-enclosed trenches also prospective? In the latter, restricted circulation resulting in a low dissolved oxygen content and preservation of organic matter could improve the prospects of hydrocarbon generation.

At the tenth session of CCOP, which had been held in Bangkok just prior to the IDOE Workshop, lengthy discussions had taken place concerning CCOP's interest in geological research in the region. The session suggested a number of topics for consideration by the Workshop, of which the more important were:

1. Investigations of pre-Tertiary foreland basins that could be considered favourable for petroleum and natural gas accumulation.
2. Heat flow investigations in eastern Asian sedimentary and oceanic basins in relation to maturation and migration of petroleum.
3. Palaeomagnetic studies to unravel plate tectonic history and its relationship to metallogenesis and hydrocarbon formation.
4. Participation in the International Programme of Ocean Drilling (IPOD), to identify problems and suggest possible drilling sites in the region.
5. Study of the drift of Japan as a former part of the Eurasian Plate and the drifting of microplates in the South China Sea area.
6. Geophysical investigation of the postulated connection between the Ryukyu and Manila trenches.
7. Consideration of the Banda Arc geophysical research and training expedition.
8. Petrological study of recent and sub-recent volcanic activity in relation to the plate tectonic concept and the genesis of metalliferous ores and manganese nodules.
9. Quaternary geology and geomorphic development of southeast Asia and its relation to exploration for tin and other detrital heavy minerals.

Organization of the meeting

The Workshop was a scientific meeting, though not in the usual format of a series of papers to be read. While short accounts were presented by several participants demonstrating the most recent research and thinking in a number of specific subject areas, these presentations did not form the core of the meeting: rather it was a consultative gathering of scientists concerned with the progress of geological and geophysical research in the marine areas of eastern Asia, with the aim of formulating a strategy for its further development and co-ordination.

At the outset, the Workshop was presented with three basic objectives which were to act as guidelines for its deliberations:

1. A review of present knowledge on the tectonic development of east Asia and its relation to metallogenesis and hydrocarbon formation.
2. Identification of major unsolved problems and how these might be investigated.
3. Development of a strategy for future research, with a programme of investigation that can be taken up by CCOP member countries by themselves or as parts of international research projects.

The meeting first reviewed current work in the region and relevant theoretical work elsewhere, in five broad subject areas:

Tectonics
Geophysics
Sedimentary Processes
Metallogenesis and Petrogenesis
Heat Flow and Maturation of Hydrocarbons.

Presentations by various members of the Workshop under these headings set the scientific context for all participants, and, apart from introductory speeches, occupied the first two days of the meeting.

In discussion of these initial contributions, it became apparent that a number of problem areas and subject uncertainties existed, and the attention of participants began to focus on the research programme to be recommended. At this stage participants were requested to make preliminary project proposals on forms distributed for the purpose; over forty proposals were returned, and while there was a degree of overlap and duplication, they formed a useful basis for consideration of the overall research programme at later stages of the meeting. Many of these preliminary proposals were incorporated into the major transect projects presented in *Section V*, the remainder being listed as individual projects in the same section.

On the third day of the meeting the participants separated into five subject panels to consider programme proposals in each of the subject areas mentioned above. They were asked to prepare statements giving an assessment of the present state of knowledge for each subject concerning the eastern Asian region, to be followed by specific recommendations for study and how such studies might be implemented. Although there was some diversity of response, each panel prepared one or more documents in this context and some panels selected geographical lines or areas upon which studies should be focussed.

Inevitably there was some overlap in the subject areas, notably between the Geophysics and Tectonics panels, and to a lesser extent between those on Sedimentary Processes and Geophysics. Even though there was little opportunity for communication between panels, there was nevertheless a significant consensus of opinion concerning areas where studies should be concentrated. At the plenary meeting at the end of the third day, when the panel chairmen presented summaries of their recommendations, this concensus became more obvious and agreement was reached on the need to study several "transects" across orogenic zones, which would yield results applicable to many of the problems in the subject areas and establish a useful basis for planning further studies.

Much attention was then directed to producing project descriptions and justifications for the transect proposals. Of the approximately eight major proposals, six were selected for this treatment and the Workshop split up again into drafting groups; the results of their work are given in the first part of *Section V*. On the final day, these proposals were discussed in full session, and geological cross-sections were presented with the proposals, illustrating the key geological features of the transects, as presently understood. It was emphasized at this time that, although the transect proposals in their final form constituted recommendations for focussing multidisciplinary studies in geographical areas or zones, and consolidated a number of the preliminary project proposals, they only had equal priority with the other projects in the programme. Consequently all proposals are listed in one form or another in the section, recognizing that smaller-scale objectives may well be more readily attainable than the larger-scale transect studies. Nevertheless, the recommendation was that, where there was geographical flexibility in the choice of areas of geological or geophysical study, an effort should be made to orient such research along the track of one or more of the proposed transects, so that results from several studies could be co-ordinated to give a comprehensive multidisciplinary picture of a critical portion of the earth's crust.

II. SCIENTIFIC AND ECONOMIC IMPLICATIONS OF RESEARCH PROGRAMMES IN MARINE AREAS OF EASTERN ASIA

As stated in the Introduction, the initial concept of the IDOE Workshop was developed from the need to promote economic development of the region based on exploitation of its natural resources, particularly metalliferous ores and hydrocarbons. The major research effort was planned to link tectonic structure and history to the genesis of these resources, and this relationship was kept in focus throughout the Workshop session. This section considers this relationship in detail, not in respect of specific areas of the region but in terms of the various tectonic elements, their economic potential and scientific significance in local and global contexts.

The relationship between geoscientific research and the economic exploitation of the earth's mineral resources has existed since early prehistoric men sought pebbles of a suitable petrological composition to make their primitive pebble tools. Early geological survey departments were established with dominantly economic ends in view, and in developing countries this orientation is maintained for the very obvious need to develop mineral resources for the benefit of the respective national economies. Scientific research in the geological sciences may be undertaken either for purely scientific reasons, in a desire to further the understanding of the nature and constitution of the earth's crust, or for economic reasons, to increase the exploration or exploitation of mineral resources; but in most cases it happens that the results of either objective turn out to have significance in both fields, there being few purely scientific investigations which have not at some stage contributed to an economic outcome in the same or an analogous geological situation. It can also be said that any contribution to the sum of geological knowledge increases the potential of the science to serve economic ends, but most contributions are more definite than this.

In the field of oceanic geoscience, scientific understanding is hampered by the presence of up to 10,000 m or more of water above the objectives of study, and by the technological and financial resources needed to penetrate the water and the underlying crustal layers. The economic justification is high, however, as the ocean floors have potential mineral yields comparable with those of the land areas of the globe. Metallic mineral deposits are important, in both deep-sea nodule fields and shallow detrital accumulations, and also in deposits of non-metallic minerals such as sand and gravel, but potentially the most valuable are the hydrocarbons (oil and gas) known or predicted in thick sedimentary sequences beneath the oceans. In 1972, daily offshore oil production averaged nine million barrels (1.23 million tonnes) and 13.7 billion (13.7×10^9) cubic feet of gas (388 million cu m), with an annual value then of more than US$10,000 million. This production came from the continental shelves of 34 countries, including several in eastern Asia, while commercial activity in search of hydrocarbons was carried out off the coasts of 110 countries encompassing all continents except Antarctica (United Nations, 1973). The production represented only 18 percent of oil and 10 percent of gas production from all sources in 1972, but by 1980 offshore production is predicted to account for between 30 and 40 percent, a three-fold growth in actual amounts produced. While the great majority of this will continue to come from thick Tertiary sequences under the shallow waters of the continental shelves, there are distinct possibilities that economically-exploitable discoveries will be made in deeper water in the deposits of continental slopes and small ocean basins. Ultimate total recoverable sub-sea hydrocarbon resources may exceed those of continental areas (McKelvey and Wang, 1969).

In the early days of the petroleum industry it was possible to make discoveries by uncontrolled wildcat drilling—indeed, one major discovery resulted from drilling at the spot where the equipment truck broke down on its way to another area. But marine exploration for petroleum requires vastly more costly equipment and technology, and careful exploration and assessment of location is essential before exploratory drilling can take place. This places an increased value on almost any item of geological information from relevant oceanic areas, particularly on the understanding of the geological history and tectonic development of those areas. Such an understanding is valuable also for aiding the exploration of offshore metallic minerals, which are beginning to make important contributions to the economies of several countries in eastern Asia, though greater benefits may result from the much larger mineral deposits of the island arcs and related continental margin areas; and this applies to the deposits of former arcs now incorporated into the continents themselves. An understanding of the tectonic, thermal and geochemical evolution of island arcs is needed for the comprehensive development of their mineral resources.

The eastern Asian region, with three prominent plate boundaries converging in an area of unique complexity, is an excellent setting for intensive research on the nature of continental-oceanic and oceanic-oceanic plate interactions and the associated geological processes that control the genesis of ores and hydrocarbons. Results of intensive research should lead either to new geological principles or the better understanding of existing ones, which may aid discovery of new metallogenic or hydrocarbon provinces not only in this region but elsewhere, both in the oceans and on land. Light would also be thrown on the processes of oceanic rifting and their associated mineral accumulations. From a scientific point of view, an understanding of island arc processes and characteristics is of considerable importance in the interpretation of older geological sequences in eastern Asia and other parts of the world, and the reconstruction of the past history and movement of the continental plates.

This section of the report deals with the implications of research in marine areas and, in particular, on the plate boundary systems of the region. A brief description of the various tectonic elements recognized in these systems is given first, as an introduction to an assessment of their economic significance, and to the use of the terms in the succeeding section on the tectonic framework of eastern Asia.

TECTONIC ELEMENTS OF PLATE BOUNDARY SYSTEMS

Physiographic expression of active tectonic elements is nowhere more clearly seen than in island arc systems, where topographic features are readily identifiable as resulting from the interaction of two converging plates, and the effects of this convergence. While the size of the topographic features relative to one another can vary considerably, and some of them may be absent, their distribution and constitution are generally correlated with tectonic elements without difficulty; but the explanation of these elements in terms of process has led to a number of theories, not all of which invoke the interaction of crustal plates. In the following description and discussion, however, it is accepted that interactions between lithospheric plates give rise to the features, in accord with general plate tectonic theory.

The theory of plate tectonics regards the crust and upper mantle of the earth as consisting of a number of lithospheric *plates*, consisting of oceanic or oceanic plus continental crust (sima and sial) together with the adjacent upper mantle, which tend to move as rigid units with most of the resulting deformation arising from interactions with other plates along their margins. New oceanic crust is in process of formation by the upwelling of basaltic material at constructive margins, while older crust is being consumed at convergent margins.

The constructive margins are referred to as *spreading axes* and commonly give rise to a "mid-oceanic" ridge (which may be located at points other than mid-ocean) where new oceanic crust is added to plates on each side of the axis, resulting in divergent movement of the two plates at velocities of up to 20 cm/yr. The convergent margins are represented by *subduction zones* where one plate descends beneath an adjacent plate in response to the relative motion, which may be perpendicular or oblique. In a few cases neutral margins involve lateral slip along the boundary to accommodate the motion, though these may revert to convergent or become dilational if one or both plates change their direction of motion.

There are several lines of evidence which indicate plate motions at the present day or in the geological past, including magnetic lineations on the ocean floor, ages and orientation of oceanic island and seamount chains, and the ages of the lowest sedimentary formations encountered in deep-sea drill holes. Magnetic lineations are the result of basaltic magma emplaced at spreading axes crystallizing and becoming magnetized according to the prevailing earth's magnetic field. Reversals of this field produce marked changes of the remanent magnetization of successive parallel zones, thus recording the earth's magnetic history; these magnetic changes can be correlated on a world-wide basis and, linked to the geological time scale, may serve to date segments of the ocean floor.

The *ocean basins* generally lie more than 4,000 m below sea level, the greater density of the basaltic crust causing them to rest at lower levels than the lighter continental crust. The oceanic crust consists of basalt formed at spreading axes, underlain by sheeted dyke complexes which pass down into gabbros and into the peridotites of the upper mantle. Evidence for this layered sequence is based partly on the study of ophiolite complexes in nappes or thrust slices, interpreted as oceanic crust brought to the surface. Pelagic sediments overlie the basaltic crust, thin near spreading axes but thickening to 1,000 m or more in older parts of the ocean basin; in areas near mouths of large rivers, thick flysch-type deposits can also form.

At convergent margins, oceanic lithosphere is carried downwards along a *subduction zone*, which refers to the zone of entry; its downward continuation is marked by the *Benioff zone*, a zone of earthquake foci which descends at an angle mostly between 30° and 70° into the mantle, in some cases as deep as 700 km. First-motion studies indicate slip directions may be perpendicular or oblique, with significant transcurrent movements not uncommon. The angle of descent, rate of movement and obliquity of convergence of the plates are variables which may account for many of the observed differences in the tectonic and petrological characteristics of the arc systems in the region. An *arc system* develops at a convergent margin in response to the subduction process, basically consisting of a chain of volcanic islands or mountains and a parallel deep oceanic trench on the convex outer side of the arc *(Fig. 2)*.

The *oceanic trench* is a deep-water arcuate feature which may be as much as 5,000 m deeper than the adjacent ocean basin floor; slopes on the arc-ward side of the trench (the frontal slope of the arc system) may average 10° or more. The subduction zone is approximately coincident with the trench, the actual plate junction being obscured in many cases by folded and faulted marine sediments, and by slump features on the frontal slope *(Fig. 27)*. The sedimentary cover of the down-going oceanic plate is also involved: this is one of the least understood elements of arc systems and one which holds an important key to the understanding of the dynamics of the system. The de-

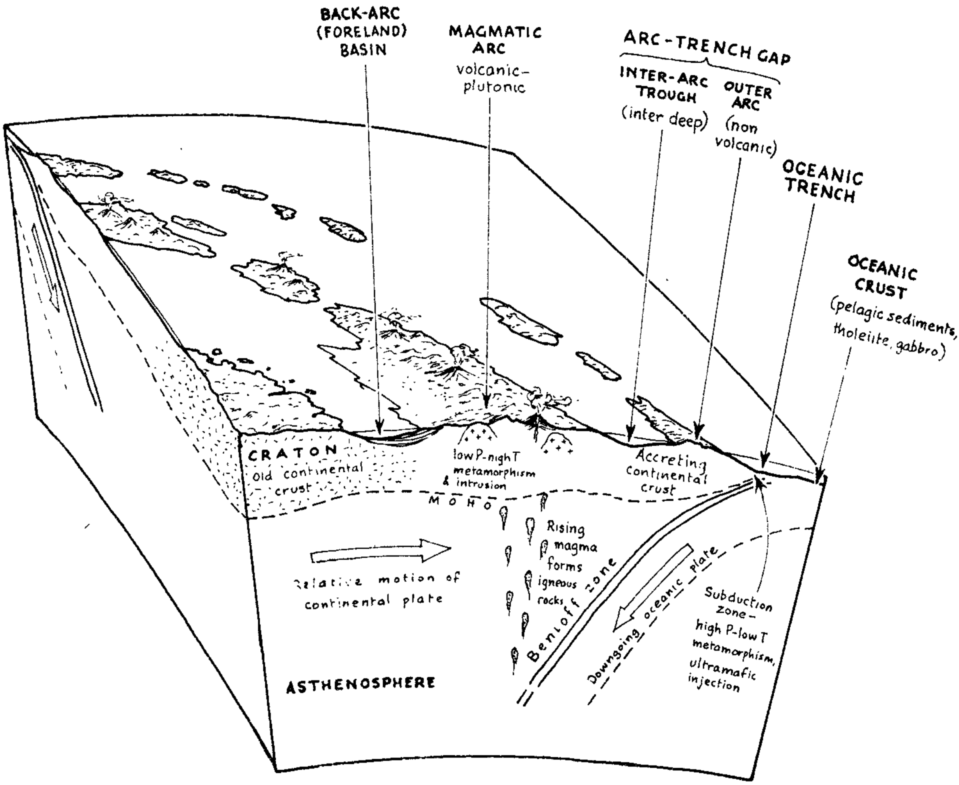


Figure 2. Tectonic elements of an active island arc system, western Indonesian type (after Katili, 1973).

pression of the oceanic crust to form the trench is apparently due to the downwarping of the plate as it descends into the mantle. In entirely oceanic areas trenches may reach depths in excess of 10,000 m, but elsewhere, closer to continents, a partial sedimentary fill is common.

The *outer non-volcanic arc* (or outer arc ridge; sometimes called the sedimentary arc, though ophiolites may be included) occurs in many arc systems as a line of islands or ridge bordering the oceanic trench. Structurally, it is believed to consist of a wedge of landward-dipping imbricate thrust slices of flysch or pelagic sediments, the dip of successive slices increasing away from the trench; ophiolite bodies may be included in the base of some thrust slices. The arc appears to consist of sedimentary material deposited in the trench and adjacent ocean basin, and this, together with portions of the underlying igneous crust, has been scraped off the downgoing plate by the overriding one at the subduction zone. What proportion of this sedimentary material is scraped off and accreted to the face of the overriding plate, and how much is carried down into the mantle on the descending plate, is unknown, and it is also not known what contribution the subducted material may have upon magmatic mobilization at depth. A large outer-arc feature indicates that a thick sedimentary layer has been scraped off the subducted portion of the downgoing plate, and/or that subduction has been long-continued or rapid; the style of tectonic deformation found in the islands of the outer arc is consistent with continued underthrusting. A marked negative gravity anomaly commonly coincides with the outer arc or adjacent part of the trench, presumably resulting from the downward displacement of the underthrusting plate, indicating the absence of isostatic equilibrium.

The *inner volcanic arc* (volcanic-plutonic or magmatic arc) consists of a chain of active volcanic centres in a surface zone located approximately where the Benioff zone is between 150 and 200 km deep. Calc-alkaline andesitic, dacitic, basaltic and rhyolitic lavas and pyroclastic rocks form either a chain of islands on a foundation of oceanic crust, or larger sub-continental units where earlier continental or island arc rocks are included. Plutonic rocks of related composition have probably been emplaced or are in process of emplacement beneath the volcanic superstructure, and in older arcs these are seen to be dioritic to granitic in composition, the latter where pre-existing continental crust or former arc systems are present and may have been remobilized. The host rocks of the magma may include deformed flysch and ophiolites of earlier outer arcs, oceanic crust and sediments, shelf carbonate successions, or rocks of earlier magmatic arcs. Metamorphic host rocks may be high pressure-low temperature or low pressure-high temperature, the two facies being interpreted as representing the deeper-seated remnants of an outer arc and magmatic arc respectively, and their relative positions can be used to determine the polarity (facing direction) of older arc systems.

A particular feature of island arc systems is the occurrence of *chaotic assemblages*, many of which appear to be due to the tectonic mixing of diverse petrological units in the outer arc. These are typically represented by sheared argillites containing scattered blocks of deformed flysch, ophiolites, blue schists and other high-pressure metamorphic rocks, to which the name *mélange* is applied (though this term is sometimes used more widely to include rock units with other styles of tectonic mixing): these are thought to be formed only in the vicinity of subduction zones, as a result of intense scraping action of one plate over another, and are more commonly found in older arc systems where erosion has removed the overlying imbricate zone. Slide and slump masses on the trench slope of the arc can form gravity slide deposits (olistostromes) which may be difficult to distinguish from mélanges when tectonized.

Between the outer and inner arcs lies the *inter-arc trough* where the sea may be moderately deep but underlain by gently tilted or folded sedimentary sequences, commonly between 3,000 m and 7,000 m thick where the outer-arc ridge is sufficiently prominent to act as a sediment dam, and exceptionally much thicker in some areas. The relationships of these deposits to the deformed flysch of the outer arc and to the volcanic rocks of the inner arc are poorly known, but the evidence suggests that there is little or no relative movement between the two major arc elements in many cases, though in some localities inter-arc trough successions appear to be thrust over outer-arc formations.

Back-arc or *foreland basins* may lie on the concave sides of volcanic arcs where these are developed on continental crust. These are commonly elongate, parallel to the arc, and contain sedimentary deposits up to 7,000 m thick, though this may vary considerably along strikes due to basement ridges or highs. Graben-type faulting may be present, particularly along the continental side of the basin, and growth faults have been noted on the volcanic arc side in some cases. The formation of the basins is poorly understood but is presumably related to subduction or to lateral slip movements along major fault trends.

Continental areas have a radically different geological constitution to oceanic, with lighter and much more complex crustal elements. The foundation of such areas appears to consist of relatively rigid crystalline blocks, *cratons*, most parts of which may be explained in terms of geosynclinal subsidence, orogenesis and consequent metamorphism and plutonic intrusion; in older cratonic areas the supracrustal portions of the orogenic belts have long since been removed by erosion leaving only the deeper crystalline zones to form stable land or shallow sea areas for significant lengths of geological time. Where exposed to surface, the older cratonic blocks (mostly of Precambrian age) are commonly referred to as *shields*, which are particularly rigid and stable. The geosynclinal-orogenesis explanation for the formation of cratonic areas can in most cases be reconciled with their origin as successive island arc systems resulting from plate interactions, welded on to one another along sutures or collision zones. Understanding of Precambrian arc systems, and the deeper seated activity in more recent systems, is far from precise; but as study of progressively older arc systems and orogenic belts reveals no marked change of process during geological history, it may be presumed that similar processes operated in the distant past as have done during the Cenozoic.

Cratons in eastern Asia vary greatly in size, and consist mainly of Palaeozoic and Mesozoic metamorphic and igneous rocks derived from successive arc systems, together with supracrustal sedimentary sequences of continental or marine origin. Cenozoic arc systems fringing the cratons in places are not generally considered part of the cratons themselves, though clearly they are continuing the process of craton enlargement by addition of their subcrustal crystalline elements. It appears, however, that two or more subduction cycles may be needed to convert the island arc materials to granitic continental crust as commonly understood.

Margins of cratonic areas are generally of two types, coupled or uncoupled (also known as passive or active, or Atlantic or Pacific type), depending on whether there is relative movement between the cratonic block and the adjacent oceanic crust. A *coupled margin* shows no relative movement, with the continental margins characterized by slow subsidence and sedimentation forming broad and well-defined continental shelves, slopes and rises, as along the shores of the North and South Atlantic Oceans. These margins originate by rifting during the commencement of ocean basin spreading, and are passive, lacking significant seismic or volcanic activity; such activity is mainly confined to spreading axes remote from the continental margin.

In contrast, *uncoupled margins* occur where oceanic lithosphere is underthrusting or being overridden by a continent, as around most of the Pacific Ocean. They are marked by complex and irregular orogenic zones, often of several geological ages, by arc-system features of violent volcanic and seismic activity, and by associated magmatic intrusion and mountain-building movements.

Many arc systems on uncoupled margins have become partly detached from a main cratonic mass, often carrying portions of the craton away with them. The separation has been accompanied by the formation of *marginal basins*, which are so called because of their locations on the margins of major plates and continents; larger representatives are often referred to as *small ocean basins*. They are partly or completely underlain by oceanic crust, with depths commonly more than 3,000 m, and longitudinal rift-fault features are evident in some of them; others have trench features, active or inactive, along one or more sides. In most cases they have formed behind arc systems, but may also be found within the systems themselves forming deeps parallel to the arc trend. Their origins are probably diverse: some are interpreted as resulting from spreading analogous to that at mid-ocean ridges, by rifting along several minor basalt-upwelling axes, or by the oceanization process where continental crust becomes progressively more basaltic by dyke intrusion accompanying rifting; others may represent segments of former ocean basins trapped or cut off from the main basin by the development of island arc systems, active or inactive. The age of some basins may, as with ocean basins themselves, be estimated by magnetic lineations and depth and age of the sediment cover.

Consumption of oceanic crust by subduction will eventually result in any arc or cratonic elements on the subducting plate being drawn into collision with the developing arc system on the overriding plate, forming a *collision zone* or *belt.* The sialic elements of the subducting plate do not descend into the mantle as the denser oceanic crust does, but are welded on to the other plate, the junction being called a *suture* when seen in older cratonic units. Cenozoic and present day collision zones involving an underthrusting cratonic plate are characterized by major thrusts displacing shallow water deposits and continental crust, and a *frontal trough* or *basin* may develop in the position analogous to the oceanic trench. These may accumulate thick alluvial or marine sediments, due to the downbuckling of the underriding plate and erosion of the uplifted overriding one.

Transcurrent faults (strike slip or wrench faults), with lateral displacements of up to 1,000 km, are significant features that occur in a variety of tectonic contexts. They may form plate boundaries where differential plate movement is neither divergent nor convergent, but more commonly occur as major displacements within plates, affecting continental or oceanic crust, occasionally both. In island arc systems they may develop parallel to the arc as a consequence of oblique plate convergence, and may be associated with either outer or inner arc features, or form boundary faults of back-arc basins; in cratonic areas they may represent reactivation of older structural lines of weakness.

MINERAL AND HYDROCARBON POTENTIALS OF THE TECTONIC ELEMENTS

The tectonic elements discussed in the previous sub-section occur in various forms in eastern Asia, but fundamental tectonic relationships between them permit their identification with respect to a hypothetical physiographic-tectonic model. Petrological and sedimentological identities also indicate interrelationships within arc systems, and on these may be based generalized estimates of the economic potential of mineral and hydrocarbon resources associated with each tectonic element, and which may be expected to be valid for many similar elements irrespective of location. It may be noted that the associations of economic minerals with such elements can be stated as objective fact, and do not rely upon any particular plate tectonic interpretation for their validity; nevertheless, a greater understanding of plate tectonic relationships will surely aid exploration for these minerals *(Fig. 3)*.

The *ocean basins* present relatively little economic potential when the difficulties of water depth and distance from land are taken into account. Nevertheless, metallic minerals are known to be accessible in the form of fields of ocean-floor nodules, rich in manganese, cobalt, nickel, copper and

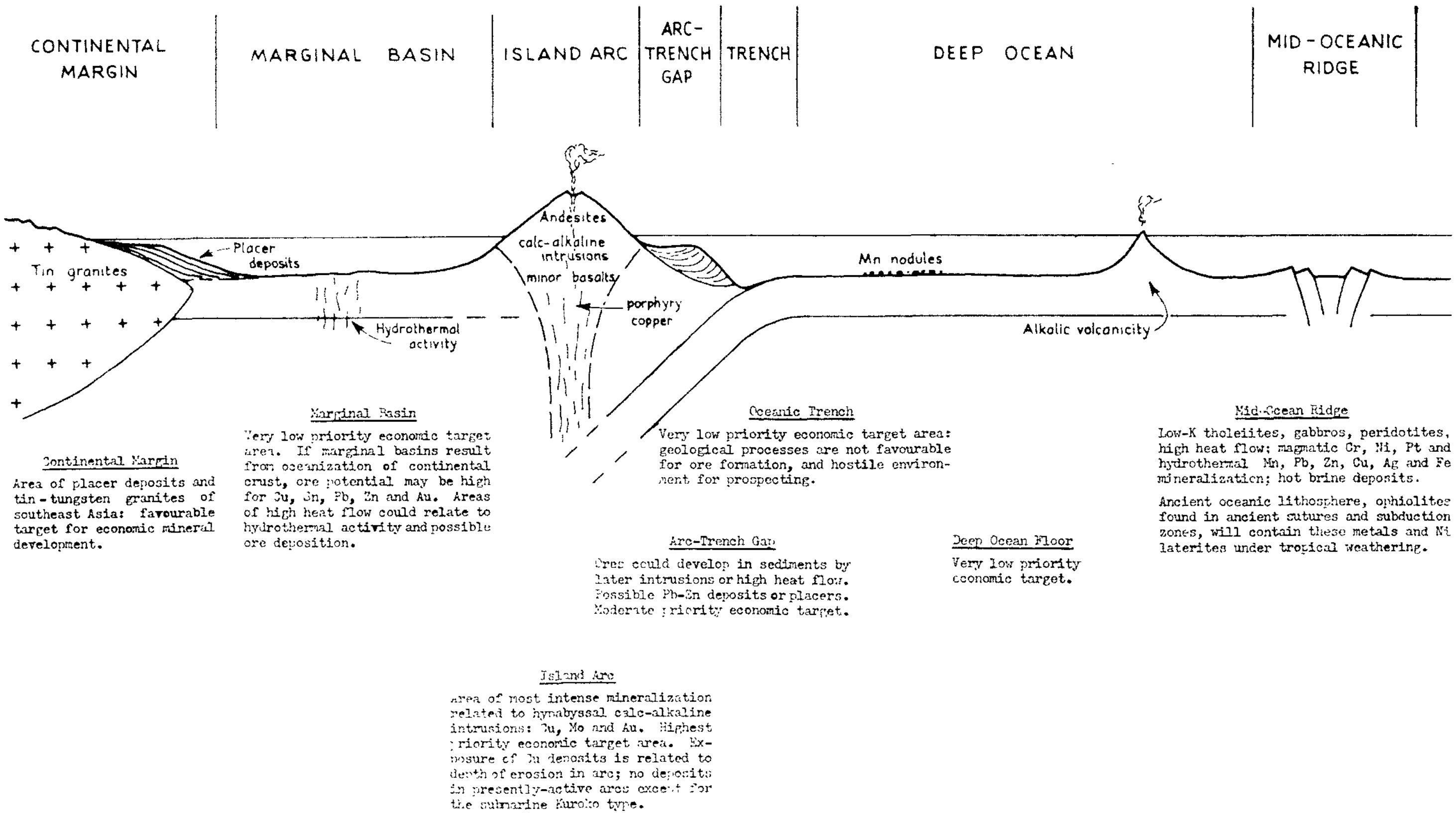


Figure 3. Economic significance of the various plate tectonic elements in the marine domain.

other metals; these are currently being mined on an experimental basis, but not enough is yet known concerning the distribution, abundance and areal variation in the metallic content of these deposits. Other possible deposits of metallic minerals include stratiform copper-lead-zinc sulphide deposits similar to those mined in Cyprus, and metalliferous brine pools analogous to the Red Sea and Salton Sea occurrences.

The hydrocarbon potential of the ocean basins is limited to areas of non-pelagic sedimentation, where thick terrigenous deposits have formed either on the basin margins adjacent to delta fans, or in the continental rises and slopes fringing land and shelf areas. While there are considerable difficulties in exploration and production from deep and open waters, it has been estimated that exploitation of hydrocarbons from these zones will not only be feasible but that a potential ultimate recovery of over 24 per cent of total world hydrocarbon resources may eventually be obtained from these areas (United Nations, 1973).

The *oceanic trenches*, where adjacent to large land areas and receiving significant sediment inflows, can also be regarded as potential hydrocarbon provinces despite the excessive depths of water involved. However, trench deposits are subject to deformation on the arc-ward side which could reduce the likelihood of suitable structures for reservoirs occurring, and study of such deformation is needed to evaluate their potential.

The *outer non-volcanic arcs* have received little investigation as hydrocarbon reservoirs because of the apparent high degree of deformation of the tectonically-emplaced sediment wedges; nevertheless, production has been obtained within this zone and oil seeps testify to the presence, in places, of the right sort of source beds. Study of the dynamics of outer arc formation coupled with information regarding the sedimentology of the deposits which form them should give useful guidelines for the prediction of suitable areas for exploration.

The metallic mineral potential of this tectonic element is mainly restricted to the ophiolites, which are considered to represent ocean-floor igneous rocks, and associated pelagic sedimentary strata. Ore bodies in these rocks may include chromite, stratiform copper-lead-zinc ores, minor platinum deposits and nickel-bearing laterites. Determination of field relations between the ophiolites and the surrounding sedimentary rocks, and their age, could be of value in predicting which ophiolite belts are most favourable for mineralization.

The *inter-arc trough* may contain great thicknesses of undeformed or only moderately deformed strata, with considerable potential for hydrocarbon accumulation in relatively shallow waters; gas has already been discovered in the trough west of Sumatra. In areas where arc activity has involved greater amounts of uplift during its development, the inter-arc trough may have been non-marine at times resulting in the formation of coal deposits of useful economic value. Sedimentological and structural study of this zone, where accessible on land and also underwater, may lead to the development of evolutionary models from which predictions of favourable areas for hydrocarbons and coal may be derived.

Inter-arc troughs show little promise of significant metallic ore deposits, although the possibility of gold placers cannot be ruled out: in ancient deformed flysch terrain, which can be interpreted as former outer arcs, gold-bearing quartz veins are found: erosion of these belts and deposition of the products in inter-arc trough continental environments could lead to concentration of the gold in economic placer deposits.

Volcanic (magmatic) arcs, in contrast, are prime targets for metallic mineral exploration, as a direct result of the magmatic activity which produced such features. Porphyry copper deposits, which account for more than half the world's present copper production, have been shown to be emplaced exclusively in magmatic arcs. Volcanogenic stratiform copper deposits, of which the Kuroko deposits of Japan are an example, also occur in magmatic arcs, and other types of mineral deposit characteristic of this zone include gold and molybdenum associated with the porphyry copper, gold in andesites and monzonites, and mercury in young volcanoes. The more acidic volcanic and plutonic rocks of magmatic arcs, which have been emplaced in pre-existing continental crust involved in the arc systems, contain most of the world's tin and tungsten deposits with associated molybdenum and bismuth, with fluorite an important associate *(Fig. 4).*

Many of the mineral deposits of magmatic arcs are formed at depth and cannot be seen in young volcanic arcs; older inactive arcs which have undergone erosional uncovering reveal the mineralization characteristic of these greater depths. Consequently it is necessary to study the relationship of mineralization to tectonic setting in arc systems of various ages, as well as of various crustal contexts (whether involving pre-existing continental crust) to arrive at a meaningful understanding of the processes involved. Why some magmatic arcs are highly mineralized while others are mainly barren, and why mineralization is concentrated in specific zones within the arcs, are questions which might be answered by this approach. These in turn should lead to predictions of other areas favourable for mineralization, and also of adjacent sedimentary or marine areas where detrital accumulations of minerals derived from the mineralized belts, which may be now largely eroded, might be found.

Back-arc or *foreland basins* have considerable potential for hydrocarbon and coal deposits, due to their slow subsidence during formation. In most

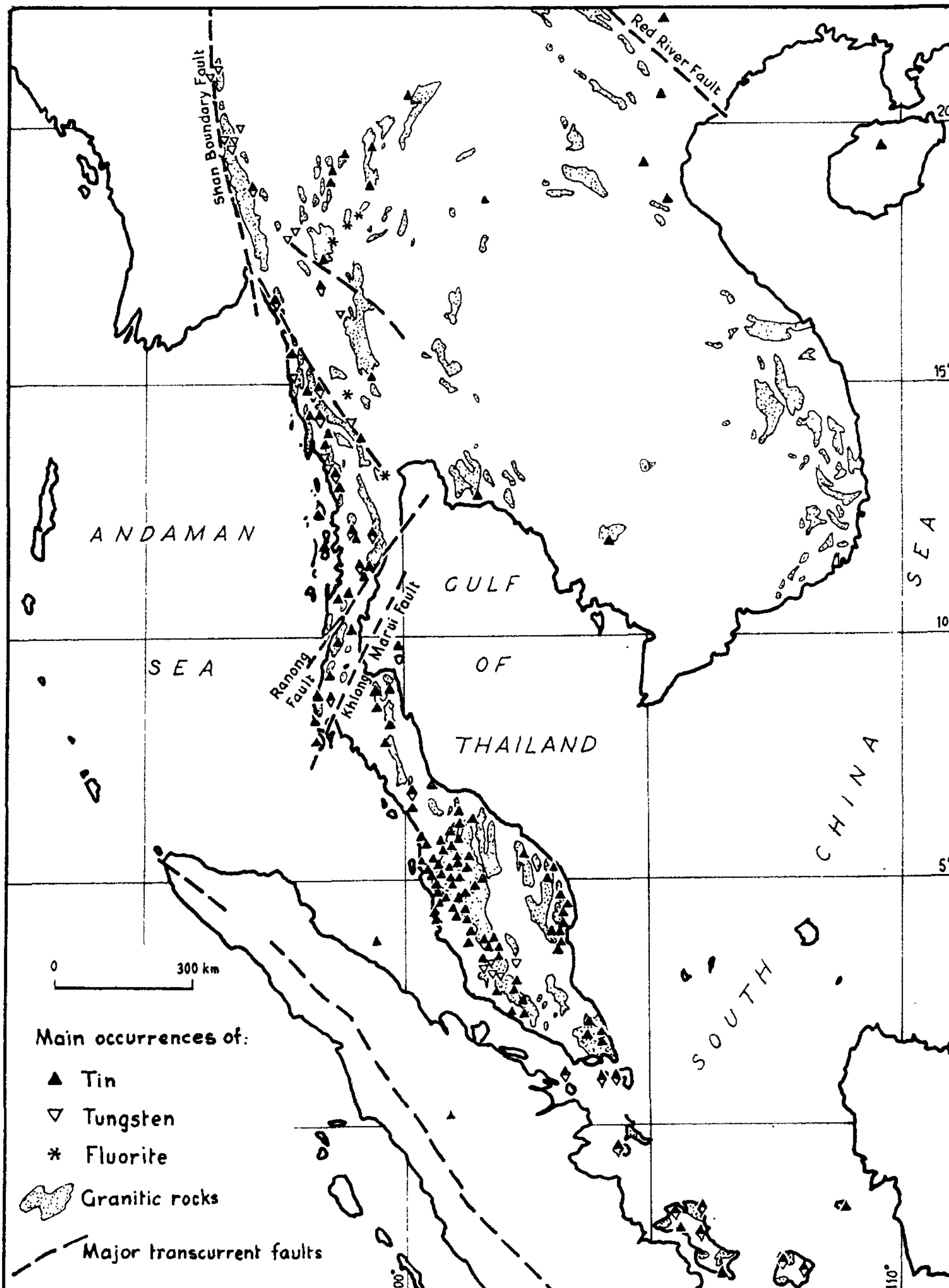


Figure 4. Distribution of tin, tungsten and fluorite mineralization in relation to granitic rocks in southeast Asia (from Mitchell and Garson, 1972).

cases they have formed adjacent to cratonic areas, and the possibilities of detrital mineral deposits such as tin within the stratigraphic succession should not be overlooked.

Marginal basins, most of which resemble ocean basins physiographically, have much of the same type of potential as regards hydrocarbons; though being more closely associated with continental areas the likelihood of thick sedimentary accumulations is greater, particularly in the older basins. There is a significant lack of information about these basins, however; for example, are there active spreading ridges that could give rise to metalliferous brine pools, and do ophiolites from the marginal basin crust, when emplaced on land, have a similar potential for copper and chromite mineralization as do those from ocean-basin crust?

Determination of the mode of formation, whether by spreading, rifting, oceanization or simply by being cut-off portions of oceanic crust, is important, to ascertain whether any mineralization concepts developed in one basin can be applied to others in the region or elsewhere in the world.

Cratonic areas have a vast and varied range of economic mineral potentials, and it is beyond the scope of this report to deal with them comprehensively. Several parts of cratons do, however, have special significance to the study of oceanic and arc system areas, and those parts of the craton covered by shallow water may include deep sedimentary basins of high economic significance in their own right.

The cratonic sedimentary basins appear to be formed by continuous or intermittent subsidence between resistant basement ridges which may represent old arc systems. The pattern of sedimentation in the basins is partly dependent on the balance of sediment supply versus subsidence, and consequently the sedimentary characteristics may be expected to vary where this balance is altered close to the basement ridges. The possibility of coal deposits having formed in such areas should be recognized, and of major evaporite sequences in more central parts of the basins. Investigation of the mode of formation and geological history of these cratonic basins, both on land and offshore, could have results of considerable significance, especially in conjunction with petroleum exploration where very large economic benefits are possible.

Frontal troughs also form on cratons where one craton is underthrusting another at a plate boundary. Commonly, thick sedimentary accumulations, shallow marine or alluvial, form in these troughs, accompanied by subsidence, tilting, folding and thrusting close to the overriding plate. The collision may also cause a significant increase in elevation of the overriding plate over a large area, which would have a considerable influence on sedimentation in areas remote from the plate boundary. Collision of a continent with an island arc may produce a dominantly marine frontal basin, but both this and the mainly continental type offer favourable areas for hydrocarbon and coal formation.

Transcurrent faults may give rise to sedimentary basins along their track, though these are more commonly formed by associated graben or normal faulting in cratonic areas. Economic potential of these basins includes coal, lignite and, in a few cases, small oil fields; metallic minerals do occur in association with faulting, but the genetic relationship is uncertain. Along major fault structures there is the possibility of emplacement of ultrabasic intrusions, with potential layered chromite and nickel sulphide deposits; it is also possible that carbonatite magmas and their associated minerals could be emplaced along these faults, in both continental and arc-system crustal areas. Detailed work along major fault zones is necessary to determine the tectonic and igneous events that accompanied their movement in the more recent geological past, to see whether mineralization can be related to these events.

SCIENTIFIC IMPLICATIONS OF STUDY OF ARC SYSTEMS AND ASSOCIATED TECTONIC FEATURES

The scientific study of any portion of the earth's crust can in virtually all cases be of value in the interpretation of other areas with similar features. When the portion of crust shows as many distinctive features as do the island arc systems of eastern Asia, it can be said that here is a type-area for such systems, and study of them may be expected to yield results of great significance not only to other similar areas in the world but relevant to an understanding of the global processes of crustal evolution. In particular, study of the presently-active arc systems should throw additional light on the constitution of older arc systems in the area (the converse is also true) and in most other parts of the world.

With the possible exception of the very old shield areas, most of the cratonic crust of the region consists of orogenic belts (orogens) of late Precambrian to Mesozoic age. It is widely considered that these and similar orogens elsewhere involved in ways analogous to the development going on in Cenozoic active arc systems and collision belts *(Fig. 5)*. Interpretation of the inactive systems and belts in terms of processes learnt from the study of the Cenozoic could greatly aid prediction and discovery of zones of mineralization, which in themselves provide information on thermal and magmatic processes operating at greater depths. Seismological and heat-flow studies in these areas would define more precisely the type and extent of seismic and thermal activity in relation to these processes and to the development of present and former arc systems in general; the implication is clear that, for most beneficial scientific results, co-ordinated research embracing several disciplines is strongly to be recommended.

On a global scale, orogenic belts exposed at various levels of erosion make up much of the world's land area, either at the surface or beneath a sedimentary cover; and they are known also to extend under the continental shelves. In many of the major orogenic belts, such as the Alpine region of Europe, continental collision following subduction of oceanic crust has greatly modified the structure of the original arc systems. In older orogens, such as the early Palaeozoic fold belts of North America and northern Europe, collision and deep levels of erosion have erased the original topographic expression of the tectonic elements, so that interpretation in terms of active arc systems and collision belt processes requires detailed geological investigation and careful comparison with more recent systems.

Detailed investigation of active arc systems in eastern Asia should provide models of processes at the higher crustal levels which can be extrapolated downwards. Comparison of these with Mesozoic and older arc systems in the region should show whether such extrapolations are valid, bearing in mind that despite obvious similarities, every segment of each arc has its own individual characteristics. Comparison with Cenozoic collision structures such as in the Alps or the Himalayas should be attempted, and then with the more deeply eroded orogens elsewhere; this should yield a series of models basically applicable to all orogenic belts. This is an ambitious objective, but one which may well be attainable within a relatively short span of years.

The recommendation for a multidisciplinary approach to these problems perhaps does not need emphasis, but it should be noted that, in addition to seismological, geothermal, structural-tectonic, petrological and mineralogical studies which have obvious relevance to active arc systems, stratigraphic, sedimentological and palaeoecological studies have much to contribute to the understanding of the earlier development of the elevated portions of the arc systems. For instance, in active arcs the study of present-day sedimentation in the inter-arc trough and oceanic trench can provide sedimentological models for the interpretation of the outer-arc ridge forming contemporaneously in the same area, but this involves land work both on the outer arc islands and shipboard work in sampling and coring the marine sediments, together with seismic profiling to establish the depth and structure of the sediments sampled. This requires a multidisciplinary team in which it would be logical to include specialists in several other fields in order to maximize the use of ship time. This presupposes a plan for co-ordination of these activities among participating scientists; and, accordingly, in subsequent sections of this report recommendations are presented for multidisciplinary programmes which provide a context for such operations.

While many of the research workers will come from developed countries, it was a recommendation of the Workshop that the interest and participation of local scientists should be encouraged as much as possible at all stages in these operations, both for scientific benefits (to the countries and to the visiting scientists who get the benefit of local knowledge and contacts) and for the increased experience of sophisticated techniques accruing to the local scientists. Training as such should also be regarded as a vital component of the operations, bearing in mind that the local scientist who has gained experience and training from such operations will remain in the region and will be able to further the research beyond the stage attainable by a ship-borne expedition on a necessarily limited time schedule.

III. THE TECTONIC FRAMEWORK OF EASTERN ASIA: A REVIEW OF PRESENT UNDERSTANDING

To understand the tectonic framework, history and present activity of the eastern Asian region, it is convenient to discuss the various features in terms of lithospheric plates and their interactions. While it may be admitted that the plate tectonic theory does not answer all problems (at least, how these problems presently appear with the limited knowledge available from many parts of the region), it is widely considered that any explanations not involving plate tectonics are in most cases less satisfactory than those that do. The progress of geological thought may alter this, or may show the plate tectonic theory to be an oversimplification of a more complex situation; but whatever the outcome, research work in eastern Asia should be instrumental in advancing knowledge of the earth's crust and its processes.

In plate tectonic terms, eastern Asia lies at the junction of three of the earth's major lithospheric elements: the Eurasian, Indo-Australian (or East Indian Ocean) and the West Pacific Plates. The plate tectonic concept suggests that the overall tectonics of eastern Asia are mainly determined by the motions and resulting interactions of these three plates; but similarly it must also be recognized that within the region there appear to be a number of smaller crustal blocks behaving like plates, some only a few tens of kilometres wide, whose motions bear only slight relationship to those of the larger plates. Knowledge of these smaller blocks is limited: some are only just being defined as to extent and activity, while others are hard to define since they appear to have lost their independence of motion and are being replaced by new configurations.

Information on which the interpretation of plate configurations and activity can be based is of uneven density in eastern Asia, and frequently capable of more than one interpretation. It has to be borne in mind that all data have been and are being obtained in, geologically, a single instant of time, and interpretations of dynamic processes inevitably depend upon extrapolation of data from oceanic trenches, Benioff zones, volcanic arcs, gravity-slide belts, fold belts seen at the surface, sedimentary basin histories and radiometric ages—and that even the last-named are not infallible records of the past. The field geologist may be swamped by a mass of seemingly contradictory facts, each fact definite but often with a gap between it and the next one that can be filled by several interpretations; the mining geologist has saturation knowledge of a local area but may distrust the sweeping regional syntheses built on scattered information. On the other hand, an earthquake seismologist has to define activity at a presumed plate boundary on the basis of only two or three first-motion determinations, and the heat flow specialist has perhaps only four thousand reliable data points over the whole of the earth's surface. However, being an expert in all aspects of crustal study is a position very few can even approach, and how each earth scientist comes to view a section of the crust depends very much upon his training, interests, and, very often, how he earns his living; so the following assessment of the tectonic framework of eastern Asia does not try to be comprehensive and authoritative at all levels and in all fields, but seeks merely to point out the major features and known interactions as an introduction to the region and its problems. Consequently, it deals more with what is presently understood about the region's tectonic constitution than with theories concerning its development: the latter are in constant flux—several changes having occurred in the period between the Workshop and publication of this report—but the known and inferred factual data presented here will, it is hoped, remain relevant for much longer.

The major plates and plate boundaries

The late Cenozoic crustal structure of the eastern Asian region is dominated by three major lithospheric plates and their interaction zones. The Eurasian Plate, consisting mainly of continental crust, adjoins the part-continental, part-oceanic Indo-Australian Plate along the Himalayan front and the Sunda arc. The oceanic West Pacific Plate meets the Eurasian Plate offshore from the Japanese islands from near Tokyo northwards, and along the Kurile arc and eastern Siberia. To the south and west, however, the two major plates are separated by a smaller oceanic crustal unit, the Philippine Sea Plate, bounded by the Marianas and Ryukyu arcs and the Philippine archipelago. All four plates converge to a complex plate junction in the Moluccas archipelago, eastern Indonesia, from where the West Pacific-Indo-Australian plate boundary leads away through the Solomon Islands and New Hebrides to the Tonga and Kermadec trenches.

The plate boundaries of the region show a variety of characteristics, which in part are due to the nature of the abutting plates: examples of continental-continental, oceanic-continental and oceanic-oceanic boundaries are all present. Some variation must also arise from the speed and angle of collision; particular differences may arise where there is a major lateral component of differential movement operative, such as near the Andaman Islands and on the north side of the island of New Guinea. However, the features by which plate subduction is recognized are developed along most of the boundaries. The Benioff zones, where earthquake foci define a zone of slippage dipping at angles between 15° and near vertical to depths as great as 700 km, give the best indication of subsurface behaviour of the subducting plates. At the surface, arc systems consisting of deep elongate oceanic trenches and volcanic island arcs are developed on the majority of plate boundaries, accompanied in many cases by subsidiary outer non-volcanic island arcs or submerged ridges; in the Banda and Andaman arcs, the outer-arc features are more prominent than the associated volcanic arcs. Characteristic assemblages of features are well-developed in the region, either in an oceanic context or associated with older sialic crustal blocks, and provide examples of arc systems that may be used for world-wide comparison, as indeed they have been used for several decades during the development of the understanding of crustal tectonic processes.

Mineralization is associated with the volcanic activity and sub-volcanic plutonism at deeper levels, such as the porphyry copper deposits of the Philippines. Uplifted igneous rocks formed within previous arc systems show mineralization characteristic of the level to which they have been reduced by erosion, as well as their level of emplacement and their regional associations, such as the tin-tungsten belt of granites in the Malay Peninsula; recognition of former arc systems is a significant step in mineral exploration. Thick Tertiary sequences have been formed in cratonic basins such as the Gulf of Thailand Basin, and these have important petroleum production and prospects; back-arc basins as in Sumatra are also petroliferous, and other habitats such as outer non-volcanic arcs and inter-arc troughs offer exploration possibilities *(Fig. 3)*.

Other crustal elements in the region contributing to the tectonic framework are various crystalline basement areas or shields which may form the cores of more extensive cratonic units, as the Kontum Massif does for the Indochina craton. These cratonic areas may be fringed by arc systems, but in a significant number of cases the arc systems are separated from the cratonic areas by marginal basins: the Andaman and Japan Seas appear to be typical examples formed by spreading and development of oceanic crust behind arc systems, but the Weber Deep in the eastern Banda arc occurs in the position of an inter-arc trough; the Banda Sea itself, the Sawu and Sulawesi Seas and the China Basin (South China Sea) may be of different origins, however, some appearing to be remanent oceanic crust formed before the surrounding arc systems were initiated.

Regional description

Of the three major plates in the region, the *Eurasian Plate* shows the greatest complexity, being a vast lithospheric construction extending from west of Ireland to eastern Siberia. Orogenic episodes throughout geological time, from the earliest Precambrian, have combined a number of old crustal elements into a generally rigid cratonic block; these elements, including Precambrian shield units, represent earlier plates which have become progressively enlarged and welded together by successive orogenic cycles along belts of folding and plutonic activity, which presumably represent former collision or subduction zones between or marginal to the plates.

Precambrian shield areas in the eastern part of the plate include the Kontum Massif in Indochina, the Sino-Korean Shield in northern China and the Korean Peninsula, and, further north beyond a late-Palaeozoic fold belt, the Aldan Shield of Siberia. Extensions of these shields under later deposits and into later fold belts is also evident: in parts, the later deposits are unfolded moderately thick continental sequences such as in the Red Basin of Szechwan, China, and the Khorat Basin of eastern Thailand (both Jurassic-Cretaceous). Palaeozoic magmatic and fold belts fringe these shield areas, which include collision zones or sutures of late Palaeozoic age (Yanshin, 1966) with later additions or re-mobilizations in the Triassic and Cretaceous. Of these fold belts, the Fukien Massif of southeastern China, which includes Precambrian and Palaeozoic folded rocks and Mesozoic granites, is a major rigid structural element extending, according to Wageman et al. (1970) beneath the Yellow Sea into the Korean Peninsula to join the Reinan (Yongnam) Massif *(Fig. 24)*, possibly being correlative with the Sikhote Alin range and the Verkhoyan-Chukhot areas of eastern Siberia. In Indochina and adjacent parts of Thailand, fold belts of the Indosinian Orogeny (Triassic-early Jurassic) surround the Kontum Massif and the Khorat Basin area, and folding of early and late Triassic age was a major culminating event in the Thai-Malay Peninsula fold belt. According to Gobbet and Hutchison (1973), mid- and late-Palaeozoic movements occurred in this area *(Fig. 5)*, but were largely overprinted by the late Triassic orogeny which formed an overthrust fold belt striking along the peninsula; uplift and granite intrusion occurred at the same time, though Cretaceous-Tertiary granites are also present. The fold belt extends northwards through western Thailand and eastern Burma into the Himalayan region, and southeastwards to the Indonesian tin islands of Bangka and Belitung, where granite has been dated as late Triassic(Hutchison, 1973). Mesozoic folding also took place in Borneo (Kalimantan), and possibly in the central ranges of the island of New Guinea, which was associated with the Australian continent at the time in a more southerly location.

The Cenozoic tectonic history of the Eurasian Plate can more clearly be related to present-day plate interactions and both active and inactive tectonic elements can easily be recognized. The major plate interactions now evident were probably already established in the Mesozoic, but structures of this age in existing arc-trench zones were generally overprinted by those of the main Tertiary orogenic phase which in many cases is still active at the present day. The main tectonic features of the region in the late Cenozoic are summarized in *Figure 1* (inside the back cover), which should be referred to throughout the succeeding description.

The tectonics of the *Sinkiang-Mongolia-Siberia* region is not the concern of this review, but it is worth noting that the Lake Baikal rift apparently represents a very slow spreading axis trending northeast-southwest, its in-

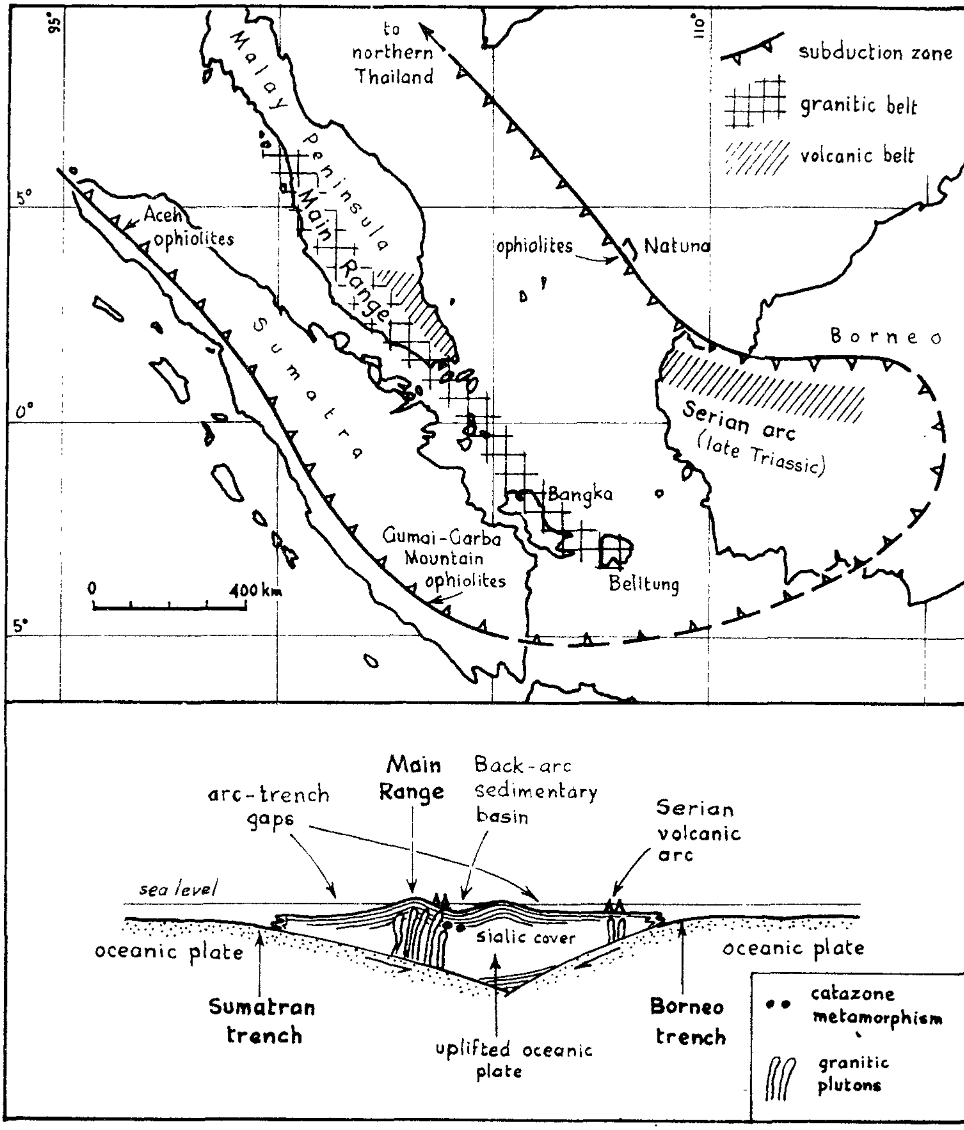


Figure 5. Palaeo-tectonic pattern of the Sunda area in late Triassic-early Jurassic, with schematic cross-section showing reconstruction of opposite-facing subduction zones and related magmatic features (from Hutchison, 1973).

ception dated by thick Miocene lacustrine deposits. Intraplate deformation in this region is known from seismological studies, the data indicating movements in old fold belts due presumably to stresses transmitted through rigid crustal blocks from the plate collision zone (Molnar, Fitch and Wu, 1973); and from the "diwa" structures, which are deep block-faulted basins with continental deposits formed within an old platform and lacking marine influences, and which have subsequently been subjected to folding, thrusting, volcanism and plutonic activity (Masaytis and Staritskiy, 1967)—orogenesis independent of underthrusting oceanic crust.

Considering the *Indo-Australian Plate* (also known as the East Indian Ocean Plate), the northward movement of *peninsular India* has been documented palaeomagnetically from the Jurassic (McElhinny, 1968). This is a cratonic segment of Precambrian to Permian age with widespread early Tertiary basaltic flows (the Deccan Traps). Its collision with the Eurasian Plate is best known from the Miocene onwards with the building of the Karakoram and Himalayan ranges, and the deposition of very thick clastic wedge deposits in the frontal trough on the underthrusting craton south of the main orogenic front; these deposits were themselves involved in thrust movements and folding in a manner consistent with them having been "scraped off" their basement as it moved beneath the leading edge of the Eurasian Plate and its associated orogenic structures. In a collision between two continental crustal units, the term "subduction" is perhaps not entirely appropriate, since it appears that the underriding craton has not sunk to the asthenosphere but has contributed to a double-thickness sialic crust in the Himalayan-Tibetan region. Whether the collision of India with the Eurasian Plate resulted in the large northern displacement of the plate's southern margin between Baluchistan and Burma, a matter of up to 1,000 km movement, is not certain; but the Himalayan structures represent a crustal shortening estimated at a minimum of 500 km (Gansser, 1964) that probably corresponds to this displacement. Evidence from the mountains west of the Indus Valley in Pakistan indicates major left-lateral faulting (Abdel-Gawad, 1971) consistent with such northward transport, and right-lateral movements are similarly noted in the Assam-Burma area.

The motions of the Indo-Australian Plate are more easily deduced from its oceanic portions, where magnetic lineations, deep-sea drilling and mantle plume tracks provide evidence unobtainable in cratonic regions. According to McKenzie and Sclater (1971) and data from Legs 22-28 of the Deep Sea Drilling Program, a very rapid (18-20 cm/year) north-south separation of India from Antarctica took place in the very early Tertiary, and renewed northward spreading began in the early Oligocene. It continued until mid-Miocene, and then changed to north-northeastward movement, presumably accompanying the collision of India with Tibet, as a major orogenic phase of this age is known in the Himalayan region (Gansser, 1964).

The *Ninety East Ridge* (or Carpenter Ridge) is an aseismic linear structure up to 3,000m higher than the adjacent ocean floor over much of its length, extending about 4,800 km almost north-south along longitude 90°E between latitudes 10°N and 30°S. Its northern part is progressively submerged

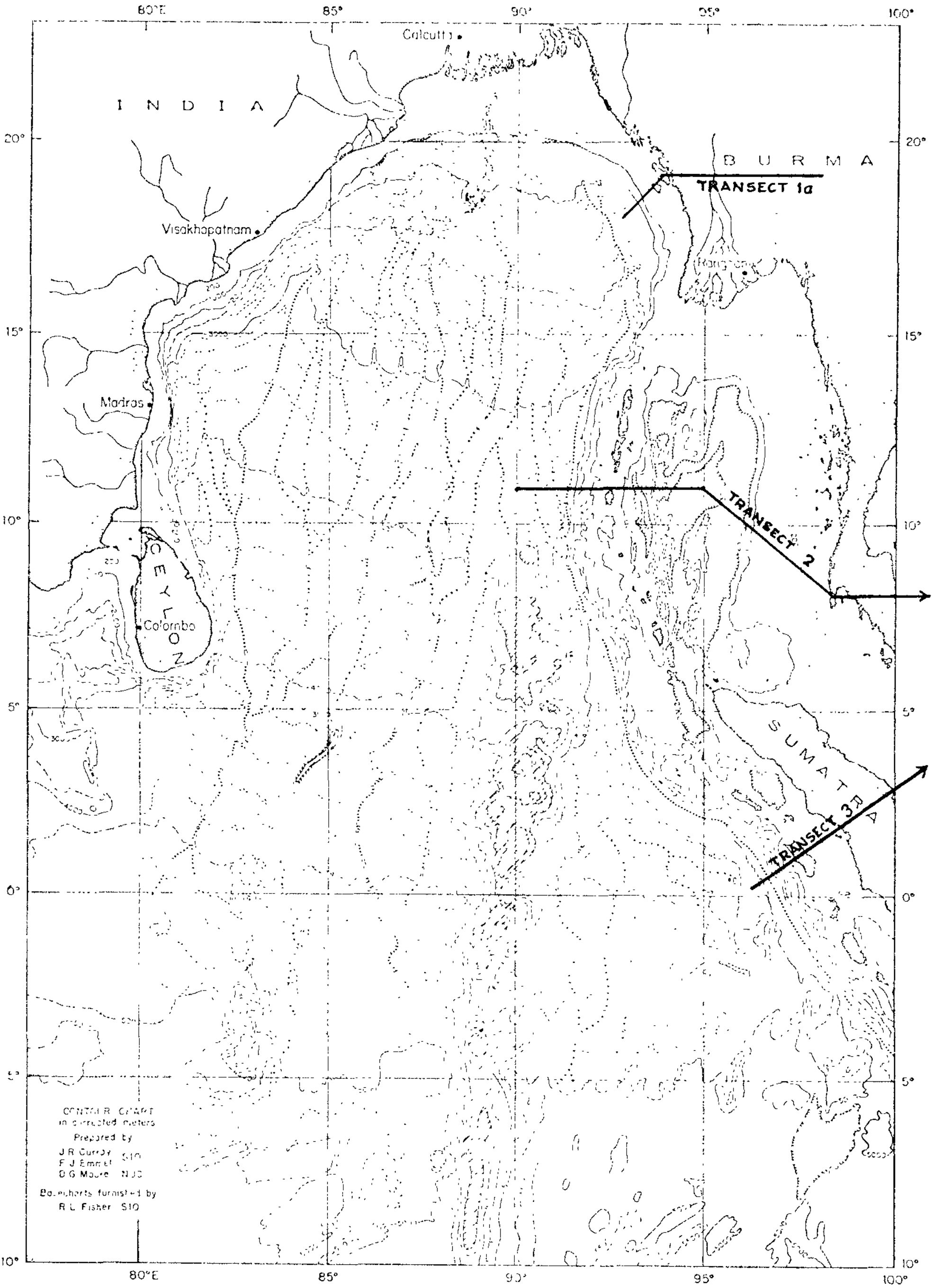


Figure 6. Bathymetry of the northeastern Indian Ocean showing the Bengal Fan and the Ninety East Ridge (shaded above the 3000 m level). Fan valleys are marked by lines of dots. (From Curray and Moore, 1971).

beneath the sediments of the Bengal deep-sea fan (see below), and it is not known whether it extends further north than 10°N *(Fig. 6)*. The ridge is volcanic in composition, and can be interpreted as having formed as the oceanic lithosphere moved northwards over a mantle plume or "hot spot". The results of Legs 22 and 26 of the Deep Sea Drilling Program (DSDP Scientific Staff, 1972, 1973a) which drilled at five stations on the ridge, indicated shallow water and even non-marine sediments as initial deposits on the volcanic formations; their age ranged from Miocene at the southern end to Upper Cretaceous at the northern, implying northward movement rates for the Indo-Australian Plate of between 2.7 and 7.8 cm/year, consistent with other magnetic evidence.

Additional evidence on the history of the northeast Indian Ocean area has been derived from study of the Bengal deep-sea fan (Curray and Moore, 1971). This huge fan *(Fig. 6)*, presumably derived from the Ganges-Brahmaputra river system and its ancestors, is composed of three major stratigraphic units separated by unconformities *(Fig. 7)*. The lowest unit is thought to be late Cretaceous to early Miocene in age *(Fig. 7)*, and to have been derived

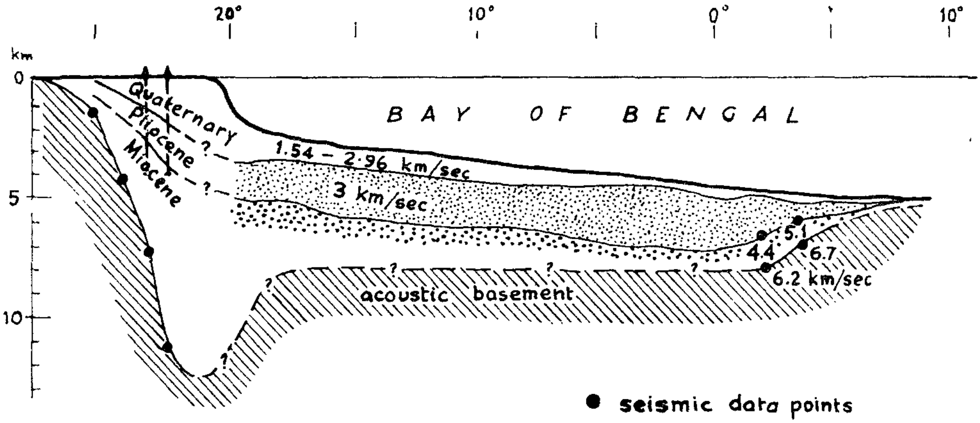


Figure 7. Hypothetical longitudinal section of the Bengal Basin, from the Ganges-Brahmaputra delta southwards through the Bengal deep sea fan, showing sedimentary units from well data and seismic reflection and refraction results. From Curray and Moore (1971).

by erosion of the Indian craton before collision. The mid-Miocene orogeny apparently initiated the huge river systems feeding the fan, as the next unit shows fan characteristics and is dated from late Miocene to Pliocene. The youngest deposits are also fan-type, Pleistocene in age, and correspond to the late Pliocene-Pleistocene orogeny that built the Himalayan ranges. From the world's highest mountain area has come the world's largest deep-sea fan; the two upper units have a maximum thickness of more than 6 km, and the underlying Cretaceous-Eocene unit extends as much as 8 km below these.

Thick alluvial accumulations are known in the Indo-Gangetic plains, and while this frontal trough is in a position relative to the mountain front analogous to that of an oceanic trench to an island arc, there are no post-Eocene volcanic rocks in the Himalayas; however, post-tectonic late-Tertiary granites (Gansser, 1964) may have been emplaced during the final stages of underthrusting.

The northern part of the *Sunda-Burman arc,* which has a general north-south alignment, does not fit easily into the major movement picture for the adjacent plates. Evidence from earthquake foci of eastward underthrusting at its northern end, in the Naga Hills of *northern Burma,* are interpreted by Molnar, Fitch and Wu (1973) to indicate that at least 200 km of oceanic crust has been subducted here in the last 10 million years, but that downward movement has slowed or ceased recently. First-motion studies show that at present a large component of right-lateral movement is involved on this boundary, consistent with the north-northeastward movement of the Indo-Australian Plate indicated by magnetic lineations, and which is the mirror image of the left-lateral movements in Pakistan already mentioned. An uncharacteristically low order of seismicity noted further south in Burma and the Andaman Islands area, between latitudes 23° and 13°N *(Fig. 8)*, is also consistent with present-day lateral slip along the plate boundary, though Shouls (1973) suggested it was due to a tensional stress field in the area east of the plate margin consistent with sea-floor spreading in the Andaman Sea and the late Cenozoic structural pattern in northern Thailand.

The predominance of lateral rather than downward slip motion on the plate boundary may also account for there being no oceanic trench feature seaward of the Burman and Andaman portions of the arc system. A definite trench does not appear as a significant feature north of latitude 5°N, off Sumatra, but a smaller bathymetric feature can be followed to 8°N where a fan-drainage ocean floor valley lies between the Ninety East Ridge and the nearby Andaman-Nicobar ridge *(Fig. 6)*. The plate margin passes between these two ridges, and can be traced northward off the coast of Burma to latitude 20°N, to the north of which it apparently lies on land but is obscured by other structures. A thick sediment accumulation is present in the low-lying Sylhet area of Bangladesh, with more than 4,250 m, of Upper Cenozoic deposits (Holtrop and Keizer, 1970) lying in the angle between the east-west Shillong-Khasi Precambrian plateau and the north-south arcuate Cenozoic Indo-Burman (Naga and Chin) Ranges. The plateau appears to have been involved in an east-southeastward collision with the northern Burma arc, as intense deformation with major nappes is found along the Naga Hills front adjacent to it, while less intense folding affects the area to the south in Mizo, Tripura and the Chittagong Hill Tracts. These ranges are formed of folded and overthrust late Cretaceous-to-Eocene flysch deposits with tectonically emplaced ultrabasic bodies, which extend down the Arakan Yomas

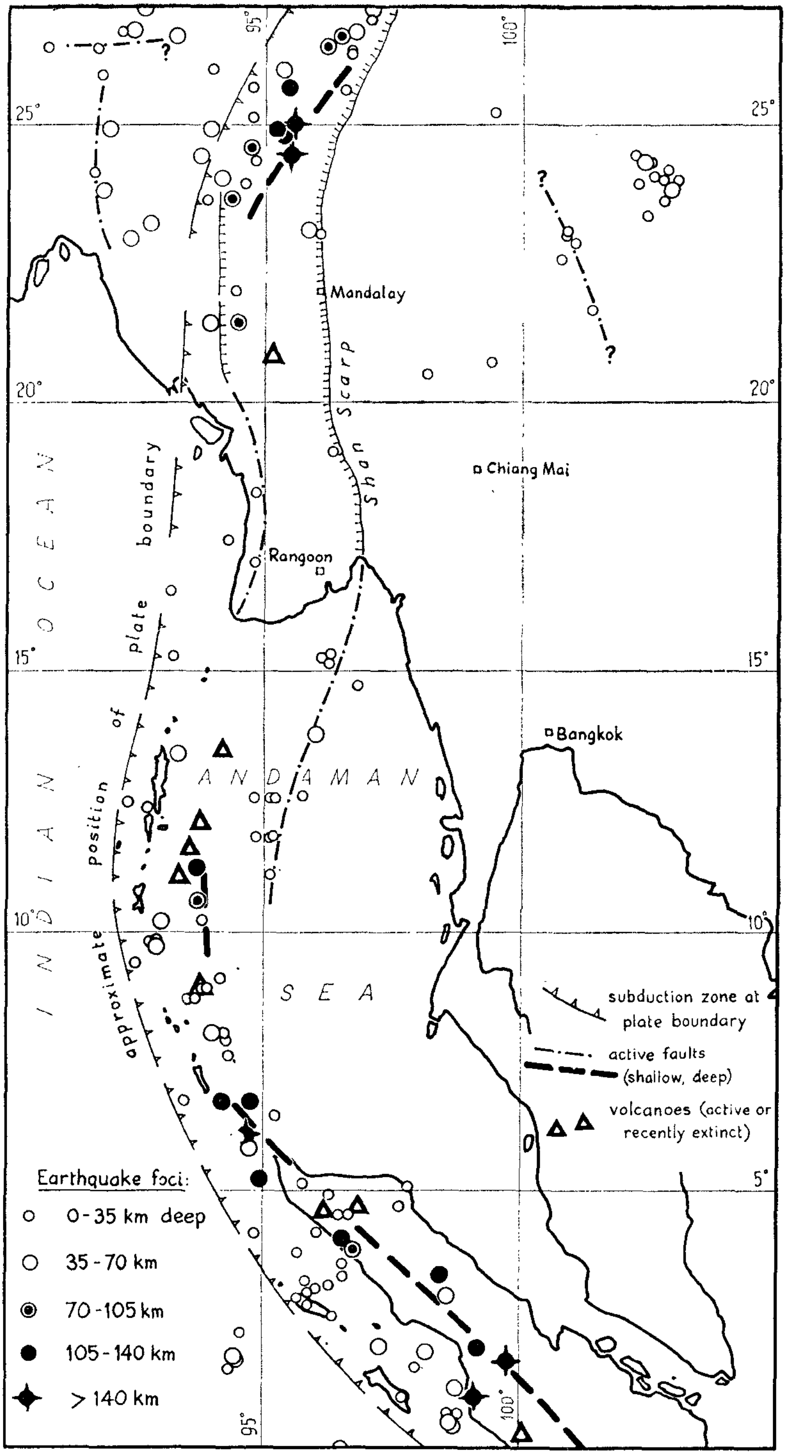


Figure 8. Earthquake foci (greater than intensity 4.3) for the Andaman Sea-Burma-Thailand area for the period 1968-1972, and presumed linear structural elements (Shouls, 1973).

(ranges) of central Burma and apparently continue offshore into the Andaman ridge. This feature represents a portion of the Bengal deep-sea fan scraped off the descending oceanic plate which, according to stratigraphic, structural and seismic evidence, was subducted in a generally eastward direction with appreciable movement during the last 10 million years; granites and volcanic rocks and the Oligocene succession in the Indo-Burman ranges suggest pre-Pliocene subduction also. This movement is difficult to reconcile with the major northerly motion of the Indo-Australian Plate, and suggests that a westerly push from the cratonic areas of northern Burma during the Pliocene was responsible, a push which ceased recently and was replaced by renewed northerly slip movement along the plate boundary. Alternatively, Burma west of the craton may have moved northwards with respect to the Indian Ocean during the Cenozoic; this could explain the evidence for recent subduction beneath the northeast-trending Naga Hills. This change of motion is also indicated by the cessation of volcanic activity in the Quaternary along the Mount Popa-Monywa trend, which had been active since the late Miocene and which had presumably been related to the subduction at the plate boundary.

Other features of central and northern Burma can be compared with the arc system model, such as the Prome (Irrawaddy) embayment which occupies the inter-arc trough position and contains gently folded thick late-Tertiary and Quaternary coal-bearing deposits. East of the volcanic ridge lies another Tertiary basin, the Sittang Valley, separated from the late Precambrian-to-Cretaceous sedimentary and metamorphic-plutonic mountainous area of eastern Burma by the major Sagaing or Shan Boundary fault. Right-lateral movement on this fault is suggested by stream offsets and the oblique truncation of the tin-granite belt against it south of Mandalay.

The direction and sequence of motions suspected to have occurred in northern Burma and adjacent areas make this one of the most interesting and complex Cenozoic tectonic areas of the region, and an understanding of its development could have an important bearing on the elucidation of the history of central Burma and the Andaman Sea.

The metamorphic complex present in parts of *eastern Burma* extends into *northwestern Thailand* and down the *Thai-Burma isthmus*, and probably under the sea on both sides. Plutonic rocks of Carboniferous, Triassic and Cretaceous age occur in this complex, with tin-tungsten mineralization in the younger granites *(Fig. 4)*. Transcurrent faults have been mapped in the isthmus, notably the Ranong and Khlong Marui faults which trend north-northeastward and which, according to Garson and Mitchell (1970), have a significant left-lateral offset. The Three Pagodas Pass fault, which runs south-southeastwards from the Sittang Valley into Thailand, and a similar one further to the northeast appear to have right-lateral offsets; movement on these latter may have been connected with the Sagaing (Shan Boundary) fault, to which they appear to be tangential.

The *Andaman Sea* represents a structural province significantly different to areas both north and south of it along the plate margin. The Andaman-Nicobar ridge is a non-volcanic (outer) arc element, with folded and overthrust Cretaceous-Miocene turbidites and younger rocks, with Cretaceous gabbro, serpentinite and enstatite peridotite (ophiolites) which have been tectonically emplaced. As with the Arakan Yomas, the sedimentary rocks probably represent a part of the Bengal fan and pre-fan deposits scraped up by subduction.

The Andaman Sea is divided into two parts by a pronounced north-south trending continental slope *(Fig. 9)*. A line of shallow earthquake foci approximately coincides with the slope, and continues along the line of the Sagaing fault (Shouls, 1973). The western part is mostly deeper than 1,000 m, and much of it beneath 3,000 m; rift structures are present (Rodolfo, 1969) and it appears to be a spreading basin with new oceanic crust being formed. A line of volcanic islands and seamounts is present to the east of the outer arc, but this includes only one active island volcano, Barren Island, plus an unknown number of active submarine volcanoes further south. Narcondam Island, to the north of Barren Island, is apparently extinct but geologically very young. It is not certain whether this line is related to the spreading of the basin or is the dying remnant of a volcanic arc associated with the plate boundary to the west. The problem with this marginal basin, as with others in the region, is how to reconcile the apparent spreading with the compressional movement that has occurred in the adjacent subduction zone: though it is probable that the compressional movement is no longer operative in this case. It is possible that the spreading could have resulted from the overridden plate descending at a steep angle and giving rise to a mantle diapir, which split the crust behind the arc along one or more lines of rifting.

The shallower eastern part of the Andaman Sea appears to be floored by an extension of the Palaeozoic-Mesozoic complex exposed on the adjacent peninsula, though there is evidence of a Tertiary sedimentary basin in the southern part. A shelf-break at the north end of the Strait of Malacca, bounding a small basin, is aligned parallel to magnetic anomalies and to the north-northeast-trending Khlong Marui fault which crosses the peninsula.

From Sumatra eastward, the *Sunda Arc* is characterized by much higher orders of seismicity and volcanic activity, resulting presumably from a more perpendicular plate collision and consequently more rapid subduction beneath the arc. This area has in past decades been studied to provide clues to orogenic processes, now more clearly understood as processes of plate collision

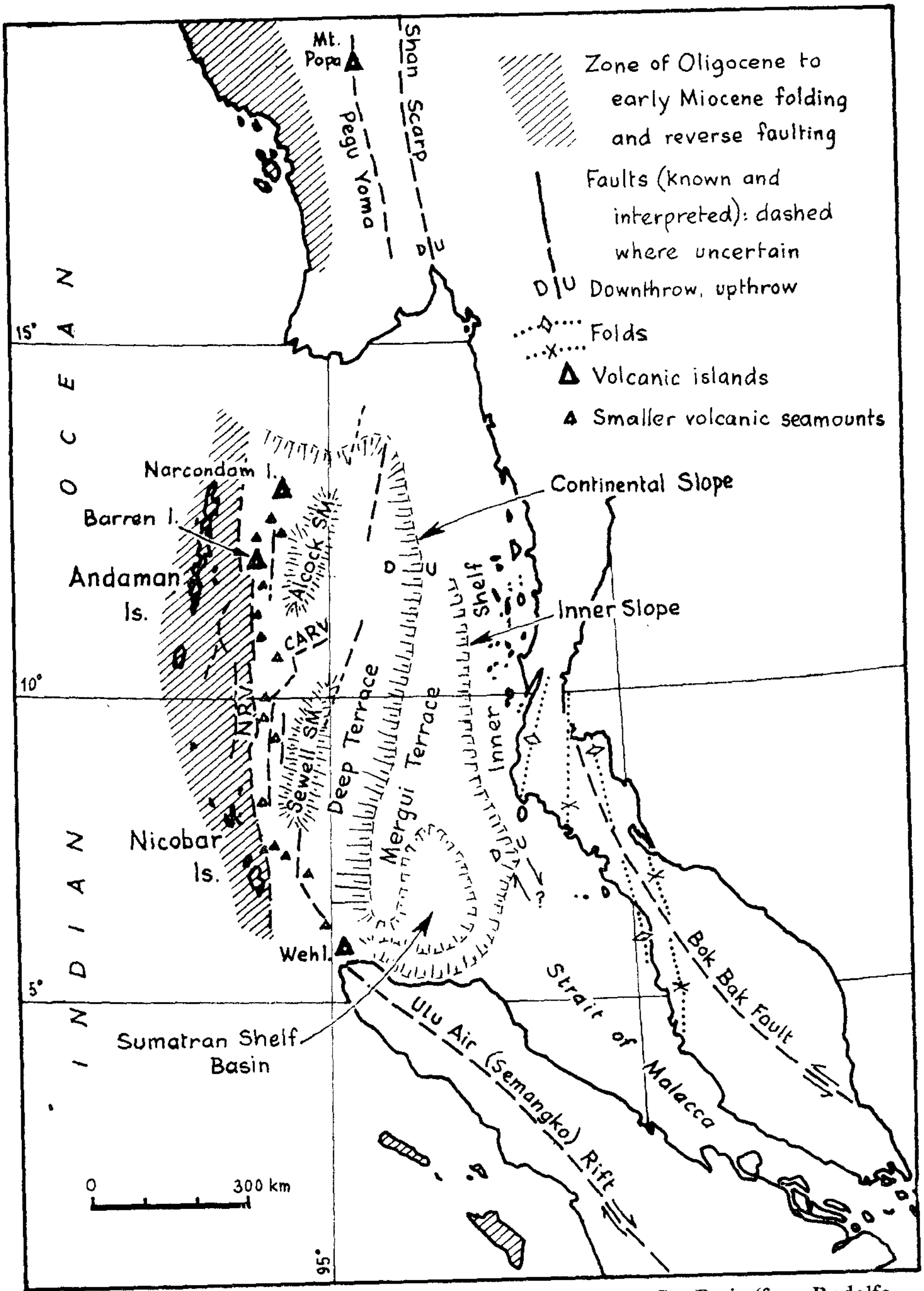


Figure 9. Structural and topographic features of the Andaman Sea Basin (from Rodolfo, 1969). Faults in the marine areas are interpreted from morphology and/or seismic profiles. Continental slope and inner slope appear also to be fault-located. CARV = Central Andaman Rift Valley, NRV = Nicobar Rift Valley, SM = seamount. The Bok Bak Fault is of Mesozoic (post-Triassic) age.

and associated magmatic activity; models of subductive activity have been constructed by Katili (1973) for both the western and eastern parts of this arc, relating geological and geophysical features to the Benioff zone and presumed magmatic processes at depth *(Fig. 2)*.

Sumatra and the *Malay Peninsula* appear to be geologically continuous, with the Strait of Malacca obscuring the transition from exposed craton in the peninsula to back-arc Tertiary basins on subsided craton; the Strait may be the site of down-faulting associated with the basin margins. The Palaeozoic-Mesozoic fold belt of the peninsula *(Fig. 5)* also outcrops in the Riau archipelago south of Singapore and in the Bangka-Belitung area, and is known beneath the Quaternary deposits of the east coast of southern Sumatra. It is also found in the central highlands of Sumatra, indicating that the cratonic unit formerly extended that far before this part of it was caught up in Cenozoic orogenesis. Tertiary back-arc basins as much as 8,000 m in depth lie between the exposed craton and the highlands, several with important petroleum fields; graben-type faults appear to separate the basins from the craton, and growth-faults, active during sedimentation, occur on the southwestern sides of the basins.

The present-day subduction zone appears to be removed only a small distance southwestward from the site of a Cretaceous-Tertiary subduction zone, so that volcanism now penetrates the older fold-belt. The Benioff zone descends to a depth of 200 km in a horizontal distance of 400 km from the Sunda Trench, and volcanic activity occurs at the surface where the zone is about 100-150 km deep; volcanic centres are located along the Semangko (Sumatran) fault zone, which extends the length of the island and shows up to 130 km right-lateral movement since the mid-Tertiary (Posavec et al., 1973). Seaward of Sumatra lie the Mentawai Islands, on a ridge which is apparently a continuation of the Andaman-Nicobar outer non-volcanic arc and which is structurally similar, with overthrust and folded Tertiary rocks, probably emplaced in mid-Miocene times from distal portions of the Bengal fan (Hamilton, 1973). Between the islands and Sumatra, the inter-arc trough contains younger deposits as much as 7,000 m thick *(Fig. 10)*. Beyond the islands is the Java (or Sunda) Trench, more than 5,000 m deep in parts but not so deep as off Java: probably sedimentation from the Bengal fan prevented such deepening.

The Indian Ocean floor south of the trench has been dated by several Deep Sea Drilling Program drillholes as latest Jurassic south of Sumbawa, becoming younger westwards to Palaeocene near the Ninety East Ridge (DSDP Scientific Staff, 1973b). The Wharton (West Australian) Basin is mainly Cretaceous, and Heirtzler et al. (1973) suggest that the ages indicate an east-west separation of Australia from India during that time.

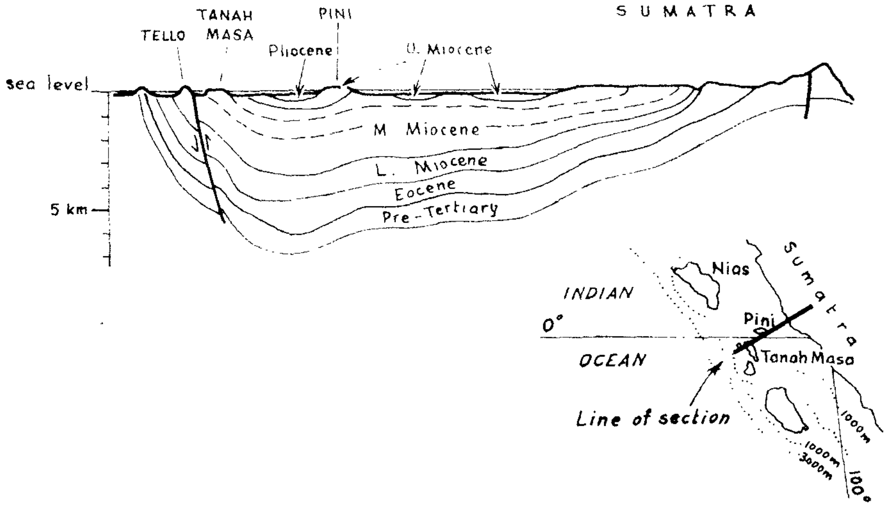


Figure 10. Schematic cross-section of the arc-trench gap between West Sumatra and the Mentawai Islands (Nias, Tanah, Masa, etc.).

Java and the *Lesser Sunda Islands* (Bali, Lombok, etc.) have, like Sumatra, an active Benioff zone and intense volcanicity, but lack the Palaeozoic core and the non-volcanic island arc. The Cretaceous magmatic arc in Sumatra is thought to veer away northeast of Java and to reappear in the Meratus Mountains of southeast Kalimantan (Katili, 1973), giving rise to the Karimunjawa Arch in the Java Sea.

The well-marked Java Ridge lies 200 km south of the islands, corresponding structurally with the outer-arc Mentawai Ridge off Sumatra, though in only a few places is it less than 1,000 m deep. It lies between the Sunda Trench, 7,450 m at its deepest point, and the Bali Trough, which is the inter-arc trough of the arc-system model. The ridge appears to represent sediments (Raitt, 1966) scraped off above the subduction zone, but as the influence of the Bengal Fan is not felt here the volume is much smaller than in the island ridges to the northwest, and consequently the ridge does not rise above sea level. Profiles across the trench and ridge were presented by Beck and Lehner (1974), showing a shallow-dipping (5°-8°) reflector interpreted as the top of the underthrusting oceanic basement which can be traced for 50 km northward beneath the ridge to a depth of 15 km. The overlying sedimentary unit appears to be imbricated and contorted, with no bedding-plane reflectors apparent. According to seismic evidence, the Benioff zone dips northward at about 30° as far as the south coast of Java (250 km from the trench axis), and can then be traced to a depth of 600 km beneath the Java Sea at an angle of about 65°, steepening to 75° north of Sumbawa (Hamilton, 1972); this steeper section of the zone is not present in the Sumatran section of the arc. Active volcanic centres are located where the Benioff zone lies 150-200 km below surface. The structure of the area is realized in the block diagram in *Figure 11.*

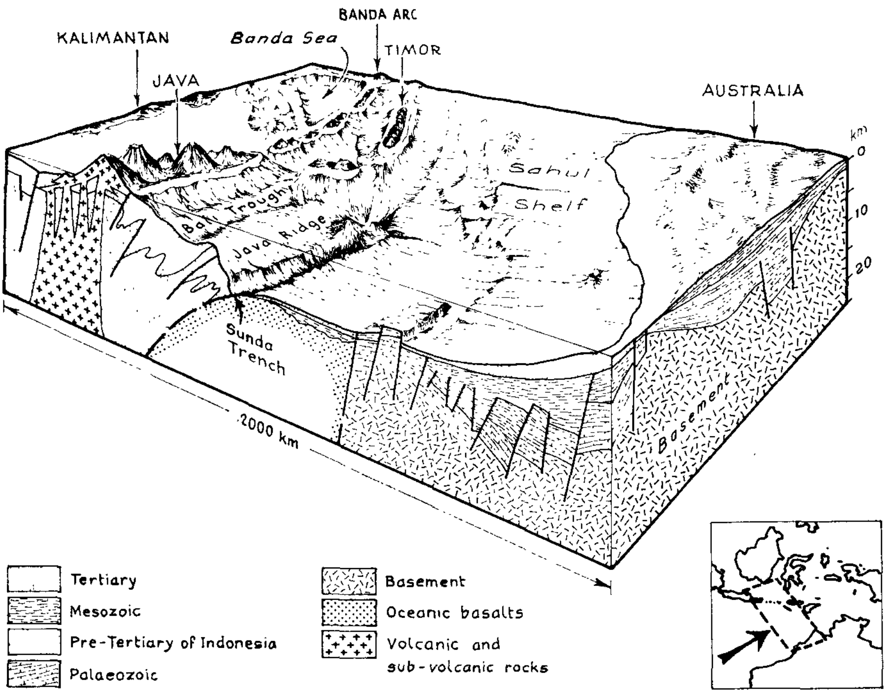


Figure 11. Block diagram showing topography and structure of a part of the Northwest Australian Shelf, Sunda Arc and the deep oceanic area between. The margin of the Australian continent is faulted and foundered, and plunges northward to abyssal depths in the ocean (see *Fig. 14*). Basalts in the abyssal plain appear to be related to the phase of block faulting in Jurassic time. The northern slope of the Java Trench-Timor Trough is a thrust front, on seismic evidence, and the axis of the negative gravity anomaly of Vening Meinesz follows the outer ridge north of the trench and extends over the length of Timor (Beck and Lehner, 1974).

Java and the other islands are composed predominantly of Miocene and younger sedimentary and volcanic rocks, with ?Cretaceous metamorphic rocks exposed at a few places. A large trough of Tertiary deposits along the north coastal area of Java is up to 2,000 m thick with east-west fold structures, forming an important petroleum exploration area, and other basins are known in the Java Sea with up to 1,500 m of Tertiary strata (Emery et al., 1972).

North of the Sunda Arc lies the cratonic area of the island of *Borneo* (Kalimantan, East Malaysia and Brunei) and the *Sunda Shelf*, between Borneo and the Malay Peninsula. The area is continuous with the peninsula, forming a stable cratonic block, and has structural links with the Gulf of Thailand area and the Indochina peninsula to the north. According to Haile (1973), concentric orogenic zones are evident which link western Borneo with the Malay Peninsula and the shelf islands *(Fig. 12)*. The oldest of these, the Malaya Zone (late Palaeozoic-Triassic), forms the peninsula and extends through the tin islands to Belitung, but is not seen beyond there. Next to this on the northeast side is the Anambas Zone and its continuation in the West Borneo Basement, the site of repeated Palaeozoic and early Mesozoic sedimentation, volcanicity, orogeny and intrusion, which has been emergent since the Triassic. The Kuching (Semitau) Zone in Borneo is characterized by thick Tertiary deltaic sedimentation and granite tectonically mixed with older orogenic elements, and extends northwards into the Natuna Swell. The Sibu (Rajang) Zone is intensely-folded, extremely thick, late Cretaceous-Eocene flysch with ophiolites, regarded as the core of the Northwest Borneo Geosyncline, with the less-intensely-folded Upper Tertiary Miri Zone, to the north, being the miogeosynclinal equivalent. A plate tectonic interpretation places an east-west Tertiary subduction zone north of Borneo, moving oceanic crust

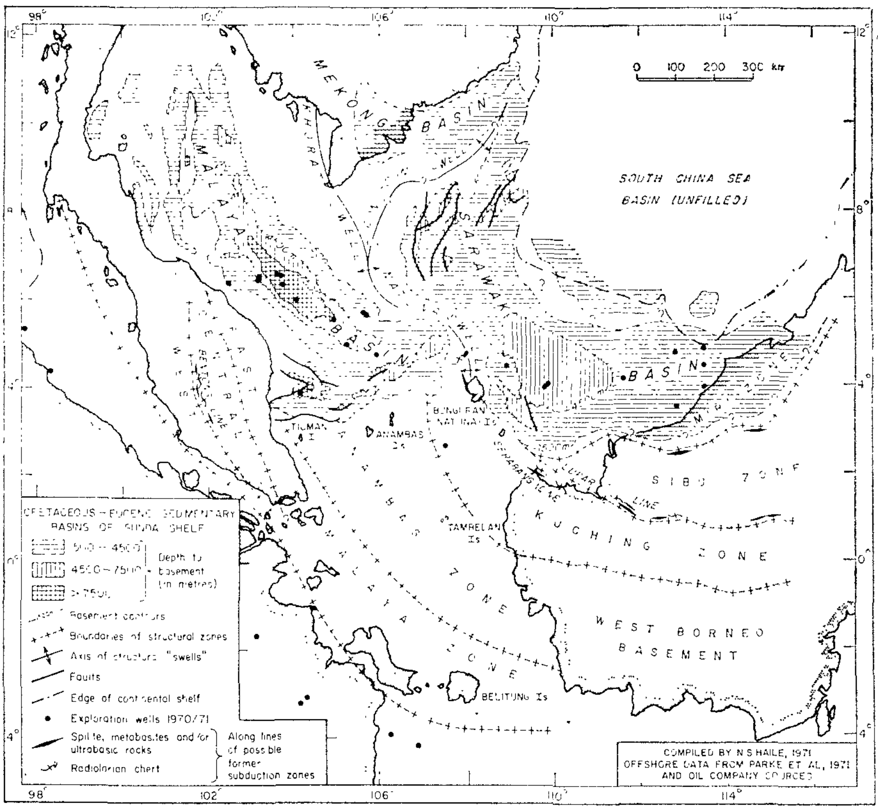


Figure 12. Sedimentary basins and structural zones of the Sunda Shelf, compiled in 1971. The sedimentary basins shown are probably mostly Cenozoic in age; the Malaya Basin shown is referred to in the text as the Gulf of Thailand Basin (Haile, 1973).

of the South China Sea (China Basin) beneath the cratonic West Borneo Basement; whereas the Kuching-Natuna Zone represents an earlier (?Jurassic) subduction zone of different orientation *(Fig. 5)*. Much of Borneo and the shelf area can be recognized, therefore, as a micro-continent in the late Mesozoic and Cenozoic, with oceanic crust sliding under it from the south or southeast, from the north, and from the east (Hutchison, 1973). Southeast Kalimantan is structurally continuous with the rise-and-trough terrain of the Java Sea.

The shallow water areas of the *South China Sea* and *Gulf of Thailand* show geomorphic features formed during the period of Pleistocene sea-level lowering, when most of the area was land: large drowned river valleys, both open and sediment-filled, are present, draining into the deeper water area to the northeast (Haile, 1973). Similar valleys are present in the Gulf of Thailand, and a depression of 25 m affecting one of these valleys is attributed by Emery and Niino (1963) to late Cenozoic tectonic subsidence. Beneath the relatively uniform shallow surface of the shelf, however, lie two extensive Cenozoic sedimentary basins, and these, together with the associated basement ridges, were investigated geophysically by Parke et al. (1971). Later information has been added by Haile (1973). The largest basinal feature is the Gulf of Thailand Basin, an elongate sediment-filled depression mainly parallel with the Malay Peninsula and adjacent tectonic trends *(Fig. 12)*. The sedimentary infill seen in seismic reflection profiles is probably all Cenozoic, as Mesozoic rocks on the basin fringes have undergone tectonic deformation and would thus be expected to show as "acoustic basement" in geophysical records; also, the basin is terminated at its southern end by an east-northeast trending apparently-faulted truncation, south of which the islands of Tioman, Anambas and Natuna show late Cretaceous granites (dated at between 87 and 73 m.y., Haile and Bignell, 1971; Haile, 1973). Diapir-like structures have been noted in several places (Parke et al., 1971; Dash et al., 1973).

The situation in the northern part of the basin, in the Gulf of Thailand, is less clear, but it is known that a series of north-south basement ridges underlie the Tertiary, probably granitic and probably Mesozoic; and that sediment thickness in the intervening troughs may exceed 8,000 m. On land, aeromagnetic data indicate 3,300 m of sediments on the coast south of Bangkok, and a drill hole at Ayutthaya, 90 km further north, showed 1,836 m of Quaternary (Emery and Niino, 1963), but a metamorphic ridge across the narrow part of the Gulf nearby appears partially or completely to close off this basin from the main basin to the south. The presence of a large late Mesozoic basin under part of the Gulf, comparable to the non-marine Khorat Basin, has been suggested (Sawamura and Laming, 1973), based on projection of shoreline outcrops and Palaeozoic basement ridges.

The Khorat-Natuna Swell (Khorat-Semitau Swell of Parke et al., 1971) is a basement ridge separating the Gulf of Thailand Basin from the Sarawak Basin (Brunei—Saigon Basin of Parke et al., 1971). Less than 1,000 m of Cenozoic cover is present, and in many places only thin Holocene sediments occur. Its internal structure shows folding and faulting and, based on island outcrops, the ridge is considered to be formed of Mesozoic rocks (Haile, 1970; Dash et al., 1971, 1973). The southern end appears to be a continuation of Haile's (1973) Kuching Zone, with Cretaceous and Tertiary orogenic activity, while the northern part is clearly continuous with the Indonesian fold belts of Triassic-early Jurassic age which include the mainly north-south Kampot fold belt of the Khmer coastal area and the Chantaburi and Phetchabun fold belts of eastern Thailand; these belts form the eastern fringe of the unfolded Khorat Basin (Jurassic-Cretaceous). The Khorat-Natuna Swell appears, therefore, to have a dual origin, which could explain the narrow S-bend link in the middle of the swell, north of Natuna Island.

The Sarawak Basin is more extensive and deeper (greater than 9,000 m in places) than the Gulf of Thailand Basin; it is arcuate, due to the tectonic strike of the confining basement ridges, and Haile's Miri Zone (Northwest Borneo Basin) is its landward extension in northern Borneo *(Fig. 12)*. The southern margin is highly folded, but the coastal and offshore areas of Sarawak and Brunei are less so and provide good petroleum and natural gas reservoirs. The basin is bordered on its western side by the Khorat-Natuna Swell and its offshoot the Con Son Swell, against which there is evidence of folding and faulting in the basin. The northeastern side is bounded by the Peripheral Ridge (Sunda Shelf Edge Swell of Haile, 1973), which forms an arcuate end wall to the China Basin, an irregular deep-sea feature that will be considered later in this review. The ridge, which has no sea-floor topographic expression, appears to consist of a line of buried seamounts, and has been compared to the volcanic or diapiric features that characterize Atlantic-type coupled continental margins, that is, where ocean floor and continental margin have not moved relative to one another (Emery et al., 1970). The ridge has acted as a sediment trap for the Cenozoic deposits of the Sarawak Basin. The basin is bordered on the north by the Con Son Swell, an offshoot of the Khorat-Natuna Swell, of unknown structure, though a granite from Trung Lon Island has been dated as 70 m.y., late Cretaceous (Hilde and Engel, 1967). This suggests that the Sarawak Basin sedimentary infill is entirely Cenozoic.

The Mekong Basin lies north of the Con Son Swell, extending inland to Tonle Sap lake south of the Khorat Basin rim. The deposits are thin on land except under the Mekong River delta, where they exceed 1,500 m, and thick deposits extend eastward offshore. Extensive late Cenozoic basalt flows, dated at 2 m.y. and younger, occur on the north side of the basin and on the Kontum Massif; some are interbedded with alluvium, and an eruption took place in 1923 near Cecir Island, 250 km east of Saigon at a location which, on the map in Parke et al. (1971), shows a high on the acoustic basement linked to the Peripheral Ridge.

The *eastern Sunda Islands, Timor* and the *Banda Arcs* form an active continuation of the Sunda arc system, with the remarkable characteristic of curving through a complete half circle at its eastern end. In contrast to the western segment of the Sunda Arc, this area has no continental crust inside the arc, having instead the deep-water Flores, Sawu and Banda Seas, the last-named being 7,440 m deep at maximum (the Weber Deep) and having several intriguing features. Continental crust is, however, present outside the arc, with the wide Sahul Shelf south of Timor being the offshore extension of the Australian craton with thin sedimentary cover. This connects with the island of New Guinea (Irian Jaya and Papua New Guinea) from which a narrow prolongation, the Sula Spur, extends westwards towards Sulawesi, forming the northern margin to the arc system.

The Benioff zone geometry in such a looped arc system could pose problems of space and movement of the underthrusting plate, but it appears that the northern arm of the arc is seismically less active, terminating west of Buru. Contouring of earthquake foci in the area northeast of Timor *(Fig. 13)*, shows that two and possibly three slip surfaces can be defined, approximately 50-100 km apart vertically (Stoiber and Carr, 1971). The dip of the zone shows the usual shallow slope down to 100 km and becomes steeper at greater depths in the southern portion of the arc, but steep dips are not found in the area of greatest curvature. Down-dip undulations have been correlated in this latter area with volcanoes of the inner arc (Wulur and small islands to the northeast) by Stoiber and Carr. East-west transcurrent fault movements, prominent to the north along the Sula Spur and elsewhere, suggest that lateral slip may be the main movement on the Benioff zone in the Seram-Buru portion of the arc.

The inner volcanic arc from Flores eastward is in direct linear continuity with the Sunda Arc, but the volcanic rocks are more basic in composition than the basic-intermediate calc-alkaline and potassic suite of Sumbawa and westwards. Active volcanism is not found on the north side of the arc, nor on Alor, Wetar and Hila, the inner arc islands north of Timor; instead, a small volcanic island (Gunung Api) and a line of seamounts occur 100 km further north in deep water.

The Banda Sea shows an intriguing pattern of linear ridges and troughs (Times Atlas, 1972). There are three areas more than 4,000 m deep, separated by the volcanic island arc and by an irregular rise from Seram to the south-eastern tip of Sulawesi. This latter rise is surmounted by ridges trending east-northeast, one of which reaches surface at the reefal Lucipara Islands. This appears to join a ridge running north and forming the island of Sanana, which

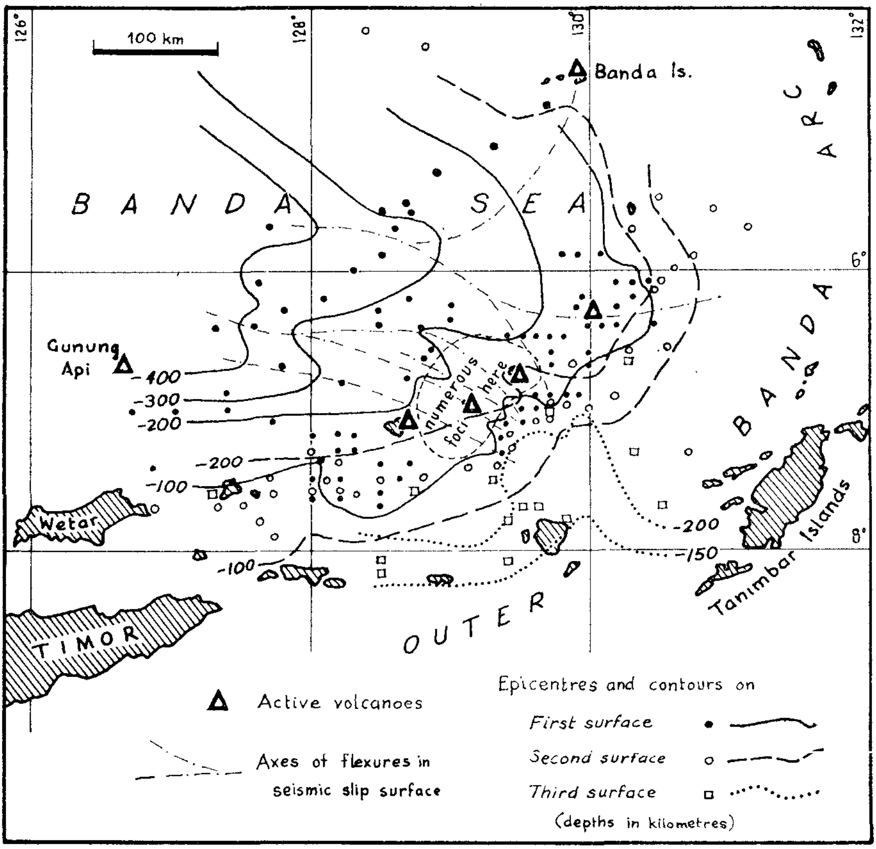


Figure 13. Earthquake foci in the eastern part of the Banda Sea (from Stoiber and Carr, 1971).

abuts onto the Sula Spur at right angles; the ridge touches the western end of Buru, and appears quite abruptly to truncate the non-volcanic arc and trench. The Weber Deep in the Banda Sea lies between the minor inner volcanic and larger outer non-volcanic arcs at the peak of the curvature, and is up to 200 km wide; in terms of an island arc model, this corresponds to an inter-arc trough, but even taking into account the nearby weak volcanicity and consequent lack of infilling sediment, it is out of proportion with the other arc elements. Beneath this deep, the Benioff zone dips westward at a low angle (20-25°) at less than 100 km depth. It was possibly formed by a rising mantle diapir separating the two arcs, by analogy with Karig's (1971b) explanation of a similar feature in the Marianas Arc (see p. 52). The Sawu Sea west of Timor is in an analogous inter-arc position, but is not so deep (3,000 m).

The outer non-volcanic arc islands are, in this area, much larger than those of the volcanic arc, and generally include much older rocks. Mesozoic strata and possibly older metamorphic complexes are known on most of the islands from Sumba round to Buru and also in the Sula Islands. Timor is the largest and best known, and has been described by Audley-Charles (1968) and in later papers by him and colleagues. The metamorphic Lolotoi Complex is overlain by Lower Tertiary rocks, resulting from a late Cretaceous-Eocene orogeny which affected all the arc islands, followed by further orogenic events in mid-Miocene and late Pliocene. Permian limestones and the metamorphic complex are thrust southwards over Mesozoic deposits. The Bobonaro olistostrome, a chaotic breccia with a scaly clay matrix, appears to have formed by sliding from the north side of the island to the south on a submarine slope during the mid-Miocene tectonism (Audley-Charles and Carter, 1972). Ophiolite bodies are included in the metamorphic complex.

The Timor Trough, regarded by Hamilton (1972) as a present-day subduction zone, is a relatively minor feature lying between the island and the Sahul Shelf of the Australian craton. Mostly less than 3,000 m deep, traced round the arc, it is found to be only poorly marked and discontinuous; westward, it appears not to be in continuity with the Java Trench, veering southward at the Sawu Sea bulge. Recently-published seismic profiles (Beck and Lehner, 1974) east of Timor show evidence of underthrusting by the Australian craton which includes, from interpretation of the seismic evidence, Mesozoic and Tertiary formations including Permian limestone. The overthrust unit shows imbrication, compressional folding and extensive gravity slides. Other profiles, taken south of Timor across the trough, are illustrated in *Figure 14*, showing similar features suggesting a collision zone between the Australian craton and an overthrust mass of contorted sediments. Collision rather than oceanic-crust subduction may be the case all round the Banda Arc as far as Buru, with the possible exception of a small area east of the Kai Islands where oceanic crust may still be present.

The *island of New Guinea* has an east-west Palaeozoic-Mesozoic core in the central mountain range, a low-lying covered platform on the south side which is continuous with the Australian craton, and folded Tertiary rocks with ophiolite bodies on the north. Hamilton (1972) showed a subduction zone off the north coast of the island, passing into a left-lateral transcurrent fault east of longitude 143°E, and it appears that left-lateral movement is predominant along the whole coast either on the subduction zone itself or on lines parallel to it. This movement is consistent with the westerly motion of the West Pacific Plate which underrides the Philippine Sea Plate along a partly dormant subduction zone near the Palau Islands-Yap arcs.

The structure of the western end of the island of New Guinea and its relation to Misöol, Obi and the Sula Islands are not clear. Hamilton's map shows east-west left-lateral faults on both sides of the Sula Islands and on the south-east side of Telok Irian (Geelvink Bay); this latter lines up with a shelf break

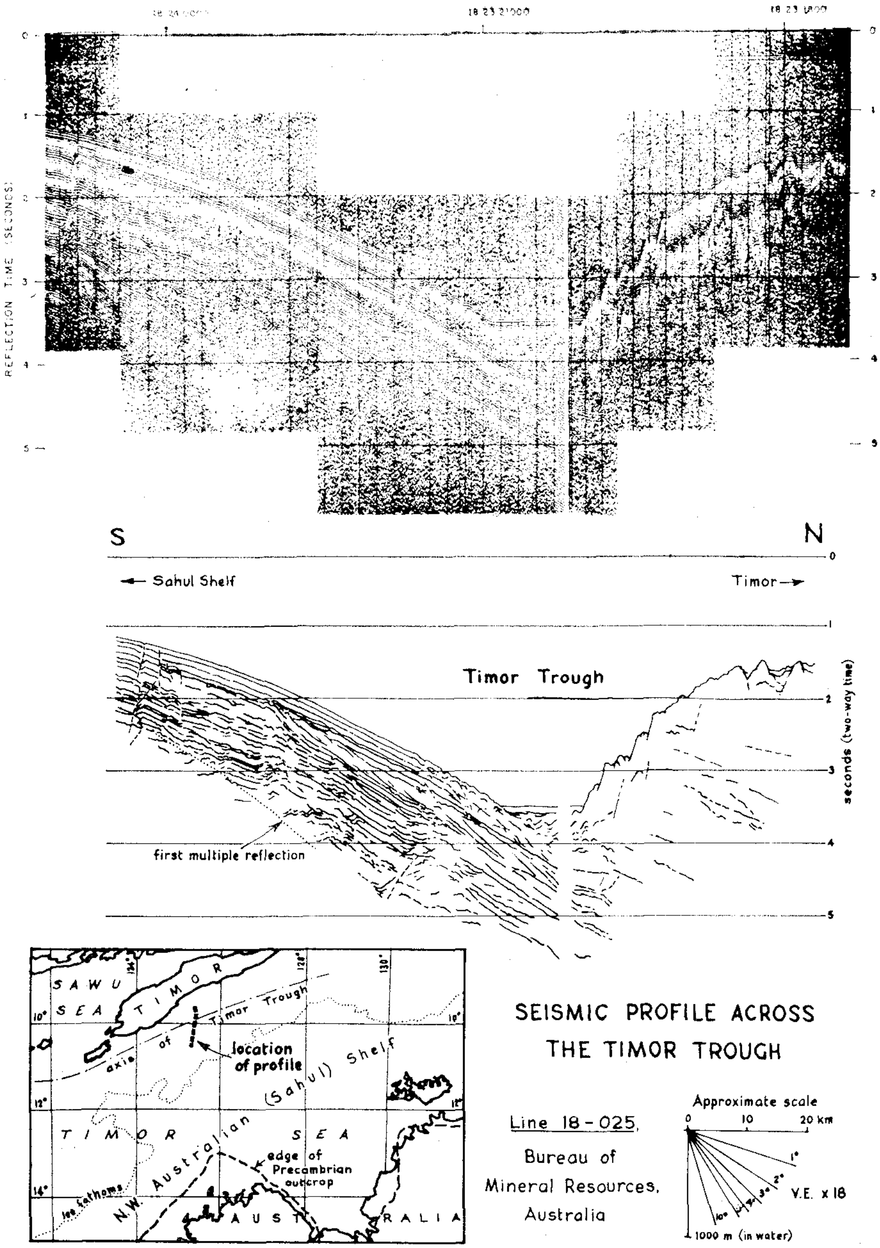


Figure 14. Seismic profile across the Timor Trough, in the Timor Sea between Indonesia and Australia. The original facsimile record is reproduced by kind permission of the Director, Bureau of Mineral Resources. Reflecting horizons on the Sahul Shelf side appear to represent sedimentary formations dipping at low angles and cut by a few normal faults. One formation shows apparent foreset bedding, and unconformities and pinch-outs can be distinguished. Deeper structures may include reefs. The trough sediments show some incipient deformation, more definite at lower levels. The north slope of the trough shows low angle reflectors which may be thrust planes, and the surface irregularities may be the result of slumping. The whole section is interpreted as showing the Indo-Australian Plate (left) underthrusting the Banda Arc segment of the Eurasian Plate (off the profile to the north), with a build-up of scraped-off sediments forming the north slope (right).

on the south side of the "neck" of the island. Nevertheless, structures appear continuous across the neck, with a pronounced double bend in strike in Mesozoic fold and thrust structures carrying these northward into Cenderawasih (Vogelkop).

The similarity in shape between *Sulawesi* (Celebes) and *Halmahera* may be more than just coincidental; in each case the eastern arcuate arms, convex westwards, consist of ophiolites in folded Tertiary strata pushed westwards onto a metamorphic complex (in Sulawesi) and against an active volcanic arc (in Halmahera). A small subduction zone on the west side of Halmahera dips eastward, suggesting that the island is still developing its form. Two well-marked westward-dipping subduction zones occur from a latitude slightly north of this, the Mindanao Trench subduction zone along the east of the Philippines archipelago and the Sangihe (Sangir) subduction zone; this underthrusts the northern tip of Sulawesi and the Sangihe volcanic island arc, dying out in Davao Gulf, Mindanao. These appear to converge at depth under Mindanao, and the Benioff zone, dipping at 50-65°, can be traced to more than 500 km depth. At its south end, the Mindanao zone is truncated abruptly by a left-lateral fault east of Halmahera, and the Sangihe zone appears to die out in favour of the south-dipping Minihassa subduction zone in the Sulawesi Sea, north of the Minihassa Peninsula, the north arm of Sulawesi. The Sulawesi Sea appears to be a small oceanic-crust basin, and both the basin and the subduction zone are cut off westwards by the very active left-lateral Palu Fault. The Moluccas Sea between Halmahera, Sula Islands and northern Sulawesi shows prominent north-south ridges, including the Talaud Islands with ophiolite bodies.

Sulawesi itself appears to be a composite island. The eastern and south-eastern arms are, as mentioned, ophiolite-Tertiary-metamorphic fold complexes, the northern arm is largely unknown except for active volcanoes, Tertiary granite and a porphyry copper deposit, and the south arm contains granitic plutons with related gneisses possibly of Cretaceous age, Tertiary alkaline trachytes and basalt flows. The Palu Fault trends south-southeast across the island, a marked bathymetric lineament continuing the alignment through Bone Gulf and into the Flores Sea. A similar trending fault-zone cuts through the southern arm and beside Kabia Island.

The *Makasar Strait* is partly shelf and partly deep water (more than 2,000 m). Although geological correspondence across the strait is not convincing, it is topographically possible to fit southern and central Sulawesi against the Borneo shelf, closing the deep water portion of the strait, by restoring presumed south-southeasterly movement as indicated by the fault lines.

The origin of the *Banda Arc* and the structural arrangement of the *New Guinea-Halmahera-Sulawesi* area is by no means agreed among research workers, though northward movement of the Australian continent and an anti-clockwise rotation of central and northern New Guinea to its present east-west orientation seem to be accepted by most. The Sula Spur is regarded as a continuation of the central New Guinea Palaeozoic-Mesozoic core, having moved with it. According to Audley-Charles, Carter and Milsom (1972), a left-lateral megashear carried the Sula Spur and southeastern Sulawesi northwestwards during the Pliocene across the end of a subduction zone which was creating the Flores-Wetar volcanic arc *(Fig. 15)*, while Timor and the outer arc round to Buru were an unbent east-west ridge riding the leading edge of the Australian continent further south. This was separated from the volcanic arc by an oceanic plate, now disappeared except for the Sawu Sea, the small inter-arc trench and the Weber Deep in the Banda Sea. On the other hand, Moberly (1972) considered the island arc system to have been deformed by northward movement of the Australian craton, of which the Sula Spur and New Guinea were a north-pointing finger *(Fig. 16)*. The northwestward movement of the West Pacific Plate, combined with this northward movement, resulted in a westerly component which bent the finger anticlockwise with transcurrent movement on its northern margin. The Sula Spur indented, curved and finally snapped the Sunda-Banda arc system, of which Timor and the outer arc islands were a part, and ocean floor material pushed up by the finger-tip during its westward motion became the eastern ophiolite belt of Sulawesi. Similar movement by another finger, northern New Guinea, presumably uplifted the ophiolite belt of Halmahera.

The motion of the *West Pacific Plate* is of prime importance in reconstructing the tectonic history of eastern Asia, as its huge areal extent, its reasonably complete magnetic anomaly record from the late Cretaceous, and the large area of Mesozoic oceanic crust present in the western part, show that the plate has been a major element in the tectonic picture for a long time. Evidence of motion is provided by the magnetic anomaly patterns, which suggest that a complex of five spreading axes created the western section of the plate during the Cretaceous, extending further eastward than the Hawaiian Islands (Larson and Chase, 1972): crust generation in the Cenozoic thus appears to have been mainly confined to the eastern Pacific region, complicated by subduction beneath the Americas cratons and resulting loss of ocean floor on that side.

Evidence for movement of the plate, once formed, is given by aseismic chains of seamounts, such as the well-marked Hawaiian-Emperor chain which extends from Hawaii to the junction of the Kurile and Aleutian arcs off Kamchatka, some 6,000 km long and with a pronounced 60° change of orientation in the middle. Two other seamount chains, the Austral Ridge-

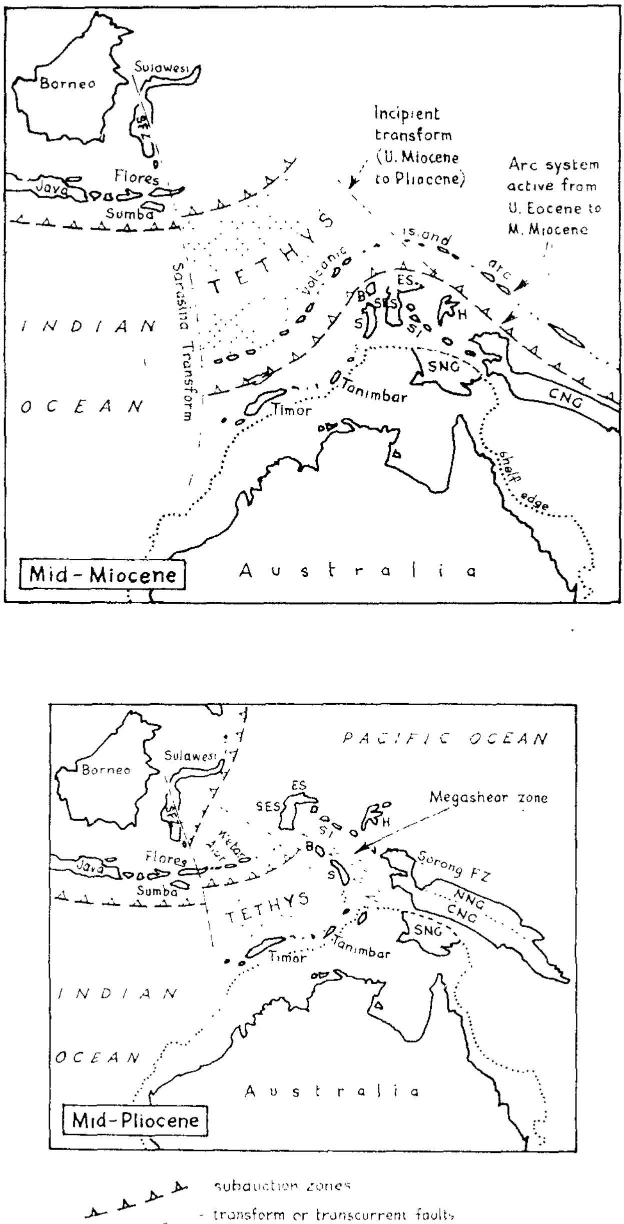


Figure 15. Development of the Banda Sea area: hypothesis of Audley-Charles, Carter and Milsom (1972), showing postulated arrangements in mid-Miocene and mid-Pliocene. The Tethys ocean basin (stippled) has mainly been subducted out of sight at the present day. NNG, CNG, SNG = northern, central and southern parts of the island of New Guinea; B = Buru; H = Halmahera; S = Seram; SES = southeastern Sulawesi; SFZ = Sarasina (Palu) Fault Zone; SI = Sula Islands.

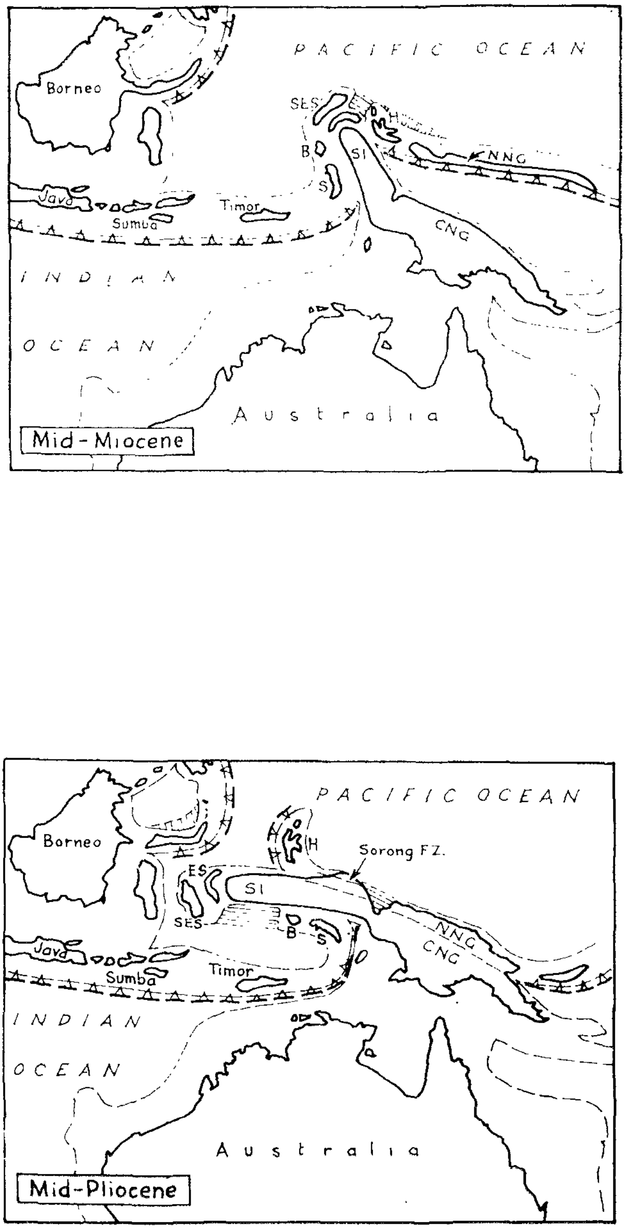


Figure 16. Development of the Banda Sea area, after Moberley (1972), showing postulated arrangements in mid-Miocene and mid-Pliocene. Symbols and abbreviations are the same as in *Figure 15*, with which this figure should be compared, except that the dashed line indicates the edge of oceanic basins, and parallel lines indicate areas and direction of crustal extension.

Samoa-Marshall Islands chain and the Tuamoto Islands-Line Islands chains show a similar extent and the same bend in the middle, as pointed out by Morgan (1972) who interpreted these features and the progressive decrease in age towards the southeast to mean that the West Pacific Plate had moved progressively over three mantle "hot spots" *(Fig. 17)*. The seamount chains were seen as resulting from mantle convection and associated volcanicity; this is still active at the chain ends, as in the island of Hawaii, the outer end, near Kamchatka, being about 70 m.y. old (end Cretaceous). The age of the bend of the seamount chains is obviously of critical importance for, if the hot spots were basically stationary, the bends record a change in the direction of plate motion. A date of 42-44 m.y. (late Ecoene) for the bend in the Hawaiian-Emperor seamount chains was estimated by Clague and Jarrard (1973). It appears that the West Pacific Plate moved slowly (about 4 cm/yr) relative to the Hawaiian hot spot from then until about 16 m.y. (mid-Miocene), accelerating to about 15 cm/yr in a west-northwesterly direction from that time onward (McDougall, 1971).

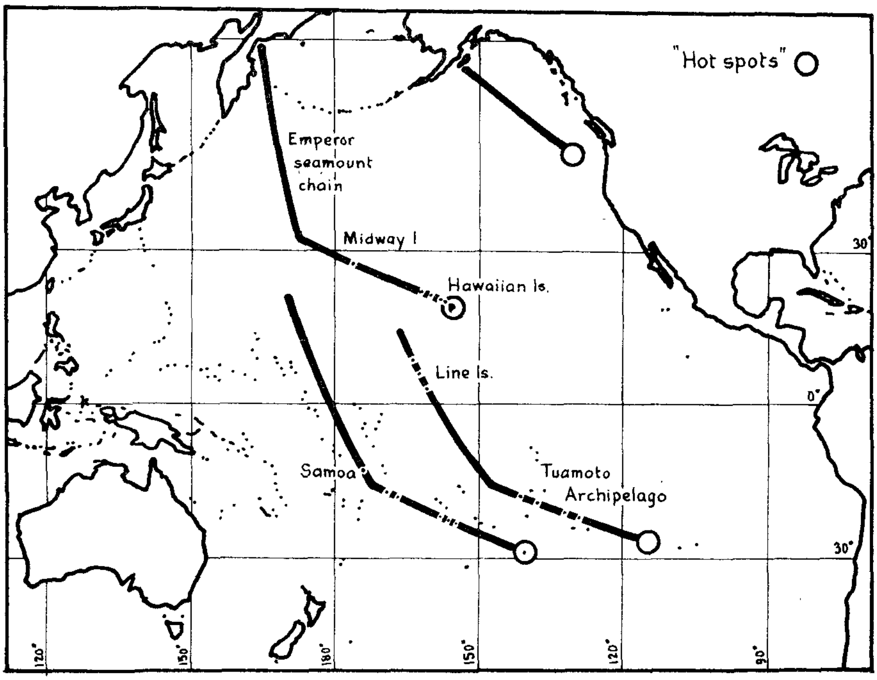


Figure 17. "Hot spot" trajectories constructed by rotating the Pacific Plate over four fixed "hot spots" (Morgan, 1972).

The general westward motion of the West Pacific Plate since the Miocene has largely been accommodated by oceanic crust subduction along its western margin from the Kurile arc-trench system through the Japan and Marianas Trenches to the Caroline Sea area, truncated to the south by a transcurrent fault zone along the north coast of the island of New Guinea. Motion appears to have been more rapid at the northern end of the plate junction, and southeast of New Guinea motion was transferred to the Tonga-Kermadec Trench. Seismological studies indicate that the Izu-Bonin and Marianas arc-trench systems are zones of active subduction with slip directions of recent earthquakes generally perpendicular to the arc at each epicentre (Fitch, 1972), and a generally east-west plate convergence with the overriding Philippine Sea Plate is indicated. Seismicity declines to the south, particularly at deep levels, and, south of the Palau Islands segment of arc, subduction is apparently inactive.

The *Philippine Sea* appears to be an entirely oceanic plate bounded on most sides by active subduction zones; on the east, the West Pacific Plate is being over-ridden, as mentioned, while on the northwest and southwest sides it appears to be underthrusting the Eurasian Plate and the Philippine archipelago along the Nankai-Ryukyu and Mindanao Trenches. Subduction northwards under Shikoku in the Nankai Trough is thought to have commenced in the last few million years (Fitch and Scholz, 1971). Left-lateral slip motion is apparent along the Philippine Fault, the Longitudinal Fault of the island of Taiwan, and right-lateral slip along the Median Tectonic Line of southwestern Honshu and the Sagami Trough; the last-named is thought to be the locus of movement of the triple-point plate junction (Fitch, 1972) with a slip velocity of 7 cm/yr *(Fig. 18)*.

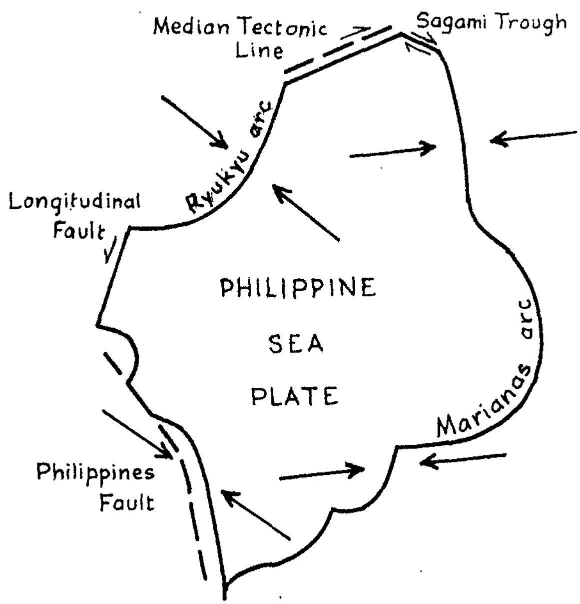


Figure 18. Convergence along margins of Philippine Sea Plate. Large arrows are inferred relative motion between adjacent plates (from Fitch, 1972).

The oceanic character of the plate was demonstrated by Murauchi et al. (1968); heat flow is normal over much of the basin (Watanabe et al., 1970), but high in the Parace Vela Basin, east of the aseismic north-south Palau-Kyushu ridge. This ridge appears to consist of seamounts in its northern part, and has a generally rugged topography draped by sediments which thicken away from the crest (Ludwig et al., 1973). Parallel with it to the east is the less well-marked Yap-Shikoku ridge, followed further east by the Marianas-Bonin arc system. The Marianas Arc consists of two ridges separated by the Mariana Trough, up to 250 km wide, which is termed an "*inter-arc basin*" by Karig (1971b). This is not the same as the inter-arc trough of the arc system model (p. 11), but is a trough feature found behind the volcanic arc of several West Pacific oceanic arcs; it is bounded on the concave side by a "third arc", which appears originally to have been part of the volcanic arc itself (Karig 1971a). Karig concluded that the basin had been formed by extension, on the basis of the steep normal faults bounding the basin, and the almost sediment-free block-faulted basin floor *(Fig. 19)*. Spreading of the basin was considered to be due to a low-density mantle diapir upwelling from the vicinity of the Benioff zone. The Palau-Kyushu Ridge may also have been a third arc, formed in pre-Miocene time as the western margin of the Parace Vela Basin.

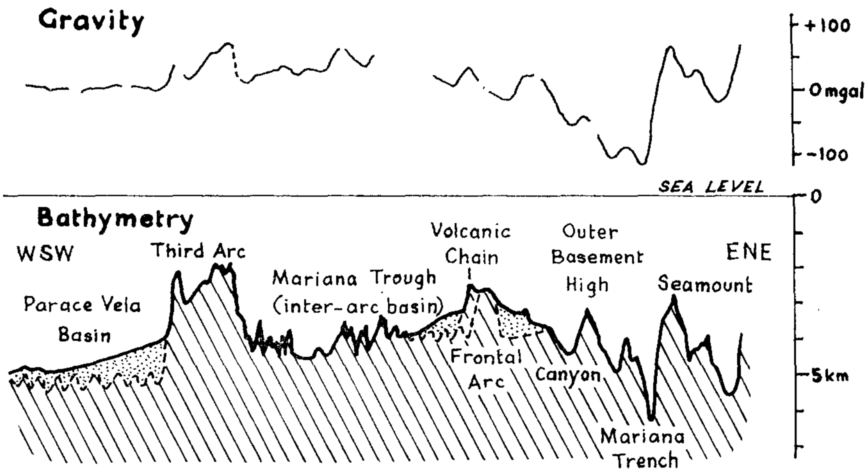


Figure 19. Bathymetric and free-air gravity profiles across the Marianas arc system between latitudes 18°N and 20°N (Karig, 1971a). Sediments shown stippled.

The high-heat-flow basinal areas of the Philippine Sea Plate may owe their origin to spreading in response to such diapirism; they become older and deeper to the westward, with generally decreasing heat flow. However, the West Philippine Sea Basin, west of the Palau-Kyushu Ridge, shows only normal heat flow, and symmetrically-disposed magnetic anomaly patterns led Ben-Avraham, Bowin and Segawa (1972) to suggest that the Philippine Ridge (Central Basin Fault) crossing the basin diagonally was an extinct spreading axis, and that the age of the oceanic crust was Mesozoic.

Results of Leg 31 of the Deep Sea Drilling Program supported a crustal-extension interpretation for the eastern part of the basin, and dated the opening of the Parace Vela Basin as late Oligocene, consistent with the pre-Miocene date for the Palau-Kyushu ridge on its western boundary. Drilling in the western part of the Philippine Sea did not, however, support the idea of an extinct spreading axis, but indicated a more complex history of formation for that plate segment, mainly Eocene in age (DSDP Scientific Staff, 1973c).

As previously mentioned, the *Mindanao Trench* and its associated subduction zone is terminated southwards in the vicinity of Halmahera by a left-lateral transcurrent fault along the north coast of New Guinea. Hamilton's tectonic map (1972) shows a similar fault, asymptotic to the other and associated with a parallel subduction zone, truncating the seismically-inactive Palau arc segment. Seismic activity is considerable along the trench and the adjacent Philippine archipelago, however, with the Benioff zone under Mindanao steepening to 65° below 300 km. Indicated earthquake motions are for westward slip on the Benioff zone (down-dip with a left-lateral component); movement on the transcurrent Philippine Fault is in the same direction (Fitch, 1972). Volcanicity appears to be concentrated partly along this fault zone (with an obvious similarity to the situation in Sumatra) but also in a parallel zone roughly 100 km further west.

The *Philippine archipelago* is a complex structural unit formed by at least four arc systems which had coalesced by late Oligocene, since tectonically-mixed "basement" formations older than this are found throughout the islands, together with large ultrabasic masses. Intermediate to acidic plutonism and late Cenozoic sedimentary basins, affected by Miocene tectonic activity, have combined to produce a proto-continental crustal unit from materials which appear to have been originally derived from an oceanic crustal environment (Murphy, 1973).

West of Luzon lies the Manila Trench, a narrow sea-floor feature below 4,000 m which appears to be the site of a subduction zone dipping eastwards beneath the island, in an opposite direction to the Mindanao subduction zone. The Manila Trench zone swings round southeastwards near Mindoro and apparently terminates there; the Mindanao zone swings to a roughly northeast alignment on the opposite side, converting (according to Karig, 1973) into a left-lateral transcurrent fault, and adjoining another short subduction zone in the north-south trench off the Sierra Madre (east) coast of northern Luzon. Seismic evidence shows this latter zone to be active, with near-westerly underthrusting, whereas on the west side the Manila Trench zone has a poorly-developed Benioff zone to 200-km depth, with near-vertical movement indicated.

The Manila Trench and several en-echelon sea-floor ridges and troughs can be traced northwards in a zone reaching the southern end of the island of Taiwan, with some correlation with features on that island. The sea-floor structure was interpreted by Karig (1973) to represent a volcanic (frontal) arc sliced by several north-northeast-trending left-lateral faults which swing more northerly east on the Taiwan coast *(Fig. 20)*. Active and late Cenozoic volcanic centres are located on this arc, probably related to the eastward underthrusting north of Luzon; this is indicated by earthquake foci, some of which show a component of left-lateral slip.

The *island of Taiwan* appears structurally to consist of two major Cenozoic arc systems in collision with one another and with the China craton. One, which now forms the major portion of the island, includes Palaeozoic-Mesozoic metamorphic and Cenozoic sedimentary rocks in major westward-vergent nappes, possibly formed by a mid-Tertiary orogeny. Karig (1973) considered these rocks to have been an eastward-facing arc system that was later thrust westwards onto the China craton, thus closing a marginal basin that may have been a northern extension of the present China Basin. The east coast mountains, however, represent a later arc system thrust onto the main part, and separated from it by a normal-faulted rift zone, the Longitudinal Valley, along which present seismic activity shows left-lateral movement. Late Cenozoic mélanges and olistostromes are present in the east coast portion, which Chai (1972) viewed as an arc system with eastward underthrusting that collided with the island in late Tertiary times. It appears to be a continuation of the west Luzon arc system, with the mélanges probably representing material scraped off in the pre-existing trench.

Both the arcs on Taiwan, the western Luzon arc and the marine area in between show west-facing systems with eastward subduction in the past, seismic activity at present day indicating similar tendencies. The east Luzon Sierra Madre, however, shows westward-dipping structures of pre-Miocene age, and offshore is the short trench and subduction zone already mentioned; further south is the far more well-marked Mindanao subduction zone, also dipping westward. East of the island of Taiwan lies the Ryukyu Trench subduction zone with westward underthrusting changing to right-lateral movement in its east-west portion near the island. Chai (1972) visualized a complex plate interdigitation accommodating the collision by mutual underthrusting in different sectors linked by transcurrent faults *(Fig. 21)*; it may be significant that the sector where eastward underthrusting has taken place is that part backed by the China Basin, while the other sectors are adjacent to cratonic shallow-water or archipelago areas.

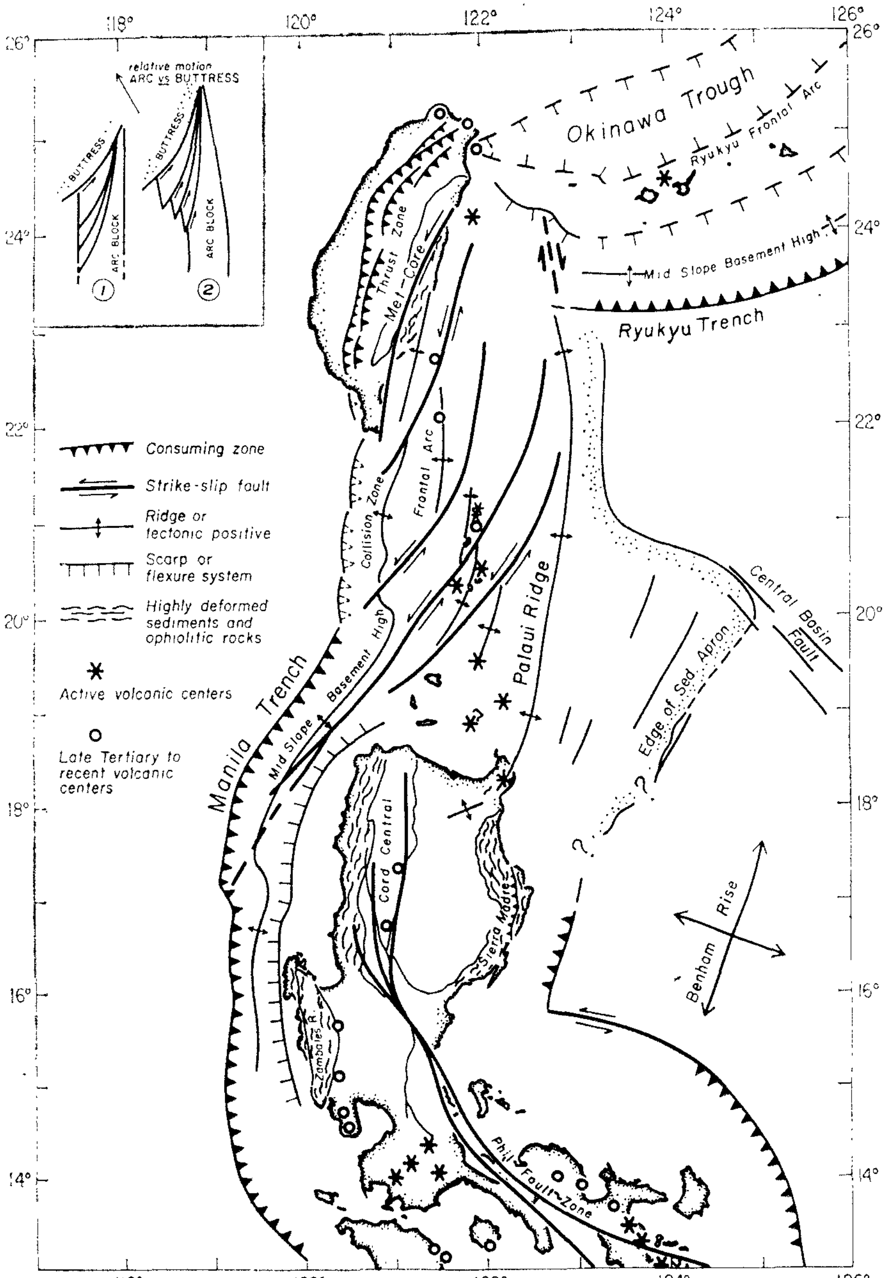


Figure 20. Tectonic elements of the Luzon-Taiwan area showing probable subduction (consuming) zones, faults, scarps, volcanic centres, etc. The inset shows a possible schematic mechanical solution to explain the internal deformation within the arc system (Karig, 1973).

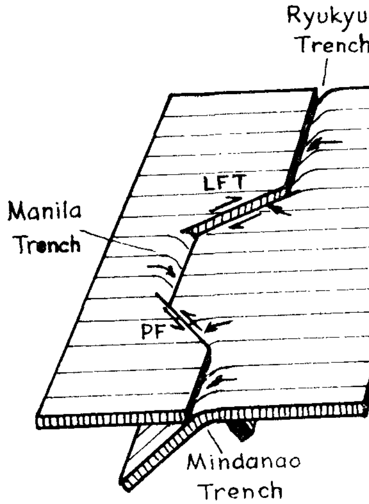


Figure 21. Visualization of the plate convergence arrangement in the Philippines-Taiwan-Ryukyu Islands area (Chai, 1972). LFT - Longitudinal Fault of Taiwan; PF - Philippines Fault.

The *China Basin*, the parallelogram-shaped deep-water portion of the South China Sea between the Indochina peninsula, Borneo, the Philippines and southern China, has part of its floor below 4,000 m, but more than half is shallower and two areas of reefal islands are present—the Paracel Islands and the large area to the south known as the Dangerous Grounds, including the Spratley and Nanshan Islands. The 2,000-m deep Palawan Trough separates these from northern Borneo and Palawan. Several northeast-southwest buried ridges, complexly folded and faulted and with some volcanic peaks, were mapped in the shallow areas by Emery and Ben-Avraham (1972); they are partly overlain by thick sediment *(Fig. 22)*. The north-south ridges associated with the Manila Trench and West Luzon Trough, as already described, appear to truncate the northeast-trending ridges. Emery and Ben-Avraham regard those ridges as having been due to northwest-southeast compression, and include the island of Palawan in this assessment.

The deeper parts of the China Basin appear to be normal oceanic crust, with magnetic anomalies in the area west of Luzon which suggest an east-west magnetic lineation; other areas are relatively "quiet" magnetically. Ben-Avraham and Uyeda (1973) regarded these lineations as resulting from oceanic crust formation by north-south spreading, though no spreading axis is evident. It was inferred from the anomalies and the related magnetic quiet zones that the age of the oceanic crust was Mesozoic, probably late Jurassic-early Cretaceous, similar to the oceanic crust of the West Pacific. From comparison of the pre-Cenozoic geology of the Indochina peninsula and the is-

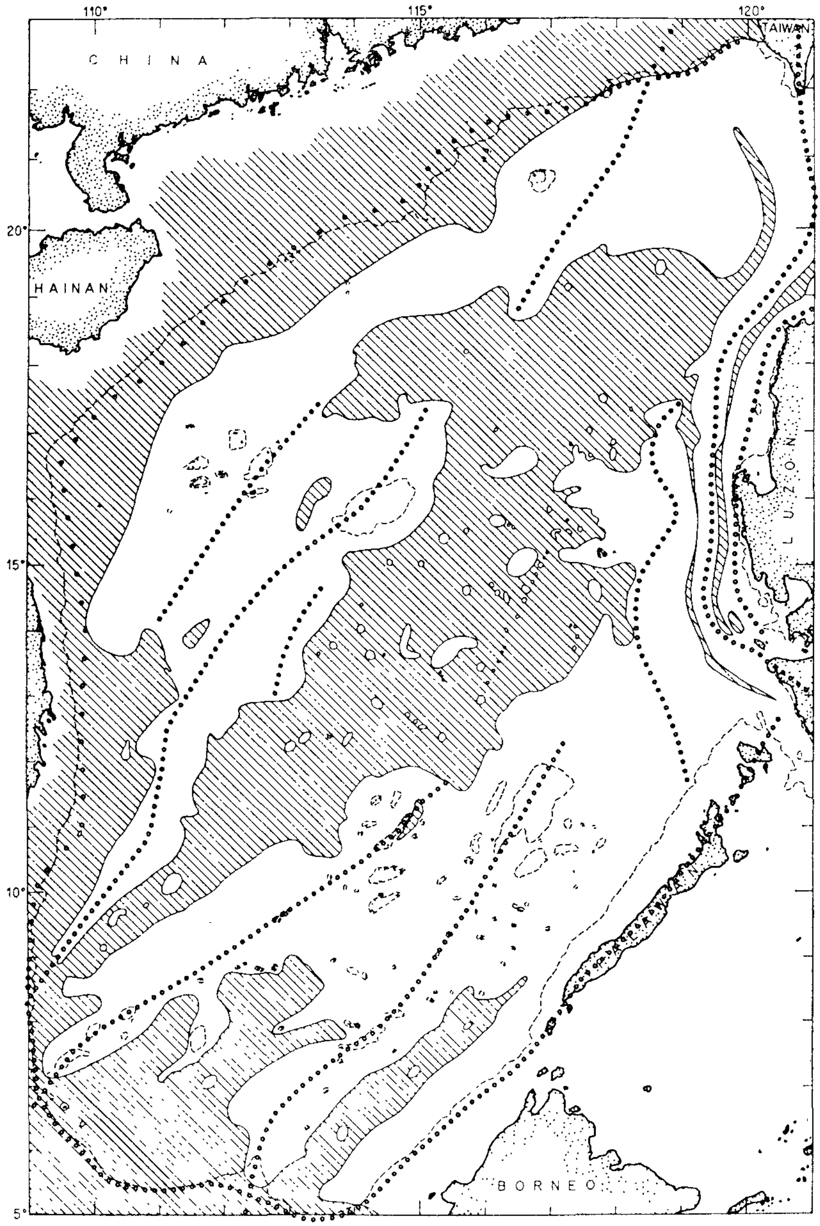


Figure 22. Ridge structure of the China Basin (South China Sea). The ridges (shown by lines of dots) are peripheral to the basin or pass diagonally across it, the latter presumably the result of compression or arc system development (as in Palawan) The shaded areas are covered by post deformational sediment which, in the basin, generally occupy the deeper water areas (Emery and Ben-Avraham, 1972).

land of Borneo, they suggested that these two cratonic units had once been continuous and that Borneo had drifted southwards at the time of sea-floor spreading. This conclusion, however, was based on disputed correlations, though recent work by Lau (1973) supports the suggestion on the palaeobiogeographic significance of rudists and associated faunas in Sarawak. The northeasterly-trending structures in the basin were possibly formed by a contrary movement, of Borneo northwestwards at the time of folding of the Northwest Borneo geosyncline (the Miri and Sibu zones of Haile, 1973) in the late Cenozoic; though an earlier date for these structures is more likely as strong early Cenozoic deformation occurred along the same strike in Palawan, and the north-south Manila Trench and associated ridges were probably active from Miocene onwards and these truncate the earlier structures. The change of compression direction from northwesterly to westerly might be correlated with the alteration of plate motion shown for the West Pacific Plate by the bend in the seamount chains, dated at 44 m.y. (late Eocene) (p. 50).

The *Sulu Sea* lies between the parallel ridges of Palawan and Sulu Islands-Zamboanga, with another submerged ridge in between, the Cagayan Ridge which reaches surface as a few reefal islands and links with the island of Panay. These northeast-trending ridges and the intervening basins meet the northeast Borneo shelf but continuity is uncertain with the cross-trending Miocene fold and ophiolite belt present in the northeast corner of that island. The Sulu Sea Basin is deep only in its southeastern portion, where about half the area is below 4,000 m; northwest of the Cagayan Ridge are terraces at 1,500 m and 2,000 m. This latter portion is underlain (Murauchi et al., 1973) by a sedimentary wedge thickening towards Palawan to as much as 7,500 m, underlain by rocks which are probably a continuation of the volcanic rocks of the Cagayan Ridge *(Fig. 23)*; these in turn are underlain by rocks which may be a continuation of the Palawan pre-Jurassic basement, involved in early Cenozoic orogenesis on that island. This portion of the sea may be an infilled graben down-faulted on its northwestern side.

The deep-water basin southeast of the Cagayan Ridge is apparently of normal oceanic character, with the trough adjacent to its southern margin representing an inactive subduction trench. The Sulu-Zamboanga Ridge is composed of volcanic, ultramafic and marine clastic rocks with some pre-Jurassic metamorphic basement, and is probably a remnant arc similar to Palawan (Karig, 1972) but not necessarily contemporaneous. Both island ridges appear to have been formed by southeastward underthrusting on the southerly margins of small ocean basins. One and possibly both basins may represent pre-Cenozoic oceanic crust cut off from the West Pacific Plate by successive subduction zones.

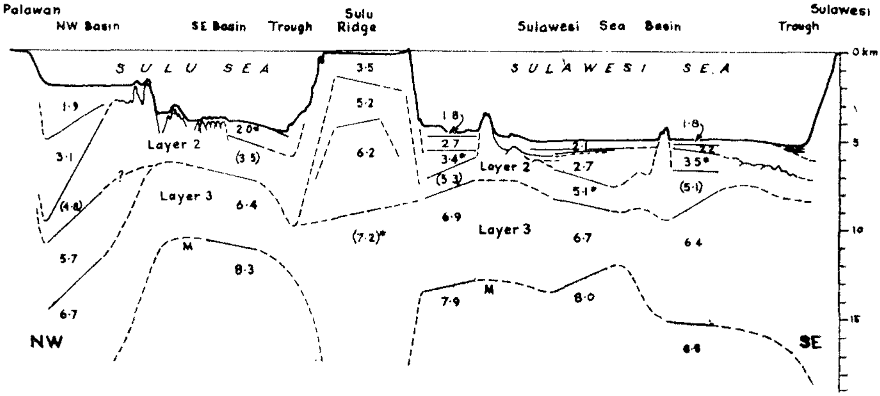


Figure 23. Geophysical structure section from Palawan to northern Sulawesi, showing the inferred velocity layering of the basins and ridges of the Sulu and Sulawesi Seas (Murauchi et al, 1973). From bathymetric, seismic refraction and seismic reflection data. Velocities in kilometres per second; asterisk, assumed velocity; brackets, velocity of layer observed at one end of line or from later arrivals.

The *Sulawesi (Celebes) Sea* presents a similar tectonic picture, with a possibly still-active subduction zone along its southern margins against the Minihassa Peninsula of northern Sulawesi (p. 46). The sea is mostly more than 400 m deep and shows no sign of any spreading axis, so this also may be older oceanic crust trapped between remnant arcs. The steep western margin may be controlled by a transcurrent fault, in line with the Palu Fault in southern Sulawesi, but partly overgrown by a reefal shelf. The eastern margin is marked by the seismically-active Sangihe arc with westward underthrusting (p. 46). In contrast to the high heat flow values in the Sulu Sea, heat flow in the northern part of the basin is about normal (Nagasaka et al., 1970).

The *Ryukyu Islands* arc appears to be continuous with the Southwest Japan Arc, but the marginal basin behind the arc, the Okinawa Trough, is poorly developed in comparison with the Japan Sea marginal basin. The Ryukyu Arc is situated on the margin of the Eurasian continent, backed by the large shallow shelf areas of the East China Sea and Yellow Sea and the adjacent delta land areas of northern and central China. At its western end, the arc appears not to be continuous with the island of Taiwan, apparently offset by a right-lateral north-south transcurrent fault in a highly seismic zone off the east coast (Wu, 1970).

The islands of the arc, of which Okinawa is the largest, consist mainly of folded Mesozoic rocks, with some Palaeozoic and Cenozoic, intruded by early Cenozoic granites; the fold zone appears to be continued in the Shimanto Zone of southern Kyushu and eastwards in the Japanese islands, and to be related to the central zone on the island of Taiwan *(Fig. 24)*. This feature occupies the position of the outer non-volcanic arc in the arc-system model, though clearly formed of rocks of an earlier cycle. The inner volcanic arc is

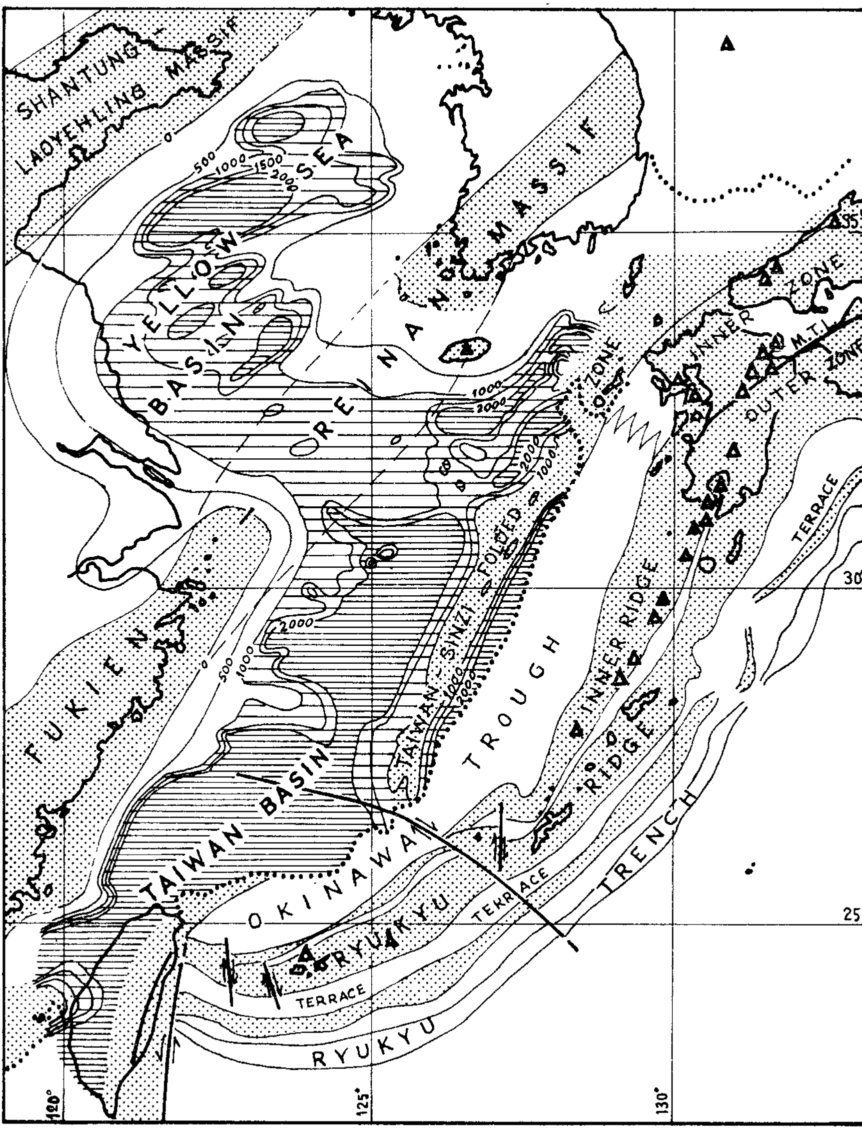


Figure 24. Major structural zones of the East China Sea and vicinity, showing total sediment thickness in the continental shelf areas; sediment thicknesses are in metres. Dotted line is the edge of the shelf; solid lines, transcurrent faults; stipple, ridge features; horizontal shading, sedimentary basins thicker than 1000 m (wide shading) or 2000 m (close shading). Triangles are active volcanoes. (From Wageman, Hilde and Emery, 1970).

represented by a line of small andesitic volcanic islands which extends over 500 km from the volcanic centres of southern Kyushu parallel to the main Ryukyu Arc, but some 70 km northwest (Wageman et al., 1970).

On the oceanward side of the arc there is a terrace at 2,000-3,000 m depth, consisting apparently of igneous basement and thick sedimentary formations. Beyond this is the Ryukyu Trench, with a maximum depth of 7,881 m, which is the depressed northwestern margin of the West Philippine Sea Basin, itself mainly 5,000-6,000 m deep. The trench contains thin undisturbed sedimentary layers, and structurally truncates several seamount ridges trending west-northwesterly, and the more prominent north-south Palau-Kyushu Ridge which may have been a former volcanic island arc.

North of the arc is the Okinawa Trough, over 2,000 m deep in its southwestern part but with relatively gentle topography; a well-marked 10° continental slope separates it from the Yellow Sea shelf. The sediment infilling of the trough exceeds 1,200 m in much of the area (Wageman et al., 1970), and is interrupted by volcanic peaks or uplifts. Deformed lower Cenozoic sediments were recognized in the trough and arc near Kyushu, probably continuous with the Mesozoic-early Cenozoic Shimanto Group. High heat flow in the trough suggests that it is a slowly spreading incipient marginal basin (Watanabe et al., 1970; Karig, 1971a).

Seismic evidence in the Ryukyu arc-trench system indicates northwestward underthrusting by the Philippine Sea Plate to depths of as much as 300 km, though this direction may be a vector resultant of the west-northwest motion of the plate with a southerly motion of the arc. Karig (1973) suggested a sharp bend in the Luzon-east Taiwan late Cenozoic fold belt to link with the Ryukyu Arc, though this is now displaced by the right-lateral transcurrent fault. The presence of the left-lateral Longitudinal Valley fault on the island of Taiwan suggests the northward movement of the east coast crustal segment, if not of the whole island. Meng (1970) suggested that the Ryukyu Arc once extended westwards across the present position of the island to the Penghu Islands (Pescadores) off the west coast during the Miocene, the ridge having acted as a sediment dam, but having been overwhelmed by the east-west orogenic compression in the Pliocene which constructed the island as now seen.

The structure of the *East China Sea* and *Yellow Sea* continental shelf, and the shallow water and coastal areas of the adjacent China mainland and Korean Peninsula, consists of large sedimentary basins separated by basement ridges, with the northeast trend which is characteristic of the whole northeastern Asian continental margin (p. 26). The structural framework of part of the area has been presented by Wageman et al. (1970), who mapped the extent of submerged sub-parallel ridges and basins in these seas, including the Ryukyu arc system *(Fig. 24)*.

The basement ridges include the Precambrian-Mesozoic metamorphic-plutonic Fukien Massif of southeastern China, which links with the Reinan (Yongnam) Massif and Okchon Geosynclinal Zone of the southern Korean Peninsula; and the Shantung Precambrian massif, which probably continues as the Lias-Gaema Massif of the northern Korean Peninsula and southern Manchuria. Another ridge, completely submerged and hidden by sediments, occurs close to the edge of the continental shelf and is known as the Taiwan-Sinzi Ridge, though this is now thought to terminate against the Okinawa Trough some distance northwest of the island of Taiwan; it apparently outcrops on Tsushima and the Goto Islands, in the Korea Strait, where folded early Cenozoic sedimentary and volcanic rocks are known.

In the sedimentary basins, two sequences were recognized from seismic profiling (Wageman et al., 1970), the lower showing some structural deformation along the prevailing strikes, probably due to Miocene movements, and a thicker undeformed Neogene sequence overlying it unconformably. The thickest Neogene occurs in the Taiwan Basin, northeast of the island, with over 2,000 m of infill (this being the limit of the seismic equipment employed), and thicknesses of 1,400 m Neogene and 2,000 m total Tertiary were recorded in the Yellow Sea. The basin north of Shantung, the Gulf of Chihli (Po-hai) appears to be another deep basin. Until the Cenozoic, the basement ridges acted as sediment dams and only non-marine rocks were laid down in these basins, but the Tertiary is thought to be mostly marine. Magnetic lineations in the shelf area are parallel to the northeast strike and presumably result from magnetic basement.

The island arc of *Japan* has been more thoroughly studied than most other arcs, and considerable structural complexity is known. Its geological history goes back to the Carboniferous or earlier, but as an island arc it appears to have been in existence only since early Miocene times, when active volcanism commenced suddenly and continued in much the same location to the present day. Its pre-Cenozoic geological development has been reviewed by Murphy (1973). The presence of Cretaceous-early Cenozoic granites suggests that most of Japan was formed in association with the Korean Peninsula and the mainland area of the continent, implying that it drifted southwards uncovering the Japan Sea Basin in so doing. The folded Shimanto Zone, with thick mid-Cretaceous—early Cenozoic geosynclinal turbidite accumulations, presumably represents trough deposits scraped off by the advancing overriding Honshu Massif, and now divided from it by the Median Tectonic Line through Kyushu, Shikoku and southern Honshu *(Figs. 25 &36)*. Concurrently

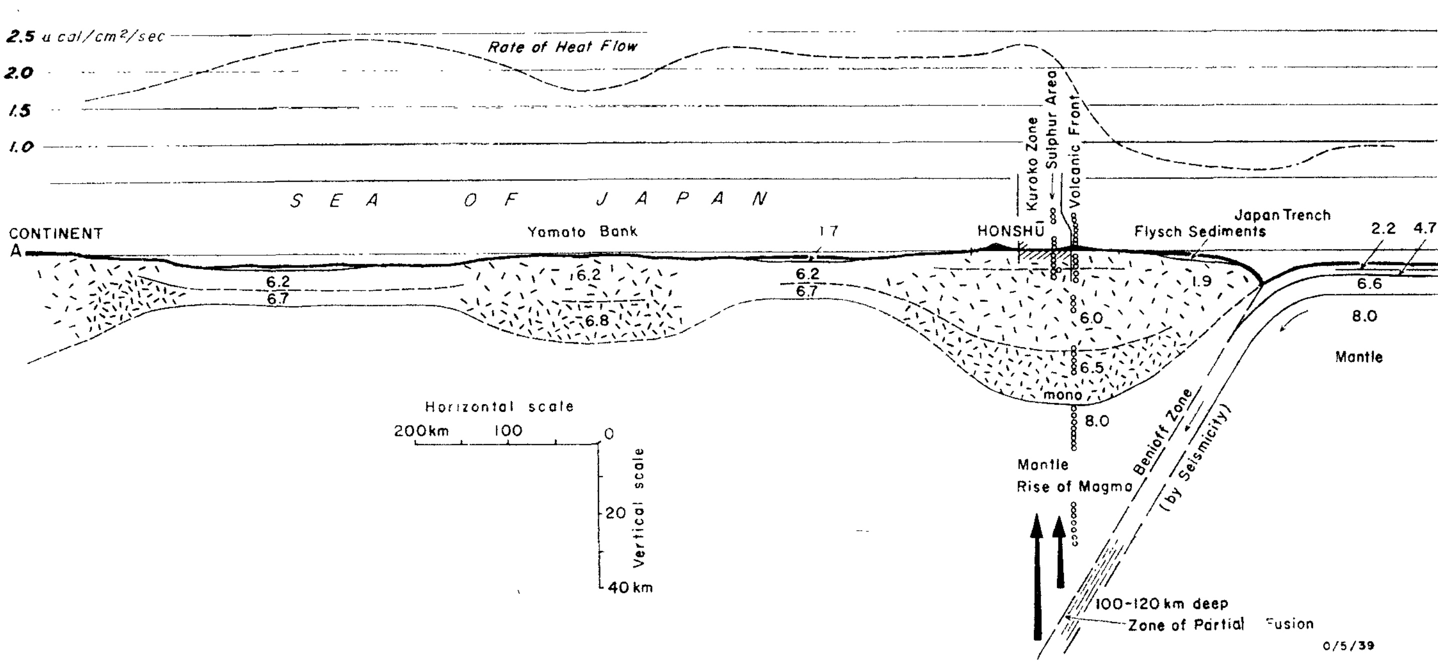


Figure 25. Schematic cross-section of the Japan arc-trench system and Japan Sea marginal basin, showing the presumed lithosopheric structure and heat-flow rates. Velocities of the various layers are given in km/sec (from Nishiwaki, 1973).

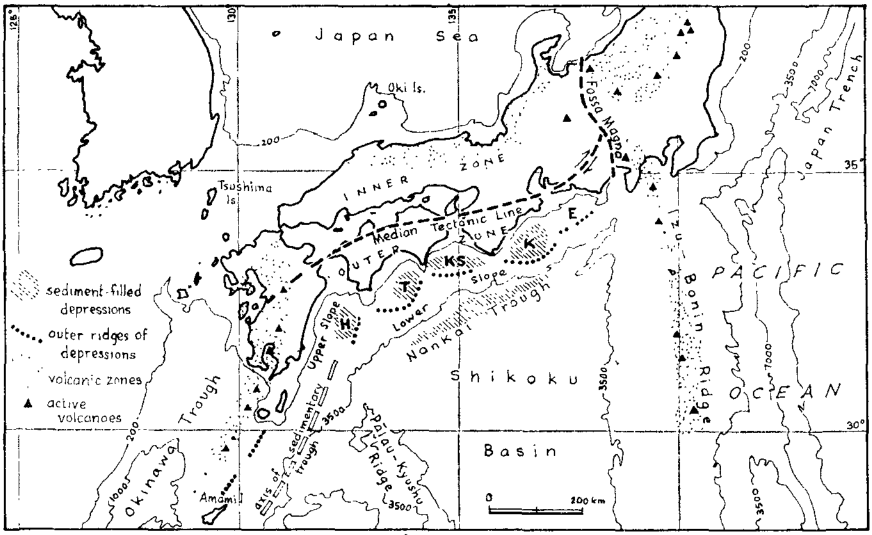


Figure 26. Major structural features of southwestern Japan. Stippled area is zone of Neogene volcanism (green tuff region). Sediment-filled basins: H = Hyuganada, T = Tosa, KS = Kii Suido, K = Kumanonada, E = Enshunada basins. Thick sediments also occupy a trough on the continental slope east of the Okinawa Trough. (From Ludwig et al, 1973).

the magmatic (volcanic) front advanced from the north coast of Honshu in early Cretaceous to the Median Tectonic Line by the end of the Cretaceous.

Shallow earthquake foci along the southern coastline indicate similar underthrusting movement by the Philippine Sea Plate in a northeasterly direction, the same as with the Ryukyu Arc. The Nankai Trough, situated offshore, is a relatively minor depression (4,500 m) on the northern margin of the Shikoku Basin, analogous to but not continuous with the Ryukyu Trench; this may be a remnant of a former subduction trench, or due to incipient renewal of underthrusting motion. Hilde et al. (1969) suggested that the trough was a juvenile oceanic trench in the tectonic sense, based on seismic reflection data interpreted as showing recent folding of the trough sediments against the inner slope. Fitch (1972) cited evidence of underthrusting having commenced 1-2 million years ago, and right-lateral slip movement on the Median Tectonic Line at 0.5 cm/year. East-southeastward movement along the Sagami Trough *(Fig. 18)*, leading to a triple-point junction at its eastern end, is in the same sense, but estimated to be 7 cm/year. The structure of the margin south of Shikoku has been examined by Yoshii et al. (1973), who found over 4,000 m of sediment in the Tosa Basin beneath a terrace on the continental slope, possibly representing marginal accretion of material scraped off the underriding oceanic crust. Results of deep-sea drill holes in the Nankai Trough (DSDP Scientific Staff, 1973c), indicated that subduction started in the Middle Pliocene (3 m.y.); one hole penetrated Pleistocene trench sediments that had been involved in thrusting and showed consolidation to half their original volume and distinct cleavage development *(Fig. 27)*.

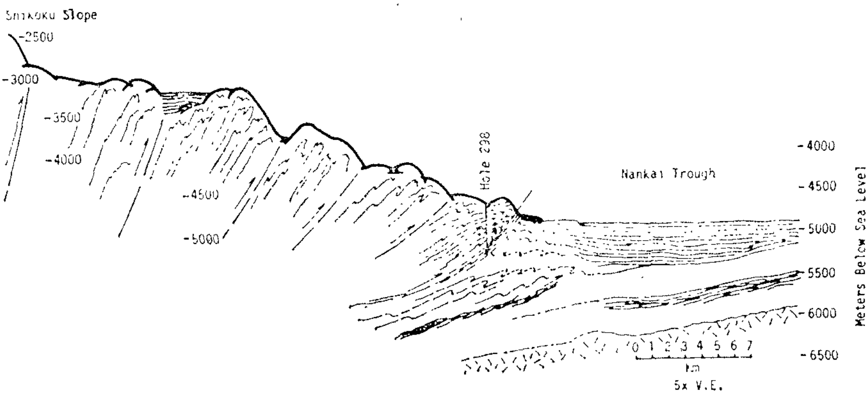


Figure 27. Geological cross-section through the lower inner wall and floor of the Nankai Trough, off southwestern Japan. Solid lines represent velocity-corrected *Glomar Challenger* seismic reflection data, and the basement is extrapolated from a nearby profile by Hilde, Wageman and Hammond, 1969. Deep Sea Drilling Project hole no. 298, in the section, was located south of Shikoku. (From DSDP Scientific Staff, 1973c).

The polarity of older arc systems in Japan has been demonstrated by the type of metamorphism, with high pressure-low temperature effects on the oceanic side (the Shimanto Zone), and low pressure-higher temperature in the inner (magmatic) zone. In southwestern Japan these zones can be traced from the Ryukyu Arc through a bend, at the southern Kyushu volcanic area, and another pronounced bend is shown in central Honshu where the Fossa Magna ("Great Trench") marks a change in trend from northeast to east-southeast; the fold belt disappears under the Kanto Plain around Tokyo. The Fossa Magna is the site of faulting and folding, crossing Honshu northwards from Sagami Bay, with strongly curved fold axes in Miocene rocks wrapped round the volcanic Izu Peninsula; this is also the point where the volcanic Bonin island arc reaches Honshu with present-day volcanic activity, including Mount Fuji *(Fig. 26)*.

The Northeast Honshu Arc is markedly different, with folded Neogene rocks prominent on the western side, extensive active volcanism and Palaeozoic-Mesozoic massifs on the east coast (Murphy, 1973). This is regarded as a more typical example of the Pacific-type orogeny (Matsuda and Uyeda, 1971), with the well-marked Japan Trench offshore mainly reaching deeper than 7,500 m, a magmatic zone reaching the east coast and including active volcanism, and a Benioff zone dipping westward beneath the arc reaching 700 km depth under the Asian continental margin. The arc is linked by angular junctions with two others, the Izu-Bonin and Kurile Arcs, which are overprinted on the former fold belts of southwestern Honshu and the similar one in Hokkaido. Volcanic activity and thick Neogene sedimentation were concentrated in the central western portions of the land area, and folding and granite intrusion took place from early Miocene onwards (Matsuda, Nakamura and Sugimura, 1967).

Although southwestern Hokkaido is structurally continuous with Honshu, the main part of the island is older, with an early Cenozoic north-south fold belt. As pointed out by Matsuda and Uyeda (1971), the polarity of the metamorphic belts is anomalous, with the high pressure-low temperature zone on the eastern side; this can be explained by late Mesozoic eastward underthrusting from the Japan Sea side, or alternatively by northerly underthrusting (as in southwestern Japan) followed by a 90° clockwise rotation *(Fig. 28)*. Intense Miocene folding occurred along the same north-south axis, parallel with structures on Honshu, and a line of volcanic centres now crosses it at right angles, continuing along the Kurile Arc. This line of volcanoes can be followed into southeastern Kamchatka, to the point where the line of the Aleutian Arc intersects at right angles. The north-south fold belt apparently continues northwards into the island of Sakhalin.

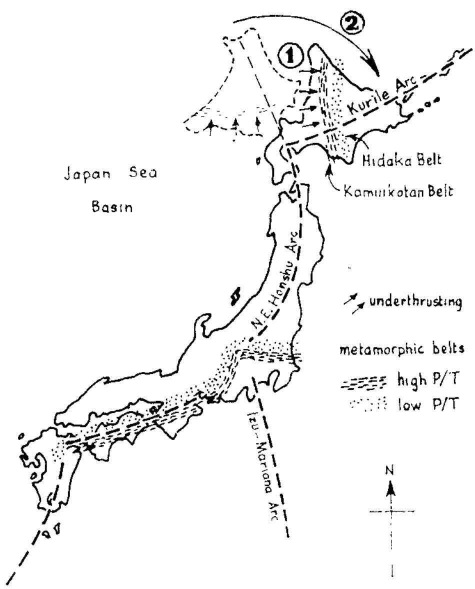


Figure 28. Paired metamorphic belts of Japan and two possible explanations of the reversed belts of Hokkaido: (1) due to eastward underthrusting by the Japan Sea plate, or (2) due to northward underthrusting, as in southwest Japan, followed by rotation to present position (From Matsuda and Uyeda, 1971).

Seaward of northern Japan lies the Japan Trench, which joins the Bonin and Kurile Trenches without break and with moderate bends. Both these latter trenches show depths in excess of 10,000 m, possibly because sediment infilling is less rapid with only small islands nearby, compared to the trench bordering Honshu. Along the Izu-Bonin Arc it has been suggested that the lack of shallow earthquake foci indicates a cessation of plate underthrusting (Kanamori, 1971); this fact, combined with the migration of the Sagami Trough triple-plate junction, prompted Fitch (1972) to suggest that rifting behind this arc was now providing the 7 cm/year displacement, consistent with the inter-arc spreading visualized by Karig for the Marianas Arc further south (p. 52).

The *Japan Sea* is a deep-water (more than 3,000 m over most of its northern part) partly oceanic-crust basin with high heat flow values, making it a typical but complex marginal spreading basin. In its centre is the Yamato Rise, approaching sea level at some points, and islands are present such as Ulnung-do, east of the Korean Peninsula, as well as others on the shelf bordering Honshu *(Fig. 29)*. Evidence from the rise and the islands indicates that the shallower areas have geology similar to the adjacent land areas (Sato and Ono, 1964) and are presumably continental crust rift slivers left behind during the spreading of the marginal basin. Matsuda and Uyeda (1971) presented the heat budget data involved in assumptions concerning this presumed marginal basin spreading, interpreting the southward drift of the Japanese islands as resulting from magma upwelling from the Benioff zone. Its formation was considered to have occurred at the same time as intense early Miocene volcanism (Minato et al., 1964) and ceased before the Pleistocene, as it now shows a mainly-undeformed sediment cover 1,000 m thick in places. Hilde and Wageman (1973) concluded that the sea was formed by rifting of the continental margin during the late Mesozoic or early Tertiary, as a consequence of subduction of an oceanic plate and resultant thermal activity. Their evidence indicated that the opening was by spreading along the present western margin of the Japan Sea until early Miocene time, when a new spreading axis developed to form the Yamato Trough to the southeast, separating the Japanese islands from the Yamato Rise continental fragment *(Fig. 29)*. This interpretation is more in accord with the suspected late Mesozoic underthrusting from the Japan Sea side.

The *Sea of Okhotsk* is also apparently a marginal spreading basin, though with more similarity to the Okinawa Trough than the Japan Sea. Behind the Kurile Arc lies a deep oceanic-crust basin, mostly below 3,000 m, separated from the much larger and shallower northern portion by a slope feature which is approximately in line with the northern margin of the Japan Sea Basin on

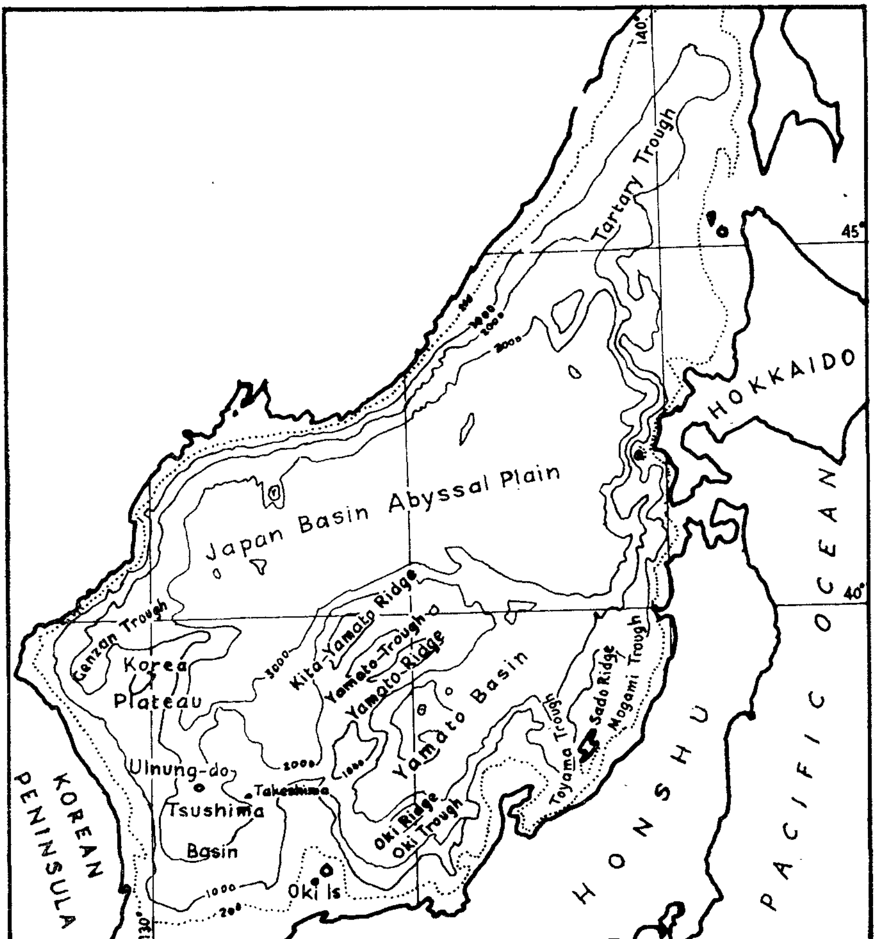


Figure 29. Bathymetry and physiographic features of the Japan Sea (from Isezaki and Uyeda, 1973). Contour interval 1000 m.

the other side of the Hokkaido-Sakhalin ridge. The northern portion has well-marked north-south steep margins with an intervening basinal area mainly between 500 m and 1,500 m deep. The relatively smooth floor of both basins (Bezrukov, 1960) suggests a fairly thick sediment cover, indicating an age comparable with that of the Japan Sea Basin.

Significant tectonic patterns

Marginal basins. Characteristic features of the tectonic framework of eastern Asia, not unique but more developed than in other parts of the world, are the marginal oceanic basins behind island arcs; they are usually deep water (more than 2,000 m) but may partly be sediment filled. There appear to be two kinds, the true *extensional* marginal basins, formed by the upwelling of mantle material to form new crust, and the *remanent*, which appear to represent segments of oceanic crust formerly part of a larger plate but cut off by arc development. It is not always possible to differentiate basins on the basis of origin, at least at the present stage of understanding.

The Andaman Sea and Japan Sea are good examples thought to be of *extensional* type, characterized by rifting and stranded blocks of continental crust; the Marianas Trough is an example in a purely oceanic domain. The Andaman Sea appears to be younger and still active, while the Japan Sea is older and probably inactive, its structural features partly shrouded by subsequent sedimentation. Minor volcanicity and high heat flow appear to be characteristic of this type of basin, due, according to theory, to the forceful injection of a magma diapir from the vicinity of the Benioff zone (Karig, 1971a) or by magmatic intrusion along more widely distributed channels from the same source (Matsuda and Uyeda, 1971). The continental or oceanic crust behind the arc has rifted apart along one or several lines and new crust formed in the gap. The possibility of sagging of the downgoing lithospheric plate, in addition to underthrusting, has been considered by Moberly (1972); this would promote new crust formation in a tensional context and outward migration of the adjacent island arc. In any case, the slope of the Benioff zone, and probably the rate of movement and consequent energy release, could influence the position of magma mobilization relative to the arc system, whether behind a well-developed arc (Japan Sea) or within the arc itself (such as the Marianas inter-arc basin). Volcanicity in the arc itself generally occurs where the Benioff zone reaches 120-200 km depth, creating the magmatic front, characterized by andesitic or more acidic volcanism indicating contamination by sialic material. Formation of basaltic ocean floor in a marginal basin therefore requires that both the underthrusting plate of the adjacent arc system and the mantle zone beneath the basin should contain no sialic material to contaminate the upwelling basaltic material. It might alternatively mean that the upwelling magma would be too cool to be susceptible to contamination on reaching the marginal basin crust.

The *remanent marginal basins*, of which the China Basin (the northern part of the South China Sea) may be an example, show characteristics related both to their former oceanic history and to their later involvement in subduction activity. Heat flow values are generally those of normal oceanic crust, suggesting no significant magmatic activity now or in the recent past. Magnetic lineations testify to their probable origin from mid-oceanic spreading ridges, which should indicate the age of the original crust when dated; the amount of sediment cover also is evidence of their age. These plate segments, however, appear to have been severed from their original larger oceanic plates by subduction and arc formation that took place in the oceanic domain, and the margins of these minor plates may show remains of both old arc segments and subduction trenches. Successive arc systems, subparallel and in age sequence, suggest that there was a systematic lopping-off of plate fragments by subduction, possibly as the result of over-extension of a major plate from its spreading axis so that its distal portions overlapped a stationary zone of mantle down-sinking. Evidence from the Philippine Sea Plate suggests a stable down-sinking zone with the plate moving over it: subduction appears first to have cut off the western portion of the plate, along the line of the Palau-Kyushu Ridge, and moved successively eastward to its present position in the Marianas Arc. As the ridge is dated as Oligocene, and is truncated by the early Miocene Shimanto Zone orogenic belt of southern Japan *(Fig. 25)*, it must be older than 23 million years; so the minimum eastward migration rate of the subduction zone to its present location is 3-4.6 cm/year (depending on position on the arc), consistent with the 3-9 cm/year spreading rates calculated for the East Pacific Rise by Herron (1972) and the 4 cm/year rate quoted for the pre-mid-Miocene segment of the Hawaiian seamount chain (p. 50). The Parace Vela Basin and others formed subsequently appear, however, to be extensional, any intervening older crust having been consumed by subduction.

Whether the China Basin, Sulu Sea and Suluwesi Sea fit into such a pattern is a matter for conjecture. As previously described (p. 56-59) the seas are separated by former arc systems, each with a subduction trench remnant along its northern side; this apparent migration might correlate with the pre-late Eocene north-northwestward movement of the West Pacific Plate recorded in the Emperor seamount chain, though high heat-flow values in the Sulu Sea suggest that this sea might instead have been an extensional inter-arc basin. The change to westerly motion of the major plate may thus have completely altered the subduction regimes in this region.

Reversed subduction zones are another significant feature of the tectonic picture in the region. The Philippines-Taiwan plate boundary appears to be a good example, with underthrusting by the Philippine Sea Plate along the Mindanao Trench line giving way to opposite motion along the Manila Trench and northwards. The island of Taiwan appears to have resulted from eastward underthrusting also, though this could be explained by obduction, the westward overthrusting of a near-surface crustal "flake" where an oceanic plate underrides a continent. It has been remarked (p. 56) that the reversed direction of subduction along this junction appears to occur only where the convergence involves two oceanic plates.

The formation of northern Japan appears, on one explanation (p. 66) to involve a reversal of subduction, with early Cenozoic eastward underthrusting creating the Hokkaido fold belts, now subject to west-northwestward underthrusting. Convergent dipping subduction zones are also a feature of the tectonic development of Sundaland (Hutchison, 1973).

Conversion of plate margin types. There are several cases where rock associations characteristic of a subducting plate margin have been emplaced in assemblages produced in a different tectonic setting. Andesitic hypabyssal rocks originating in the Sunda Arc Benioff zone are intruded, for example, into Triassic shelf deposits in northern Sumatra and into Cretaceous subduction mélanges in Java, each representing a radical change in tectonic setting.

Even more intricate mixing is known. In the south arm of Sulawesi, Tertiary shelf-type clastic rocks and limestones overlie a deformed rock sequence suggestive of a pre-Tertiary or earliest Tertiary plate margin. These rocks include garnetiferous eclogites, blue-schists and ultramafic bodies (Rab Sukamto, personal communication) which may record past subduction activity.

Continental accretion. Small cratonic crustal units have been and are being formed in eastern Asia, where the accretion process is best exemplified and is instructively applicable to almost any cratonic area of the world, from late Precambrian to Cenozoic.

The tectonic development of Sundaland, comprising Borneo, the Sunda Shelf and the Malay Peninsula, together with Thailand and Indochina, has served as an example of accretion for some years, though understanding of the area's geological history is by no means complete (van Bemmelen, 1949; Hutchison, 1973). The fact that present orogenic zones exist alongside younger and older zones of the geological past makes it particularly interesting, compared with most other areas where only the eroded deeper-level structures of past orogenies are available for study. A Precambrian core is present in the Kontum Massif, around which are ranged fold belts which, in general, become younger outwards; this microcontinent became attached to the main Asian craton in the Triassic, along the Red River suture which runs northwestwards from Hanoi *(Fig. 4)*. A similar old microcontinental unit appears to have originated on the west side of the Malay Peninsula, where Lower Palaeozoic rocks form the nucleus of a series of roughly concentric orogenic zones which become younger outwards. Subduction of oceanic crust appears to have commenced in a loop round this core in the Permian, with successive belts of trench and trough deposits being added during peaks of orogenic activity in the Triassic, Cretaceous and mid-Cenozoic, together with granite intrusion *(Fig. 5)*. Only the southern margin of the loop is now active, off Sumatra and the Sunda Islands; but, until late Cretaceous or early Tertiary, orogenesis was in progress in the eastern and northeastern portions of the loop in Borneo and the Natuna Ridge (Hutchison, 1973; Haile 1973). The whole microcontinent is now attached to the Asian craton, forming part of the Eurasian Plate, by north-south fold belts along the Malay-Thai-Burma peninsula, and the Khorat-Natuna Swell; the shallow marine area between these is the site of Tertiary subsidence and sedimentation in an epicontinental tectonic environment (the Gulf of Thailand Basin) *(Fig. 12)*.

Japan and the Philippines are further examples of continental accretion, but in a lesser stage of development. Japan began as a detached segment of the main craton, as shown by Mesozoic and older rocks in many areas, which in themselves represent oceanic, island arc and continental rise facies from former arc systems. Later development of the arc involved the accretion (scraping off) of sea-floor deposits to form the Shimanto Group in the south, and folding of Neogene rocks in the north, together with considerable volcanic additions.

The Philippines archipelago shows a history of arc-building along substantially the same trend since the Jurassic, the components of which have apparently been derived from entirely oceanic sources (except for the pre-Jurassic basement rocks, which may predate the adjacent ocean floors). This points up another aspect of the understanding of continental accretion, that of geochemical differentiation of crustal types from the primary basic materials of the oceanic domain to andesite-granodiorite crustal units such as the Philippines, achieved apparently in three or four volcanicity-sedimentation -orogenesis-plutonism cycles which result from the subduction process. How many cycles are needed for complete conversion to granitic crust may possibly be found by study of more mature continental accretions.

IV. ASSESSMENT OF CRITICAL UNSOLVED PROBLEMS IN SPECIFIC SUBJECT AREAS AND GENERAL RECOMMENDATIONS OF SUBJECT PANELS

The Workshop was divided up, for part of the session, into panel groups concerned with specific subject areas (see p. 4) which were asked to prepare an assessment of the state of knowledge for their respective topics as they related to eastern Asia, to outline problems and critical areas of study, and to make general recommendations for research. The documents that were produced varied in layout, and several subsidiary statements were also submitted; these have been assembled into six reports of panels, below, but in reading these their diverse origins should be borne in mind.

REPORT OF THE GEOPHYSICS PANEL

The marginal seas of eastern Asia are bounded on their oceanic sides by major arc-trench systems and backed by portions of the Asian continent. Submarine morphology, seismicity and geology of the island arcs indicate that the area is composed of several small lithospheric plates, but the present relative motions (kinematics) of these are virtually unknown: the only existing evidence for the movement and for the actual plate boundaries comes from study of the earthquake foci. These studies are at present inadequate to identify present day or former plate motions, because the sizes of the inferred plates are small in comparison with the resolution capability of earthquake-location and fault-plane-solution techniques presently available in the region. Other indirect evidence of past plate convergences can be obtained from the known geology of the region, specifically the distribution of deformed flysch-ophiolite belts, mélange zones and other structural and metamorphic indications which are interpreted as indicators of subduction or obduction at plate boundaries. The presently available marine geophysical data—although capable of providing a reasonable reconnaissance picture of the morphology, gravity and thickness of marine sediments, the gross crustal structure and magnetic lineation fabric—do not provide a sufficient basis for a non-controversial plate tectonic interpretation.

In any geophysical study of the region, two major objectives should be to determine the minor-plate motions and to understand their role in influencing the zones of underthrusting. From these, present or past areas of geothermal and magmatic activity may be located, with their associated zones of mineralization. One of the first steps should be to obtain data relevant to present and past plate motions for as many small plates as possible, utilizing seismicity and magnetic lineations as well as gravity and heat flow data. Within the region there are two relatively large autonomous plate-like structural units, marginal basins possibly of remanent type (p. 70): the China Basin (the deeper part of the South China Sea) and the western part of the Philippine Sea Basin; within these areas existing data strongly suggest the presence of sea-floor magnetic lineations. Further work is needed to map these and to relate them to the known geomagnetic time scale; evidence should be sought also for unusual tectonic or thermal activity which may be responsible for the apparent magnetic "quiet zones".

Recommendations for studies

The Geophysics Panel recommended four major categories of study, of which the fourth related to three specific sub-disciplines: seismology, palaeomagnetism and heat flow. The prime objective of all four is to increase the understanding of the tectonic framework of eastern Asia and its relationship to the genesis and evolution of ore deposits and hydrocarbon accumulation.

1. *Compilation and synthesis of all existing marine geophysical data:* particular emphasis should be given to the largely-unpublished gravity, magnetic and heat flow data accessible in research institutions in various countries. One product might be a marine geophysical atlas, including magnetic lineations, sediment thicknesses, crustal thicknesses, free air and simple Bouguer gravity anomalies, and regionally-averaged heat flow data. These compilations must, of course, include existing land-based geophysical data and detailed offshore seismic information which may be made available from various oil company exploration activities. The preliminary compilation work covering the entire Pacific recently initiated by the AAPG-CCOP Circum-Pacific Energy and Mineral Resources Conference should be expanded and extended to synthesize the detailed geophysical results.

2. *Detailed multidisciplinary geophysical/geological traverses* across selected island-arc, trench and marginal basin areas. The primary objectives of these observations are to improve the understanding of the processes of crustal subduction and/or obduction, particularly in terms of the creation and nature of mélange and other tectonically mixed zones, concentrations of metals in sedimentary strata or crustal rocks, and to study the way in which stored thermal and seismic energy is released along preferred zones beneath island arcs.

3. *Broad marine geophysical surveys in the deep marginal basins of eastern Asia:* these surveys would utilize standard deep-ocean multidisciplinary geophysical techniques, which could be conducted at relatively low cost. The primary objectives of such surveys would be to define the age and past kinematic relationships of small crustal plates within the region. As the inferred plates are small relative to the major plates which form the principal crustal elements of the region, it is likely that many of the typical tectonic expressions observed at major plate boundaries may be obscured by the

effects of multiple small-plate interactions. In these situations the importance of vertical motions relative to horizontal ones in mineralization processes may be enhanced; this aspect should be taken into account in any detailed investigations of land and sea-floor morphology, for instance when interpreting data from ERTS imagery, and is dealt with in more detail on p. 82-83.

4. *Regional studies in specific geophysical disciplines* are needed in addition to the studies outlined above. These could be conducted independently, although some might be combined (such as palaeomagnetic and radiometric sampling) to minimize the necessary field effort. The results of all studies should complement each other and should serve to improve understanding of the tectonic evolution of the region.

Seismology. Interpretation of current orogenic activity and reconstruction of past orogenies marginal to eastern Asia would be less ambiguous if deep and intermediate earthquakes as well as shallow activity were more accurately located. Since seismological stations are sparsely distributed in the region, determination of earthquake foci positions is subject to inaccuracies of up to 50 km, the accuracy varying from one part of the region to another; uncertainty of this magnitude is critical when subduction mechanisms are being investigated.

A long term project involving as many as 20 permanent recording stations and a five-station portable network has been suggested as a minimum requirement for improved focus determination throughout the region. This would be very expensive, so, in conjunction with the suggested geophysical traverses across selected parts of the region (*Section V*), a portable network equipped with reliable tape recorders and playback equipment should be utilized.

In the eastern Sunda Arc and the complex regions farther north, subduction zones have been plotted from studies of seismicity, submarine morphology and scattered seismic profiles. Yet first-motion studies and analysis of seismicity generally have provided little evidence of the mode of deformation at shallow depths. It may be that the structure of the outer arc inhibits large shallow earthquakes: if so, the energy that results from friction between the descending slab and overlying wedge of sediments is probably absorbed in the form of heat, and in the structural deformation of the sediments. This energy, together with the rich assortment of minerals and fluids in the wedge, possibly at high pressure, could combine to create a metamorphic environment with potential for economic mineral concentrations.

On the eastern and northern margins of the Banda Sea and along the north coast of the island of New Guinea, the level of seismicity is much too low to be compatible with many plate models. For example, Le Pichon's model (1968) predicted a rate of convergence of 12 cm/year between the Pacific and Indian Ocean plates in that area. What are the processes by which this convergence is taken up, and where? Strain hardening of the lithosphere in the arc could set up resistance to seismic activity, so that for a short period vertical movements and internal deformation could be the major determinant of the subsequent evolution of the subduction zones. Detailed seismic as well as geodetic, geomorphic and gravity surveys of the coast, islands and offshore shelves of this region might reveal anomalously high rates of vertical movement. Such a tectonic uplift stage may be important in bringing ore deposits to the near-surface zone.

In addition to the land stations, it is suggested that ocean bottom seismometers should be used to improve delineation of major, minor and incipient plate boundaries, and to determine the attitude of major faults and the mechanisms acting on them. These recording stations could also help to define the detailed velocity and crustal layering in conjunction with seismic refraction experiments.

Regional palaeomagnetic studies. These were dealt with in detail by the Tectonics Panel, but the Geophysics Panel endorsed these studies in principle as having great potential in unravelling the relative configurations of the various island arcs and tectonic units in geological time.

Regional heat flow studies. The details of proposed heat flow studies are presented elsewhere in this section (see p.105). However, the panel considered that a proper understanding of the present-day pattern of heat flow was important in recognizing potential areas of thermal metamorphism and hydrocarbon maturation. There are numerous large marine areas where no data exist; some of these data gaps would be eliminated as a result of the marginal basin surveys proposed in study category 3 recommended above.

A comparison of heat flow in the outer island arc of Indonesia with the low heat flow values found in other frontal arcs of the western Pacific should be undertaken to complement the seismic studies.

Areas of special interest

The Geophysics Panel proposed that multidisciplinary studies should be undertaken along transects or zones crossing the plate margins of the region at critical locations, as outlined in study category 2 recommended above. Two high priority and two lesser priority locations were proposed, chosen with more than just geophysical reasons in mind: the high priority transects were across central Sumatra and the Sunda Shelf, and across southwestern Japan and the Korean Peninsula; the lesser priority ones were across the east end of Java and across south-central Luzon. The recommendations of the panel carried considerable weight in later deliberations of the meeting, and three of these transect locations were included in the six finally chosen as specific recommendations of the Workshop (detailed in *Section V*).

The primary objective of the transect studies should be to delineate the detailed crustal and sedimentary structure of the island arc systems and their associated subduction zones, well-developed in Sumatra but apparently only incipient locally off southwestern Japan. It is important to determine whether the internal structure of the tectonically-mixed zones (including mélange zones) can be resolved by high-resolution, deep-penetration, multi-channel digitally processed seismic profiling results. Detailed seismological studies using portable recording stations should be used to complement the analysis of geophysical profiling information from the transect studies.

In study category 3, the broad geophysical surveys, priority should be given to the western part of the Philippines Sea Basin, the China Basin (South China Sea) and the Wharton Basin, with a primary objective being to delineate the presumed magnetic lineation fabric in those areas, and secondarily to complete the geophysical reconnaissance coverage of the areas with special emphasis on heat flow observations. Approximately four to six weeks of ship time would be required in each area. Proper identification of the magnetic lineation pattern would permit inferences regarding the age, age gradient, rate of sea-floor growth, possible rates of subduction, and quantities of sediment available at potential mélange sites in these areas. Similar additional surveys should also be conducted within the Banda, Sulawesi and Sulu Seas and across the arc-ridge systems separating them, with the major objective of comparing the actual geophysical properties of these semi-enclosed small ocean basins with those predicted on the basis of present theories of plate motion and collision, and associated magmatic and geothermal processes and ore concentrations.

REPORT OF THE TECTONICS PANEL

The tectonic framework of eastern Asia is reviewed in *Section III* of this publication, so this report is primarily concerned with consideration of the general project recommendations developed by the Tectonics Panel. Inevitably these grade into the proposals put forward by the Sedimentary Processes Panel: sedimentary regimes and their history cannot be divorced from tectonics, because sedimentary records contribute to the interpretation of tectonic events and processes, and, in turn, strongly reflect the influence of these selfsame events and processes. The two reports have been arranged, therefore, to be read in continuity with each other.

General recommendations

Research work should be concentrated on selected transects across the diverse tectonic features of the region. In this way the results of the various studies should interlock into a more comprehensive framework of knowledge than if they were randomly scattered; although many institutions and individual scientists will be involved, and direct co-ordination of their work would be impracticable and frequently inadvisable, the results of focussing studies on or near transect lines offer considerable advantages, both scientific and economic. Selection of the transects was made bearing in mind the general objectives of geoscientific research in the region, and the availability of suitable sites, accessibility, company seismic profiles, deep drill-holes, economically interesting areas and those with economic potential, and the relationship of each transect to adjacent ones. The proposals, detailed in *Section V* (p. 111-139), give geographical precision to the transect lines, but it should be borne in mind that studies within ten or a hundred kilometres of these lines will still have great significance in any synthesis or compilation of results that may eventually be made for each transect line. As work progresses, the availability of data in adjacent areas may suggest modifications or additions to the transect lines, possibly in different directions for different disciplines. It could be possible and probably desirable that some co-ordination of such modifications should be made by the main participants in transect studies at progress meetings organized, on an *ad hoc* basis, for each transect as and when opportunity or need arise.

In the oceanic field, the most-needed and most-expensive data are high-resolution seismic reflection profiles defining the geometry and structural character of subduction systems. Such records have already been obtained by various oil exploration companies in many of the critical areas. The co-operation of these companies, and the national hydrocarbon agencies of the countries of the region, should be sought to obtain the release of relevant records which have scientific value but little direct economic importance. Such records would further guide research and, by avoiding costly duplication, free research funds for the many other tasks to be done. It is expected that much other data—gravity, magnetic, thermal, structural, stratigraphic, lithological—could be obtained from commercial organizations without jeopardizing the information they need to keep secret for economic or contractual reasons.

Publication of released data directly by company scientists, or by them as co-authors with institutional scientists, would be desirable both to encourage their involvement and properly to allocate credit for the work.

However, it must be recognized that some studies cannot be geographically constrained along arbitrary transect lines. For example, the magnetic lineation patterns of the oceanic crust of the Indian Ocean between the Java Trench and Broken Ridge to the south, and between Australia and the Ninety East Ridge, are very poorly known, yet are critical for the understanding of the broad pattern of Mesozoic and Cenozoic plate growth and motions. Pre-Jurassic plate interactions must be deduced from geological relationships on land, with little or no contribution possible from marine studies, and the location of terrain of the relevant geological age must control where research is undertaken: this may not coincide with a transect line. Additionally, some studies should be conducted along, rather than across, some linear elements such as trenches, magmatic arcs and mineralized belts. However, in all of these cases the existence of integrated transect studies should provide relatively firm baseline data at those locations to which the regional investigations can be pegged, and indicate relationships with other geological or geophysical features established within the transect zones.

Deep-sea drilling

Much significant information on the history of oceanic plates in the region and adjacent land areas has been obtained from the drill holes put down in deep water by D/V *Glomar Challenger* in the current phases of the Deep Sea Drilling Program (DSDP). These holes, which are drilled to depths of as much as 1,000 m in water depths generally between 2,000 m and 6,000 m, have cored the sedimentary column overlying the basaltic crust of the ocean basins, and plans exist for coring deeper into the basalt itself. Over 300 holes have so far been drilled in this programme, in most parts of the world's oceans, and the information from the holes has thrown light on many aspects of the history of the ocean basins—depth and temperature of water at various times, sedimentary facies and sedimentation rates, gaps in deposition, volcanic events seen as tuff layers, etc. From the data obtained, deductions can be made regarding the relationship of each site to adjacent tectonic features such as trenches and island arcs, its subsidence/uplift history, and potential economic resources. The history of large sections of ocean floor and their motions, and of individual features such as seamounts, ridges and trenches can also be determined, supporting or refuting various theories previously held concerning such features.

The acquisition of definitive stratigraphic and petrological data by deep-sea coring in the ocean basins is recommended, as well as in the deeper parts of the shelves and marginal basins. This provides information obtainable in no other way, which has a vital function in confirmation of deductions made from more remotely-sensed data such as seismic and magnetic profiling. These latter, of course, can in turn serve to elucidate the results of drilling. An important part of the programme should be to promote, plan and operate such deep-sea drilling in eastern Asia, preferably within the framework of the International Programme for Ocean Drilling (IPOD) (CCOP, 1973).

It is important that sites for deep-sea drilling be selected with care and that all existing information should be assembled during the planning stages. Petroleum companies should be approached for their co-operation as they may have considerable information on file that they might be prepared to release for such planning purposes; the best way to encourage such help is to invite company scientists to participate in the planning. Data from the files of mines departments in individual countries should also be sought, and scientists from governments and universities in these countries should also be invited to participate.

The deep-sea cores should be made accessible to scientists in all the countries involved, so that work on them may be undertaken by people who may also be involved in the on-going work along the transects *(Section V)*, both within and outside the region.

Palaeomagnetic studies

In view of the great mobility of the eastern Asian region as a whole, together with the apparent mobility of the large number of microplates inferred to exist in the area and the probability of rapid changes in subduction regimes through time, attempts to reconstruct tectonic conditions prior to the last few million years have so far foundered on lack of data on the relative dispositions of the continental fragments through geological time, and the dating of their movements. This can be well seen from a study of recent literature on the subject wherein it is variously asserted that Indochina and the Malay Peninsula were, at one time or another, adjacent to India, Tibet, North Africa or Australia; that Borneo was adjacent to either Indochina or Australia; and that eastern Sulawesi (Celebes) was sutured onto the rest of the island after moving northward from Australia, from Antarctica or merely separating from eastern Borneo! These are all serious hypotheses advanced more or less simultaneously by various authors. They cannot all be true, and in order to provide the necessary factual constraints on imaginative reconstructions of the continental masses of the region, more data are urgently required. Palaeomagnetic studies represent one significant possible approach to a solution of these problems.

Such studies may, quite quickly, yield data on the palaeolatitudes of various sections of the presently-exposed continental crust, and, as the data accumulate, should permit a more precise and detailed reconstruction of the history of the individual microplates. It should also help to determine whether heavily curved arcs, such as the Banda Arc, originated in their present shape, or became curved with time (both the Banda Arc and Sulawesi are prime subjects for detailed palaeomagnetic investigations).

The palaeomagnetic work should be planned so that it relates closely to the problems to be investigated by the proposed transect studies *(Section V)*, but the actual rocks tested will, in most cases, come from areas well away from the transects. For example, the reconstruction of the Sumatra/Malay Peninsula structural belt must take into account the former position of Sumatra relative to the peninsula, and the relative positions of Sumatra east and west of the Semangko (Barisan) Fault Zone.

The University of Malaya is presently engaged in palaeomagnetic studies in co-operation with the Australian National University and the University of Newcastle upon Tyne, and, in addition, it is setting up its own palaeomagnetic facilities. Studies of the type proposed should be undertaken by the universities and research centres of the CCOP region, with co-operation from state surveys and industry-organized geological surveys in collection of the samples and provision of the necessary background stratigraphic, geochronological and structural data on the samples themselves.

Study of recent surface movements on major tectonic lineaments in eastern Asia

Recent vertical and lateral movements involving the upper 10 km of the crust, and consequent erosion, have strongly influenced the present configuration of many land areas of the region and the geomorphic characteristics of both land and coastline. In emergent volcanic arcs such movements determine whether or not sub-volcanic intrusions will be exposed, or the deeper hypabyssal or plutonic bodies. Each level has a different mineralization potential, which usually decreases with depth of emplacement; for porphyry copper-gold deposits, the most favoured habitat appears to be at or near the top of the sub-volcanic intrusions of the more acidic differentiates within and beneath large sub-aerial andesitic strato-volcanic complexes. The mineralization may extend outward from within the top of the mineralizing intrusion to the enclosing pyroclastic or flow rocks at the base of the volcanic pile, often involving both underlying submarine volcanic and overlying sub-aerial pyroclastic rocks.

In eastern Asia there is a broad regional correlation of very young deposits of porphyry copper and Kuroko-type mineralization with magmatism originating apparently from active Benioff zones. This regional association can be used for the generalized selection of large areas likely to repay prospecting for these types of mineralization. However, in the case of porphyry copper, only those volcanic complexes from which one to six kilometres have been removed by erosion can be regarded as prime prospecting territory. Less erosion would probably not expose the optimum level for porphyry copper mineralization, and more erosion would result in removal of the optimum economic zone. Thus, the most important factor in selecting areas for detailed exploration for porphyry coppers could be the recognition of those parts of volcanic arcs which, by the right combination of uplift and erosion, were exposed within the optimum zone, bearing in mind that current economics of porphyry copper mining necessitate open-pit operations with a low stripping ratio. Following this theme, much ground within the genetically favourable volcanic arcs could be readily dismissed as non-prospective on the grounds that volcanic landforms or coastline characteristics indicated either subsidence or no uplift since cessation of volcanism.

Many major fault lineaments (up to 200 km in length), with pronounced physiographic expression of Holocene vertical (or lateral) movements, cannot be correlated with the well-documented deep (more than 100 km) earthquake data. More subtle vertical movements over large areas due to tectonic or isostatic upwarping do not show on the available earthquake epicentral plots; nor can the vertical components of low-angled thrust movements or essentially strike-slip displacements be deduced from available earthquake data. Recognition of the vertical movements in the desired one-to-six km range can be most effectively achieved by photogeological interpretation supplemented by geological mapping.

An analysis of landforms and coastlines throughout southeast Asia initially to distinguish between areas of recent uplift and subsidence, and to identify these movements with major surface structures, would be of considerable value not only for future porphyry copper search, but also for the prediction of lateritized areas with bauxite or nickel laterite potential, mineral-bearing beach sands, and onshore and offshore alluvial deposits of tin, chromite and gemstones. The results of such a study would also aid the correlation of deep earthquake-indicated lineaments with surface features through the shallow (0-50 km) zone of deficient earthquake data. It is stressed that the scale of the initial study should be broad, so that regionally significant movements are not confused with local compensatory movements of small amplitude.

Presently existing data and new data required. Existing geological mapping coverage is, in general, good enough for the tracing of long lineaments throughout the land areas of the region. Further field or literature investigation to identify the sense of the most recent lateral and vertical movements, both on fault lineaments and coastlines, would be needed. This could be most effectively and expeditiously done by photogeological interpretation using ERTS imagery, where and as available, together with all recent vertical aerial photography available from industry and governments, and wartime and postwar vertical and oblique photography held by the United States, Japan and other governments in the region.

The extent and quality of earthquake epicentre data for the shallow realm (less than 50 km depth) in the region is not known but there has undoubtedly been much shallow earthquake data collected by various government authorities and institutions in connection with volcanological and earthquake studies. These data should, quality permitting, be related to geomorphically-indicated near-surface fault movements.

It has elsewhere been proposed in connection with the multidisciplinary transect studies that onshore seismic recording should be undertaken in an attempt to relate deep crustal structure to surface geology and geomorphology. This is a long term project worth starting now but it will be many years before enough data are collected for meaningful interpretations. It is also probable that marine seismic, gravity, magnetic, bathymetric data will be relevant to the vertical movement study along the proposed transect lines.

The proposed work of the sedimentological groups along the various transect lines would be complementary to the vertical movement study, but onshore geomorphological investigation should not be restricted to the vicinity of transect lines.

Area of study. While studies of these movements should be concerned with the entire region of interacting crustal plates in eastern Asia, it is strongly recommended that initial work be directed to one of the larger land masses where several crustal segments with differing petrological and physical characteristics are in obvious contact but have no deep seismic expression and only minor associated contemporary volcanism. The landmass of Borneo would seem appropriate for first attention.

Implementation. A programme of two years' duration is recommended. Initially assistance should be sought from the appropriate United States authority for the acquisition and interpretation of ERTS imagery, where not already available, and for expert guidance for governmental or university staff in the countries involved.

Some new high-level aerial photography may be required in the second year of the investigation after the quality and availability of existing photography has been assessed. At this stage the use of special multi-spectral imagery or side-looking radar techniques would be considered as too detailed for the type of regional reconnaissance investigation envisaged. However, where already available, imagery of these types could be used. On the question of contracting new photography, the need of other natural science disciplines should be investigated and, where possible, photography of a scale and type acceptable to all interested disciplines should be decided.

Cost in the first year would be minimal because the study would commence on already available data, most of which could probably be obtained at the cost of copying. Recommendations for any additional photography in year two or beyond would be dependent on year-end reviews of progress and potential benefits.

Release of classified aerial photography from the various governments is seen as the only significant problem.

The project should be initiated by joint discussion between the Governments, universities and the oil and mineral exploration groups in the area concerned to pool knowledge and data, to ensure local co-operation and involvement. It is assumed that people selected to work within the project would be drawn, as individuals or small working parties, from those already having considerable geological experience in the region and living in it. Possible overlap with sedimentological, petrogenetic and metallogenic aspects of other programmes is not seen as a problem but as desirable.

The above fundamentally structural study relates well to proposals for sedimentological work in the region, particularly in the Quaternary. The following proposals also emphasize the interrelationship between sedimentation and tectonics, and with metallogenesis, but have been included in this panel report as being more appropriate.

Conversion of plate-margin features to cratonic

In many parts of the region, active tectonic elements of subduction zones and adjacent areas have been converted ultimately to elements of cratonic crust. As such they may become involved in subsidence structures of foreland basins, downfaulted blocks and grabens, and marginal basins and inter-arc basins may also be related. Studies should be undertaken on the extent, structural style and history of vertical collapse of these various features, together with the reconstruction of these various features, together with the reconstruction of the different basin-filling processes and the respective tectono-sedimentary environments (molasse, paralic, etc.) involved: from this, the general conditions for the maturation of hydrocarbon source beds in the region may be studied.

Study of older inactive arcs in relation to present-day subduction

As discussed in *Section II* (p. 12), structural, sedimentary and petrological studies of the tectonically disturbed and chaotically intercalated rocks of widely diverse types (typically comprising deformed flysch- and pelagic-type deposits, deformed ophiolites, blueschists and mélange-type formations), commonly found along the inferred older inactive arcs and former convergent boundaries or suture zones between crustal plates, may provide an important guide to determining the positions, polarities and stages of development of ancient subduction systems. Thus it is necessary to study the mélange-type formation and ophiolite belts of the older inactive arcs and their corresponding volcanic-plutonic arcs, and to compare the inactive arc systems with active ones in order to establish a link between present-day subduction processes and Tertiary and older subduction events.

The outer Sunda-Burman Arc, extending from the Indo-Burman Ranges through the Andaman-Nicobar and Mentawai Islands, and continuing as a submarine ridge south of Java, is recognized as a good location for intensive investigations. The deformed ophiolites and mélange-type formations of varying characteristics and ages along this arc presumably represent scraped-off and tectonically emplaced deep-sea sediments together with oceanic crust and upper mantle rocks of the subducting Indo-Australian Plate. Studies of the sedimentary and tectonic history of these rocks would permit a record to be unravelled of subduction processes and tectonic events in the outer arc and adjacent belts since late Cretaceous time, including the subduction-related processes prevailing during and immediately prior to the late Cretaceous mineralization behind the arc.

Suggested research work:

1. The sedimentary and structural characteristics and the inferred present subduction processes along and immediately adjacent to the outer Sunda Arc should be investigated using geophysical and other methods, similar to those planned for investigating the accretion of sediments above the subduction zones.

2. Deformed sedimentary formations and ophiolites on land should be investigated by geological mapping and structural and palaeontological methods; gravity data should also be obtained across the major negative anomaly associated with the Sunda-Burman Arc.

3. The deformed deposits and ophiolites should be interpreted in terms of the understanding of present subduction processes obtained from 1, and from this the subduction history and successive tectonic settings of the older arc since the late Cretaceous could be deduced.

4. The structural and petrological aspects of the late Cenozoic volcanic-plutonic arc behind the outer Sunda Arc should be investigated, including studies of igneous rocks associated with both porphyry copper and tin mineralization. Potassium-argon and rubidium-strontium dates on the igneous rocks and ore minerals should be obtained.

Expected results. The subduction history of the plate margin prior to and during emplacement of economic mineral deposits on the Eurasian Plate should be determined by this work programme. This would provide a plate-margin model or models which could be used for interpreting the origins of the mineralization and of similar mineralization elsewhere. This, in turn, would provide a basis for inferring potentially favourable areas for mineralization and hydrocarbon genesis in or behind other arcs of various ages.

Mineralization within the deformed sediments and ophiolites is of lesser economic interest. These rocks would be used mainly as a key to interpret the subduction plate margin setting at the time when minerals were emplaced on the Eurasian Plate in Burma, Thailand, Malaysia and Indonesia. The deformed flysch and ophiolite belts should provide evidence for parameters such as perpendicular or oblique descent of the lithosphere, the angle and rate of descent, any or all of which may be related to mineralization above the Benioff zone.

Other suggested studies in tectonics

Geochronological determinations in major outcrop belts should be made where possible, using several radiometric methods.

Polarity should be determined for those outcrop belts which appear to have been deposited at a continental margin or arc system, relative to pre-existing ocean basins or marginal seas.

Major unconformities identified in the stratigraphic sequences of the region should be correlated to the history of adjacent ocean basins.

REPORT OF THE SEDIMENTARY PROCESSES PANEL

Most problems relating to sedimentary processes are not unique to the region. However, there are sedimentological projects which can be undertaken in this region which may help towards the solution of major local problems in tectonics and mineral prospecting, and also contribute towards a basic understanding of sedimentary processes worldwide.

Particular comment should be made on one of the recommendations, namely the study of the Quaternary geology of Sundaland and adjacent areas. This is important for several reasons. Firstly, it will help to elucidate some of the major problems of stratigraphy on and adjacent to continental shelves, which remain unsolved in spite of the vast amount of work done elsewhere on the dynamics of shore zone and continental shelf sedimentation. Secondly, during the lower sea-levels of the Pleistocene, much of this broad continental shelf was land and the changes in the climate and the oceanic circulation of the region must have been profound (as indicated by the data presently available on Quaternary drainage patterns in the area). Thirdly, a broadly based, systematic geological study such as this should contribute greatly to the search for economic mineral deposits. This type of study is best done by geologists of the region, and would provide valuable opportunities for training and educational exchanges; the cost of the necessary equipment and support services would not be great.

Quaternary geology of Sundaland and adjacent areas in southeast Asia

Sundaland is the name given to the stable cratonic block of Peninsular Malaysia, most of Sumatra and Borneo and the intervening marine areas including the Sunda Shelf *(Fig. 12)*. The name may also be extended to include the stable areas of Thailand and Indochina and adjacent shallow seas, and it is used in this sense here. During the sea-level lowering of the Pleistocene much if not all of this area lay above sea level, giving rise to a variety of sedimentary regimes, each characterized by its unique marine and/or sub-aerial environments and sedimentary provenances. Moreover, the pronounced and repeated eustatic sea-level changes, and vertical and lateral movements of land and offshore areas referred to in the report of the Tectonics Panel, strongly influenced regional depositional and erosional patterns, and sub-aerial and marine sedimentary regimes.

Thorough studies of Quaternary geology and geomorphology, and detailed stratigraphic correlation, would provide useful data to increase the understanding of the Quaternary tectonic history of the region. This work would make a major contribution to the precise dating of the deformation of Quaternary strata in the area and should contribute substantially to the search for economic mineral deposits.

Recommended studies. Although much drilling has been done, both onshore and offshore, cuttings and cores from the Quaternary are very rare, and the stratigraphy and palaeontology of the Quaternary sections penetrated have not been systematically studied (mainly through lack of samples), with few exceptions such as Biswas (1973). Consequently, the Quaternary stratigraphic sequences in many areas have not been established and the Plio-Pleistocene boundary is often not defined. A co-ordinated land-sea Quaternary stratigraphic correlation programme should be undertaken throughout the region in order to relate the non-marine sedimentary and volcanic units and geomorphic surfaces to the marine units in neritic to abyssal water depths. In addition to the descriptive aspects of such a study, it is most important that the programme should also investigate the processes of sediment distribution.

Any list of topics which the study will ultimately comprise should include, but not be limited to, the following:

1. *The palaeogeography of the pre-Quaternary surface* is virtually unknown, and with few exceptions the ages of coastal and river terraces are not established.

2. *Regional variations in sedimentation rates* both in time and location are in urgent need of study and have important economic connotations relative to porphyry copper deposits.

3. *Sea-level history* should be studied, comprising the charting of eustatic changes, uplift and subsidence, tilting and horizontal movements; this is a topic also dealt with by the Tectonics Panel proposal for work on recent surface movements on major tectonic lineaments (p. 81).

4. *Climatic changes*, as recorded in faunas and floras, and weathering conditions that might be related to sub-aerial enrichment of mineral deposits.

5. *Magnetic reversals* as recorded in Quaternary deposits and volcanic rocks.

6. *Extreme variations in dynamic oceanic conditions* should be sought which might have affected the concentration of placers in beach and shelf areas.

7. *Relict drainage systems of Sundaland*, mostly now under water, and the impact of active volcanic centres on the drainage (e.g. diversion, impounding of water), should be further studied.

8. *Superficial Quaternary deposits* should be related to older sedimentary rocks in subduction zones.

9. *Environments for placer and residual mineral deposits* on the shelf area should be identified and the processes of distribution and concentration of minerals investigated.

10. *Entrapment and conversion of organic material* in Quaternary deposits should be studied.

Implementation. The recommended work could be undertaken by several modes of investigation, either in connexion with the proposals for transect studies detailed in *Section V* or independently:

(i) *compilation of Quaternary geology* by local geological survey agencies on land, and in adjacent coastal and shelf areas, from existing data;

(ii) small ship traverses in *near-shore areas* (bottom sampling, seismic, side-scan sonar work) to obtain more information;

(iii) co-operative traverses of *outer shelf* and *continental slope areas* by oceanographic research institutes and local agencies (in particular, local universities);

(iv) joint studies by local and visiting scientists on the distribution of *volcanic and mineral deposits* in coastal and near-coastal Quaternary formations;

(v) co-ordination, comparison, and discussion of results should be regular and frequent, preferably through *regional meetings.* Consideration of basic processes of sediment distribution should be encouraged, in addition to the purely descriptive studies which might otherwise tend to dominate the data acquisition phase of the project;

(vi) once the programme is underway every effort should be made to encourage development of specific programmes of *graduate research* (M.Sc. or Ph.D.) on selected sectors of the overall study in the universities of the region.

Quaternary studies should also be undertaken within the *multidisciplinary transect studies*, as well as by local agencies. Precise stratigraphic correlation is particularly critical to these studies since many of these areas have been orogenically active not only in the Tertiary but throughout the Quaternary, and some areas, such as the arcs and trenches, are strongly active today.

Stratigraphic zonation of the Quaternary, including definition of the Plio-Pleistocene boundary, should first be established for each transect zone on the basis of all available evidence of fauna, flora, radiometric dating, magnetic reversals, and mineralogical evidence such as sedimentary records of volcanic eruptions. These studies should be linked with the more general studies mentioned above, or extended to areas where such studies are not being done.

The repeated changes in sedimentary regimes revealed by these studies could be key factors in understanding the continuously evolving tectonic picture combined with eustatic sea-level changes and climatic changes. The increased capability for correlation could also be useful in the study of scraped-off oceanic sediments accreting above subduction zones (see p. 92), as detailed correlation could help outline the structure of these complex units.

Core data from offshore drilling in the superficial sediments is limited and it is anticipated that valuable information relating to the Quaternary geology of the region should result from the piston coring programme, which is an integral part of the next proposal.

Marginal and small ocean basins

The eastern Asian region contains a number of marginal and small ocean basins which form an integral part of the tectonic pattern of the region and must, therefore, be related to the adjacent island arcs and the inferred large subduction zones nearby. An understanding is needed of their origin and age, also the tectonic processes that gave rise to these basins and the tectonic processes that gave rise to them, and the sedimentology of their bottom sediments.

Questions to be answered: are these basins formed by "oceanization", that is, the absorption of foundered continental crust into mantle material resulting in the formation of oceanic crust by intrusion and/or replacement, or is their formation due to lateral spreading of the crust behind a subduction zone in response to an upwelling mantle diapir derived from the downgoing lithospheric slab? It is conceivable that both processes are operative, not necessarily at the same time or in the same basin, and two different types of basin might result.

Arising from this question, it must also be asked what relationship some marginal basins have to nearby subduction zones, as most of these basins in the region are close to presumed subduction zones. What is the significance of high heat flow values found in some of these basins?

The application of sedimentology to the problems: where dateable magnetic lineaments are absent, the age of the sediments overlying oceanic rocks in the basins is of prime importance. Information about the age distribution of these deposits may enable a distinction to be made between basins due to oceanization and basins due to drift of crustal units. If the age of the sediments overlying the oceanic crust is uniform or shows an irregular patchy distribution, oceanization must be considered seriously as a possibility. If alternatively the age distribution is from young to old in one or more directions, it can be assumed that oceanic crust was formed by horizontal movements akin to the plate movements known from the open ocean. Determination of the vertical distribution of strata and the composition and the structure of the sediments would also be of value in helping to determine the history of each basin, as well as the erosional history of the adjacent arcs and orogenic belts. The nature of the deposits filling the marginal basins merits close attention: their facies, whether of abyssal, normal oceanic, shallow marine, paralic or continental character, would be of obvious diagnostic value in determining the tectonic history of the basins.

The presence or absence of unconformities and buried older shelf basins are also of diagnostic value in analyses of basin evolution. The presence, nature, and distribution of volcanic rocks in the sediments could have a direct bearing on the understanding of development of the small ocean basins.

Sedimentology of long piston cores would contribute to knowledge of Quaternary changes in climate and circulation in the region (and also be significant for the Quaternary work outlined above).

Marginal basins that merit consideration in the region are the Andaman Sea, the deeper part of the South China Sea (the China Basin), Sulu Sea, Sulawesi (Celebes) Sea, Makasar Strait, Banda Sea and the Japan Sea. The Okinawa Trough of the East China Sea and parts of the Philippine Sea may also be worth investigating on the same basis. In deciding on the relative merits of these basins as subjects for investigation, available geological information, tectonic setting, size, proximity to known economic resources, and, in order to combine activities, location relative to other areas of investigation proposed, are very important.

On this basis, the *Andaman Sea* is considered to be the most attractive, and the transect studies proposed on p.114 should be of great value. Its tectonic setting is unique in that the sea lies behind an island arc convex to and possibly moving towards the west instead of the east *(Fig. 9)*. In its northern part there is an influx of sediment on a considerable scale from the Irrawaddy river system. In the east it is known that thick sedimentary sections underlie parts of the shelves off Thailand, Malaysia and Sumatra. It is believed that in the western part of the Andaman Sea basin, sediments decrease in thickness to a very thin veneer overlying oceanic material with the ocean bottom showing very irregular relief *(Fig. 32)*. It contains submarine and emergent volcanoes which are probably the continuation of the Sumatran volcanic arc. These volcanoes form a link between this arc and the Burman volcanic zone. The sediments in the eastern part of the Andaman Sea are of economic importance as a possible oil province.

The *Banda Sea* is of interest also primarily because of its tectonic setting. It is convex eastwards, where it is surrounded by the Australian-New Guinea continent. The island of Timor, although possibly underthrust at present by the Australian continent, shows affinities with Australia *(Fig. 15)*. Thus the original northern margin of Australia might lie north of Timor in the Banda Sea. The same situation seems to apply in the area of the island of Seram where the Irian shelf might be in process of disappearing below the island. A study of the Banda Sea sedimentary section north of Timor and south of Seram might shed some light on dynamic conditions in these areas. Oil seeps occur on both Seram and Timor, although no economic accumulations have been found on the latter island yet.

Of the remaining marginal basins those situated along transect proposals for investigation of tectonic and metallogenic processes would be candidates for investigation: for example, the South China Sea area west of Luzon.

The *Makasar Strait* basin is of interest, as drifting of Sulawesi south-southeastwards relative to Borneo is suspected.

The *Sulu* and *Sulawesi Seas* are of interest from a strictly sedimentological standpoint, and also because little is known about their tectonic setting.

Plan of investigation: The following is a suggested sequence of study and work:

(i) Prepare a compilation of published data and seek access to other commercial data as may be available for the basins chosen for study, with particular attention to:

(a) high resolution seismic reflection surveys

(b) heat flow data

(c) gravity data

(d) magnetic data;

(ii) interpret data and prepare maps of sediments overlying the oceanic material, and determine whether the evidence is good enough to say unequivocally that ocean bottom spreading has or has not occurred;

(iii) from geophysical data, plan profiles for coring to obtain samples of basin sediments and propose drilling sites for the International Programme of Ocean Drilling (IPOD). The type of coring equipment to be used should be selected at this stage:

(a) use gravity core barrels where thickness of sediments permits; or

(b) use oceanographic vessel equipment to drill through the sediments, collecting adequate samples and cores of the sedimentary section and, specifically, cores and/or samples of the basal deposits;

(iv) prepare an analysis of sedimentary samples collected;

(v) combine the results with a study of observed geophysical/geological data;

(vi) draw conclusions on the processes that were active in the development of each basin studied.

Interaction of tectonic and sedimentary processes in the accretion of sediments above subduction zones

The studies proposed by the Sedimentary Processes Panel involve not only stratigraphy and structural geology in the field, but also studies of geotectonic significance. Subduction and the origin and nature of chaotic assemblages (mélanges) were constantly recurring themes at the IDOE Workshop, and in accord with this interest, the final proposal from the panel comprised a study of the interaction of sedimentary and tectonic processes above subduction zones. This study was considered to be of fundamental importance, and to ensure that it had a reasonable chance of obtaining definitive results, the utmost utilization of the latest and most sophisticated geophysical, oceanographic and drilling techniques was recommened.

The results of such a study of the processes of subduction in the eastern Asian region could have global application. An understanding of the geological history of ocean floors is a prerequisite for full exploitation of the mineral resources of the sea-bed. Two-thirds of the surface of this planet lie beneath the sea, and before a start can be made on a sensible inventory of the potential mineral resources of the marine realm, let alone on attempt to exploit these resources, it is necessary to improve the understanding of the geological history of the ocean basins and their margins, and the processes of their formation and growth.

The problems: what is the fate of sediments riding an oceanic plate into a subduction zone? How much sediment is subducted, and how much is scraped off? What is the mechanism of scraping-off and what structures result? Is there more than one basic mechanism of transferring sediment from one plate to another? How do structural style and the proportion of sediment subducted versus sediment scraped-off vary with thickness of the sediment column, nature of the sediment, rate and direction of convergence, rate of supply from the landward side or arc, and whether the overthrusting plate is continental or oceanic? How are these processes related to the formation of mélanges, imbricate thrust sheets, nappes, and olistostromes?

Background: early marine geophysical studies of deep-sea trenches presumed to be associated with active subduction zones showed that some were filled with flat-lying undeformed sediments, while others were devoid of any sediment or had only thin pelagic deposits over the oceanic crust. The sections showing undeformed sediments were initially viewed as strong evidence against the subduction process, but were later rationalized on the grounds that the decoupling andde formation presumed to be occurring was confined to the immediate junction of the trench floor and landward wall. The landward wall of the trench on these records appeared as acoustic basement, no penetration or resolution of sedimentary structure was achieved, and the sections in question were interpreted as being too completely distorted to be resolved by the available methods. This interpretation offered no clue as to the relative amounts of sediment subducted or incorporated onto the face of the overthrust plate, nor to the tectonic and sedimentary processes interacting to produce the supposedly highly-contorted deposits in the trench wall.

Sampling of the presumed disturbed accretionary wedge is difficult; it does not therefore contribute much to the solution of the controversy. Spot sampling by cores and dredges is only fortuitously successful. Outcrops are uncommon because of the blanketing effect of sediments coming down the slope from the continent or arc, including slide masses. Spot samples of young sediment or rock cannot demonstrate subduction of older crust.

Geophysical resolution is equally difficult. Seismic reflection surveys rarely reveal internal structure of the acoustic basement wedge because of lack of continuity of reflectors with sufficiently low dips. Relatively high frequency sparker or air-gun profiles locally do show some internal folding of strata, but results have generally been poor because of diffraction and acoustic repetition rates which are too low to delineate strata of poor continuity.

Recently more convincing evidence for subduction has been presented. Silver (1971) was able to demonstrate that young sea floor with identifiable magnetic anomalies underlay deformed older Tertiary rocks of the continental slope off northern California. Silver was fortunate in this regard, in that he was working in an unusual region of subduction affecting very young oceanic crust. However, Leg 18 of the Deep Sea Drilling Project was successful in sampling deformed and compressed young mudstones with incipient slaty cleavage from the landward wall of the Aleutian Trench in acoustic basement (DSDP Scientific Staff, 1971) and similar results have recently been obtained in the Nankai Trough (DSDP Scientific Staff, 1973c: see p.64). Curray and Moore (1971) collected seismic profiles over the Andaman-Nicobar sections of the Sunda Arc showing the thick section of the Bengal Fan becoming gently folded as the subduction zone was approached, and more tightly folded and grading into apparent thrusts or nappes at the island-arc wall. Quite a different kind of deformation has been convincingly recorded further south along the Sunda Arc off Java, where Shell Oil Company has utilized 24-fold, digitally processed seismic reflection cover to record the sea floor apparently extending beneath the trench wall, and overlain by landward dipping reflectors in the sediments of the trench wall which have been interpreted as imbricate thrusts.

Accepting for now the probability that at least a part of the sediment carried into converging plate edges may be scraped off from subducting plates, some important questions can be formulated and work proposed which may help to answer those questions:

Firstly, what proportion of the sediment on a subducting plate is scraped off and what proportion is lost by subduction, and what are the important variables to evaluate? Geological evidence can contribute here through interpretation of depths of burial by metamorphic facies. Metamorphism provides evidence that some of the sediment has in fact undergone considerable burial and/or heating in the old subduction zones, but where those metamorphosed sediments are now exposed, the bulk of the overlying shallow scraped-off deposits have been eroded away.

In contrast, there is no apparent obvious evidence that any sediment does in fact ride the subducting plate down a Benioff zone. Calculation of a sediment budget for a given period of time offers the best possibility of deciding this; it requires good knowledge of the thickness of sediment, history of deposition, history of plate motion, and sufficient geophysical data to estimate the volume in the wedge of scraped-off, deformed sediment, down to a given depth. At best, only a crude estimate of the proportion of material subducted to that superficially accreted can be expected, but any quantitative evaluation would advance understanding studies of the formation of chaotic assemblages.

The Sunda-Burman Arc from Burma to Java appears to provide the most suitable area for attempting such an evaluation. Thickness of the sediment column on the subducting Indo-Australian Plate varies from over 10 km off Burma to a few hundred metres off Java; direction of convergence varies from normal off Java to oblique off the Andaman Islands; nature of the sediment varies from sandy off Burma, through muddy farther south, to pelagic off Java; rate of convergence does not vary much because the pole is located about 90° away; and already there is a considerable amount of background geological and geophysical information for interpretation of the history. Furthermore, the upper parts of the scraped-off wedge are sub-aerially exposed in the Indo-Burman Ranges, and the Andaman, Nicobar and Mentawai Islands *(Figs. 31-33)*.

Secondly, what is the mechanism of scraping off, what is the structural style of the deformed deposits, and how are these related to the variables? Answering these questions will require better seismic reflection records of the internal structure of the sediment wedge. Experience in the region to date, however, indicates that careful, properly-designed analogue systems are able to provide useable data in parts of the arc and when interpreted in the light of proposed commercial seismic traverses should yield even more useful results. It is apparent, from the very small sampling of available data, that the Sunda Arc is well suited for study of this problem. At least two fundamentally different kinds of deformation have been recorded and it is not unlikely that additional styles of deformation will be found.

Proposed work: a network of analogue or single-trace air gun and 3.5 kHz lines should be undertaken to:

(i) establish the thickness and structure of sediments being carried on the oceanic plate into the trenches;

(ii) resolve, to the capability of the seismic system, the structure in the trench wall and detect the presence of slope basins and basins formed at the crest of the sedimentary pile landward of the trench;

(iii) to define the structures in the sedimentary section which may be present within these arc-front and arc-trench-gap basins.

These traverses should be supplemented, on the landward wall of the trench, by high-frequency sparker profiling to assist in resolution of possible complexly folded and faulted sediments. The high-frequency data would be essentially surficial, that is within the upper few hundred metres of section, but could provide insight into deformational style. These various reflection profiling lines should be interpreted in the light of the selected multidisciplinary transect studies planned for key regions in the Andaman-Nicobar and Sumatran sectors of the Sunda Arc (p.114 and 122). Specifically, the reflection data should be examined as it is received for evidence of structure which could be interpreted as having originated from gravitational slides. If these are detected, additional traverses should be carried out, as necessary, to achieve a three-dimensional picture of the olistostrome or slide mass.

In addition to the reflection data, the trench wall should be sampled by piston coring and dredging where appropriate, and photographed by deep-sea camera where geophysical data suggest the outcrop or near outcrop of strata. Observation and sampling of trench walls could also be achieved through use of the United States Navy's CURV (Cable-controlled Undersea Remotely-operated Vehicle) which is capable of transmitting instantaneous television pictures of the sea floor to the surface and of sampling outcropping rock which may be detected as the vehicle traverses the trench wall.

Some form of drilling to sample the trench wall to depths of a few hundred metres would be required. This could be achieved through IPOD if that project is successfully launched, or could be accomplished through contracting a slim-hole core drilling ship such as D/V *Cal-Drill* used in the preliminary phase of the present Deep Sea Drilling Project.

Gravity, magnetic profiling and wide-angle reflection and refraction studies are proposed, to allow the best possible estimate of the thickness of the wedge of sediment accumulated over the subduction zone. With data on the thickness of the accreted wedge, and on the amounts of sediment which have been carried into the trench on the oceanic plate, estimates of the percentage of sediment preserved and subducted could be attempted. Many variables would have to be considered in this attempt, such as thickness and kind of sediment supplied, rate and angle of convergence, supply of sediment from the landward side of the trench, and the quantity carried by turbidity currents axially down the trench from sources in the Bengal Fan distributary system.

The area of investigation proposed would extend along the Sunda-Burman Arc from the Indo-Burman Ranges to the east end of the Java Trench, crossing the lines of Transects 1a, 2 and 3 (see *Section V*). It is important that the marine geological and geophysical work should be closely integrated with onshore studies of exposed, presumedly scraped-off, sedimentary rock sections, both in the transect lines and elsewhere along the arc.

REPORT OF THE METALLOGENESIS AND PETROGENESIS PANEL

It is now generally acknowledged that important metallogenic provinces are related to zones of interaction of lithospheric plates, and these provinces may show direct spatial relationships to present-day plate tectonic features such as spreading axes or Benioff zones; in some cases older provinces can be related to the inferred boundaries of ancient plates. Ore accumulations can be genetically related to differentiation of basaltic magma, hypabyssal intrusions in island arcs and to hydrothermal alteration of igneous and sedimentary rocks developed on oceanic ridges and continental margins. In this report, the petrological processes and metallogenic significance of plate tectonic activity are considered for four major domains: spreading axes, island arc-trench systems, marginal basins, and inactive arcs and suture zones.

Sea-floor magmatic, metamorphic and metallogenic processes

Spreading axes

Currently acceptable models and hypotheses. Models for magmatic, metamorphic and metallogenic processes at constructive plate margins can be produced from a combination of marine geophysics and examination of moderately deformed ophiolite terrains such as the Troodos Massif (Cyprus), the Semail Nappe (Oman) and Macquarie Island, and the more strongly deformed ophiolites of east Liguria (Italy), Greece and Turkey. Studies of ophiolites suggest a layering in the uppermost part of the oceanic lithosphere: the base consists of massive, often gneissose, harzburgite, considered to be depleted mantle, and is overlain by a cumulate-layered sequence grading upwards from chromitites and dunites through peridotites and melagabbros to gabbros and trondjemites. This gives way upward to a sheeted dyke complex which is in turn overlain by a sequence of pillowed lavas. On top of the pillowed extrusive rocks, massive sulphides and iron and manganese-rich sediments occur in what were originally sea-floor basins. Only rarely is a complete sequence present in any one ophiolite zone.

Currently, the most acceptable hypothesis, which reconciles the ophiolite sequence with heat flow, seismic, magnetic and gravity data over active spreading axes, proposes a narrow vertical column of hot mantle, probably only a few tens of kilometres wide, rising beneath the axis of the ocean ridge. This column contains in the order of five per cent liquid fraction which increases to some 30 per cent as the surface is approached. At this stage liquid and solid phases separate to give a discrete magma body at shallow depths (about 1-2 km) beneath the ridge axis. Some of this magma is injected through dyke-like fissures to be erupted at the surface as mainly pillowed lava sequences; the dykes solidify as a vertically-sheeted complex. Within the magma mass, crystallization begins as the fluid body moves outwards from the central high heat zone. Refractory minerals such as chromite and olivine are the first to be precipitated onto the semi-solid surface of harzburgite (depleted mantle). Ortho- and clinopyroxenes follow and are then joined by plagioclase. This magmatic sedimentation produces the layered cumulate sequence. All such rocks, intrusive and extrusive, are characterized by low potassium, titanium, phosphorus, caesium, rubidium, barium, lanthanum and light rare earth elements when compared to other basalts.

Studies, particularly in Iceland, Troodos and Liguria, indicate that shortly after its creation, a prograde metamorphism becomes imprinted on the oceanic crust. This occurs in an environment where load pressure is low (about one kilobar) but where geothermal gradients are of the order of 200°C per km. A metamorphic stratification, grading downwards from zeolite through green-schist to amphibolite facies, is produced. In areas of thermal excess, where geothermal gradients can be as high as 1300°C per km, recycling of sea water appears to deplete the oceanic crust, in particular the basaltic layer beneath oceanic sediments (layer 2), of its transition metals.

Zones of thermal excess are not uniformly distributed along the constructive axes of the world but occur spasmodically. Seventeen systems have been identified along a 250-km stretch in Iceland, about 15 along the Red Sea Rift and about nine along a 120-km across-strike section in Cyprus. In these areas of high heat incidence, any one part of the basaltic crust can heat three times its volume of sea water to 300°-400°C. This water is apparently flushed through the hot basaltic crust, each cubic kilometre of basalt probably being host to three or more times its volume of brine during the cyclic process which, it has been calculated, operates at a rate of up to 3,000 litres per second. On passing downwards into the oceanic crust the oxygenated brine is progressively reduced and reacts, mainly with the magnetite and olivine, so that divalent iron and manganese as well as the transition metals, copper, silver, gold, nickel, molybdenum and vanadium, go into solution; silicon also goes into solution. This heavy-metal brine returns to the rock/sea interface along discrete channels where, on discharge, it reacts with the sea water and precipitates the heavy metals by a process of colloidal absorption. Silicon is not precipitated but seems to be dispersed into the sea water. This local precipitate accumulates in sea-floor basins and, on passing away from the spreading axes, may well crystallize into the massive sulphide deposits often found on the tops of ophiolite complexes.

During the passage of the oceanic plate across the oceanic basin away from the constructive margin, mineralogical activity is at a minimum. Hot-spot magmatism produces off-axis seamounts, guyots and volcanic islands whose products overlie the igneous-metamorphic sequence produced at the spreading axis. Such sequences are commonly alkalic and their magma seems to have equilibrated at greater depths than those of the axis sequence. Metamorphism within the zeolite facies is common, but this does not seem to be accompanied by any significant metallogenesis.

Island arc and trench systems

Igneous activity. In the plate tectonic model, island arc-trench systems are interpreted as plate interactions which have a strong component of convergence. Trench regions are regarded as the main loci of crustal subduction where lithospheric plates begin their descent down the Benioff seismic zones. The island arcs occur above the dipping Benioff zones and are constructed of volcanic rocks of the calc-alkali suite (basalts, andesites, dacites, etc.), and derived volcanoclastic sediments. Beneath and within the arcs, hypabyssal and plutonic equivalents of the extrusive lavas occur, particularly quartz monzonites, granodiorites and diorites.

These arc-trench systems are particularly well developed in the eastern Asian region, in the zone of interaction between the large Pacific, Indo-Australian and Eurasian Plates. Magmatism in the active arcs is characterized by a fairly regular change in the chemistry of the lavas with depth to the Benioff zone, strongly suggesting a close genetic relationship between the volcanism and the descending lithospheric slab. Typically the magmatism occurs where the Benioff zone is between 100 and 300 km deep.

From various geochemical arguments, a two-stage derivation of these magmas from the upper mantle is indicated, the first stage being the formation of oceanic crust and lithosphere at spreading axes or in the marginal basins, and the second stage being the partial melting of this lithosphere as it descends down a Benioff zone. This partial melting occurs as a result of elevation of temperature as the slab descends, possibly assisted by frictional heating, and by dehydration reactions in the altered upper part of the lithospheric plate. This release of water is probably one of the main factors in lowering the temperature at which first melting occurs and may also facilitate partial melting in the mantle above the descending slab. On the way to the surface the magmas may be modified by processes such as fractional crystallization and reaction with wall rocks. The two-stage process, by which the calc-alkali magmatic assemblage of the arc systems is developed from the upper mantle, is regarded as the main mechanism by which continental crust is differentiated.

Island arcs may develop on oceanic crust remote from or adjacent to continental regions, or directly on continental crust, usually close to the margin of the continent. All these types are represented in the region. The magmatism in each of these different environments shows similar characteristics, although a greater abundance of the more silicic members of the calc-alkali suite is found in those arcs developed on continental crust. Volcanic arcs may remain relatively fixed in space for a long or short time, may change their location gradually or rapidly, and be short- or long-lived, depending upon the changing patterns of sea floor spreading. For example, collision of continental crust with an arc-trench system ultimately results in the cessation of the magmatism, and development of an arc-trench system elsewhere.

Recognition of inactive and eroded older arc systems is commonly possible by the characteristics of the igneous rock association and enables more accurate reconstruction of the geological history and evolution of a region.

Mineralization. Within presently-active arc regions, where large andesitic volcanoes dominate the landscape, evidence for mineralization is small, though some exhalative deposits can be important. However, in terrains where erosion has cut through the superficial volcanic products, evidence of mineralization becomes much more common. Gold-silver deposits of epithermal type are frequently found in the slightly altered lavas, while porphyry copper deposits are found associated with intrusive diorites and granodiorites in this sub-volcanic environment. The implication is strong that the copper mineralization is genetically related to the subducting system, but the mechanism of concentration of the copper into economic ore bodies is poorly understood.

Tin and tungsten are other major types of mineralization in the eastern Asian region. These deposits are also associated with granitic rocks, generally in cratonic areas which are likely the site of earlier arc systems. It appears that pre-existing continental crust is a necessary condition for the formation of such deposits, but their close geographic relation to the arc systems in parts of southeast Asia may be significant *(Fig. 4)*.

In volcanic piles of ancient island arc systems, there occur strata-bound massive copper-lead-zinc deposits whose genetic environments are thought to be submarine volcanic exhalative processes of metal concentration similar to the Kuroko-type mineralization of Japan.

Marginal basins and the continental margin

Eastern Asia and the Western Pacific have the largest area of marginal basins in the world and thus the processes of their development are extremely important to an understanding of the region. The island arc systems and the marginal basins of this region are intimately related, the creation of marginal basins and remnant arcs resulting in migration of the active arc systems away from the continental edge. There appears to be a decrease in sea-floor age across these marginal basins and remnant arcs in the direction of the actively-forming basin. It is assumed that at least some of these marginal basins are developed by a spreading mechanism similar to that visualized for the deep oceans. However, it has also been suggested that marginal basins may represent attenuation and transformation of continental crust or "oceanization".

The products of the formation of new crust within marginal basins appear to be identical to the basaltic crust of deep oceans. Therefore, the processes of ore formation and concentration may be similar to those previously described for a spreading axis. If the concept of oceanization is correct, then contamination of basaltic magmas by older continental crust would lead to a different suite of ore minerals than those formed at a spreading axis. Granites intruding through continental margins at the edges of marginal basins seem characteristically to contain tin, whereas intrusions giving rise to porphyry copper have no such association.

Inactive arcs and suture zones

Along the margins of the Circum-Pacific belt, there are elongate tectonic zones parallel to the regional structures, which are considered to represent former convergent boundaries between oceanic crust and continental edge and are referred to generally as *suture zones*. Actualistic concepts involving kinematic emplacement of slabs of oceanic crust (ophiolites) in these zones are difficult to visualize: it has been suggested that in some tectonic situations of plate convergence, slabs of oceanic crust and mantle may actually over-ride the continental edges (obduction). It is further visualized that large sheet-like masses (flakes) can be detached by a "wood-plane" action and then driven over the continental plate during subduction. In contrast to these mechanisms some geologists prefer gravity sliding during isostatic uplift as an emplacement mechanism for these crustal flakes. Associated with these large slabs of oceanic crust are areas of chaotic assemblage often containing dismembered parts of an ophiolite complex, flysch sediments, deep water pelagic sediments and metamorphic rocks. These tectonically disturbed rocks, basically chaotic mega-breccias consisting of blocks of the above-mentioned rocks floating in a matrix of serpentine or scaly sheared sedimentary material, are commonly referred to as *mélange* (though other definitions of this term are also current). The mélange units can be mapped, and they apparently delineate zones of major tectonic dislocation related to subduction or obduction. Because mélanges have not been precisely defined and may often confused with olistostromes (gravity slide deposits) their tectonic and geological character needs to be carefully studied before their significance in ancient collision zones can be established. Concomitant with emplacement of ophiolites is the development of metamorphic rocks which require high pressures relative to temperature (blue-schists). It has been shown that such pressure-temperature conditions are characteristic of subduction and also of obduction zones. Thus a grouping of ophiolites, mélanges and blue-schists can be used to indicate certain kinds of ancient plate boundaries.

Ore deposits of suture zones. Ophiolites in suture zones may carry with them metallic concentrations developed during their formation at a spreading ridge. The peridotites contain chromite segregations, and tropical weathering of these rocks may also produce vast accumulations of nickel laterite. Copper deposits can be formed with the diabase-basalt sequences, either at the spreading ridge or by later superimposed hydrothermal alteration. Important strata-bound lead-zinc-copper-barium ores occur in older trench deposits, often in the vicinity of ophiolites or intermediate lavas; they are commonly embedded in overturned thrust shale-quartzite sequences with intercalations of greenstones and tuff bands. Platinum may be expected in some cases, but no known commercial deposits have been discovered. The mélange itself does not appear to be a favourable area for the development of ore deposits; however, mechanical transport of pre-existing ore deposits is a possibility and post-mélange intrusions may find these rocks an attractive host-rock such as exemplified by silica-carbonate replacement by mercury and antimony deposits. As an economic target area for prospecting, mélange-ophiolite sequences have only a moderate potential.

Some major unanswered questions

1. Is the development of massive sulphide ores over spreading axes limited to regions where the hot brines may be derived from evaporites, that is,

to Red Sea-Salton Sea conditions, or can they develop over truly oceanic axes?

2. What are the conditions for the formation of porphyry copper deposits in island arcs? Why are some areas, for example the Philippines, highly mineralized, and others such as Sumatra apparently barren?

3. Do tin deposits require the presence of old continental crust? If they are formed by its remobilization, what is the mechanism of concentration? Why are rich tin deposits restricted to small areas of much larger granitic belts? What is the relationship between tin occurrence and age of granite, and are petrological variations in granite related to mineralization? Why are some areas rich in alluvial and disseminated primary cassiterite, while others have rich lode deposits?

4. Are all ophiolites formed at oceanic spreading axes? Can some be produced in marginal basins or by oceanization? If the latter, what kinds of ore deposits are associated with the different classes of ophiolites?

Recommendations for study

Arc systems

1. Present *arc systems* in the region should be investigated to improve the understanding of their constitution, origin and evolution, and particularly to establish the tectonic context in which metallic ore deposits were emplaced in and behind them. The tools of the structural geologist and geophysicist are appropriate to this task, and stratigraphy and palaeontology can also be usefully employed in the outer sedimentary arcs. Interpretation of the deformed sediments and ophiolites of the sedimentary arcs, in terms of the subduction processes investigated by geophysical means, should include the subduction history and tectonic setting during mineralization, such as from Cretaceous to the present and possibly earlier. Investigations of the structural and petrological aspects of associated igneous rocks, and of those not associated with mineralization, will throw light on the nature of igneour activity during subduction and related mineralization phases. The outes Sunda Arc is a promising area for such investigations, where deformed sediments and ophiolites can be related to present-day subduction which can be investigated geophysically; additionally, young tin, tungsten and antimony deposits and a major porphyry copper deposit are present behind the outer arc. This recommendation is dealt with in more detail in pages 84-86.

2. Systematic *geochemical analyses* of major and trace elements and isotopes should be undertaken on selected parts of the active arc systems for better determination of the relationship between volcanism and the Benioff

zone. Comparisons should also be made between magma chemistry, depth of magma generation, crustal thickness and the position of mantle material under arc systems and inter-arc troughs. Studies should be undertaken where the underlying crust is continental as well as where it is oceanic. The result should be an improved understanding of the genesis of the arcs and their resulting magmas. An important application of this data would be to assist in the recognition of inactive older arc systems, where ore deposits are generally more common.

3. In older or inactive arc regions the *age relations of volcanic and intrusive rocks to mineralization* should be studied. This can be done by combined geological and isotopic dating studies, the latter to be done by appropriate methods including Rb/Sr, U/Pb and K/Ar. This will require considerable assistance and co-operation from laboratories outside the region.

4. *Regional geochronological programmes* should be undertaken as an aid in the reconstruction of the history and evolution of the complex eastern Asian region.

5. *Heavy mineral analyses* of available cores from exploration wells should be made in order to identify possible tin placers, both recent and lithified. This will contribute to ideas of mechanical concentration processes and provenance of the deposits. It would be necessary to obtain cores and mineral analyses to establish baseline parameters.

6. An attempt should be made to detect *brines*, or bottom sediments formed in former brine pools, that have concentrated metals. This work would be confined to the vicinity of present or ancient spreading axes.

7. To improve understanding of the conditions of formation of *porphyry-copper deposits* in island arcs, petrological studies should be undertaken of acidic magmatism in relation to island arcs, and of the processes leading to the ultimate exposure of the deposits at the surface. Mapping and classification of acidic intrusions in the region, chemical studies of rock variation as related to porphyry deposits, relationships between erosion and vertical zonation of metals in calc-alkaline intrusions and studies related to the geomorphic history of island arcs should all provide evidence. *A separate symposium on this problem for economic geologists of the region is recommended.*

8. *Lead isotope studies* should be undertaken on lead deposits, which are emplaced in host rocks of widely different ages in Burma, Thailand and elsewhere. Interpretation of the origin of this mineralization in terms of tectonic and thermal events and processes requires data on the isotopic composition of the leads; this data could also provide evidence for ages of mineral deposits associated with or adjacent to the lead (silver, barite, etc.). It is suggested that lead isotope work should be carried out on different deposits within

individual lead provinces, and that a number of lead provinces distributed as widely as possible within the region should be studied on a comparative basis.

9. Dredging should be undertaken to obtain *basaltic rocks from marginal basins* for petrological study to compare them with basalts from spreading axes. Also, as some ophiolites may represent oceanic crust developed in marginal basins, an attempt should be made to compare ophiolites from these two environments.

10. Possible *spreading axes* in marginal basins should be sought in order to locate any Red Sea-type metalliferous sediments.

11. *Heat flow measurements* in marginal basins where they coincide with magnetic "quiet" zones should be collected and analysed: these quiet zones may reveal areas of hydrothermal alteration and possible metal concentrations.

12. *Basaltic pillow lavas* obtained from Deep Sea Drilling Project cores should be analysed for important trace elements such as copper, zinc and lead to search for systematic variations in either space or time which may influence the amount of ore metal being fed into present or older subduction systems.

Inactive arcs and suture zones

13. General compilation of *geological and tectonic maps* showing distribution of ophiolites, mélanges and blue-schists would indicate sites of suture zones. This should be undertaken by local geologists in the region.

14. Careful study should be made of the larger *ophiolite complexes*, to establish distribution of rock types, and variations in petrology and geochemistry within the complexes. Chemical analysis of rock types as well as geochemical survey for nickel, copper and chromium concentrations could also be undertaken by local geologists.

15. Detailed study of *mélange bodies* would help establish their tectonic history and relationship to subduction or obduction. Detailed mapping and comparison where possible with offshore information from ocean-floor studies might serve to establish the mechanics of mélange formation.

16. Careful *tracer studies*, using strontium and lead isotopes, might show whether island arc ore deposits are related to materials carried into the subduction zone and subsequently mobilized (the "geostill" concept): some method of "finger-printing" source rocks is needed. Tracer studies should be undertaken in sediments about to be subducted, underlying volcanic rocks and those on island arcs and hypabyssal intrusions. Such studies could be carried out only by well-established isotope laboratories, and co-operation

between geologists of the region, marine geologists and specialized geochemists is needed.

Training

Continued training of earth scientists from the region could be realized in all of the recommendations mentioned above, particularly in geological mapping, participation in oceanographic expeditions and other multidisciplinary efforts. Financial support by oil companies, United States Agency for International Development (USAID) and Colombo Plan for advanced training in institutes carrying out the research work should be actively sought to promote the implementation of the above recommendations.

REPORT OF HEAT FLOW AND HYDROCARBON MATURATION PANEL

Present-day heat flow and geothermal data as well as palaeogeothermal observations are of crucial importance in evaluating geodynamic models, and this is particularly true where the concepts of oceanization, sea-floor spreading or other alternatives are involved. In sedimentary basins of interest to the petroleum industry, the same sort of thermal data may be used for geothermal studies involving the maturation of oil from organic-rich hydrocarbon source beds.

Present-day heat flow data

Heat flow measurements have been made in both land and sea areas, and in recent years considerably more of these have been made in sea areas. In general, all these measurements indicate that low heat flow is encountered around continental shield areas, average heat flow in cratonic areas, and higher heat flow in some continental margin areas. In the oceanic areas, high values have been measured along active oceanic ridges and in marginal basins, while low values are often associated with subduction zones (Lee, 1965; Oxburgh and Turcotte, 1970; Sclater and Francheteau, 1970; Watanabe et al., 1970).

In the Western Pacific area approximately 1,200 published and unpublished measurements from heat flow stations have been made. These stations are not evenly distributed as most of them occur north of latitude 20°N and around the Tonga Islands. A characteristic heat flow profile across the Japan island arc (Vacquier et al., 1966) shows uniformly subnormal heat flow in front of the trench, very low values at the trench and remarkably high values in the marginal sea (Japan Sea) *(Fig. 26)*. This general relation has been confirmed in the Kurile Islands (Yasui et al., 1968) and the Ryukyu Islands arc (Yasui et al., 1970).

Sclater (1972) and Horai and Langseth (1973) have independently suggested an inverse correlation between mean heat flow values and depth of basement in marginal basins, and have attempted to estimate the age of these basins using this assumption.

Palaeogeothermal studies

Present as well as past geothermal gradients in various hydrocarbon-producing basins appear to have had an influence on the relative magnitude and type of hydrocarbon generation. Evidence suggests that high geothermal gradients in sedimentary rock sequences enhance the processes of formation of oil and gas. Several basins associated with significantly high heat flow zones are located along various continental plate margins and areas of possible incipient sea-floor spreading associated with upwelling of basic igneous material. These basins tend to yield more hydrocarbons per cubic kilometre of sediments than basins from low heat flow areas, assuming that all the other limiting geological factors for hydrocarbon accumulations are present [Klemme, 1971, 1972 and 1974 (in press)].

Petroleum geologists commonly now agree that hydrocarbons are generated from source beds which have a relatively high content of organic carbon (Bray and Evans, 1961; Erdman, 1965; Philippi, 1957; Smith, 1954; Tissot et al., 1971). Subsequent deeper burial of these source beds promotes a maturation process by which commercial hydrocarbons are formed. This process is similar to the coalification process which results in the formation of coals of varying rank (lignite to anthracite). Both processes are essentially temperature-dependent, with time and detailed burial history both of some importance. Pressure, however, does not appear to be a major influence in the formation of hydrocarbons (Baker and Claypool, 1970; Bray and Evans, 1961; Brooks et al., 1971; Kartsev et al., 1971; Landes, 1967; Philippi, 1965; Staplin, 1969; Tissot et al., 1971; Vassoyevich et al., 1970; Welte, 1965, 1966; and White, 1915). Bacterial biodegradation may be a factor in maturation, particularly in respect of high-sulphur crudes and bitumens (Bailey et al., 1973).

To determine the optimal burial condition for oil- and gas-generating phases, it is important to try and determine the temperature history of a sedimentary sequence, and to this end several methods have been developed:

(i) for routine reconnaissance, spore carbonization studies are very useful and they can be undertaken with little additional efforts as a by-product of palynological work (Correia, 1967; Gutjahr, 1966; and Staplin, 1969);

(ii) the reflectance of vitrinite particles provides a useful tool for a more detailed approach to the problem (Alpern and De Sousa, 1970; Castano, 1973; Castano and Sparks, 1974, in press; Gutjahr, 1966; Suggate, 1959; and Teichmuller, 1971);

(iii) electromagnetic spin resonance which measures the number of free radicals in kerogen is another useful tool; these are known to increase with depth of burial (Binder, 1965; Marchand, Libert and Combaz, 1968, 1969; Pusey, 1973).

Using these techniques (many more expensive ones are also available) the maximum temperatures to which sediments have been exposed during their history can be determined with reasonable approximation. In Tertiary basins which have been subjected to continuous subsidence, temperature indications at various depths should be generally compatible with present-day temperature gradients. Basins which have been uplifted would show palaeo-geothermal values higher than the present-day geothermal gradient. Therefore maximum isotherms can be integrated in structural sections to determine burial preceding folding (folded isotherms), tilting or burial after folding (discordant isotherms), synorogenic subsidence, post-orogenic uplift, or the amount of overburden associated with the upper units of a tectonic sequence associated with a subduction zone.

Of course, present-day temperature gradients as determined in deep wells and maximum palaeotemperature studies can and should be combined with heat conductivity measurements to obtain both recent and ancient heat flow information.

Recommendations

It is readily apparent that some of the possible geodynamic models of an area are capable of explaining regional tectonics as a consequence of thermal processes in the crust; heat flow and geothermal gradients are measurable quantities with which such models would have to be compatible. It has also been shown that the geothermal history of basins is of great importance for an understanding of hydrocarbon-generating processes as well as for the distribution of coal deposits of differing quality. Such studies in the adjacent land and shallow water areas have to be viewed as a integral part of any project which tries to assess resource potential of the deeper ocean.

1. *Heat flow measurements in oceanic basins:* it is necessary to obtain heat flow measurements in the areas between the Asian and Australian continents, that is, the areas between latitudes 20°N and 10°S. These measurements should be taken on islands, peninsulas and continental margins, as well as on deep sea floors. In this connection special new instrumentation has to be developed: for instance, in shallow water areas one of the principal assumptions that the water-bottom temperature is stable is not satisfied, so

new techniques to measure heat flow in shallow water have to be developed (see Leclerc, 1969 and Nomura, 1971).

Also for an area as large as the one under consideration, it would be desirable to utilize free-fall heat-flow marine instrumentation packages which could be recovered subsequently; these are already in use in some institutions.

Additionally, data from existing deep sea drilling sites and potential IPOD sites should be integrated with heat flow studies of the area.

2. *Heat flow and geothermal gradient map of eastern Asia:* compilation of such a map would integrate oceanic heat flow data with data from offshore and onshore wells. The map base ought to be the same as the base used for the planned tectonic map so that comparisons can be readily made. Conceivably such a project could be patterned after the American Association of Petroleum Geologists (AAPG) North America Geothermal Gradient Map (Schoeppel et al., 1970), and advice on this project is freely available.

It is recommended that a committee be established, with representatives from national governments, mining companies and oil companies to encourage their co-operation in such a project. Such a committee would be responsible for data acquisition and integration, compilation and standardization procedures, and ensure that the project was organized on a basis relevant to the nature of the problems in the region.

3. *Palaeogeothermal studies:* it has been shown that such studies, using measurements of organic metamorphism, help to resolve the tectonic history of an area, and are of substantial importance for an overall understanding of the distribution of hydrocarbons in the area. It is recommended that such studies be undertaken with the assistance of governments, universities, oil and coal companies located in the area. To limit the initial scope of such a project it is recommended that work be conducted in those areas which have been recommended for transect studies. Such studies could help to resolve problems of structural evolution along these transects. It is also suggested that, at present, these studies be limited initially to geothermal history of Tertiary sequences, which would be simpler to understand than the more complex history of older deposits.

Training

The implementation of heat flow and palaeogeothermal studies should properly include some training of local specialists. It is estimated that the training time required will be fairly short (say one to two months) provided that the basic equipment is available. It is recommended that coal companies or oil companies be contacted for suggestions and help in training.

V. SPECIFIC RECOMMENDATIONS FOR MULTIDISCIPLINARY RESEARCH PROJECTS

As stated in the Introduction, numerous project proposals submitted to the Workshop were assessed and, in many cases, incorporated into "transect" study projects for specific zones cutting across arc-trench systems and adjacent basins and continental areas. This consolidation of projects resulted in the promulgation of multidisciplinary research proposals for six such transect areas, covering the major areas of plate interaction in the region.

The transect study proposals concern six areas *(Fig. 30)*, each with their

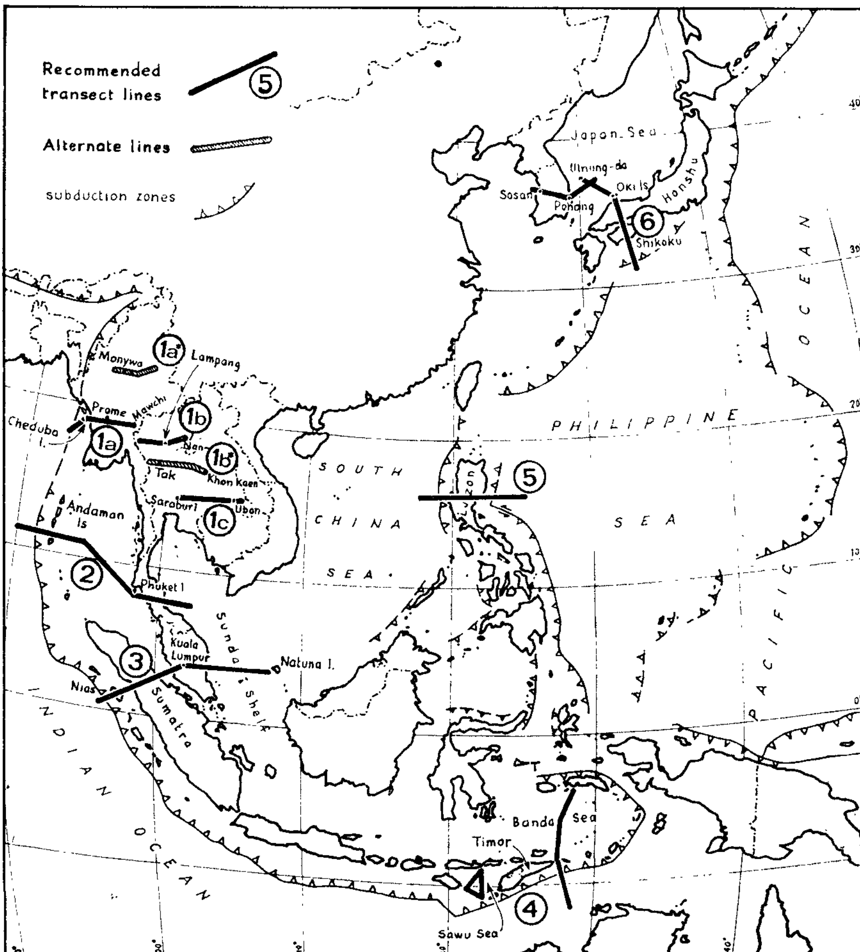


Figure 30. Location of the recommended multidisciplinary study transects in eastern Asia, in relation to the major plate boundaries.

own individual characteristics. The Burma-northern Thailand transect (1) is largely an on-land study, crossing at its western end the presumed site of subduction of the Indo-Australian Plate beneath the Eurasian Plate; it includes petroleum-bearing basins and some volcanic activity, and extends to a stable plateau on the edge of Indochina Palaeozoic massif. The Andaman Sea-southern Thailand transect (2) crosses a marginal sea that may include a spreading axis behind an island arc of low seismicity, crosses an area in southern Thailand known for its tin mineralization, and ends in a major hydrocarbon-bearing Tertiary basin. The Sumatra-Malay Peninsula-Sunda Shelf transect (3) crosses a tin area, an active subduction zone and outer arc island chain, a mountainous area with transcurrent faulting, and adjacent petroliferous basins. The Timor-Banda Sea transect (4) lies in an area where three plates are in collision and where the origins of the materials making up the island arcs are in question; both ore minerals and petroleum are involved in these arcs, and the nature of the small ocean basins in the vicinity is of scientific significance. The Northern Philippines transect (5) crosses two opposing subduction zones, one perhaps only incipient, and an area of porphyry copper mineralization. Finally, the Southwest Japan-Korean Peninsula transect (6) crosses an oceanic trench thought to be related to an early-stage subduction zone and passes across the adjacent more mature island arc into the marginal Japan Sea, which may be the site of sea-floor spreading or oceanization, and across the abrupt continental margin of the Korean Peninsula where mineralization is associated with Mesozoic and Cenozoic granites.

In drawing various project proposals together into transect study proposals, the Workshop did not wish to indicate any degree of priority with respect to proposals for other areas or other types of work. The intention was to suggest to potential workers the areas where, in the opinion of the meeting, research work in several fields of earth science would give the most significant results. The transects, therefore, are an attempt to focus attention, to coordinate effort, and to increase scientific productivity by concentrating on key areas. The effect of several workers or groups of workers studying a strip of land and sea should, given adequate communication, be more productive than those same workers expending their efforts in more diverse areas. Additionally, once extensive investigations and a synthesis have been made and a cross-section constructed for any transect, comparative studies along lines parallel to the transect may be undertaken for comparison with the integrated information from the transect. The results of the transect studies themselves, though separated by an average of some 2,000 km, should provide highly interesting comparisons and contrasts along the plate margins of the region, and serve to stimulate further work on the plates themselves.

MULTIDISCIPLINARY TRANSECT PROPOSALS

1. **Burma-northern Thailand transect** *(Fig. 31)*

The aim of this transect study is to establish a land-control reference section across the margin of the Eurasian Plate from the plate boundary to the stable continental hinterland to the east. Examination of the structural elements of the western part of the transect, which show many features associated with subduction and where the geology can be examined directly,

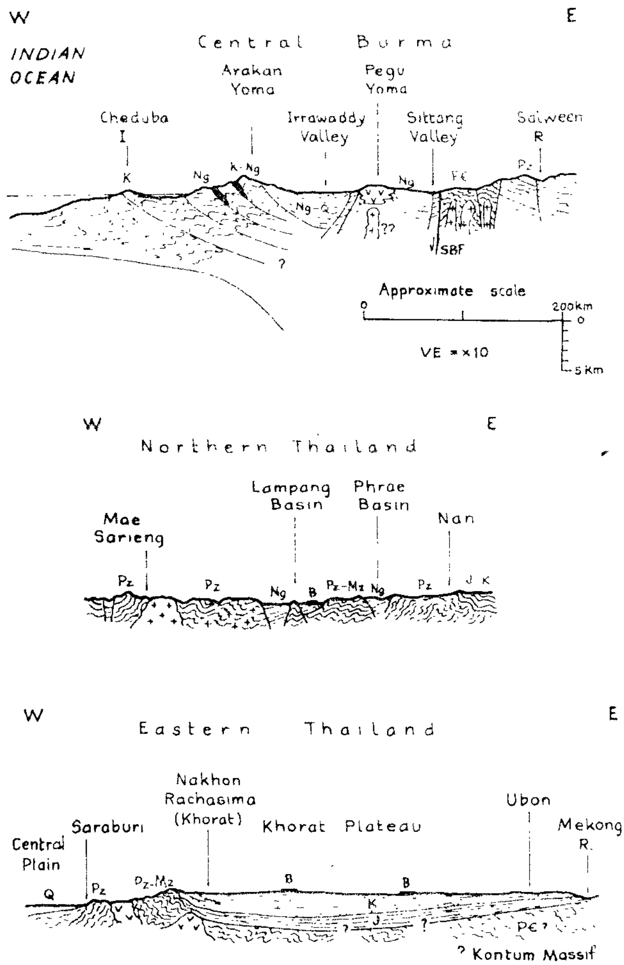


Figure 31. Schematic cross-sections showing inferred structure along the segments of the proposed Burma-Thailand transect (for location of profiles, see *Figure 30*). For these and subsequent profiles, age symbols are conventional (e.g. Pz = Palaeozoic, K = Cretaceous, Ng = Neogene). vv = volcanic rocks ; + = granites B = Cenozoic basalts ; SBF = Shan Boundary Fault.

would provide a significant cross-section for comparison with analogous tectonic features in the Andaman Sea area. The boundary with the Indo-Australian Plate is thought to lie off the west coast of Burma as far north as Hunter's Bay at latitude 20°N, but there is no marked trench feature either under the sea or on land to the northward. Differential movement on the boundaryis probably right-lateral slip at the present time (see p. 31), though subduction has clearly occurred in the past on the evidence of the Arakan Yomas, which represent an outer-arc feature composed apparently of the very thick Bengal fan formations scraped off the over-ridden Indo-Australian Plate. Other island arc features are also present, including a volcanic arc and a back-arc trough bounded by the graben-type Shan Boundary Fault. In the pre-Cenozoic terrain east of the fault there have been several periods of folding, and Mesozoic fold belts fringe the stable Khorat Plateau which may be an extension of the Precambrian Kontum Massif covered with unfolded Mesozoic strata.

Metallogenic and oil habitat models may be derived from the study which could be of significance for the Andaman Sea and arc systems in adjacent parts of the region.

Location of the transect. Three segments are recommended for study, based on geologically interesting features, information that is already available, and accessibility.

Transect 1a includes a short marine section from the shoreline southwestwards for up to 100 km, to cross the inferred position of the plate boundary. This should be located at or near the latitude of Cheduba Island (18° 45′ N), and investigations should be conducted on Cheduba and Ramree Islands. Road access is possible across the Arakan Yoma for study of the undifferentiated Cretaceous-Tertiary flysch-ophiolite complex imbricate zone (the outer non-volcanic arc) with associated chromite deposits; the transect line then crosses the thick Cenozoic succession with open folds and oil fields in the Prome embayment and the folded Neogene of the Pegu Yoma to the Sittang Valley, probably also a late Cenozoic back-arc trough. From there the line crosses the Shan Scarp and the pre-Tertiary terrain to the eastward, including the Mawch Mine area with tin- and tungsten-bearing granites.

An alternative line for this segment of the transect *(1a*)* would pass further north through the Monywa porphyry copper deposit in the volcanic arc and cross the Shan Scarp north of Mandalay.

The marine segment would require seismic reflection, gravity and magnetic profiling, and some seismic refraction work to determine total sediment thickness. It could be undertaken in connection with similar work on transect 2 (the Andaman Sea).

Data available in this area include some geological field mapping and gravity measurements in the Arakan ranges and the islands, some geological maps and seismic, gravity and aeromagnetic data in the Prome embayment, geological mapping in the Pegu ranges, and some local mapping of the granites in the Mawchi area. Geological maps made by the Burmah Oil Company in 1940-1943 may possibly be available also.

Transect 1b extends from the Salween River on the Burma-Thailand border, near Mae Sarieng, across northern Thailand between latitudes 18° and 19°N through Lampang to Nan. This line mainly traverses folded Precambrian and Palaeozoic metamorphic and Mesozoic sedimentary terrain intruded by granites of several ages, with associated tin, tungsten and antimony mineralization. There are also several late Cenozoic sedimentary fault-bounded basins and young basalt flows. The line ends in a late Mesozoic folded belt on the margin of the stable Khorat Plateau. A geological and structural map on a scale of 1:1,000,000, and a geological map at 1:250,000 for the Lampang sheet are available, the latter based on 1:50,000 field data. Well data from the Chiang Mai and Fang Basins may be available later.

An alternative line for this part of the transect, designated *1b**, lies just south of latitude 17° N, about 150 km south of *1a* along a line of mostly good east-west highway access. It runs from Mae Sot on the Thailand-Burma border eastwards through Tak, Sukhothai, Phitsanulok, Lom Sak and Chumphae to Khon Kaen, crossing several significant geological features. Fold belts of Himalayan and Indosinian age are prominent in the western and central parts of the line, and the structural transition from the Indosinian fold belt to the undeformed Khorat Plateau is well displayed at the eastern end. A north-south belt of serpentinite and other basic rocks lies east of Phitsanulok, which may represent an ophiolite complex related to a possible pre-Permian subduction zone. Mineralogical interest is provided by tin granites, a possible porphyry copper deposit east of Tak, hematite-magnetite, manganese and base metal deposits east of Phitsanulok, and oil shales at Mae Sot. Geological map data on a scale of 1:250,000 is available for the whole of the line.

Transect 1c runs from Saraburi, north of Bangkok, across the Khorat escarpment to Nakhon Ratchasima (Khorat) and across the Khorat Plateau to the Mekong River. This segment traverses a rigid portion of the continental plate, a probable extension of the Kontum Massif, that underwent slow subsidence in the Mesozoic with deposition of continental sediments and thick salt accumulation; basalt flows were extruded on the southern part of the plateau during the Cenozoic. Geological maps at 1:1,000,000 and 1:750,000 are available. Seismic and airborne geophysical data and data from one well may be available from oil companies; aeromagnetic surveys have been made.

ERTS imagery is available for all three segments of the transect.

Recommended studies. Geological mapping on a 1:50,000 scale should be undertaken within a belt 25-50 km wide along *transect 1a*, and then aeromagnetic lines flown at 5 km intervals parallel to it; gravity determinations should be made along the line of the transect itself. Heat flow data should be obtained for the Tertiary sedimentary basins on this line and on *transect 1a** to the north, to provide information for the oil habitat model. Determination of the geological controls of mineral deposits should be made where possible, including the Monywa porphyry copper deposit, to provide data for the metallogenic control model. A seismic survey offshore from the coast past Ramree and Cheduba Islands across the inferred location of the plate boundary is highly desirable, to investigate the near-surface characteristics of the plate margin and the untypical boundary.

Aeromagnetic, gravity and heat-flow data (where there are wells in basin areas) should be obtained for *transect 1b* and *1b** similar to that prescribed for *1a*. Some seismic reflection and refraction profiles should be run, especially in the Cenozoic basins, to gain information on their tectonic development and mechanism and the genesis of the oil in the Fang Basin. The geological, geochemical and mineralogical controls of ore deposits should be determined, with emphasis on the radiometric dating of igneous rocks and, where possible, the related mineralization; and the petrology and geological setting of mineralized igneous rocks, specifically those associated with tin, tungsten, antimony and molybdenum.

A gravity profile should be obtained along *transect 1c* across the Khorat Plateau, and a detailed geophysical investigation made of the late Cenozoic basalts, together with an attempt to relate them to contemporaneous sedimentary formations. A basin study of the Khorat Group in the area might reveal economic deposits of potash or other salts, and the tectonic implications of basinal subsidence.

Palaeomagnetic investigations should be made on *all three transect segments*, investigating the different geological units to study their former locations relative to each other and the location of southeast Asia as a whole in the geological past.

As much of the transect study programme as possible should be undertaken by local geologists and organizations.

2. Andaman Sea-Malay Peninsala transect *(Fig. 32)*

The Andaman Sea is one of the most interesting and least known of the marginal basins of eastern Asia, lying between the continental mass and a presently inactive island arc facing the Indian Ocean *(Fig. 2)*. The plate

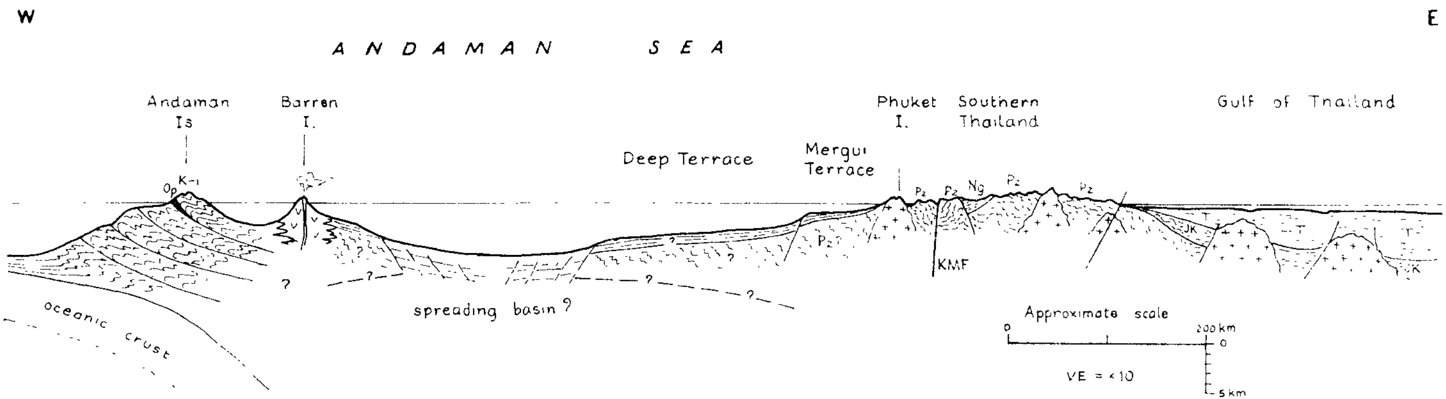


Figure 32. Schematic profile showing inferred structure along the proposed Andaman Sea-Southern Thailand transect (for location of profile, see *Figure 30*). Op = ophiolite bodies; KMF = Khlong Marui Fault.

boundary runs parallel to the outer Sunda Arc islands further south, and apparently extends northward west of the Andaman-Nicobar Islands arc; active underthrusting is largely confined to the Sunda Arc, slip motion apparently being dominant in the Andaman Sea area. The eastern margin and probably much of the eastern terrace area of the sea consist of Palaeozoic metamorphic rocks intruded by mineralized (tin-tungsten) granites. Sediments of the Irrawaddy delta have obscured the northern margin of the basin, and the exact nature of the southern margin, against northern Sumatra, remains to be discovered. Volcanic islands in the northwestern part of the sea suggest the possible presence of a spreading axis.

Geological-geophysical transect studies are proposed to investigate the geological features and tectonic relationships of the various structural elements of the Andaman Sea, together with adjacent islands and the southern Thailand peninsula, extending westwards across the presumed site of the subduction zone and eastwards into the Gulf of Thailand. In detail, the transect should follow a line approximately along the 11°N parallel of latitude from 90°E longitude, north of Little Andaman Island, across Invisible Bank (the end of the possible spreading axis) to about 95°E; from there southeastwards to Phuket Island and thence eastwards at about 8°N latitude across the peninsula to the Gulf of Thailand north of Songkhla, a total distance of about 1,500 km. The Phuket area is highly important for tin mining, and some shallow-penetration geophysical work has already been undertaken there; surveys of the peninsula have also been made in connection with the proposed Kra Canal in the Songkhla area, and 1:50,000 scale geological map of the peninsula will shortly be published by the Institute of Geological Sciences (London).

The various geological elements of the transect are described in turn, giving present knowledge, some important problems and possible means of solution for each segment, numbered 2a, 2b, etc.

2a. *The Bengal deep-sea fan.* This fan appears to owe its origin to massive influxes of sediment from the Indian sub-continent, delivered through an outlet in the vicinity of the present Ganges-Brahmaputra delta. In form it is a gently sloping surface, filling the floor of the eastern Indian Ocean for a distance of some 3,000 km southwards, with a steeper surface slope (about 1 in 600) in the proximal portion than in the distal (about 1 in 1,200) *(Fig. 6)*. The surface is furrowed by several valley-like features, and a submarine canyon is present in the continental slope and shelf at its head, off the Ganges delta. Several features, including the Ninety East Ridge, protrude through the fan in its distal portion; the ridge shows topographic expression as far north as 10°N latitude, and may or may not be present at the latitude of the proposed transect.

Investigations have shown that the sediments of the fan may be up to 16 km thick in the northern part, with ages ranging back to the Cretaceous *(Fig. 7)*. At the latitude of the transect, the sediment thickness appears to be about 6 km with mantle reflections coming from 13 km. Extrapolation from Deep Sea Drilling Project sites 217 and 218 suggests that the oldest strata are mid-Cretaceous, and that major breaks in sedimentation and tectonic events took place at the end of the Palaeocene and in late Miocene. Deformation of fan deposits, eastward dips and thickening of the fan units are known to extend about 50 km west of the base of the continental slope off the Andaman Islands. Locally, there are great slide masses on the fan surface which have moved down the slope. At the latitude of the transect the fan sediments may be predominantly muddy rather than sandy, of distal to central fan facies, with some interbedded pelagic units.

Problems in this segment of the transect include:

(i) does the Ninety East Ridge extend to this latitude, either at surface or buried beneath fan sediments? Fully processed digital multi-trace seismic profiling, with refraction, magnetic and gravity profiling may help to answer this.

(ii) how extensive is deformation of the fan sediments on and at the foot of the slope? Again, better seismic profiling is required.

2b. *The non-volcanic island arc.* The Andaman and Nicobar Islands form part of an arc ridge continuous with the Indo-Burman Ranges (Arakan Yoma) to the north and the Mentawai Islands off Sumatra to the south; the presumed position of the plate boundary, on seismological evidence, lies immediately to the west of these features, though seismicity is of a much lesser order between 13° and 23°N latitude (Shouls, 1973) *(Fig. 8)*. Structure, stratigraphy and geological history of the Andaman and Nicobar Islands have been described by the Geological Survey of India (Karunakaran, Ray and Saha, 1964a, 1964b; Karunakaran, Pawde, Raina, Ray and Saha, 1964). Flysch and pelagic deposits and ophiolites are present in generally eastward-dipping thrust sheets, ranging from Cretaceous to Miocene in age, with the older rocks commonly forming the eastern margins. The descriptions suggest that the entire section is a tectonically-mixed chaotic assemblage. Emergent reefs of Pleistocene age give evidence of uplift in recent times.

The internal structure of the submerged part of the ridge is not clear from available profiling records. Even unpublished commercial 24-fold seismic records do not clearly indicate structure, though air-gun surveys of relatively low power and high frequency locally suggest tight folding in some of the ridge areas. Eastward-dipping reflectors, which might be thrust sheets, are suggested in some profiles. The ridge topography is characteristic of the arc flank of many subduction zones, with irregular ridges and basins apparently perched on a chaotic assemblage of scraped-off sedimentary material. The basins, like those off Sumatra, show deformation of their margins that must have occurred during basin infilling.

Problems that require solving in the island arc area include:

(i) what is the mechanism of accretion of the chaotic assemblage? Is it due to "scraping-off" of the oceanic sediments as one plate slides under the other in the subduction zone, and what proportion of the sediments is carried down on the descending plate? How is this affected by the variables of sediment-column thickness, sediment type, rate of sediment supply from the islands, and rate and direction of convergence? How is the structural style of the chaotic assemblage affected by these variables?

(ii) if the concept of sediments being scraped off to form chaotic assemblages is correct, then the strata exposed on the islands will correlate with sedimentary units under the Bay of Bengal. Because of the great thicknesses involved, these sub-bottom units are totally inaccessible, so only by study of the formations exposed on the islands can the history of the depositional basin, from commencement onwards, be clarified.

(iii) the direction of relative motion along the presumed plate margin at the foot of the continental slope is not clear from past seismicity studies. If the Andaman Sea is extensional, a component of subduction must operate (or have operated); otherwise, the northern part of the Andaman chain is affected by strike-slip relative motion. More first-motion seismological studies should be undertaken to resolve the movement direction and to evaluate the magnitude of the subduction component.

2c. *The inner volcanic island chain.* The active portion of the volcanic arc in the Andaman Sea includes only one emergent active volcano, Barren Island; there are a number of submarine active volcanoes to the south, and Narcondam Island, to the north, is apparently extinct but geologically very young. These form part of an arc that includes the more continuous chain of volcanoes in Sumatra and those in Burma *(Fig. 9)*.

The most conspicuous phenomenon is the negative gravity anomaly (–150 m gal, free air) in the vicinity of the volcanic arc *(Fig. 32)*, in contrast with the positive anomalies (up to +150 m gal) associated with volcanoes in Java; this suggests a different crustal structure for these two segments of the tectonic arc. The possibility of continental crust underlying the Barren Island chain should not be excluded: the volcanoes are andesitic and dacitic, with low potash content, but are not well studied. In Burma, on-land volcanoes range from Eocene to Pliocene in age, but ages are unknown in the Andaman Sea.

Problems in this segment include:

(i) the petrology of the volcanic arc, both islands and submerged, is poorly known and should be sampled and investigated extensively.

(ii) the crustal structure is also poorly known, and geophysical investigations should be undertaken to determine the velocity structure, thickness and nature of the crust.

2d. *The Andaman Sea Basin.* Structural belts from the eastern Himalayas trend southwards into Sumatra and further east, and apparently pass through the Andaman Sea. Unlike the trend of the island arcs, in the basin itself the trends are north-northeast; these trends include old features such as the continental slope of the Malay Peninsula and the submarine slope at the northwestern end of the Strait of Malacca. Projected northwards, this trend coincides with the Khlong Marui transcurrent fault across the peninsula that may be early Cretaceous in age *(Fig. 4)*. Active spreading in the Andaman Sea Basin along this trend probably began no earlier than Miocene times, and geomorphic and seismic data suggests that active extension is still in progress.

Problems in this area include:

(i) investigation of the possible occurrence of hydrothermal mineral deposits in the basin centre (similar to those in the Red Sea).

(ii) the few heat-flow measurements so far taken indicate anomalously high values: systematic mapping of heat flow in the basin should be undertaken.

(iii) study should be made of the volumes of sediment present in the basin and of the sedimentation rates.

(iv) the crustal structure, age and pattern of rifting of the basin should be investigated.

(v) the zone of extension should be defined accurately by mapping of microseismicity.

(vi) possible extension(s) of the Sumatran (Semangko) fault system should be mapped to determine their relationship to the spreading history of the basin.

(vii) systematic magnetic profiling should be undertaken to determine any pattern of magnetic lineation and thus detect the pattern and rate of spreading away from a possible axis or axes.

2e. *Andaman Sea continental margin.* The eastern portion of the Andaman Sea consists of continental shelf and the deeper Mergui Terrace, separated from the basin by a continental slope *(Fig. 9)*. Near shore, the shelf is known to consist of a thin sequence of Tertiary deposits, thickening seawards, overlying Palaeozoic rocks intruded by granites presumably similar to those exposed in the southern Thailand peninsula. There is an indication from early work that the Tertiary thickens markedly towards the edge of the shelf; if this is the case there may be petroleum potential in the deeper parts. Considerable core-hole exploration has been done in recent years to evaluate Holocene tin-bearing gravels and sands within a few kilometres of the shoreline, but little work has been done further offshore or around the offshore islands.

Problems in this segment include:

(i) determination of thickness of Palaeozoic rocks and the Tertiary sequence on the shelf and slope.

(ii) examination of the structure of the Palaeozoic rocks.

(iii) examination of the structure of the Tertiary rocks.

(iv) location of intrusive rocks, particularly granites which might be tin-bearing.

A geophysical seismic reflection profile (processed) should be run across this area, along the transect line running northwest from Phuket, and supplementary seismic coverage with well control (where obtainable from oil companies) added. This should serve to show structure in both Tertiary and Palaeozoic rocks, identify intrusions and relate these to the geology of the peninsula; it should also help the study of the Tertiary sedimentary wedge and any structures in it that might constitute hydrocarbon traps.

2f. *The southern Thailand peninsula.* Phuket Island and adjacent areas of the peninsula are the site of extensive tin mining operations, and offshore dredging contributes an important percentage of the production. The area is underlain by sedimentary and metasedimentary rocks of Lower Palaeozoic to early Permian age intruded by granites of several ages, many of which are mineralized with tin and tungsten; associated lepidolite pegmatites also occur. Permian limestone outcrops in places, and a belt of Mesozoic clastic rocks occur to the east of the major sinistral transcurrent Khlong Marui Fault which trends north-northeast across the peninsula *(Fig. 4)*. Undated granites intrude Ordovician to Devonian mainly metamorphic rocks in a north-south mountain range from the Langkawi Islands (Malaysia) to islands in the Gulf of Thailand (Samui Island).

Extensive offshore tin placers occur on both sides of Phuket Island and northwards along the Andaman Sea shore for about 300 km. No extension of the tin belt is known south of Phuket except for minor occurrences on islands near the border with Malaysia.

Major unresolved problems in this area include:

(i) the age of the tin-belt granites and age of the associated tin mineralization.

(ii) nature and direction of movement along the Khlong Marui Fault and parallel Ranong Fault.

(iii) the origin of the granites—are they due to crustal melting and, if so, what was the source of the heat? and what was their level of emplacement?

(iv) why is tin mineralization so rich around Phuket?

(v) does the tin granite zone extend further south than Phuket under the Strait of Malacca?

Programmes of work to study these problems could include collection of granite samples for radiometric dating and determination of Rb/Sr and Sr^{87}/Sr^{86} ratios, and similar studies to determine the age of the tin mineralization and associated alteration envelope. Datable material will have to be found by trial and error involving much communication between collectors and analysts. Petrological and geochemical work should be undertaken on the granites in conjunction with the isotopic work, and the combined results compared with other tin-bearing and tin-barren granites to throw light on the reasons for the localization of tin concentrations.

Marine geophysical surveys across the northeast and southwest extensions of the Khlong Marui Fault and adjacent areas should help define its location, extent and tectonic significance, and whether it cuts off the tin belt extension south of Phuket. Seismic, magnetic and/or gravity profiling of the sea areas together with sediment coring should produce information highly relevant to tin exploration in these and adjacent areas.

As much of the programme as possible should be undertaken by local geologists and organizations.

2g. *Southwestern Gulf of Thailand.* A thick Tertiary sequence, locally in excess of 8,000 m thick, has been shown to be present in grabens formed by major north-south faults in the Gulf of Thailand *(Fig. 32)* though on land in the peninsula only relatively thin deposits are preserved. Oil and gas shows in wells drilled in the Thai sector of the Gulf and elsewhere are encouraging. High bottom-hole temperatures have been noted in these wells, but more temperature and heat flow data is needed.

In order to link studies of the Andaman Sea with those of the Gulf of Thailand, it is suggested that the proposed transect work be continued eastward along latitude 8°N, possibly as far as 103°E; this will take it across the strike of the basement ridges underlying the Tertiary basin.

Work needing to be done in this area includes:

(i) heat flow measurements should be obtained to study the heat flow patterns in this abnormally hot sedimentary basin. Study of this data integrated with other information on sediments and structure should lead to an understanding of the thermal characteristics and possibly of the origin of the basin.

(ii) more information should be obtained on the nature, age and structure of the pre-Tertiary rocks of the basin, both offshore and onshore.

(iii) sedimentary characteristics of the Tertiary deposits in the basin should be studied to throw more light on the facies distribution and geological history.

(iv) relative dating of the strata should be improved by use of micro-palaeontology and palynology.

(v) granites which outcrop on the islands or are encountered in wells should be studied to see if there are important relationships with intrusions in the peninsula and to the north of the Gulf in eastern Thailand, where tin mineralization is known. Radiometric dating of the granites should be undertaken.

(vi) structural information should be assembled for the Gulf and its margins to improve understanding of its origin, and the dates and modes of faulting and folding.

High quality seismic work has been undertaken recently in the area by oil companies holding leases, and some of this data may be available for study in the future. Available velocity data should be studied to estimate the rock types underlying the Tertiary sequence in the Gulf. Utilizing well data, sample descriptions and well-log data, where available, a detailed study of the sediment types should be undertaken; a representative standard sequence should be worked out using palaeontological methods, and the obtained results compiled and reviewed to improve correlation.

3. **Sumatra-Malay Peninsula-Sunda Shelf transect** *(Fig. 33)*

The Sunda tectonic arc, which stretches some 6,000 km from the Andaman Islands to the Banda Sea, shows its best development in the Sumatra-Malay Peninsula area, where the features of outer arc, inner volcanic arc with transcurrent faulting and foreland sedimentary basins are well-developed and accessible to investigation. As with the two previous transects, the boundary of the Indo-Australian and Eurasian Plates is the underlying crustal feature, but without the marginal basin of the Andaman Sea; tectonically this transect has more in common with the Burma-northern Thailand transect, though that lacks the oceanic trough features present off Sumatra.

Transect studies are recommended along or near a line running from the Indian Ocean through Nias Island, across central Sumatra and the Strait of Malacca to Kuala Lumpur, and then eastward across the Sunda Shelf to the vicinity of Natuna Island. The line was selected on the basis of the availability of information and accessibility, and particularly the economic significance of

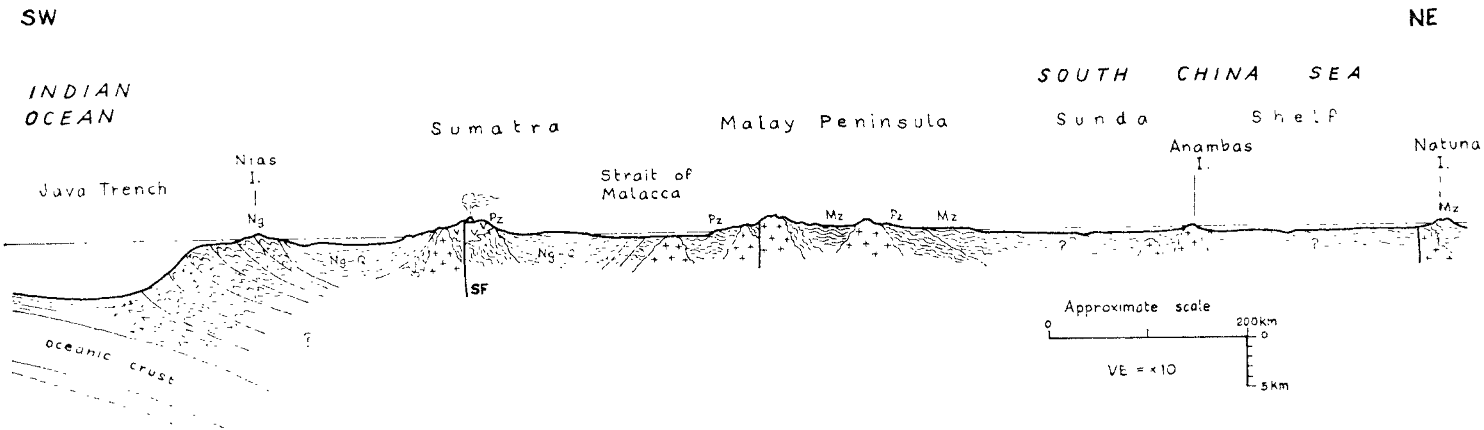


Figure 33. Schematic profile showing inferred structure along the proposed Sumatra-Malay Peninsula-Sunda Shelf transect (for location see *Figure 30*). SF = Semangko Fault.

the areas to be crossed: important metallogenic and hydrocarbon-producing areas are to be studied in relation to the igneous, structural and tectonic features of the transect. The presence of islands along the line is also valuable for seismic investigations.

Tectonic, metallogenic and hydrocarbon provinces. The line of the transect crosses the following major crustal elements:

The *Indian Ocean floor*, which in this area is deeper than 4,000 m, is covered by the distal part of the eastern lobe of the Bengal deep-sea fan and intercalated pelagic sediments; further to the southeast, only thin pelagic sediments are found.

The *Sunda Trench*, which has gentle inner and outer slopes, is more than 5,000 m deep; to the southeastward, off Java, it deepens to over 7,000 m, but northwestward its topographic expression is lost possibly due to infilling by material from the Bengal Fan.

The *non-volcanic outer arc ridge* is represented on the transect line by Nias Island, of sedimentary composition, and one of the Mentawai Islands that extend along the western coast of Sumatra; these appear to be continuous with the Nicobar and Andaman Islands. In the other direction the ridge is submerged, mostly more than 2,000 m, and extends in the direction of Timor.

The *inter-arc basin* between Nias and Sumatra is filled deeply by sediment layers which lap onto the Sumatra side but towards the ridge are progressively more deformed. This basin is more properly called a trough when traced southeastwards, where depths of over 1,000 m are found; it is probably continous with the 4,000-m deep Bali Trough *(Fig. 11)*.

The *volcanic inner arc*, a mountainous belt extending the length of Sumatra and containing numerous active volcanoes, rises to over 3,000 m above sea level. An uplifted core of Palaeozoic to Lower Tertiary crystalline and sedimentary rocks is overlain by late Cenozoic calc-alkaline volcanic rocks and is cut by Cenozoic plutonic and hypabyssal intrusions. The Semangko (Barisan) Fault Zone along the length of the mountain belt shows right-lateral transcurrent movement and some thrusting. Gold and minor base metal deposits are associated with part of this belt.

The *back-arc* or *foreland basin*, a broad lowland, lies between the mountains and the Strait of Malacca. Large and small sub-basins are filled with middle to late Cenozoic deposits, mostly clastic, with considerable thickness in some cases. Oil production and continued exploration is a feature of these basins, which are better developed southeast of the designated line of transect. Extensions of known coal-bearing basins are also crossed by the line.

The *Malay Peninsula -Sunda craton* has an uncertain relationship with the back-arc basins in the Strait of Malacca area. The pre-Cenozoic crystalline basement is exposed in the Malay Peninsula and on islands off the east coast of Sumatra, consisting of Palaeozoic and Triassic metamorphic rocks intruded by granites with extensive tin mineralization and associated tungsten and other minerals. Tertiary deposits are scattered and thin along the transect line, though a basin off the east coast of the peninsula north of the line has thick deposits in which petroleum has recently been discovered. Important economic Quaternary tin placer deposits are known on land, but the offshore extent of these and the mineralized granites from which they were derived is unknown.

Fault lines of uncertain significance extend northwards from the area west of Kalimantan towards the Indochina peninsula; these are associated with the Natuna Ridge and other features of the South China Sea substructure, and may be related to the formation of that sea.

Problems needing study. Fundamental tectonic processes can be studied along the line of this transect, particularly in its western portion, notably subduction along the plate boundary and associated structural deformation, and igneous activity and mineralization in the adjoining portion of the Eurasian Plate. The prime objective should be to attempt an identification of the structural factors controlling ore mineralization and hydrocarbon accumulation. Some of the major problems and processes to be studied are as follows:

(i) *mechanisms of formation and the geometry of the plate boundary*: present plate-tectonic interpretation suggests that the Indo-Australian lithospheric plate is moving northward or north-northeastward relative to Sumatra, and is sliding beneath it at a velocity of about 10 cm/yr. A Benioff zone dips moderately northeastward from the landward side of the Sunda Trench. The active volcanoes are present mostly in a narrow belt above that part of the Benioff zone which is about 150 km deep. Beyond this, the seismic zone continues downward to depths of 250 km or so (much less than the 750 km or so that the same zone reaches farther east beneath the Flores and Banda Seas). The very active right-lateral transcurrent Semangko Fault Zone along the length of Sumatra is oblique to the motion between the major lithospheric plates.

The acquisition of high-resolution, deep-penetration seismic reflection profiles across the tectonic elements southwest of Sumatra is essential to advance knowledge beyond that provided by presently available shallow-penetration profiles obtained by oceanographic institutions. It is anticipated that these new profiles will show the trenchward slope of the outer-arc ridge to be the top of a wedge of contorted sediments lying above a gently-dipping subducting oceanic plate, and that the thick sedimentary strata of the inter-arc basin becomes increasingly contorted toward the outer-arc (Mentawai) ridge from the Sumatran side; but the relation between basin sediments and wedge contortions, and the deeper configuration of the subduction zone beneath both ridge and basin, cannot be predicted from available data. Lacking this information, it is not possible to define the geometry of tectonic accretion of continental margins—one of the most important tectonic problems presently in sight.

Deep-sea drill holes should be put down at perhaps three places along the seismic line or lines that may be shot across the outer-arc ridge: on the trenchward slope, near the crest, and on the basinward slope. Is this contorted material in the form of imbricated slabs of coherent rocks; of disrupted formations; of chaotically-sheared mélange; or of something else? All these possibilities can be argued on the basis of present interpretations of the poorly-known geology of the islands on the outer-arc ridge. Where did the rocks of the wedge form—are they abyssal sediments, outer-arc basin sediments, oceanic crustal and mantle rocks, or metamorphosed sedimentary or igneous rocks? Many such questions have been asked, and can best be answered by drilling, coupled of course with careful geological studies on the islands.

Seismic velocities of the components of the crust and upper mantle should be measured using sonobuoys, by wide-angle reflection and refraction shooting, the last perhaps from ship to portable seismographs on the islands and mainland. The portable instruments would also be used precisely to locate earthquakes nearby in the Benioff zone, to define the zone's geometry and to delineate the configuration of the down-going lithospheric slab or slabs.

Integration of the various geophysical data will go far towards defining the geometry of the subducting plate and of the accreting wedge above it, and of the seaward edge of the continental crust.

(ii) *the inner volcanic arc and mineralization*: in Sumatra, the mountain belt presents a host of problems, to be tackled primarily by geological and petrological methods. Recent reconnaissance geological and geochemical surveying by the Geological Survey of Indonesia and by Riotinto Bethlehem Indonesia add much to the Dutch reports on the region, but fundamental relationships have been little studied. What is the relationship between magma formation (near the Benioff zone, 150 km beneath), the composition of the final magma as seen in volcanoes and shallow intrusions, the transcurrent faulting coincident with the magmatic belt, the regional geanticlinal uplift of the pre-magmatic rocks, and the sparse mineralization of the region?

(a) *porphyry copper*: how are the mineralization characteristics of the porphyry-copper bodies of Sumatra related to the pattern of subduction and high heat flow zones? What are the localizing mechanisms, ages of mineralization and level of emplacement? How can exposure of mineralized zones be related to rates of vertical uplift of the region?

Why are the Sumatran mineralized centres so low in copper? In the centre of the southern Malay Peninsula the flat-lying alkaline Cenozoic Segamat Basalt contains vesicles and amygdules which are richly endowed with copper minerals. Does this represent the upper cover of a buried porphyry copper deposit with slight leakage of copper solutions into the overlying basalt? How can present-day weathering rates be extrapolated into the Tertiary, so that the degree of erosion and uncovering of economic material can be predicted longitudinally along the calc-alkaline magmatic belt where other porphyry copper deposits can be expected to occur?

(b) *alluvial gold*: how is the contribution of lode gold to placers to be divided among the various sources—contact metamorphic bodies, quartz lodes in pre-Tertiary rocks and Neogene volcanic rocks? How are the controls on the depth and fineness of gold placers to be related to vertical movements arising from subduction? In Peninsular Malaysia the gold mineralization forms roughly a north-south trending belt in the central area. What is the age of this belt and to what type of granite migh it be related? Has it any connection with the western tin belt?

(c) *tin-tungsten mineralization*: this cannot at present be simply related to plate tectonics. An essential requirement for such mineralization appears to be the existence of well-established old sialic basement which may be the original source for the tin *(Fig. 4)*. This basement appears to be an essential component of the continental hinterland of active or former plate interactions. To understand the origin of tin belts it may be necessary first to identify the structure of this basement. The emplacement of tin-tungsten ores into the accessible crust would appear to result from the interaction of high heat flow zones, perhaps originating in the Benioff zone, with this old sialic basement.

Specific questions on this topic may be stated: in Sumatra, what is the age of the tin mineralization in the Suligi-Lipatkain Mountains of central Sumatra, and how does it relate to the main tin belts of Malaysia and to the tin belt of Thailand? In the Malay Peninsula, what is the relationship between the late Carboniferous tin-tungsten mineralization and the Triassic mineralization? How do these relate to the late Cretaceous tin mineralization of Thailand, and why do the granites of this age in Malaysia appear not to be associated with the mineralization?

The transect study is planned to cross all the tin-tungsten belts and might result in an understanding of how these belts relate to each other, and to the basement and contemporary tectonic activity.

(d) *coal:* what are the controls on the palaeogeography of the Tertiary coal basins? Can they be explained entirely by vertical movements of the platform arising from Tertiary subduction or are structures in the pre-Tertiary basement also important? How does the quality of coal relate to age, depth of burial and thermal gradients?

The proposed transect includes the Sumatran and Peninsular Malaysian Tertiary basins which contain coal, lignite and oil shale.

(e) *petroleum and natural gas*: recent geophysical data reveal that the East Sumatra oil-producing Tertiary basins are fundamentally fault-controlled. Fault movements appear to have been continuous from the commencement of basin subsidence and to have controlled sedimentation strongly (giving rise to growth faults). Less differential movement took place in the late Tertiary, strata of this age generally being less dissected by faulting, but folding was apparently localized by the fault trends. Major fault zones dissect the Tertiary strata as well as the pre-Tertiary "basement" (mainly Cretaceous), pointing towards basement block faulting as the controlling mechanism; this also broke up the Sunda Shelf which had been consolidated towards the end of the Mesozoic. In addition to vertical movements, the subsurface fault zones also show evidence of lateral movement.

During deposition of the Tertiary, the pre-Tertiary basement was subject to erosion, resulting in a considerable topographic relief on the basement surface. Local "highs", due either to this topographic relief or to upfaulting of basement blocks during later phases of sedimentation, had an important bearing on the sedimentation in the basins. Better knowledge of the configuration of the basement surface, and of its internal structure and stratigraphy, could well be derived from studies undertaken along the transect zone, and would be of great significance in the undertanding of the oil basins and their history. Recognition of particular patterns and characteristics of the major fault zones in relation to the Semangko (Barisan) transcurrent fault zone situated to the westward might reveal fundamental information on the present and past stress fields of the area and their relationship to fundamental crustal movements.

(iii) *The cratonic foreland area (Malay Peninsula-Sunda Shelf)*. Pre-Tertiary rocks near the transect line include Palaeozoic and early Mesozoic metamorphic formations intruded by granites of late Palaeozoic and Mesozoic age. This pre-Tertiary platform appears to extend over a large area of the Sunda Shelf to the east and south, but its westward extent is uncertain. However, late Palaeozoic granites are present in west-central Sumatra, indicating that a portion of Sumatra was a continent during part of the Palaeozoic. The question arises as to the relation of these Palaeozoic and Mesozoic massifs to other continental massifs: did rifting in the Mesozoic create the present-day continental margin, modified subsequently by subduction in the Cenozoic? This is one of many complex options. If it is a rifted margin, what is the relationship of the petrological and structural belts of the Malay Peninsula to this margin? Is the western Malay Peninsula belt of tin granites truncated by this margin, and if so, where is the missing piece and is it similarly mineralized? Since primary tin mineralization along the coast and alluvial cassiterite in the nearshore areas is well-known, the tracing of the tin granite belt in the offshore areas could be a major exploration target. What is the relationship of the older granitic rocks to past subduction zones, and were their patterns greatly different to modern ones?

There is a strong possibility that mineralization in this area is a result of interaction between the present and past subduction of oceanic material under a sialic continental mass, with resulting localized high heat flow zones rising through this older sialic crust. Of fundamental importance will be the understanding of the nature of this basement, its depth and its structure.

Cambrian deposits of the miogeosyncline in the region of the Langkawi Islands indicate that the area has a Precambrian basement, though its nature is unknown; a gravity profile and some airborne geophysical surveying is needed to study it. Possibly a closer look at areas where the basement is close to the surface may be informative.

The distribution of ore deposits is apparently strongly controlled by deep-seated faults. Some of these are transcurrent, but a study of the importance of vertical movements along these faults is in order. The suggested geophysical surveys will help to understand this. The question to be asked is: have these faults simply offset previously-formed ore bodies, or have they played a significant role in the movement of mineralization solutions forming them?

Of special importance is the determination of the age of tin-tungsten mineralization. Much of this is of hydrothermal origin and occurs within well-dated granite batholiths, but it is dangerous to assume that the hydrothermal events were closely synchronous with the granite formation. The batholiths are often complex, with magmatic ages mainly of Upper Carboniferous, Lower and Upper Triassic and Cretaceous-Tertiary. Dating of muscovite and tourmaline in greisens associated with the tin-tungsten lodes may define the ages of the lodes more closely.

A question of basic importance is: why do tin-tungsten belts of widely divergent ages either coincide exactly or are slightly offset parallel to each other? It might be concluded that this is because the underlying Benioff zone(s) have remained fairly stable in these position(s) under the sialic crust through the period of formation, and that only the trench positions have migrated oceanwards. High heat flow zones might therefore be stable through considerable time. Alternatively the parent rocks at depth may have been of limited geographical extent. Present heat flow measurements may also show that mineralized areas are still ones of high heat flow. The granites themselves should be studied petrologically, chemically and isotopically with a view to determining if they represent remobilized sialic crust or come from the vicinity of a Benioff zone, and to determine their levels of emplacement. Attempts should be made to differentiate the tin-bearing granites from the tin-barren ones, as this would aid future mineral exploration. Ancient subduction zones may also be located from alkalinity polarity in the volcanic and plutonic bodies.

4. Timor-Banda Sea transect *(Fig. 34)*

This recommended transect study is intended to examine the crustal configuration of a collision zone between a continent and an island arc; the northern edge of the Australian continent appears to have been thrust against the Banda island arc system, which itself is involved in complex plate movements to the east and north of Timor. Timor is a non-volcanic outer-arc island, and may contain tectonically deformed Australian rocks; the transect also includes the oceanic crustal area of the Banda Sea.

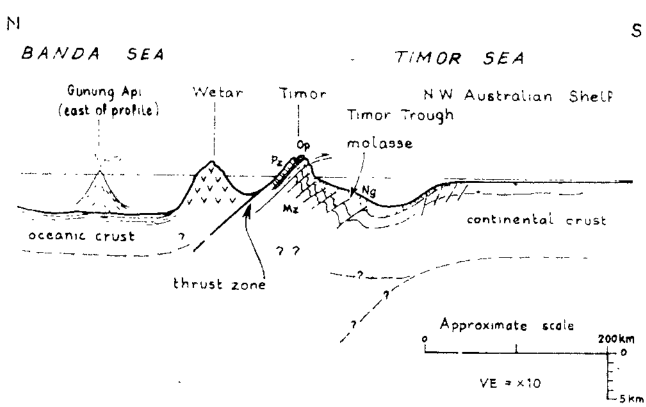


Figure 34. Schematic profile showing inferred structure along the proposed Timor-Banda Sea transect (for location of profile, see *Figure 30*). Op = ophiolite bodies.

Tectonic elements of the area crossed by the transect:

The *Australian continental shelf* consists of a series of predominantly flat-lying Mesozoic sedimentary layers which continue underneath the Timor

Trough. Reflection profiles show that these strata are gently folded, forming possible oil traps *(Fig. 14)*.

The *Timor Trough*, with mostly less than 3,000 m water depth, is floored by Cenozoic sediments above a possibly Mesozoic sequence, which may continue into Timor.

Timor, which rises to nearly 3,000 m above sea level, consists largely of Permian and Mesozoic fossiliferous marine strata, strongly folded and faulted; these appear to form an imbricate zone overlain by thrust sheets and other gravity-emplaced units. Above these allochthonous units, Neogene molasse, Quaternary reefs and alluvial terraces are found. Stratigraphic studies indicate a complex tectonic history since the late Mesozoic. The southern half of the island is characterized by a large negative gravity anomaly. Rates of uplift and subsidence are quite well known from stratigraphic studies.

The narrow *inter-arc trough* lies between Timor and the volcanic arc with water depths greater than 3,000 m covering a sea floor of unknown composition; the feature is characterized by a large positive gravity anomaly.

The *inner Banda (volcanic) Arc*, a chain of volcanic islands rising to about 1,000 m above sea level, is composed mostly of calc-alkaline extrusive and intrusive rocks. In the region immediately north of Timor (Alor, Wetar, Romang) these volcanoes are thought to have been inactive during the Quaternary, in contrast to the islands of the arc to east and west (Wulur, Flores, etc.) which have active volcanoes.

The *Banda Sea* is a marginal sea enclosed to the north, east and south by the volcanic islands of the inner Banda arc. It is mostly between 3,000 and 5,000 m deep. Very little is known of the superficial rocks on the floor of this sea or of the underlying crust: it is generally thought to be floored by thin oceanic lithosphere. In the centre of the Banda Sea lie the anomalous Lucipara Islands, which also are not understood.

The seismicity of the area. The Timor Trough and the island of Timor show a scatter of weak, shallow-focus earthquake epicentres, all of which have been interpreted as having strike-slip motions. The inter-arc trough, together with the inner volcanic arc and the Banda Sea, display a well-developed Benioff zone dipping steeply north with hypocentres from 200-600 km depth. Earthquake data available from this region are insufficiently precise to allow the surface trace of the Benioff zone to be plotted with confidence.

Tectonics and metallogenesis in the Banda Arcs. One of the published tectonic models for this region involved the subduction of a short-lived volcanic island arc, the defunct island arc being drawn down into a trench system that dips away from the northern Australian continental margin.

The partial melting of this descended island arc may have resulted in metallogenetic concentrations or diffusions different from those implied by the Sillitoe hypothesis (Sillitoe, 1972), which involves subduction of only oceanic lithosphere. The islands of the inner (volcanic) Banda Arc may be hosts for metals distilled from the partial melting of the descended defunct volcanic arc.

Hydrocarbon accumulations and tectonics in the Banda Arc. Neogene sequences in onshore and offshore sedimentary basins in the outer Banda Arc have been folded and probably offer petroleum prospects. The pre-Cenozoic rocks (Permian-Mesozoic) of the outer arc consist of a thick sequence of marine sediments that have been strongly deformed, and include some very large fold structures. If these rocks are part of a tectonic mélange (in the sense of being a "total chaotic mixing") and extend for 6,000 km around the whole Sunda Arc they are unlikely to have any petroleum prospects. On the other hand if they form part of the more local imbricate zone in the outer Banda Arc they may contain prospective hydrocarbon traps worth investigating. These two models of tectonic interpretation can be tested by the seismic programme outlined below.

Tectonic problems in the Banda Arcs. All available information suggests that in this region the leading northern edge of the Australian continent has collided with an island arc system in which the Benioff zone dips away from the continent.

Two very different interpretations of this region have been proposed. One regards the outer Banda Arc as a tectonic mélange and requires that during the Cenozoic the Timor basement lay separate from the Australian shelf with oceanic crust and a Benioff zone in between. Another model regards the outer Banda arc fundamentally as a part of the Australian continent that has been imbricated during collision with a northward-dipping subduction zone on the Asian side. This model interprets the "Asian" rocks in Timor as superficial overthrusts and gravity-slide deposits emplaced from the north *(Figs. 15 & 16)*.

The outstanding problem that may be solved in this area is a definition of the position and orientation of the Moho in this region. In addition, the seismic properties of the Banda Sea inward of the volcanic arc could be determined, as this could assist the tectonic evaluation of this complex region.

Methods. A seismic refraction survey extending from the northern edge of the Australian shelf to the south of Timor across the Timor Trough to southern Timor should be able to define the Moho in the area between the outer Banda Arc and the shelf. The continuation of this traverse from the inner volcanic arc to the Lucipara Islands in the Banda Sea, and then to the south coast of Seram, would complete a refraction traverse across the Banda Sea to the opposite side of the Banda Arc, which curves round through 180 degrees.

A triangular series of traverses in the Sawu Sea linking Sawu, Sumba and Flores should define the Moho in the actual collision zone. Land stations would be established on these three islands.

All these refraction surveys would be accompanied by continuous reflection seismic, magnetic and gravity profiling, and bathymetric data would be collected. Approximately 1,600 km of marine traverses would be needed.

Equipment. The section between Timor and the inner Banda Arc would require a two-ship refraction system, shooting a series of strike lines parallel to the arc and trough.

The "root zone" of the island of Timor would be investigated by locating stations on the north and south coasts of Timor. The section across the Banda Sea would establish three land stations on Romang (inner Banda Arc), Lucipara (Banda Sea) and Seram (outer Banda Arc).

Equipment needed at sea would include a seismic refraction system (for two-ship and land recording station operation), seismic profiling and echo sounding (12 kHz) systems for deep-sea sediment studies, marine gravimeter and magnetometer, and associated data recording and processing equipment. A radio communication system and shot-firing device is also necessary. Navigation and positioning at sea would require either a satellite navigation system, Decca Hi-Fix or Radio-ANA system; two buoys (anchored) with radar reflectors or transponders would also be needed.

5. Northern Philippines transect *(Fig. 35)*

The Philippine archipelago lies at the junction of the Eurasian and Philippine Sea Plates, the latter underthrusting the former along the east coast of the archipelago as far as about 15°N latitude, the site being marked by the Mindanao Trench (maximum depth 10,497 m). North of this, however, the tectonic picture is not so clear, with a possibly cratonic Philippine Sea Mount (Anson Block or Benham Rise) (less than 3,000 m water depth) lying offshore Luzon, and the Manila Trench (below 5,000 m in places) on the west side of the archipelago, possibly representing an eastward-dipping subduction zone. So two opposed subduction zones are apparently present, dipping towards each other under Luzon, though it is likely they do not impinge at depth due to their separation (600 km at surface) or because the east side zone may be inactive at the latitude where the west side zone becomes active. The possibility of "flip-over" of the subduction direction at or near 16°N, associated with a twist in the tectonic strike, suggests this as the

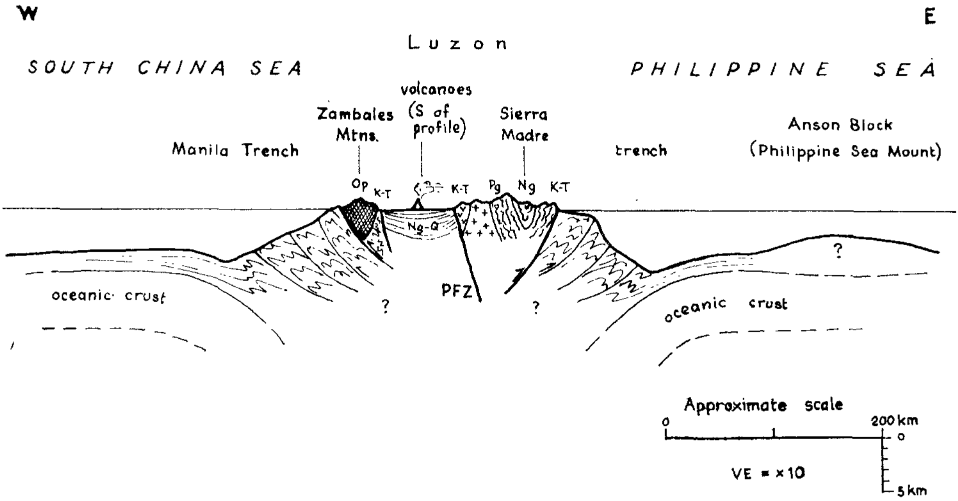


Figure 35. Schematic profile showing inferred structure along the proposed Northern Philippines transect (for location of profile, see *Figure 30*). Op = ophiolite bodies; PFZ = Philippine Fault Zone.

best site for the transect; presumed transcurrent faults are known on land at this latitude. Onshore near the two subduction zones the land appears to be underlain by north-south mélange zones.

The line of the transect was selected at latitude 16°N, with possible variation of one degree (110 km) north or south of this to take in critical areas; end limits may be taken as approximately 118° and 126° E longitude. This gives about 350 km of the traverse on land, and the remaining 500 km in marine areas. Onshore, the geology consists of:

A complex basement of metasedimentary and metavolcanic rocks of probable early to late Cretaceous age (no age determinations are available);

Ophiolite bodies in the Zambales Mountains (western coastal range), probably Middle to Upper Cretaceous;

Volcanic and sub-volcanic rocks with gold, silver and minor copper deposits (early Tertiary to Holocene) including some active volcanoes with recent deposits of gold, silver and copper in Pliocene tuffs; lead and zinc mineralization is present in the subvolcanic rocks in some places; and

Intrusions of intermediate rocks (diorites, quartz diorites, andesites, trachytes and related porphyries), with porphyry copper deposits mainly in the cupolas of the batholiths and minor amounts of gold, silver and molybdenum.

The northwest-southeast trending Philippine Fault Zone, a system extending through the archipelago to Mindanao, has apparently no connection with metallogenesis. Mineralization, mainly porphyry copper, seems to be related to a system of transverse faults (major and minor), shear zones and breccias in and along lineaments more or less parallel to the trend of the subduction zones, giving rise to metalliferous ore belts.

The two lowland basins of central Luzon and Cagayan have 7,000-8,000 m of Tertiary deposits, the former basin lying directly on the line of the traverse. Gas and oil shows have been noted in these basins.

Problems and objectives. The main aim of studies along this transect would be to relate known onshore mineral occurrences, of various types and geological settings, to the structural features of a Cretaceous-Tertiary island arc complex and to plate movements, past and present. Specific points to be examined would include:

(i) determination of the relationships of porphyry copper deposits to the two subduction zones, including age relationships;

(ii) search for evidence of the possible development and deposition of hot brines and metalliferous muds rich in gold, silver, copper, lead and zinc in small ocean basins, as indicated by comparable developments that took place in late Tertiary-Holocene along the exposed geosynclinal areas inland;

(iii) determination of the age relationships of the bordering subduction zones, to permit better definition of the tectonic history, and their relationship to metallogenesis;

(iv) further general research on the Manila and Mindanao Trench systems, and the relationship between these and the Philippine faults;

(v) identification of recent movements in order to aid exploration for concealed porphyry copper and gold-silver mineralization in breccia pipes;

(vi) study of the relations between ophiolites, ultrabasic rocks and related nickel-chromium-cobalt mineralization and the subduction zones;

(vii) examination of the nature of the Philippine Sea Mount, and definition of its relationship to the eastern subduction zone;

(viii) heat flow data and deep crustal information should be obtained and compared with data obtained on the Southwest Japan-Korea Peninsula transect, the latter traversing an interaction zone of oceanic and continental crust; and relation of these comparisons to copper, gold and silver metallogenesis in the Philippines and to the molybdenum, tin and tungsten mineralization in southern Japan; and

(ix) location and investigation of potential geothermal energy sources, particularly along the active volcanic zone in north central Luzon.

The above objectives should be aimed for using a combination of methods and disciplines, and utilizing the resources of both indigenous governmental agencies and universities as well as scientific help from elsewhere. Land geological surveying should be undertaken along and near the line of the transect to study the field characteristics and relationships of the sedimentary and volcanic rocks, ophiolites and intermediate intrusions, together with a genetic study of the metalliferous deposits. Detailed structural, petrological, geochemical and radiometric age studies should be done concurrently, with stratigraphic and palaeontological control.

Marine, terrestrial and aerial geophysical traversing along the transect should include an airborne magnetometer survey with closely spaced lines; high-resolution marine seismic reflection and refraction profiles crossing the trench axes; extension of gravity control to the offshore areas out across the trench axes; and deep seismic refraction profiling over the land areas. Echo-sounding and heat-flow measurements should be undertaken in the vicinity of the Manila Trench in connection with the possibility of hot brine sources.

Additionally, as much relevant data as possible should be obtained from governmental and private geological/geophysical and marine institutions, including those overseas, and also private industrial companies where possible. Throughout the work, the training of local personnel and subsequent encouragement for them to follow up the initial research work should be regarded as a very important segment of the programme.

6. Southwest Japan-Korean Peninsula transect *(Fig. 36)*

The complex arc system of the Japanese islands has been studied extensively, particularly in the field of seismology, but its relationship to the continental areas to the north require further study and interpretation. Additionally, the results of work on this transect, conducted in an area of relatively high data density, should be valuable for comparative purposes to the other transect studies.

The proposed transect is in two segments which intersect in the Japan Sea. One segment crosses southwest Japan in a nearly north-south direction, with one end on the oceanic crust of the Philippine Sea Plate, in that part of the plate between the Izu-Bonin volcanic ridge and the Palau-Kyushu aseismic ridge; it crosses the Nankai Trough, Shikoku and southwestern Honshu, where a great deal of geological and geophysical work has already been carried out; then to the island of Oki and across the Japan Sea in a northwesterly direction to Ulnung-do. The other segment crosses the Korean Peninsula from Sosan on the west coast to Pohang on the east, and then east-northeastward to cross the other segment of the transect about 100 km southeast of Ulnung-do, ending in the Japan Sea near the Takeshima (Tok-do, Liancourt Rocks) seamount.

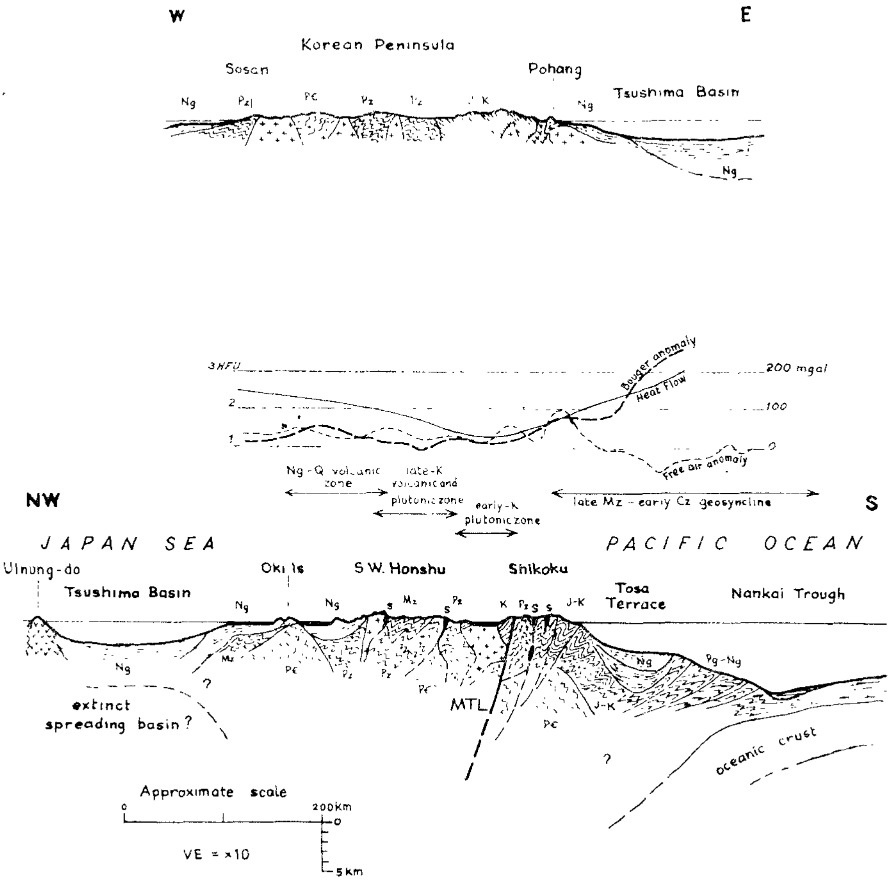


Figure 36. Schematic cross-sections showing inferred structure along the proposed Southwest Japan-Korean Peninsula transect (for location of profiles, see *Figure 30*). S = serpentine bodies; MTL = Median Tectonic Line.

Available data on both segments of the transect is considerable. Gravity, aeromagnetic and other surveys have been carried out over most of southwestern Japan, and some gravity measurements have been made on the Korean Peninsula and in adjacent marine areas. In Japan, seismological, geomagnetic and geodetic surveys and palaeomagnetic measurements have been made, but further work is needed; heat flow studies and radiometric age determinations have also been undertaken.

Seismic reflection and refraction work has been undertaken both in the Japan Sea and the Philippine Sea. On the east coast of the Korean Peninsula elongate sedimentary basins, thickening seaward, have recently been discovered. South of Shikoku, although work has not been systematic, the results support the suggestion that the Nankai Trough is an embryo subduction zone between the Philippine Sea Plate and the Eurasian Plate.

The geology of southwestern Japan has been well mapped and petrology has also been well studied. Radiometric studies have shown an asymmetrical zonation, and more of this work is needed.

In the Korean Peninsula, the transect crosses the Kyongsang Basin, the Ryongnam Massif, the Okchon Geosynclinal Zone and the Kyonggi Massif. The two massifs are similar Precambrian metamorphic blocks, trending northeastwards, and the Okchon zone is formed of low-temperature-intermediate-pressure metamorphic rocks with scattered probable ophiolite masses. The Kyongsang Basin, in the southeast part of the peninsula, contains thick Cretaceous deposits probably underlain by Cambro-Ordovician rocks on a Precambrian metamorphic basement; a thin layer of Miocene strata overlies the Cretaceous. A thick sequence of Tertiary rocks is also expected to be found in the transect in the western part of the Japan Sea.

Mineralization related to Cretaceous magmatism has been studied in detail in Japan, and the asymmetrical zoning shown was probably due to the behaviour of volatile components of the magma; the zoning is consistent with that found in the associated granitic intrusions. The Miocene Kuroko mineralization has also been examined in detail on land; however, most of this is thought to be under the Japan Sea, so marine investigations are now needed. Miocene tin mineralization has been studied, particularly with regard to petrology and mineralogy, but the source of the magma which produced the mineralization is uncertain.

Several mineralization zones are known on land in the Korean Peninsula, including gold, tungsten and molybdenum deposits and some tin. There is also a copper zone in the southeast coastal area and one of the deposits may be porphyry copper. Hydrocarbon potentials in the Korean area are expected both on land in the Kyongsang Basin and on the east coast continental margin.

Problems to be studied in this transect include:

(i) in the Nankai Trough, much data was obtained independently by different organizations in different disciplines, and the results are too unsystematic for a typical profile to be drawn of the early-stage subduction zone, or to classify the detail structures such as the nature of the continental slope and outer ridges, or the nature of the contact zone. It is highly desirable that one organization should undertake the compilation of all available data along the Japan segment of the transect.

(ii) detailed high resolution profiling should be carried out in the Nankai Trough to examine the fine structure of the sediments there, and deep drilling to obtain basement material is also recommended;

(iii) more data relating to the sea floor spreading in the Japan Sea should be obtained;

(iv) evidence concerning a possible subduction zone of Miocene age, to which the metalliferous intrusive and extrusive rocks could be related, should be investigated;

(v) the geological relationship of southwest Japan with the Korean Peninsula should be studied, by trying to correlate various factors such as metamorphic facies, major structural elements, fault systems and mineral zoning;

(vi) the mechanism of the formation and emplacement of late Miocene and older acidic intrusions (which are associated with molybdenum, tungsten, tin and base metal deposits) in the upper crust should be studied;

(vii) the magmatic source of Miocene volcanic rocks, related to the Kuroko and other base and precious metal deposits, should be sought; and

(viii) with regard ot hydrocarbon genesis, study should be made of the nature of Tertiary and younger sediments which have accumulated in the Japan Sea both on the Korean coast and the coast of southwest Japan.

Methods to be employed in the above problems have been indicated in some cases, but in general it is considered advisable that additional seismic refraction and reflection work should be carried out on land over the sedimentary areas along the transect in both countries, to define the nature of the deposits and the depths to basement. Gravity and magnetic profiling at sea together with seismic refraction and reflection and sediment coring should be included. Probably sufficient equipment and manpower are available in these countries to carry out this work.

Equipment: with regard to the geophysical and geological investigations proposed along the marine portions of the transect, Japan possesses the capability to carry out most of the techniques suggested, but the work should be done in co-operation with groups from other countries. The Republic of Korea has a ship, but insufficient equipment to carry out the suggested programme off the Korean coast; they would welcome assistance both in instrumentation and from senior scientists, and wish to carry out this programme in collaboration with groups from other countries.

OTHER PROJECT PROPOSALS

During the first day of the Workshop a Preliminary Project Suggestion Form was issued to all participants. This form asked for suggestions for projects covering the full range of interests of the workshop. It was indicated that these suggestions would form the basis for informal discussions leading to the development of a research programme.

Forty-seven suggestion forms were returned, and most of these suggestions were incorporated into the general research recommendations and into the specific transect proposals (numbered 1 to 6). However, there were a number of project suggestions which formed independent projects and these are listed independently below; as they were from individuals, and some were not discussed during the Workshop, the order in which they are listed does not imply any kind of priority.

7. Tectonic study of the Fang Basin, northern Thailand

This study would give a better understanding of the mechanism involved in the geological development of an "intraplate" basin which is known to be oil-producing. The Fang Basin is of particular scientific interest as its vertical dislocation is of the order of 2,000 m. Geophysical methods including seismic refraction and reflection, gravity and magnetic profiling are recommended.

8. Transect of northern Hokkaido from the Japan Sea to the Sea of Okhotsk

This profile crosses a strongly imbricated zone in northern Hokkaido, flanked by marginal basins floored by oceanic crust, and would provide useful information on the movement of Japan in the Cenozoic and possibly the Mesozoic. A part of the area crossed by the transect is unusual in that it is thought to have thick sedimentary deposits, which may have oil and gas potential, lying on oceanic crust. High resolution seismic work is essential for understanding the offshore structural relationships and this work should be supplemented by gravity, magnetic and heat flow measurements, etc. Although this transect was not included as one of the major multidisciplinary recommendations, it is nevertheless an area where important information is required and should provide results of significance to adjacent areas.

9. Study of the pre-Tertiary ophiolite basement of northern Borneo and its relation to the Sulu Sea

Investigations should be carried out on the extensive and complete ophiolite basement in northern Borneo, and the relationship of its formation with that of the surrounding ocean and the Philippines (with particular reference to chromite and nickel deposits). Details of the geology and structure of the ophiolites are known in particular areas in northern Borneo. It is also recommended that selected gravity profiles be made across northern Borneo and the surrounding marine areas.

10. Similarities and contrasts between volcanic chains in the Sunda Arc

Comparison of volcanoes and volcanic material from Sumatra, Java and the Banda Sea area should be undertaken to discover whether arc-trench sedimentary wedge material has become included in the volcanic products, and whether deep-seated faults have any influence on the location of the volcanoes. Petrological and geochemical studies are necessary; studies in Java are already in progress at the Australian National University.

11. Studies of the sedimentology of key areas in eastern Asia

Selected stratigraphic units of key interest should be studied with a view to identifying the source of important sedimentary sequences, such as the Cretaceous-Tertiary flysch of northwest Borneo with its associated ophiolitic and mélange units and the Lower Palaeozoic rocks of the Malay Peninsula (Malaysia and Thailand) and the Palaeozoic and Mesozoic rocks of Sumatra.

12. Tectonic settings of coal basins

Coal basins of late Mesozoic and Tertiary age occur in various tectonic settings in the region (such as the inter-arc trough of Burma, the back-arc basins of Sumatra). These basins should be investigated and compared with regard to their sedimentology, tectonic setting during sedimentation and subsequent deformation. Expected results include correlations between the tectonic setting and type and rank of coals, and this may provide models for coal-basin evolution applicable to arc systems and collision belts of various ages elsewhere.

13. Comparative palaeontological studies

Assessment of fossil evidence in all parts of eastern Asia would assist in verifying the details of present theories of plate tectonics, particularly in Palaeozoic and Mesozoic time.

14. Study of tectonic patterns of eastern Asia

Studies should be undertaken to reconstruct basic tectonic patterns in the region, particularly of former periods, based on plate tectonic theory and models. In addition to structural and sediment-facies analyses, geochemical studies of plutonic and volcanic rocks should be made to discover any alkalinity polarities; polarities of metamorphic facies and zoning of mineral deposits should also be studied with the same objective.

15. Preparation of a geodynamic atlas of eastern Asia

Compilations should be undertaken of maps plotting the tectonism and igneous activity for the following: Holocene, Neogene, Palaeogene, Upper Cretaceous, Lower Cretaceous, Jurassic, Triassic, and older periods where possible.

16. Establishment of a data bank for radiometric age determinations

A data bank should be set up in the region for the collection and analysis of absolute age determination information, preferably by computer. This should be coupled with the compilation of age determination maps.

17. Experimental modelling of the deformation of trench, arc and basin sediments due to a subducting plate

Various experimental models of the different types of subduction should be constructed and these should be compared with those actually found in arc systems.

Summary of other proposals made by the panels

In the panel reports a number of general and more specific recommendations were made, most of which overlapped with or were included in the transect proposals. In the list below are those which were not included, or which merit mention of their own account.

Geophysics Panel:

18. Compilation and synthesis of all existing marine geophysical data should be made, particularly unpublished gravity, magnetic and heat flow data held by research institutions. A marine geophysical atlas could result (p. 74).

19. Broad marine geophysical surveys in the deep marginal basins of eastern Asia should be made to define age and past kinematic relationships of the small crustal plates of the region: (a) western part of the Philippine Sea basin, (b) the China Basin (South China Sea), (c) the Wharton (West Australian) Basin of the eastern Indian Ocean, and (d) the Banda, Sulawesi and Sulu Seas and intervening ridges (p. 74, 76 and 77).

20. Regional seismological studies ought to be undertaken, including more accurate determination of deep and intermediate earthquake foci in the active zones, first-motion studies and detailed work in selected areas using portable seismographs (p. 75).

21. Transect studies: in addition to those transects dealt with in *Section V*, a further study was recommended crossing the arc system at the east end of Java (p. 76).

Tectonics Panel:

22. Palaeomagnetic studies should be undertaken to determine rotations and palaeolatitudes of the various crustal units in eastern Asia, to determine more clearly their movement history and to narrow the range of possible interpretations of tectonic history (p. 78).

23. Study of recent movements on major tectonic lineaments both vertical and horizontal movements in critical areas could be determined by study of aerial and satellite photography, giving a clearer understanding of the present-day tectonic environment (p. 81).

24. Conversion of plate-margin features to cratonic crust should be studied, particularly where downfaulted and downwarped basin features are developed. The extent, structural style and history of vertical collapse of such basins should be investigated (p. 84).

25. Study of older inactive arcs in relation to present-day subduction: tectonically disturbed zones, mélanges and deformed ophiolite belts should be studied in both active and older arc systems; the outer Sunda-Burman arc is a good location for such work, which would largely be done in connection with the transect studies (p. 84).

26. Geochronology of major outcrop belts (p. 85).

27. Polarity of older arc systems (p. 85).

28. Correlation of major unconformities (p. 85).

Sedimentary Processes Panel:

29. Quaternary geology of Sundaland and adjacent areas: systematic study should be made of Quaternary sequences from offshore wells, correlation with land geology, geomorphic surfaces and recent movements (p. 86).

30. Marginal and small ocean basins: are they formed by "oceanization" or by spreading analogous to main ocean basins? What are their relationships to nearby subduction zones? Studies on the transect lines and in other areas such as the Makasar Straits and Sulu Sea should seek to answer this (p. 89).

31. Tectonic and sedimentary processes in accretion of sediments above subduction zones: are ocean-floor sediments carried down by the subducting plate, or scraped off at the junction? What structural styles are involved? Much of this would be studied in the transect areas, but the whole trench from the Bengal Fan to the east end of the Java Trench is suitable; use of deep submersibles and deep sea drilling should be attempted where possible (p. 92).

Metallogenesis and Petrogenesis Panel:

32. **Arc systems:** major and trace element and isotopic analyses should be undertaken to understand better the relationship of volcanism to the Benioff zone. The age relations of volcanism and mineralization in older arcs, petrology of acidic magmatism in relation to porphyry copper, and a regional geochronology are recommended studies (p. 102).

33. **Geochemical analyses** of major and trace elements in active arc systems should be undertaken to improve understanding of the relation of arc magmatism to the underlying crustal processes (p. 102).

34. **Heavy mineral analyses** of cores from offshore wells should be made for possible location of tin placers (p. 103).

35. **Lead isotope studies** should be undertaken to trace the origin of mineralization (p. 103).

36. **Detection of brine pools** should be attempted at present or ancient spreading axes (p. 104).

37. **Dredging for basaltic materials** in marginal basins should be undertaken for petrological comparison with basalts from spreading axes, detection of any such axes in marginal basins, and trace element analysis of pillow lavas (p. 103—104).

38. **Heat flow measurements** should be made in marginal basins where they coincide with magnetic "quiet" zones, for indications of possible hydrothermal localities (p. 104).

39. **Inactive arcs and suture zones** may be indicated by a compilation of ophiolite, blue-schist and mélange occurrences in the region (p. 104).

40. **Large ophiolite complexes** should be studied with geochemical surveys for metals (p. 104).

41. **Mélanges** should be studied to establish relationships to other tectonic features (p. 104).

42. **Tracer studies** using strontium and lead isotopes should be done to establish whether island arc ore deposits are related to subduction zone materials (p. 104).

Heat Flow and Hydrocarbon Maturation Panel:

43. Heat flow measurements in oceanic basins should be made, both on shore as well as in deep sea areas; new instrumentation is required for shallow water determinations (p. 107).

44. Heat flow and geothermal gradient map of eastern Asia (p. 108).

45. Palaeogeothermal studies in the transect study areas should measure organic metamorphism and burial history of Cenozoic sequences (p. 108).

VI. LIST OF PARTICIPANTS

Participants of the IDOE Workshop on Tectonic Patterns and Metallogenesis in East and Southeast Asia, Bangkok, 1973.

Charan (POOTHAI) ACHALABHUTI, Department of Mineral Resources, Thailand

Prayong ANGSUWATHANA, Department of Mineral Resources, Thailand

Payome ARANYAKANON, Department of Mineral Resources, Thailand

M.G. AUDLEY-CHARLES, Imperial College of Science and Technology, United Kingdom

Guillermo R. BALCE, Philippine Bureau of Mines, the Philippines

A.W. BALLY, Shell Oil Co., United States of America

A.J. BARBER, Chelsea College, University of London, United Kingdom

Fritz BAUM, Bundesanstalt für Bodenforschung, Federal Republic of Germany

Zvi BEN-AVRAHAM, Israel Oceanographic and Limnological Research Ltd., Israel

Sakuntala BHODHIPRASART (Mrs.), National Research Council and National Marine Science Committee, Thailand

Louis B. BROWN, Office of the IDOE, National Science Foundation, United States of America

W. BULLERWELL, Institute of Geological Sciences, United Kingdom

Sangad BUNOPAS, Department of Mineral Resources, Thailand

K.V. CAMPBELL, Chieng Mai University, Thailand

D.J. CARTER, Imperial College of Science and Technology, United Kingdom

Fateh CHAND, Geological Survey of Malaysia, Malaysia

Adul CHAROENPRAVAT, Department of Mineral Resources, Thailand

Chongpan CHONGLAKMANI, Department of Mineral Resources, Thailand

B. COFFINIÈRES, Compagnie Française des Pétroles, France

Robert G. COLEMAN, United States Geological Survey, United States of America

Joseph R. CURRAY, Scripps Institution of Oceanography, United States of America

René C. DAME, ELF-ERAP, France

Thawisak DANUSAWAD, Department of Mineral Resources, Thailand

Veerote DAORERK, Chulalongkorn University, Thailand

Bibhu P. DASH, Imperial College of Science and Technology, United Kingdom

Edward M. DAVIN, Office of the IDOE, National Science Foundation, United States of America

F.E. DEKKER, Union Oil Company of Thailand, Thailand

Patrick H. DE RHAM, UNESCO Field Science Office for Southeast Asia

Boonthom DHAMCHAREE (Mrs.), National Research Council and National Marine Science Committee, Thailand

H.F. DOUTCH, Department of Minerals and Energy, Australia

Alfred G. FISCHER, Princeton University, United States of America

Thomas J. FITCH, Australian National University, Australia

I.G. GASS, The Open University, United Kingdom

Frederick GRAY, United Nations Development Programme (CCOP)

Philip W. GUILD, United States Geological Survey, United States of America

William C. GUSSOW, Japan Petroleum Development Corp., Japan

N.S. HAILE, University of Malaya, Malaysia

Warren HAMILTON, United States Geological Survey, United States of America

Dennis E. HAYES, Lamont-Doherty Geological Observatory, Columbia University, United States of America

Colin J. HOLCOMBE, P.T. Riotinto Bethlehem Indonesia, Indonesia

Charles S. HUTCHISON, University of Malaya, Malaysia

Shunso ISHIHARA, Geological Survey of Japan, Japan

Sa-ngob KAEWBAIDHOON, Department of Mineral Resources, Thailand

John A. KATILI, Ministry of Mines, Indonesia

Chaiyudh KHANTAPRAB, Chulalongkorn University, Thailand

Chong Su KIM, Geological and Mineral Institute of Korea, Republic of Korea

Ok Joon KIM, Yonsei University, Republic of Korea

H. Douglas KLEMME, U.P. Exploration, United States of America

Wolfgang KREBS, Technical University. Braunschweig, Federal Republic of Germany

R. LAKEMAN, BP Singapore Ltd., Singapore

Deryck J.C. LAMING, United Nations Development Programme (CCOP)

F.G. LARMINIE, BP Petroleum Development of Thailand, Ltd., Thailand, and Commission for Marine Geology, International Union of Geological Societies

Xavier LEPICHON, Centre Océanologique de Bretagne, France

C.Y. LI, United Nations Development Programme (CCOP)

William J. LUDWIG, Lamont-Doherty Geological Observatory, Columbia University, United States of America

M. MAINGUY, ELF-ERAP Far East, Singapore

J.B.P. MARAMIS, United Nations Economic Commission for Asia and the Far East

John F. MASON, Continental Oil Company, United States of America

James F. MCDIVITT, UNESCO Field Science Office for Southeast Asia

Ian MCDOUGALL, Australian National University, Australia

Amorn METHIKUL, Department of Mineral Resources, Thailand

A.H.G. MITCHELL, United Nations Development Programme (Burma)

David G. MOORE, Scripps Institution of Oceanography, United States of America

Richard W. MURPHY, Esso Exploration Inc., Singapore

Veerasak NAKHINBODEE, Department of Mineral Resources, Thailand

Chikao NISHIWAKI, Institute for International Mineral Resources Development, Japan

Srigul NONZI, Ministry of Communications, Thailand

A.G. OBERMULLER, Directorate of Technology, Industrial Environment and Mines, France

Swasdi PACHIMKUL (Maj.-Gen.), Royal Thai Survey Department, Thailand

Charal PHANDHUDAWI (Capt.), Meteorological Department, Thailand

Pongsak PHONGPRAYOON, Chulalongkorn University, Thailand

Twesukdi PIYAKARNCHANA, Chulalongkorn University, Thailand

Tavorn PONGSAPIPATT (Capt.), Royal Thai Navy, Thailand

Suparb POOBRASERT, Chulalongkorn University, Thailand

A. PULUNGGONO, Pertamina, Ministry of Mines, Indonesia

Piyamit RASRIKRIENGKRAI, Department of Mineral Resources, Thailand

John A. REINEMUND, United States Geological Survey, United States of America

Suvit SAMPATTAVANIJA, Department of Mineral Resources, Thailand

Shun-ichi SANO, Geological Survey of Japan, Japan

K. SAWAMURA, United Nations Development Programme (CCOP)

SOEPRAPTONO, Directorate General of Petroleum and Natural Gas, Indonesia

Ying SRIHONG (Adm.), United Nations Development Programme (CCOP)

Leo W. STACH, United Nations Economic Commission for Asia and the Far East

Richard D. STEWART, Union Oil Co. of California, United States of America

Sanarm SUENSILPONG, Department of Mineral Resources, Thailand

Rab SUKAMTO, Geological Survey of Indonesia, Indonesia

Puthorn SUKHATO, Department of Mineral Resources, Thailand

Chalit SUKROONGRUENG (Lt.-Cdr.), Royal Thai Navy, Thailand

Swai SUNDHAROVAT, Chulalongkorn University, Thailand

Preecha SUPALAK, Department of Mineral Resources, Thailand

Akanit SUWANASING, Department of Mineral Resources, Thailand

B.K. TAN, University of Malaya, Kuala Lumpur, Malaysia

Absornsuda TANTHANASIRIPONG (Mrs.), Chulalongkorn University, Thailand

Tatsuo TATSUMI, University of Tokyo, Japan

Dennis TAYLOR, Conzinc Riotinto Malaysia, Malaysia

Jack E. THOMPSON, Amax Exploration (Australia) Inc., Australia

M.J. VALENCIA, United Nations Development Programme (CCOP) and Universiti Sains Malaysia, Malaysia

Manus VEERABURUS, Department of Mineral Resources, Thailand

Frank F.H. WANG, United States Geological Survey, United States of America

T.R. WATTS, United Nations Development Programme (CCOP) and Cundill, Meyers & Associates Pty. Ltd.

E.W. WESTRICK, Thailand Gulf Oil Company, Thailand

F. WILCKENS, Federal Ministry for Research and Technology, Federal Republic of Germany

D.R. WORKMAN, Mekong Committee, United Nations Economic Commission for Asia and the Far East

Masashi YASUI, Japan Meteorological Agency, Japan

VII. BIBLIOGRAPHY

Abdel-Gawad, M., 1971, Wrench movements in the Baluchistan arc and relation to Himalayan-Indian Ocean tectonics: *Bull. Geol. Soc. America*, vol. 82, p. 1235-50.

Alpern, B., and M.J. Lemos De Sousa, 1970, Sur le pouvoir réflecteur de la vitrinite et de la fusinite des houilles: *Compt. Rend. Acad. Sci. Paris*, Ser. D, t 271, p. 956-959.

Audley-Charles, M.G., 1968, The geology of Portuguese Timor: *Mem. Geol. Soc. Lond.*, no. 4, p. 1-76.

Audley-Charles, M.G., and D.J. Carter, 1972, Palaeogeographical significance of some aspects of Palaeogene and Early Neogene stratigraphy and tectonics of the Timor Sea region: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, vol. 11, p. 247-264.

Audley-Charles, M.G., D.J. Carter and J.S. Milson, 1972, Tectonic development of eastern Indonesia in relation to Gondwanaland dispersal: *Nature Phys. Sci.*, vol. 239, p. 35-39.

Bailey, N.J.L., H.R. Krouse, C.R. Evans and M.A. Rogers, 1973, Alteration of crude oil by waters and bacteria—evidence from geochemical and isotope studies: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 57, p. 1276-1290.

Baker, D.R., and G.E. Claypool, 1970, Effects of incipient metamorphism on organic matter in mudrock: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 54, p. 456-468.

Beck., R.H., and P. Lehner, 1974, Oceans, new frontier in exploration: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 58, p. 376-395.

Ben-Avraham, Z., C. Bowin and J. Segawa, 1972, An extinct spreading centre in the Philippine Sea: *Nature*, vol. 240, p. 453-455.

Ben-Avraham, Z., and K.O. Emery, 1973, Structural framework of Sunda Shelf: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 57, p. 2323-2366.

Ben-Avraham, Z., and S. Uyeda, 1973, The evolution of the China Basin and the Mesozoic palaeogeography of Borneo: *Earth and Planetary Sci. Letters*, vol. 18, p. 365-376.

Bezrukov, P.L., 1960, Bottom sediments of the Okhotsk Sea: *Repts. Inst. Oceanology* Acad. Sci. USSR, vol. 32, p. 15-95.

Binder, C.R., 1965, Electron spin resonance: its application to the study of thermal and natural histories of organic sediments: Ph.D. thesis, Penn. State Univ., 129 p.

Biq, C.C., 1972, Dual-trench structure in the Taiwan-Luzon region: *Proc. Geol. Soc. China*, no. 15, p. 65-75.

Biswas, B., 1973, Quaternary changes in sea-level in the South China Sea: *Geol. Soc. Malaysia Bull.*, no. 6, p. 229-256.

Bracey, D.R., and T.A. Ogden, 1972, Southern Mariana arc: geophysical observations and hypothesis of evolution: *Bull. Geol. Soc. America*, vol. 83, p. 1509-1522.

Bray, E.E., and E.D. Evans, 1961, Distribution of n-paraffins as a clue to recognition of source beds: *Geochim. et Cosmochim. Acta*, vol. 2, no. 1, p. 2-15.

Brooks, J.D., et al., 1971, The natural conversion of oil and gas in sediments in the Cooper Basin: *Austr. Petroleum Expl. Assoc. Jour.*, p. 121-125.

Burton, C.K., 1965, Wrench faulting in Malaya: *Jour. Geol.*, vol. 73, p. 781-798.

Burton, C.K., and J.D. Bignell, 1969, Cretaceous-Tertiary events in southeast Asia: *Bull. Geol. Soc. America*, vol. 80, p. 681-688.

Burton, C.K., 1970, The palaeotectonic status of the Malay peninsula: *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, vol. 7, p. 51-60.

Castano, John R., 1973, Application of coal petrographic methods in relating level of organic metamorphism to generation of petroleum: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 57, no. 4, p. 772-773.

Castano, John R. and Dennis M. Sparks, 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks and determination of burial history using vitrinite reflectance and authigenic minerals: in Geol. Soc. America Special Paper 153, in press.

CCOP, 1973, CCOP proposes co-operation with International Programme of Ocean Drilling (IPOD): United Nations ECAFE, *CCOP Newsletter*, vol. 1, no. 2, p. 1-3.

Chai, B.H.T., 1972, Structure and tectonic evolution of Taiwan: *Am. Jour. Sci.*, vol. 272, p. 389-422.

Clague, D.A., and R.D. Jarrard, 1973, Tertiary Pacific plate motion deduced from the Hawaiian-Emperor chain: *Bull. Geol. Soc. America*, vol. 84, p. 1135-1154.

Coleman, R.G., 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: *Jour. Geophys. Res.*, vol. 76, p. 1212-1222.

Correia, M., 1967, Relations possibles entre l'état de conservation des éléments figurés de la matière organique (microfossiles palynoplanctologiques) et l'existence de gisements d'hydrocarbures: *Rev. Inst. Franç. Pétrole*, vol. 22, p. 1285-1306.

Curray, J.R., and D.G. Moore, 1971, Growth of the Bengal deep-sea fan and denudation in the Himalayas: *Bull. Geol. Soc. America*, vol. 82, p. 563-572.

Dash, B.P., K.O. Ahmed and P. Hubral, 1970, Seismic investigations in the region of Poulo Panjang, offshore from southwestern Viet-Nam: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 3, p. 37-54.

Dash, B.P., C.M. Shepstone, S. Dayal, S. Guru, B.L.A. Hains, G.A. King and G.A. Ricketts, 1972, Seismic investigations on the northern part of the Sunda Shelf south and east of Great Natuna Island: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 6, p. 179-196.

Dickinson, W.R., 1973, Widths of modern arc-trench gaps proportional to past duration of igneous activity in associated magmatic arcs: *Jour. Geophys. Res.*, vol. 78, p. 3376-3388.

DSDP Scientific Staff, 1971, Deep Sea Drilling Project, Leg 18: *Geotimes*, vol. 16, no. 10 (October 1971), p. 12-15 (Hawaii to Alaska).

DSDP Scientific Staff, 1972, Deep Sea Drilling Project, Leg 22: *Geotimes*, vol. 17, no. 6 (June 1972), p. 15-17 (northeastern Indian Ocean).

DSDP Scientific Staff, 1973a, Leg 26, Deep Sea Drilling Project, Across the southern Indian Ocean aboard *Glomar Challenger: Geotimes*, vol. 18, no. 3 (March 1973), p. 16-19.

DSDP Scientific Staff, 1973b, Deep Sea Drilling Project, Leg 27, In the eastern Indian Ocean: *Geotimes*, vol. 18, no. 4 (April 1973), p. 16-17.

DSDP Scientific Staff, 1973c, Leg 31, Western Pacific floor: *Geotimes*, vol. 18, no. 10 (October 1973), p. 22-25.

Emery, K.O., and H. Niino, 1963, Sediments of the Gulf of Thailand and adjacent continental shelf: *Bull. Geol. Soc. America*, vol. 74, p. 541-554.

Emery, K.O., E. Uchupi, J.D. Phillips, C.O. Bowin, E.T. Bunce and S.T. Knott, 1970, Continental rise off eastern North America: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 54, p. 44-108.

Emery, K.O., and Z. Ben-Avraham, 1972, Structure and stratigraphy of China basin: *Bull Amer. Assoc. Petroleum Geologists*, vol. 56, p. 839-859.

Emery, K.O., E. Uchupi, J. Sunderland, H.L. Uktolseja and E.M. Young, 1972, Geological structure and some water characteristics of the Java Sea and adjacent continental shelf: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 6, p. 197-223.

Erdman, J.G., 1965, Petroleum—its origin in the earth: Amer. Assoc. Petroleum Geologists, Mem. 4 (Fluids in Subsurface Environments), p. 20-52.

Fitch, T.J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and the Western Pacific: *Jour. Geophys. Res.*, vol. 77, p. 4432-4460.

Fitch, T.J. and C.H. Scholz, 1971, A mechanism for underthrusting in southwest Japan: a model for convergent plate interaction: *Jour. Geophys. Res.*, vol. 77, p. 7260-7292.

Gansser, A., 1964, Geology of the Himalayas: Wiley, London.

Garson, M.S., and A.H.G. Mitchell, 1970, Transform faulting in the Thai peninsula: *Nature*, vol. 228, p. 45-47.

Gervasio, F.C., 1967, Age and nature of orogenesis of the Philippines: *Tectonophysics*, vol. 4, p. 379-402.

Gobbet, D.J., and C.S. Hutchison (eds.), 1973, Geology of the Malay Peninsula (West Malaysia and Singapore) : Wiley-Interscience, New York, 438 p.

Gutjahr, C.C.M., 1966, Carbonization of pollen grains and spores and their application: *Leidse Geologische Mededelingen*, vol. 38, p. 1-30.

Haile, N.S., 1970, Notes on the geology of Tambelan, Anambas and Bunguran (Natuna) Islands, Sunda Shelf, Indonesia : United Nations ECAFE, *CCOP Tech. Bull.*, vol. 3, p. 55-75.

Haile, N.S., and J.D. Bignell, 1971, Note on two radiometric age determinations on granites from the Tambelan and Bunguran Islands, Sunda Shelf, Indonesia: *Geol. en Mijnb.*, vol. 50, p. 687-690.

Haile, N.S., 1973, The geomorphology and geology of the northern part of the Sunda Shelf and its place in the Sunda mountain system: *Pacific Geol.*, vol. 6, p. 73-89.

Hamilton, W., 1972, Preliminary Tectonic Map of Indonesia: Open-file report, United States Geological Survey.

Hamilton, W., 1973, Tectonics of the Indonesian region: *Geol. Soc. Malaysia Bull.*, no. 6, p. 3-10.

Heirtzler, J.R., J.V. Veevers, H.M. Bolli, A.N. Carter, P.J. Cook, V.A. Krasheninnikov, B.K. McKnight, F. Proto-Decima, G.W. Renz, P.T. Robinson, K.Rocker, Jr. and P.A. Thayer, 1973, Age of the floor of the eastern Indian Ocean: *Science*, vol. 180, p. 952-954.

Herron, E.M., 1972, Sea-floor spreading and the Cenozoic history of the east-central Pacific: *Bull. Geol. Soc. America*, vol. 83, p. 1671-1692.

Hilde, T.W.C., and C.G. Engel, 1967, Age, composition and tectonic setting of the granite island Hon Truong Lon, off the coast of South Vietnam: *Bull. Geol. Soc. America*, vol. 78, p. 1289-1294.

Hilde, T.W.C., and C.G. Engel, 1969, Cretaceous-Tertiary events in southeast Asia: *Bull. Geol. Soc. America*, vol. 80, p. 1887-1888.

Hilde, T.W.C. and J.M. Wageman, 1973, Structure and origin of the Japan Sea : *in* The Western Pacific: Island Arcs, Marginal Seas, Geochemistry, University of Western Australia Press, p. 415-434.

Hilde, T.W.C., J.M. Wageman and W.T. Hammond, 1969, The structure of the Tosa Terrace and Nankai Trough off southeastern Japan: *Deep-Sea Res.*, vol. 16, p. 67-75.

Holtrop, J.F, and J. Keizer, 1971, Some aspects of the stratigraphy and correlation of the Surma Basin wells, East Pakistan: *in* Stratigraphic Correlation between Sedimentary Basins in the ECAFE Region (second volume), United Nations ECAFE *Min. Resources Development Ser.*, no. 36, p. 143-154.

Horai, K., and M.G. Langseth, 1973, Heat flow in the marginal seas in the western Pacific (abstract): Programs of the Scientific Assembly, IASPE, Lima Meetings from August 20-31, 1973, p. 169.

Hutchison, C.S., 1973, Tectonic evolution of Sundaland: a Phanerozoic synthesis: *Geol. Soc. Malaysia Bull.* no. 6, p. 61-86.

Isezaki, N., and S. Uyeda, 1973, Geomagnetic anomaly pattern of the Japan Sea: *Marine Geophys. Res.*, vol. 2, p. 51-59.

Kanamori, H., 1972, Faulting of the great Kanto earthquake of 1923 as revealed by seismological data: *Bull. Earthq. Res. Inst.*, Tokyo Univ., vol. 49, p. 13-18.

Karig, D.E., 1971a, Origin and development of marginal basins in the Western Pacific: *Jour. Geophys. Res.*, vol. 76, p. 2542-2561.

Karig, D.E., 1971b, Structural history of the Mariana island arc system: *Bull. Geol. Soc. America*, vol. 82, p. 323-344.

Karig, D.E., 1972, Remnant arcs: *Bull. Geol. Soc. America*, vol. 83, p. 1057-1068.

Karig, D.E., 1973, Plate convergence between the Philippines and the Ryukyu Islands: *Marine Geol.*, vol. 14, p. 153-168.

Kartsev, A.A., et al., 1971, The principal stage in the formation of petroleum: 8th World Petroleum Conf. (Moscow), Panel Discussion 2, Paper 1, p. 3-11.

Karunakaran, C., K.K. Ray and S.S. Saha, 1964 a, Sedimentary environment of the formation of Andaman flysch, Andaman Islands, India: Rept. of the 22nd Int. Geol. Congress, New Delhi, India, 1964, Part XV, p. 226-232.

Karunakaran, C., K.K. Ray and S.S. Saha, 1964 b, A new probe into the tectonic history of the Andaman and Nicobar Islands: Rept. of the 22nd Int. Geol. Congress, New Delhi, India, 1964, Part IV, p. 507-515.

Karunakaran, C., M.B. Pawde, V.K. Raina, K.K. Ray and S.S. Saha, 1964, Geology of South Andaman Island, India: Rept. of the 22nd Int. Geol. Congress, New Delhi, India, 1964, Part XI, p. 79-100.

Katili, J.A., 1970a, Large transcurrent faults in southeast Asia with special reference to Indonesia: *Geol. Rundschau*, vol. 59, p. 581-600.

Katili, J.A., 1970b, Additional evidence of transcurrent faulting in Sumatra and Sulawesi: *Bull. Nat. Inst. Geol. Mining Bandung*, vol. 3, no. 3, p. 15-28.

Katili, J.A.,1973a, Geochronology of West Indonesia and its implications on plate tectonics: *Tectonophysics*, vol. 19, p. 195-212.

Katili, J.A., 1973b, On fitting certain geological and geophysical features of the Indonesian island arc to the new global tectonics: *in* The Western Pacific: Island Arcs, Marginal Seas, Geochemistry, University of Western Australia Press, p. 287-305.

Klemme, H.D., 1971a, Trends in basin development: possible economic implications: *World Oil,* October 1971.

Klemme, H.D., 1971b, What giants and their basins have in common: *Oil and Gas Jour.* 1, 8 and 15 March 1971.

Klemme, H.D., 1972, Geothermal gradients: *Oil and Gas Jour.*, vol. 69, no. 29, p. 136, 141-144; and vol. 70, no. 30, p. 76-78.

Klemme, H.D., 1974 (in press), Geothermal gradients, heat flow and hydrocarbon recovery: Princeton University Press.

Landes, K.K., 1967, Eometamorphism and oil and gas in time and space: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 51, p. 828-841.

Larson, R.L., and C.G. Chase, 1972, Late Mesozoic evolution of the western Pacific Ocean: *Bull. Geol. Soc. America*, vol. 83, p. 3627-3644.

Lau, W.E., 1973, *in* Annual Report of the Geological Survey of Malaysia.

Leclerc, B., 1969, A new apparatus to measure temperature gradient and conductivity in the sea floor: (Technical preprint).

Lee, C., and T.W.C. Hilde, 1971, Magnetic lineations in the western Philippine Sea: *Sci. Rep. Nat. Taiwan Univ.*, no. 1, p. 69-76.

Lee, W.H.K.(ed.),1965, Terrestrial heat flow: American Geophysical Union, Monograph 8.

Le Pichon, X., 1968, Sea-floor spreading and continental drift: *Jour. Geophys. Res.*, vol. 73, p. 3661-3697.

Ludwig, W.J., N. Den and S. Murauchi, 1973, Seismic reflection measurements of southwest Japan margin: *Jour. Geophys. Res.*, vol. 78, p. 2508-2516.

Ludwig, W.J., S. Murauchi, N. Den, P. Buhl, H. Hotta, M. Ewing, T. Asanuma, T. Yoshii and N. Sakajiri, 1973, Structure of East China Sea-West Philippine Sea margin off southern Kyushu, Japan: *Jour. Geophys. Res.*, vol. 78, p. 2526-2536.

Luyendyk, B.P., 1970, Dips of downgoing lithospheric plates beneath island arcs : *Bull. Geol. Soc. America*, vol. 81, p. 3411-3416.

McDougall, I., 1971, Volcanic island chains and sea floor spreading: *Nature Phys. Sci.*, vol. 231, p. 141-144.

McElhinny, M.W., 1968, Northward drift of India—examination of recent palaeomagnetic results: *Nature*, vol. 217, p. 342-344.

McElhinny, M.W., 1970, Formation of the Indian Ocean: *Nature*, vol. 228, p. 977-979.

McKenzie, D., and J.C. Sclater, 1971, The evolution of the Indian Ocean since the late Cretaceous: *Geophys. Jour. Roy. Astron. Soc.*, vol. 25, p. 437-528.

McKelvey, V.E., and F.F.H. Wang, 1969, World subsea mineral resources (preliminary maps): Map 1-632, *Misc. Geol. Investigations*, United States Geological Survey.

Marchand, A., P.A. Libert and A. Combaz, 1968, Physiochemical criteria of the diagenesis of kerogen: *Compt. Rend. Acad. Sci. Paris*, Ser. D., vol. 266, p. 2316-2319 (in Fr.).

Marchand, A., P.A. Libert and A. Combaz, 1969, Physiochemical characterization tests of the diagenesis of several, biologically homogeneous, organic rocks: *Rev. Inst. Pétrol. Ann. Combust. Liquides*, vol. 24, p. 3-20 (in Fr.).

Masaytis, V.L., and Y.G. Staritskiy, 1967, The "Diwa" structures of east Asia: *Internat. Geology Rev.*, vol. 9, p. 230-238.

Matsuda, T., K. Nakamura and A. Sugimura, 1967, Late Cenozoic orogeny in Japan: *Tectonophysics*, vol. 4, p. 349-366.

Matsuda, T., and S. Uyeda, 1971, On the Pacific-type orogeny and its model—extension of the paired belts concept and possible origin of marginal seas: *Tectonophysics*, vol. 11, p. 5-27.

Meng, C.Y., 1970, 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: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 3, p. 109-126.

Mitchell, A.H.G., and M.S. Garson, 1972, Relationship of porphyry copper and circum-Pacific tin deposits to palaeo-Benioff zones: *Trans. Inst. Mining and Metallurgy*, sec. B, vol. 81, p. B10-B25.

Mitchell, A.H.G,. and J.D. Bell, 1973, Island arc evolution and related mineral deposits: *Jour. Geol.*, vol. 81, p. 381-405.

Mitchell, A.H.G., 1973, Metallogenic belts and angle of dip of Benioff zones: *Nature Phys. Sci.*, vol. 245, no. 143, p. 49-52.

Miyashiro, A., 1972, Pressure and temperature conditions and tectonic significance of regional and ocean-floor metamorphism: *Tectonophysics*, vol. 13, p. 141-159.

Miyashiro, A., 1973, Paired and unpaired metamorphic belts: *Tectonophysics*, vol. 17, p. 241-254.

Moberly, R., 1972, Origin of lithosphere behind island arcs, with reference to the western Pacific: *Geol. Soc. America, Mem. 132*, p. 35-55.

Mogi, K., 1973, Relationship between shallow and deep seismicity in the western Pacific region: *Tectonophysics*, vol. 17, p. 1-22.

Molnar, P., T.J. Fitch and F.T. Wu, 1973, Fault plane solutions of shallow earthquakes and contemporary tectonics in Asia: *Earth Planetary Sci. Letters*, vol. 19, p. 101-112.

Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 56, p. 203-213.

Murauchi, S., N. Den, S. Asano, H. Hotta, T. Yoshii, T. Asanuma, K. Hagiwara, K. Ichikawa, T. Sato, W.J. Ludwig, J.I. Ewing, N.T. Edgar and R.E. Houtz, 1968, Crustal structure of the Philippine Sea: *Jour. Geophys. Res.*, vol. 73, p. 3143-3171.

Murauchi, S., W.J. Ludwig, N. Den, H. Hotta, T. Asanuma, T. Yoshii, A. Kubotera and K. Hagiwara, 1973, Structure of the Sulu Sea and the Celebes Sea: *Jour. Geophys. Res.*, vol. 78, p. 3437-3447.

Murphy, R.W., 1973a, Diversity of island arcs: Japan, Philippines, Northern Moluccas: *Austr. Petroleum Expl. Assoc. Jour.*, p. 19-25.

Murphy, R.W., 1973b, The Manila Trench-West Taiwan foldbelt: a flipped subduction zone: *Geol. Soc. Malaysia Bull.*, no. 6, p. 27-42.

Nagasaka, K., J. Francheteau and T. Kishii, 1970, Terrestrial heat flow in the Celebes and Sulu Seas: *Marine Geophys. Res.*, vol. 1, p. 99-103.

Nishiwaki, C., 1973, Metallogenic provinces in Japan: *in* Fisher, N.H. (ed.), Metallogenic Provinces and Mineral Deposits in the Southwestern Pacific, Bureau of Mineral Resources, Geology and Geophysics, Bulletin 141, Canberra, p. 81-94.

Nomura, K., 1971, Measurement of heat flow in shallow seas: M.Sc. thesis, Institute of Geophysics, University of Tokyo.

Oxburgh, E.R., and D.L. Turcotte, 1970, Thermal structure of island arcs: *Bull Geol. Soc. America*, vo. 81, p. 1665-1688.

Packham, G.H., and D.A. Falvey, 1971, An hypothesis for the formation of marginal seas in the western Pacific: *Tectonophysics*, vol. 11, p. 79-109.

Parke, M.L., Jr., K.O. Emery, R. Szymankiewicz, and L.M. Reynolds, 1971, Structural framework of continental margin in South China Sea: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 55, p. 723-751, and United Nations ECAFE, *CCOP Tech. Bull.*, vol. 4, p. 103-142.

Philippi, G.T., 1957, Identification of source beds by chemical means: Internat. Geol. Congr. (20th, Mexico City), Session 3, p. 25-38.

Philippi, G.T., 1965, On depth, time, and mechanism of petroleum generation: *Geochim. et Cosmochim. Acta*, vol. 29, p. 1021-1049.

Posavec, M., D. Taylor, Th. van Leeuwen and A. Spector, 1973, Tectonic controls of volcanism and complex movements along the Sumatran Fault System: *Geol. Soc. Malaysia Bull.*, no. 6, p. 43-60.

Pusey, Walter C., III, 1973, Paleotemperatures in the Gulf Coast using the ESR-kerogen method: *Trans. Gulf Coast Assoc. Geol. Societies*, Houston, Texas, October 1973.

Ridd, M.F., 1971a, Faults in south-east Asia, and the Andaman rhombochasm: *Nature Phys. Sci.*, vol. 229, p. 51-52.

Ridd, M.F., 1971b, South-east Asia as a part of Gondwanaland: *Nature*, vol. 234, p. 531-533.

Rodolfo, K.S., 1969, Bathymetry and marine geology of the Andaman basin, and tectonic implications for southeast Asia: *Bull. Geol. Soc. America*, vol. 80, p. 1203-1230.

Roeder, D.H., 1973, Subduction and orogeny: *Jour. Geophys. Res.*, vol. 78, p. 5005-5024.

Sato, T., and K. Ono, 1964, The submarine geology off San'in district, southern Japan Sea: *Chishitsugaku Zasshi*, vol. 70, p. 434-445 (in Japanese with English abstract).

Sawamura, K., and D.J.C. Laming, 1973, Possible Mesozoic sedimentary basin in the Gulf of Thailand: United Nations ECAFE, *CCOP Newsletter*, vol. 1, no. 2, p. 24-27.

Schoeppel, Roger J., et al., 1970, Geothermal survey of North America, second annual report, 1970: Amer. Assoc. Petroleum Geologists research project and sponsorship.

Sclater, J.G., 1972, Heat flow and elevation of the marginal basins of the western Pacific: *Jour. Geophys. Res.*, vol. 77, p. 5705-5720.

Sclater, J.G., and J. Francheteau, 1970, The implications of terrestial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth: *Geophys. Jour.*, vol. 20, p. 509-542.

Shouls, M.M., 1973, Seismicity and plate tectonics in the Thailand-Burma-Andaman Sea area: United Nations ECAFE, *CCOP Newsletter*, vol. 1, no. 1, p. 17-19.

Sillitoe, R.H., 1972, Relation of metal provinces in western America to subduction of oceanic lithosphere: *Bull. Geol. Soc. America*, vol. 83, p. 813-818.

Smith, P.V., 1954, Studies on origin of petroleum-occurrence of hydrocarbons in recent sediments: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 38, p. 377-404.

Staplin, F.L., 1969, Sedimentary organic matter, organic metamorphism, and oil and gas occurrence: *Bull. Canad. Petrol. Geol.*, vol. 17, p. 47-67.

Stoiber, R.E., and M.J. Carr, 1971, Lithospheric plates, Benioff zones, and volcanoes: *Bull. Geol. Soc. America*, vol. 82, p. 515-522.

Suggate, R.P., 1959, New Zealand coals, their geological setting and its influence on their properties: *New Zealand Dept. Sci. Industr. Res. Bull.*, p. 134.

Technical Secretariat of CCOP, Explanatory note to accompany the map, "Tertiary basins of eastern Asia and their offshore extensions (Revised, April 1971)": United Nations ECAFE, *CCOP Tech. Bull.*, vol. 6, p. 225-227.

Teichmuller, M., 1971, Anwendung kohlenpetrographischer Methoden bei der Erdöl-und Erdgasprospektion: *Erdöl und Kohle*, vol. 24, p. 69-76.

Times Atlas, 1972, Atlas of the World, comprehensive edition: *The Times* and John Bartholomew and Son, London and Edinburgh, 123 pl.

Tissot, B., Y. Califet-Debyser, G. Deroo, and J.L. Oudin, 1971, Origin and evolution of hydrocarbons in early Toarcian shales, Paris Basin, France: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 55, p. 2177-2193.

United Nations, 1973, Economic significance, in terms of sea-bed mineral resources, of the various limits proposed for national jurisdiction: Report of the Secretary-General to the Committee on the Peaceful Uses of the Sea-Bed and the Ocean Floor Beyond the Limits of National Jurisdiction, General Assembly document A/AC. 138/87, 39 p.

Uyeda, S., and Z. Ben-Avraham, 1972, Origin and development of the Philippine Sea: *Nature Phys. Sci.*, vol. 240, p. 176-178.

Vacquier, V., S. Uyeda, M. Yasui, J. Sclater, C. Corry and T. Watanabe, 1966, Studies of the thermal state of the earth, the 19th paper: Heat flow measurements in the northwestern Pacific: *Bull. Earthq. Res. Inst.*, vol. 44, p. 1519-1535.

van Bemmelen, R.W., 1949, The Geology of Indonesia: Government Printing Office, The Hague, 732 p.

Vassoyevich, N.B., Yu. I. Korchagina, N.V. Lopatin and V.V. Chernyshev, 1970, Principal phase of oil formation : *Internat. Geol. Rev.*, vol. 12, p. 1276-1296.

Wageman, J.M., T.W.C. Hilde and K.O. Emery, 1970, Structural framework of East China Sea and Yellow Sea: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 54, p. 1611-1643.

Watanabe, T., D. Epp, S. Uyeda, M. Langseth, and M. Yasui, 1970, Heat flow on the Philippine Sea: *Tectonophysics*, vol. 10, p. 205-224.

Welte, D.H., 1965, Relation between petroleum and source rocks: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 49, no. 12, p. 2246-2268.

Welte, D.H., 1966, Kohlenwasserstoffgenese in Sedimentgesteinen: Untersuchungen über den thermischen abbau von Kerogen unter besonderer Berücksichtigung der n-Paraffinbildung: *Geol. Rundschau*, vol. 55, p. 131-144.

White, D., 1915, Some relations in origin between coal and petroleum: *Wash. Acad. Sci. Jour.*, vol. 5, no. 6, p. 189-212.

Workman, D.R., 1972a, The tectonic setting of the Mesozoic granites of Korea: *Jour. Geol. Soc. Korea*, vol. 8, no. 2, p. 67-76.

Workman, D.R., 1972b, Geology of Laos, Cambodia, South Viet-Nam and the eastern part of Thailand—a review: Report no. 19, Institute of Geological Sciences, Overseas Division, London, 49 p.

Wu, F.T., 1970, Focal mechanisms and tectonics in the vicinity of Taiwan: *Bull. Seismol. Soc. America*, vol. 60, p. 2045-2056.

Wu, F.T., 1972, The Philippine Sea Plate: a "sinking towel"?: *Tectonophysics*, vol. 14, p. 81-86.

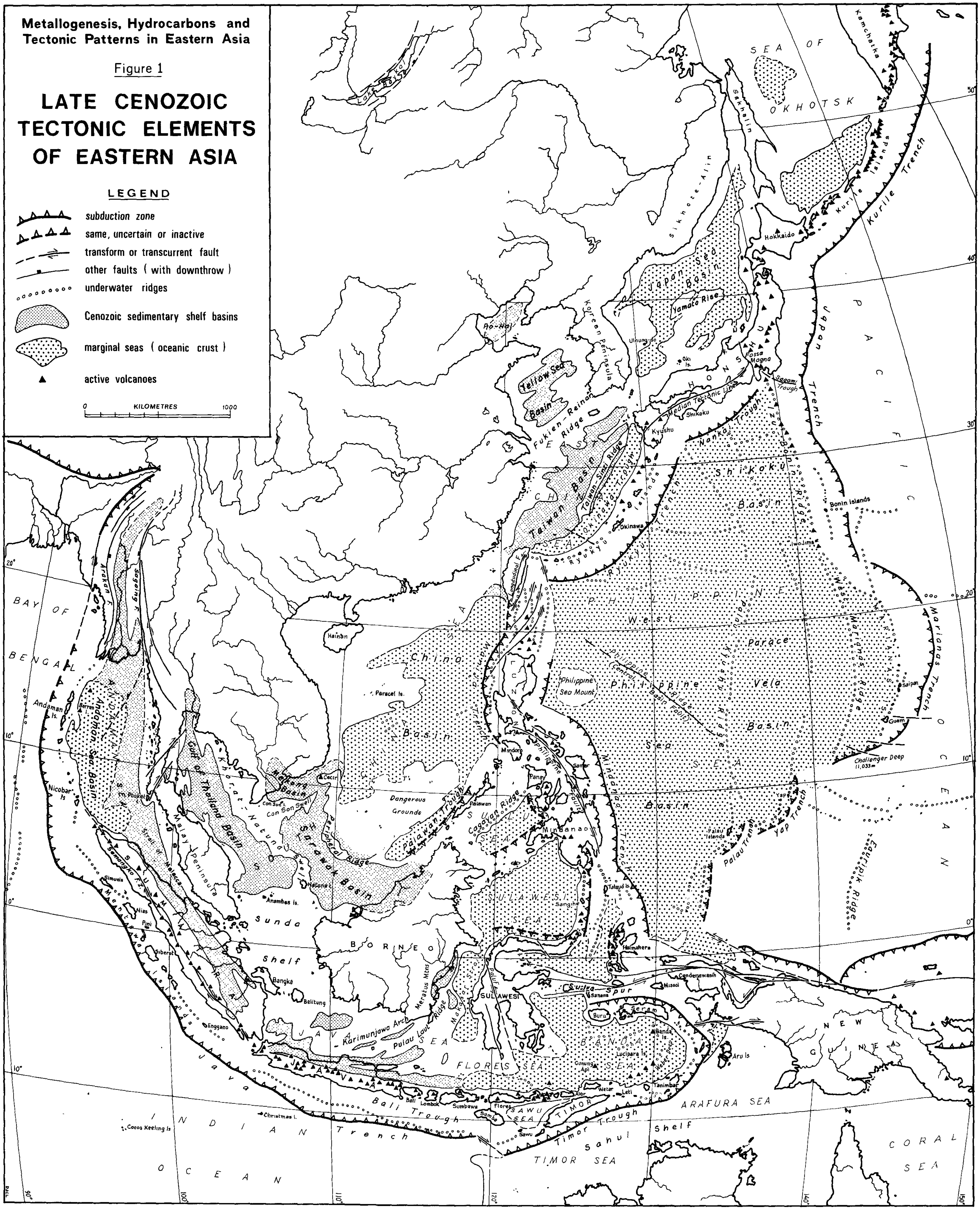
Yanshin, A.L. (ed.), 1966, Tectonic map of Eurasia, 1:5,000,000: Geol. Inst. Akad. Nauk SSR and Ministr. Geol. SSR, Moscow.

Yasui, M., T. Kishii, K. Nagasaka and A.J. Halunen, 1968, Terrestrial heat flow in the Okhotsk Sea (2): *Oceanogr. Mag.*, vol. 20, p. 73-86.

Yasui, M., D. Epp, K. Nagasaka and T. Kishii, 1970, Terrestrial heat flow in the seas around the Nansei Shoto (Ryukyu Islands): *Tectonophysics*, vol. 10, p. 225-234.

Yoshii, T., W.J. Ludwig, N. Den, S. Murauchi, M. Ewing, H. Hotta, P. Buhl, T. Asanuma and N. Sakajiri, 1973, Structure of southwest Japan margin off Shikoku: *Jour. Geophys. Res.*, vol. 78, p. 2517-2525.

PRINTED BY THAI WATANA PANICH PRESS CO., LTD., 891 RAMA I ROAD, BANGKOK.
MRS. BOONPRING T. SUWAN, PRINTER. B.E. 2517.


Metallogenesis, Hydrocarbons and Tectonic Patterns in Eastern Asia
Figure 1
LATE CENOZOIC TECTONIC ELEMENTS OF EASTERN ASIA
LEGEND
subduction zone
same, uncertain or inactive
transform or transcurrent fault
other faults (with downthrow)
underwater ridges
Cenozoic sedimentary shelf basins
marginal seas (oceanic crust)
active volcanoes
0 KILOMETRES 1000
SEA OF OKHOTSK
Kamchatka
Sakhalin
Kurile Islands
Kurile Trench
Hokkaido
Sikhote-Alin
Japan Sea Basin
Yamato Rise
Ulnung-do
Oki Is.
HONSHU
Fossa Magna
Sagami Trough
Median Tectonic Line
Shikoku
Kyushu
Nankai Trough
Japan Trench
PACIFIC OCEAN
Korean Peninsula
Po-Hai
Yellow Sea Basin
Fukien-Reinan Ridge
EAST CHINA SEA
Taiwan Basin
Taiwan-Sinzi Ridge
Okinawa Trough
Okinawa
Ryukyu Islands
Ryukyu Trench
Shikoku Basin
Bonin Ridge
Bonin Islands
Iwo Jima
PHILIPPINE SEA
West Philippine Basin
Parace Vela Basin
Philippine Sea Mount
Philippine Ridge (Central Basin Fault)
Kyushu-Palau Ridge
West Marianas Ridge
Marianas Trench
Saipan
Guam
Challenger Deep 11,033m
Yap Trench
Yap
Palau Trench
Palau Islands
Eauripik Ridge
Hainan
Paracel Is.
South China Basin
Manila Trench
Luzon
Mindoro
Philippine Fault
Samar
Panay
Palawan
Palawan Trough
Cagayan Ridge
SULU SEA
Mindanao
Mindanao Trench
Dangerous Grounds
Cecir
Mekong Basin
Con Son Is.
Con Son Swell
Peripheral Ridge
Sarawak Basin
Natuna Swell
Natuna I.
Khorat-Natuna
Gulf of Thailand Basin
Malay Peninsula
Malay Basin
Strait of Malacca
Phuket
Andaman Sea Basin
ANDAMAN SEA
Andaman Is.
Barren
Nicobar Is
BAY OF BENGAL
Arakan F.
Sagaing F.
SUMATRA
Semangko F.Z.
Simuelu
Nias
Pini
Siberut
Mentawai Islands
Enggano
Anambas Is.
Sunda Shelf
BORNEO
Bangka
Belitung
Meratus Mtns
Karimunjawa Arch
Pulau Laut Ridge
Makassar Str.
JAVA SEA
Java Trench
SULAWESI SEA
Sangihe
Talaud Is.
SULAWESI
Halmahera
Sula Spur
Banggai
Sanana
Buru
Seram
Misool
Cenderawasih
Banda Is.
BANDA SEA
Lucipara Is.
Weber Deep
Gunung Api
FLORES SEA
Bali
Lombok
Sumbawa
Flores
Alor
Wetar
Leti
Tanimbar
Aru Is
Sumba
Sawu
SAWU SEA
TIMOR
Timor Trough
Bali Trough
Christmas I.
Cocos Keeling Is
INDIAN OCEAN
Sahul Shelf
TIMOR SEA
ARAFURA SEA
NEW GUINEA
CORAL SEA
90°
100°
110°
120°
130°
140°
150°
50°
40°
30°
20°
10°
0°