TECHNICAL BULLETIN

VOL. 8

ECONOMIC AND SOCIAL COMMISSION FOR ASIA AND THE PACIFIC
COMMITTEE FOR CO-ORDINATION OF JOINT PROSPECTING FOR MINERAL RESOURCES IN ASIAN OFFSHORE AREAS (CCOP)

December, 1 9 7 4

ECONOMIC AND SOCIAL COMMISSION
FOR ASIA AND THE PACIFIC

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

SUPPORTED BY THE
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PREFACE

Since 1968, the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (referred to briefly as the Co-ordinating Committee for Offshore Prospecting, and abbreviated to CCOP) has been issuing Technical Bulletins annually, containing technical and scientific studies on marine geology and offshore prospecting for mineral resources as well as the results of surveys undertaken through CCOP's sponsorship. Apart from contributions to scientific knowledge, these studies and survey reports have helped in arousing interest in the mineral potentials of the marine shelves of the region, particularly for petroleum, and have played an important part in attracting risk capital from industry to east Asia. The publication of the Technical Bulletin series is contributed by the Government of Japan, with the Geological Survey of Japan responsible for editing and printing.

The Committee is an inter-governmental body, established under the aegis of the United Nations Economic Commission for Asia and the Far East (ECAFE) which is now known as the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) and, since 1972, assisted by the United Nations Development Programme (UNDP) through a project entitled "Technical Support for Regional Offshore Prospecting in East Asia." The Committee consists of the following member countries: Indonesia, Japan, the Khmer Republic, the Republic of Korea, Malaysia, the Philippines, the Republic of Viet-Nam, Singapore and Thailand.

Three main types of publications are produced by the Committee: Technical Bulletins, Reports of CCOP sessions and CCOP Newsletters. All CCOP publications, including Technical Bulletins, are distributed to the appropriate organizations and authorities concerned in member countries of CCOP. Enquiries as to their availability to institutions and organizations in other countries may be directed to: Office of the Project Manager/Co-ordinator, CCOP, ESCAP, Sala Santitham, Bangkok-2, Thailand.

FOREWORD

During the six years since the publication of the first volume of the Technical Bulletin of CCOP in 1968, great progress has been made in both basic scientific research and prospecting of the offshore areas of the ESCAP region. This, of course is reflected in the activities of CCOP and naturally in the contents of the Technical Bulletin. In the earlier volumes, reports of various surveys of specific areas of the member countries constituted significant portions of the paper contained, whereas in the later volumes papers dealing with regional and basic geologic problems are being published together with survey reports. This, I feel is reflection of the progress of the state of the science in the countries of the region and at the same time is one of the major achievement of CCOP.

Under these circumstances, I am happy to present the eight volume of the Technical Bulletin which I am sure will contribute to the scientific advancement of the region. I appreciate the cooperation of the various individuals and organizations for preparing this volume.

Isamu Kobayashi
Director,
Geological Survey of Japan

NOTE BY THE EDITOR

It is a great pleasure for the editor to present Volume 8 of the CCOP Technical Bulletin to the Committee for Co-ordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP). Among the seven articles included in this volume, the editor is happy to have four contributions from geoscientists of the countries of the region, prepared either by themselves or in co-operation with the scientists of the supporting countries of CCOP. The editor finds pleasure also in having a paper on hydrocarbon exploration contributed from an adjacent region, which would give an impetus to the activities of the CCOP member countries.

Immediately after the Bangkok session of CCOP in September 1973, an IDOE (International Decade of Ocean Exploration) Workshop on "Metallogenesis and Tectonic Patterns in East and Southeast Asia" was convened under the joint sponsorship of CCOP and the Intergovernmental Oceanographic Commission of UNESCO, the research proposal by CCOP being originally recommended at the Bandung session in 1972. Besides the report of the Workshop, two articles based on the outstanding presentation made at the Workshop are published in this volume; one is concerning organic metamorphism in relation to hydrocarbon maturation, the other the geology and petroleum prospects of the Banda Arcs, Indonesia. Geothermal studies including palaeotemperature measurements in East Asia were recommended at the Workshop as well as at the Bangkok session of CCOP, and the review article on organic metamorphism contributed by one of the pioneer research groups in this field must be informative and useful not only for scientists concerned with the IDOE project, but also for all readers. The Workshop also recommended multidisciplinary studies along the six selected transects as major part of the IDOE programme in East Asia. The paper on Banda Arcs, contributed by the authors who have long been studying the area, must be valuable for the proposed studies of Timor-Banda Arc transect. In addition, two Korean papers dealing with the geology and tectonics of Korean Peninsula also should be useful as background papers for the proposed transect studies from Southwest Japan to Korean Peninsula.

The editor feels that discussion of the technical contents of the articles appearing in the Technical Bulletins would be highly desirable for the advancement and promotion of geological and geophysical studies in the region. For example, the application of plate tectonics concepts would bring much dispute, in understanding of the principles in one side and in recognition of geological evidences on the other. If readers wish to comment or raise questions regarding them, the editor will willingly act as intermediary and forward them to the contributors, who alone are responsible for the statements made and opinions expressed in their respective articles.

According to the discussion made at the Bangkok session of CCOP, the articles included in this Volume were reviewed by the Special Advisers to CCOP or other outstanding scientists involved in the CCOP activities. The editor wishes to record herewith the names of these scientists with his sincere gratitude:

Dr. W. Bullerwell, Institute of Geological Sciences, London, Prof. Dr. H. Closs, Bundesanstalt für Bodenforschung, Hannover, Prof. Masami Hayakawa, Tokai University, Shimizu, and Dr. Chikao Nishiwaki, Institute for International Mineral Resources Development, Fujinomiya.

The editor expresses his sincere gratitude to Dr. C. Y. Li, Project Manager/Coordinator of the UNDP Technical Support for Regional Offshore Prospecting in East Asia, and to Dr. J.D.C. Laming, former Senior Geologist of the project, for their kind co-operation and valuable suggestions. His deepest thanks are extended to the Director of the Geological Survey of Japan for the printing of this volume, as well as to the members concerned of the Geological Survey, particularly of its Publication and Library Office, for their co-operation in completing this volume.

It is to the editor's regret that the publication of Volumes 7 and 8 be delayed than expected. In view of the experience, the editor considers that the deadline date for submission of manuscripts for the next regular volume will firmly be set at the end of March 1975.

November 1974

Shun-ichi Sano
Editor-in-Chief

CCOP TECHNICAL BULLETIN, VOLUME 8

CONTENTS

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I. SEISMIC SURVEYS OFF THE EAST COAST OF KOREA

By

H. U. SCHLÜTER[1] and W. C. CHUN[2]

(with figures I–1 to I–7; and maps I–1 to I–4 in envelope on back cover)

ABSTRACT

An offshore seismic refraction and reflection survey conducted in 1972 jointly by the Geological Survey of Korea and the Geological Survey of the Federal Republic of Germany covered an area off the east coast of the Republic of Korea between Kangneung and Pohang, in an attempt to locate offshore coal-bearing formations and to assess the potential for hydrocarbon reservoirs. Two reversed seismic refraction profiles were shot, and reflection profiles were run on 35 traverse lines and nine tie lines, totalling 2,592 line-km.

From the seismic study it appears that sedimentary strata correlative with the onshore coal-bearing Permo-Carboniferous rocks near Mukho are not present more than two miles from the coast. Offshore from Mukho, neither Mesozoic nor Palaeozoic strata could be identified seismically, and Cenozoic sediments are thin and lack structures. Consequently there is little likelihood of economically significant hydrocarbon accumulations in this area.

The Pohang Basin, with Cenozoic strata, extends northwards to near Ulchin and is bordered on the east by a ridge which can be traced over a distance of 120 km northward from the Kuryongpo Peninsula. To the east of the ridge, thick Cenozoic sediments were deposited up to a maximum of 2,500 m. Within the 850 m thick sedimentary succession in the Pohang Basin, no geologically interesting structures were recognized, but structures are present in the underlying older Tertiary strata, however, the likelihood of economically significant hydrocarbon accumulations is not favourable because of the thinness of the overlying sedimentary section.

It is recommended that additional refraction surveys of the narrow shelf area within two miles from shore from 36°N to 36°30′N should be conducted to fill the gap between the shoreline and the area surveyed.

INTRODUCTION

The offshore geophysical survey, conducted in the marine shelf area off the east coast of the Republic of Korea in 1972 was a joint effort by the Geological Survey of Korea and the Geological Survey of the Federal Republic of Germany. This survey had been recommended by CCOP as a national project and was designated project number CCOP–1/ROK. 6.

1: Bundesanstalt für Bodenforschung, Hannover, Federal Republic of Germany

2: Geological and Mineral Institute of Korea, Seoul, Republic of Korea.

The objectives of the survey were to study (i) the seaward extension of the Palaeozoic Pyeongan System which contains coal onshore near Mukho, and (ii) the northern offshore extension of the Tertiary sedimentary basin of Pohang in order to determine the potential for hydrocarbon reservoirs.

Field operations were conducted from 26 May to 26 July 1972. The Geological Survey of the Federal Republic of Germany sent one scientist and two technical staff and a complete seismic recording system, air gun and compressor; the Geological Survey of Korea provided the research vessel R/V *Tam Yang* (530 tons), Raydist navigation system, and dynamite and a shooting boat for seismic refraction work. The Geological Survey of Korea also provided counterpart scientists and technical staff. Geological interpretation was undertaken and the final report prepared at the office of the Geological Survey of the Federal Republic of Germany in Hannover, with the participation of a Korean geophysicist.

THE SURVEY AREA

The survey area lies between 36°N and 37°50′N latitude and 129°10′E and 130°10′E longitude off the east coast of the Korean Peninsula, covering the coastal shelf and adjoining continental slope. Of the bays along the shore of the survey area, the R/V *Tam Yang* could only use Pohang harbour in the south and Mukho harbour in the north as base ports. There are no large river estuaries on the east coast because of the steep mountain range parallel to and adjoining the coast, and the coastline itself shows mainly monotonous features.

Geology

There are four major structural elements in southern Korea (Kobayashi, 1953, Kim, 1970, 1974 (*this volume*), S. M. Lee, 1972, 1974 (*this volume*)). Across the central area, trending northeast-southwest, lies the Ogcheon[1] Geosynclinal Zone (the Yokusen Trough of Kobayashi, 1953), which divides the Precambrian areas of the peninsula into two: on the northeast, the Gyeonggi[1] Massif (the Keiki Land of Kobayashi) and the Sobaegsan[1] Massif (Reinan Land of Kobayashi) on the southeast. Both massifs are composed of schists and gneisses and formed a basement for succeeding deposition. To the southeast of the Sobaegsan Massif lies the Gyeongsang[1] Basin, composed of a thick series of Jurassic-Cretaceous continental sedimentary and andesitic rocks. A few small Tertiary basins are found in the east coastal area and southwestern tip of the peninsula, and on islands including Cheju Island (*Map I–1*) which is composed of marine sedimentary and basaltic rocks.

The northeastern portion of the Ogcheon Geosynclinal Zone, which has been designated the Ogcheon Neogeosynclinal Zone (Kim, 1970, 1974), was an area of continuous sedimentation from the Cambrian to the end of the Jurassic. During the Permo-Carboniferous, minable coal deposits were laid down in this zone, including those in the Mukho area. These are overlain by Triassic and Jurassic formations (*Map I–1*).

Following a period of Triassic folding, the Songrim Disturbance (the Shorin Phase of Kobayashi, 1953) in the Neogeosynclinal Zone, the sedimentary formations were folded again during the Cretaceous and overthrust towards the northeast (the Daebo Orogeny,

1: These spellings conform to the recommended orthography for romanized Korean place names. Alternative spellings are used in Articles II and III of this volume.

Kim, 1971; Taiho Orogeny, Konno, 1928); they were partly metamorphosed by granitic intrusions (the Daebo Granite, Kim, 1971). Subsequent erosion affected both the Mesozoic and the coal-bearing Upper Carboniferous Sadong Formation, and, on-shore, preservation of these is mainly in synclinal structures (Y. J. Lee, 1966).

In the Gyeongsang Basin, the oldest exposed Upper Jurassic and Lower Cretaceous rocks are slates, sandstones and conglomerates. They are overlain by Upper Cretaceous tuffs, andesites and agglomeratic quartz porphyries. In the Pohang coastal area, the Upper Cretaceous rocks are in turn overlain by transgressive Tertiary conglomerates, mudstones and sandstones. These strata thicken seawards and dip 10 degrees to the east, and are potential hydrocarbon reservoir rocks. Unlike Japan, where 85 percent of the coal deposits are of Tertiary age (Schwind, 1967), only isolated thin unminable coal beds are developed in Tertiary strata. Near the survey area, isolated basaltic eruptions occurred in Cenozoic time (Tateiwa, 1960).

The Gyeongsang Basin appears to join with the Tsushima Basin (Kobayashi, 1953) offshore to the southeast of the peninsula, on the evidence of the thickening of strata to seaward and on the geology of the islands between Japan and Korea (*Map I–1*).

The fjord-like morphology of the west and south coasts of the peninsula indicates recent submergence in those areas, while the steep and little-dissected east coast indicates uplift.

Bathymetry

The bathymetric chart of the study area (*Map I–1*) is based solely on the results of the seismic reflection survey. A velocity of Vp = 1,500 m/sec was assumed for calculation of water depths.

The predominant physiographic feature of the southern part of the survey area is a 120 km-long submarine ridge aligned parallel to the coast, which may represent a continuation of the outcrop of volcanic rocks forming the Kuryongpo Peninsula. This swell, which varies in width from two to nine kilometres, separates Yongil Bay from the open East Sea (Japan Sea), and for a considerable distance forms the boundary between the shelf and the continental slope. The ridge is in the form of a "table mountain" or elongate plateau; it rises about 125 m above the adjacent sea floor and is, on average, 115 m below the water surface. Since the Mesozoic, this ridge has probably served as a sediment barrier and might have been responsible for the morphology of the continental shelf north and east of Pohang. In the northern part of the survey area, where the ridge is no longer recognizable morphologically, the sea floor shows only slight relief variations to a depth of 200 m. Detail morphological features, such as channels or evidence of gravity sliding, are completely lacking on the shelf and adjacent continental slope.

Previous geological and geophysical work

Previous geophysical reconnaissance work on the deeper subsurface along the east coast of the Republic of Korea was concentrated on the potentially oil-producing Tertiary Pohang Basin in the southeast, and the adjacent continental shelf.

Since 1966, onshore in the Pohang area, geological mapping and seismic and gravity work have been conducted and several boreholes were drilled through the Tertiary rocks and penetrated the Upper Cretaceous agglomerate at depths ranging from 602 m to 738 m. These were DH 301, total depth 698 m; DH 201, 870 m; PY 1, 852 m; PY 2, 726 m; PY 3, 749 m.

In DH 302 and PY 2, methane gas shows (11 cu m/day, 388 cf/d) were recorded from Miocene sandstones.

An onshore refraction seismic study near Pohang in 1967 found velocities from Vp = 2.0 to 2.05 km/sec for the Tertiary sediments and from Vp = 4.7 to 4.9 km/sec for the Upper Cretaceous agglomerate and tuff. A seismic reflection study in 1966, undertaken by Huntec Ltd., Toronto, with support from ECAFE and the United Nations Development Programme, covered the Pohang offshore area (Huntec, Ltd., 1967).

Both the USSR (Beloussov and Ruditch, 1961, Kovylin and Mirlin, 1971, Gnibidenko and Sychev, 1972) and Japan (Yasui et al., 1968, Kaseno, 1972) have conducted geological-geophysical studies to determine the crustal structure of the western part of the Japan Sea (East Sea of Korea).

SURVEY METHODS AND INSTRUMENTS

Refraction seismic work

Two profiles were studied by the refraction seismic technique, one in the Pohang area and the other in the Mukho area.

Off Mukho, a reversed seismic refraction profile was taken along a line 12 km long which ran northeast from 70 m to 300 m water depth (*Map I–1*). In the Pohang area, a similar profile was run along an 18 km line north of Pohang in an eastward direction, crossing the Pohang Basin normal to the basin axis.

Dynamite was used for the energy source in the refraction shooting, with charges from 3 kg to a maximum of 67 kg. These were detonated by the shooting boat at distances varying from 0.5 to 2.0 km and at depths of 2 to 40 m. The transmission of the shot time-break took place over radio. For reception of signals, a free-floating telemetry buoy equipped with a Lennartz modulator and amplifier, a VHF transmitter and a low frequency hydrophone were used. The recording apparatus installed on the R/V *Tam Yang* consisted of a Lennartz demodulator, a Siemens-Oszillomink direct plotter and magnetic tape. Time marks and shot-break were added to the frequency-multiplexed signal. The distance between the shot-point and the receiver was determined from the direct water wave (assuming Vp = 1520 m/sec) and by Raydist.

Reflection seismic work

Reflection seismic work was done along a series of traverse lines roughly perpendicular to the coast in an east-west direction at intervals of about 10.8 km, with tie lines set at both ends and in the middle of the traverse lines and generally parallel to the coast (*Map I–1*). A total of 2,520 line-km was run, consisting of 35 traverse lines and 13 tie lines. Because of the rather deep draft of the R/V *Tam Yang*, the traverse lines could not be extended close to the shore (two-mile zone).

The continuous seismic profiling was conducted with a one-channel seismic reflection system belonging to the Geological Survey of the Federal Republic of Germany. It consisted of a trigger unit (quartz clock and ignition device), preamplifier, filter (Telco) and final amplifier, ELAC control amplifier and ELAC recorder (LAZ 32) with a digital unit and magnetic tape (Revox). The seismic signals were produced by air guns of 5-litre chamber size fed by a Bauer compresser (3.5 cu m/min capacity, operating pressure 130–150 atm) and were recorded by an Aquatronics streamer (100 hydrophones/trace). When recording, the ship's speed was about 8 knots (15 kph).

Positioning

The ship's position was determined every ten minutes by a Raydist Navigation System (two-range system). During the subsequent interpretation, navigation errors of between 0.5 and 1.5 nautical miles were found when profile intersections were evaluated.

INTERPRETATION OF THE SEISMIC DATA

Refraction seismic data

Interpretation of the profile sections followed determination and correlation of the seismic arrivals according to the intercept-time method and the Wiechert-Herglotz procedure. In addition, wave-front procedures and model studies were used for the Mukho profile: this will be presented first.

Mukho profile. After correlation of the first arrivals, the seismogram compilation showed a refraction line with an apparent velocity of 4.69 km/sec for profile 3 (*Fig. I–1*) and an apparent velocity of 7.83 km/sec for the reverse profile 4 (*Fig. I–2*). Considering both inclination and refraction, a true velocity of 5.6 km/sec was determined for this refractor. On the recordings near the shot-points, later refraction arrivals appeared with a velocity of Vp = 1.98 km/sec.

In the derived model (*Fig. I–3*) a layer (layer 2) with Vp = 1.98 km/sec lies beneath the water layer (1) and the eastward-sloping sea bottom. The shickness of this layer 2 is 60 m at

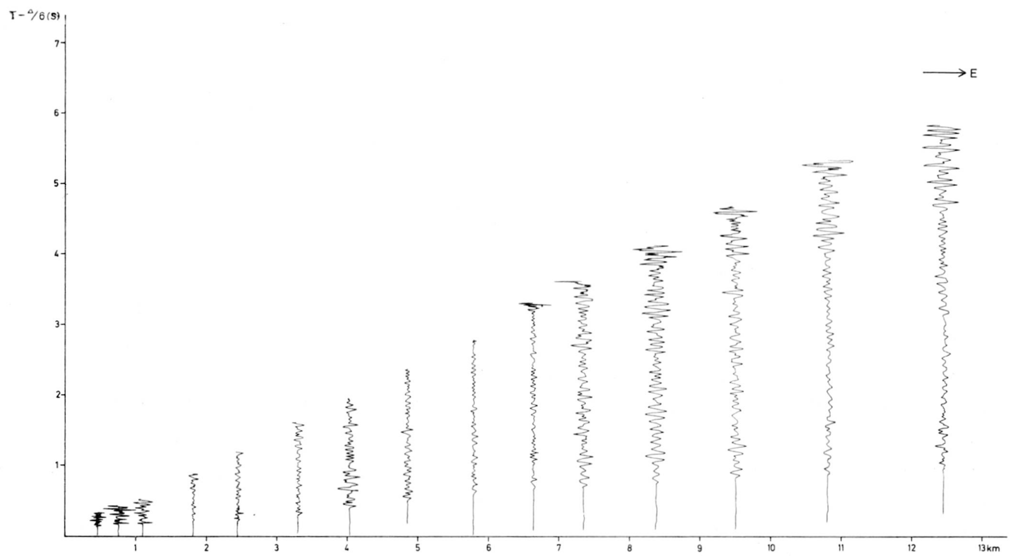

Figure I–1. Record section of refraction profile 3, off Mukho.

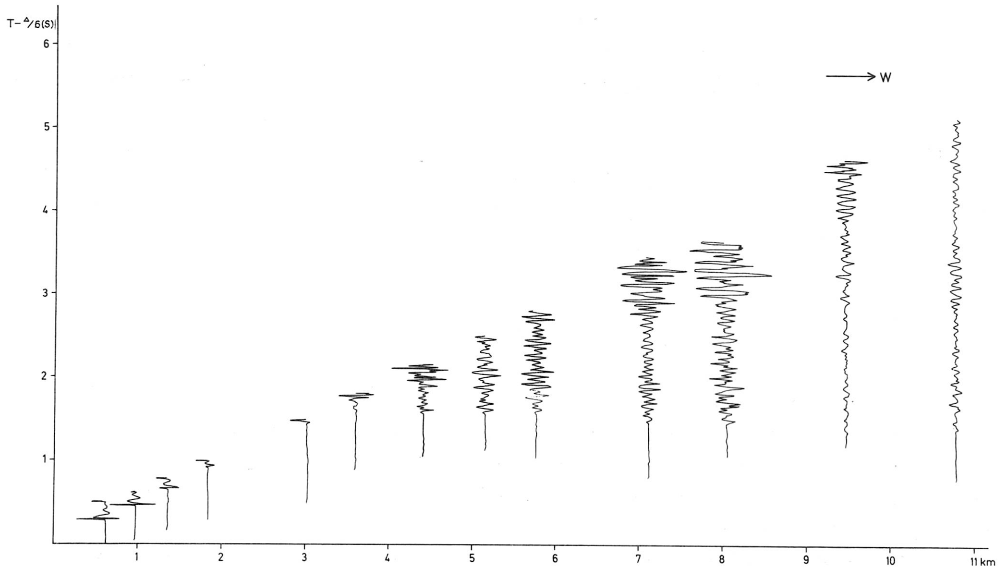

Figure I–2. Record section of refraction profile 4, off Mukho, the reverse of profile 3.

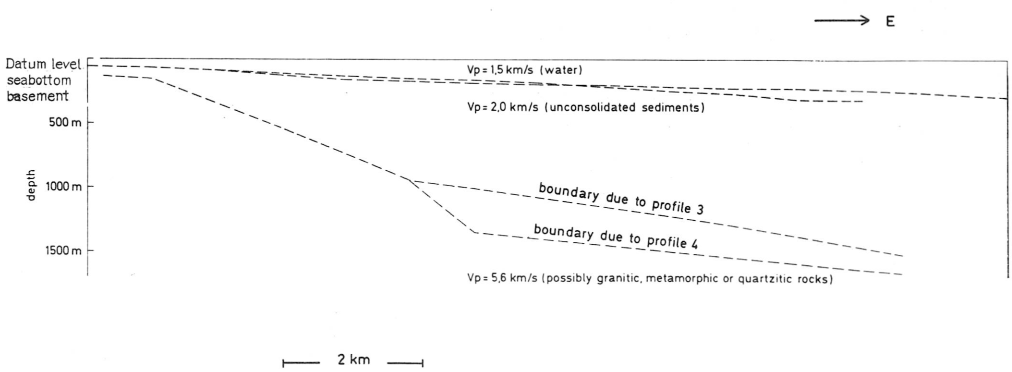

Figure I–3. Geological-seismic model derived from refraction data, off Mukho.

the southwest end of the profile, and 1,400 m to the northeast. Layer 2 overlies rocks with a velocity of Vp = 5.6 km/sec.

According to the airgun profiles, the nearly horizontal and, presumably, slightly consolidated sediments of layer 2 overlie a deeper rock complex which shows no coherent reflections. The work of Kovylin and Shayakhmetov (1971, in Kaseno, 1972) in the northern and northwestern parts of the Japan Sea showed sediments 1.5 to 2.0 km thick on the continental margin of the Asian mainland; according to Kaseno (1972, p. 104) they are of Miocene to Pliocene age. Koizumi (1970, in Kaseno, 1972) postulated a sedimentation rate of 6 to 7 cm/1,000 years on the continental rise of Honshu; utilizing this sedimentation rate, an estimate of the time of deposition of the up-to-1,400 m thickness of sediments on the continental slope off Mukho may be put at Miocene to Plio-Pleistocene.

The surface of the underlying layer (layer 3) is a marked refraction horizon at a depth of 120 m below sea level at the southwest end of the profile, dropping to 1,600–1,700 m depth at the northeastern end. On the basis of the observed velocity of 5.6 km/sec, layer 3 can be interpreted as a crystalline rock complex. As Cambrian quartzite and Precambrian crystalline limestones are exposed in the coastal area, in addition to granites and gneisses, a clear-cut stratigraphic classification of layer 3 is not possible, in particular since seismic observations on land have not been made. The seismic refraction records give no indication of the presence of any Permo-Carboniferous coal-bearing rocks in the offshore survey area off Mukho.

Pohang profile. From first arrivals in line 1, apparent velocities of Vp = 4.4 and 6.3 km/sec were obtained (*Fig. I–4*). Refracted waves with greater amplitude appear in traces 6 to 8 as later arrivals with an apparent velocity of 2.1 km/sec. The true seismic velocities could not be determined as the first arrivals of the reverse line 2 (*Fig. I–5*) could not be correlated because of the high noise level. The interpretation was therefore made on the basis of the apparent velocities observed in profile 1 and on an assumption of horizontal layering.

From the data it may be stated that beneath a water layer (layer 1) of 100 m thickness lies a 450 m thick complex (layer 2) which, in its upper part, is presumably of poorly consolidated sediments for which no refraction arrivals were observed. A velocity of 2.1 km/sec was only found below a depth of 500 m. In the airgun recordings, layer 2 is marked by closely-spaced reflections of mostly horizontal layering, which overlie older, slightly

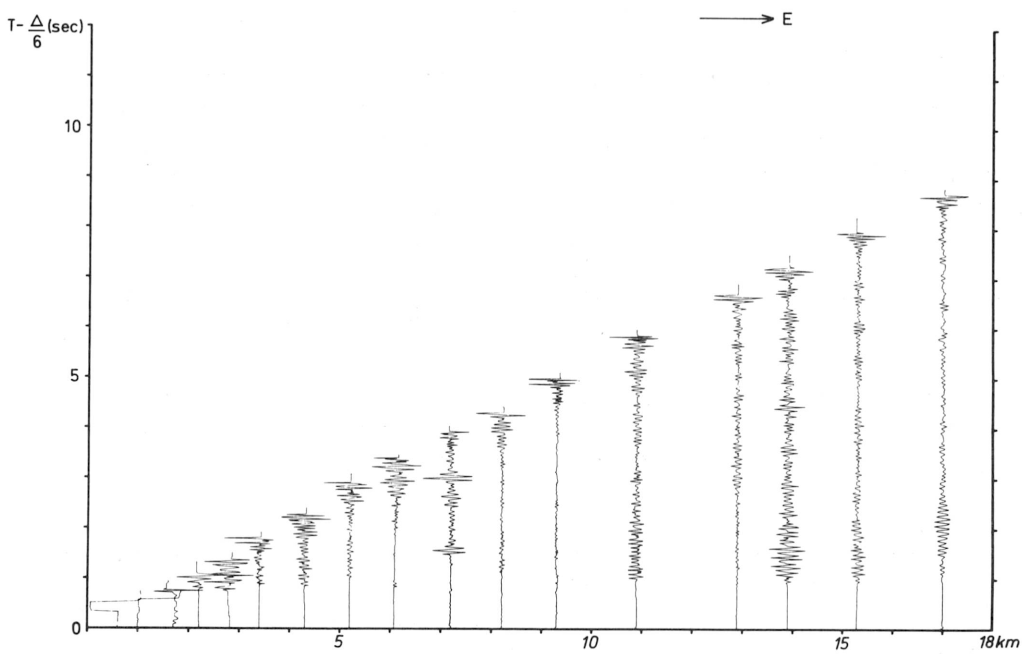

Figure I–4. Record section of refraction line 1, off Pohang.

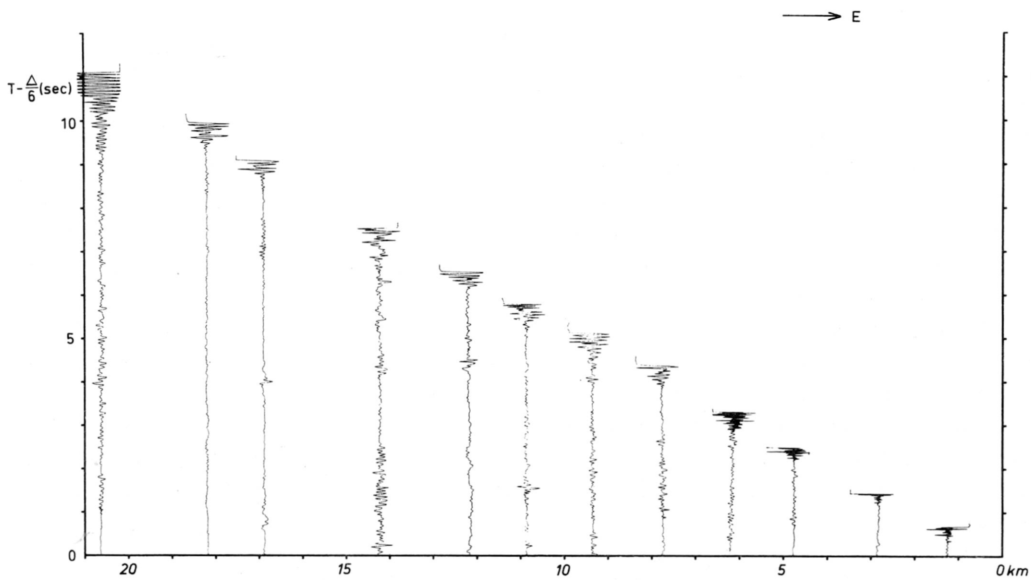

Figure I–5. Record section of refraction line 2, off Pohang, the reverse of line 1.

folded strata.

According to geological-geophysical investigations on land made by the Geological Survey of Korea, Miocene strata lie beneath a Quaternary cover 100 m thick. A velocity of Vp = 2.05 km/sec was determined for the Miocene sediments. Comparing this with the offshore geology, the slightly folded sediments starting at a depth of 500 m might be correlated stratigraphically with the onshore Miocene strata.

Layer 2 is underlain by a rock complex (layer 3), 1,300 m thick, with an apparent velocity of 4.4 km/sec, horizontal layering assumed. This complex overlies crystalline rocks (apparent velocity 6.3 km/sec) at a depth of 1,900 to 2,000 m. As already mentioned, Upper Cretaceous tuffaceous sandstones and andesitic conglomerates with velocities of 4.7 to 4.9 km/sec were encountered in boreholes near Pohang at depths of 600 to 700 m. In the vicinity of the profile, layer 3 might be interpreted as correlating with these Upper Cretaceous agglomerates and sandstones.

The first arrivals from the surface of the underlying fourth layer were recorded at a distance of 11 km. Petrologically, layer 4, with an apparent velocity of 6.3 km/sec might be interpreted as a granitoid or highly metamorphosed rock complex.

Reflection seismic data

During the interpretation of the seismic reflection recordings, horizons which appeared important were digitized with a D-MAC pencil follower. Using the velocity values determined from the seismic refraction recordings, a special program on an IBM 1620 computer transformed the travel-time records into vertically migrated depth sections. To calculate depth values from the travel-time values, the following velocities were assumed:

		Mukho area (profiles 21–35)	Pohang area (profiles 1–20)
Layer 1	(water)	Vp = 1,500 m/sec	Vp = 1,500 m/sec
Layer 2	(mostly unconsolidated sediment)	2,000 m/sec	2,000 m/sec
Layer 3	(acoustic basement)	5,600 m/sec	4,400 m/sec

The calculated depth values were punched on tape and automatically plotted with a Zuse plotter (Z 64) to the scale of the navigation charts (1: 244,000) with a vertical exaggeration of five (*Maps I–2 and I–3*).

Mukho area. An example of a seismic reflection recording is shown in *Figure I–6*, from profile 33. The corresponding depth profile and other recorded profiles are shown in *Maps I–2 and I–3*. In almost all profiles, presumed Cenozoic unconsolidated sedimentary strata were penetrated and reflections from the surface of an acoustic basement were recorded. The top of the acoustic basement (presumably crystalline rocks) shows up in the seismic recordings as a strongly marked darker zone, beneath which structural detail is sparse or absent. In the survey area the basement has an irregular relief, rising nearly to the sea floor in some places.

The sediments unconformably overlying the basement are characterized by numerous repeated reflections, indicating stratification. It can be seen (for instance in the eastern part of the profile shown in *Fig. I–7*) that the oldest sedimentary strata follow the relief of the basement surface, and are themselves unconformably overlain by younger strata. In the northernmost profiles the reflections within the unconsolidated sediments mostly dip to the eastward, towards the basin centre. In profiles 29 to 32 there are opposing dips in the lower horizons which indicate that there must have been variable rates of subsidence within the sediment-filled basin. The uppermost horizons, lying just beneath the sea floor, appear to wedge out along the ridges or to have been upwarped by the ridges. In profile 27, at the northern end of tie-line 9 and south of tie-line 12 (*Maps I–2, I–3 and I–4*) weakly marked horizons with completely different inclinations occur as intercalations within the normal sedimentary sequence. These convex layers, heavily imbricated and dipping northwards, are suggestive of foreset and topset bedding in deltaic deposits. In this case, the acoustic basement nearby to the south, which rises up almost to the sea floor, might have been above sea level during glacial times and thus been a source of sediment for adjacent deltas.

The largest known sedimentary basin in the shelf area off Mukho is 20 km wide and 35 km long (*Map I–4*). The unconsolidated sediments of presumed Cenozoic age in the central part of this northward-striking trough have a thickness of at least 1,400 m in the north, assuming Vp = 2,000 m/sec. On the east and the west, the trough is bordered by the steeply rising, presumably crystalline, acoustic basement.

Between the shore and a buried acoustic basement ridge, which lies off the coast between Kangneung and Mukho, there is another basin striking north-south with over 500 m of sedimentary infill, which terminates close to Mukho. Its form suggests that it is bounded on the east by normal faulting or basement ridge.

Pohang area. In the shelf area north of Pohang the subsurface structure is similar to that off Mukho. There are several basins filled with sediments and separated from one another by mainly north-south striking ridges of acoustic basement. The most prominent

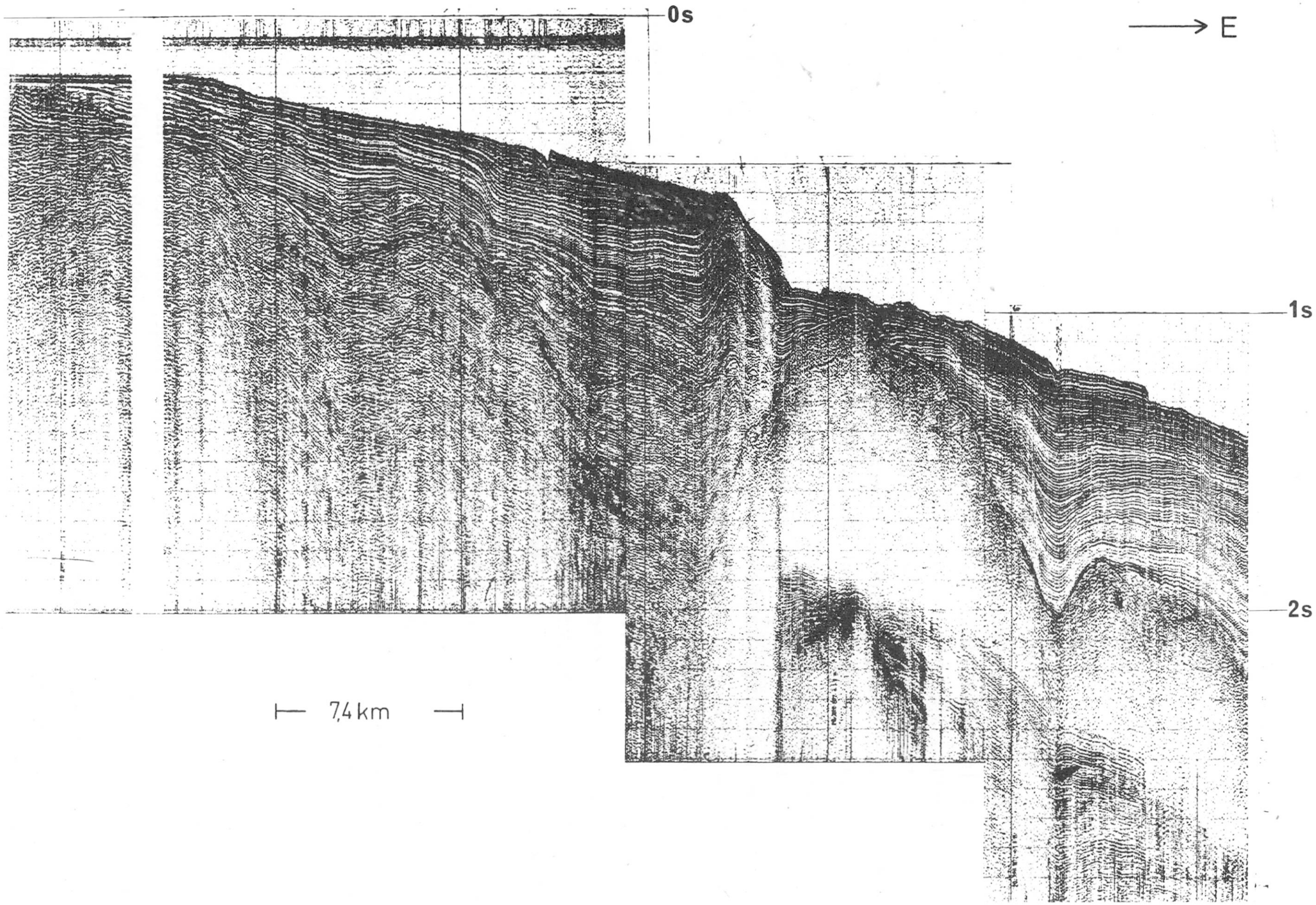

Figure I-6. Seismic profiling record for profile 33, off Mukho.

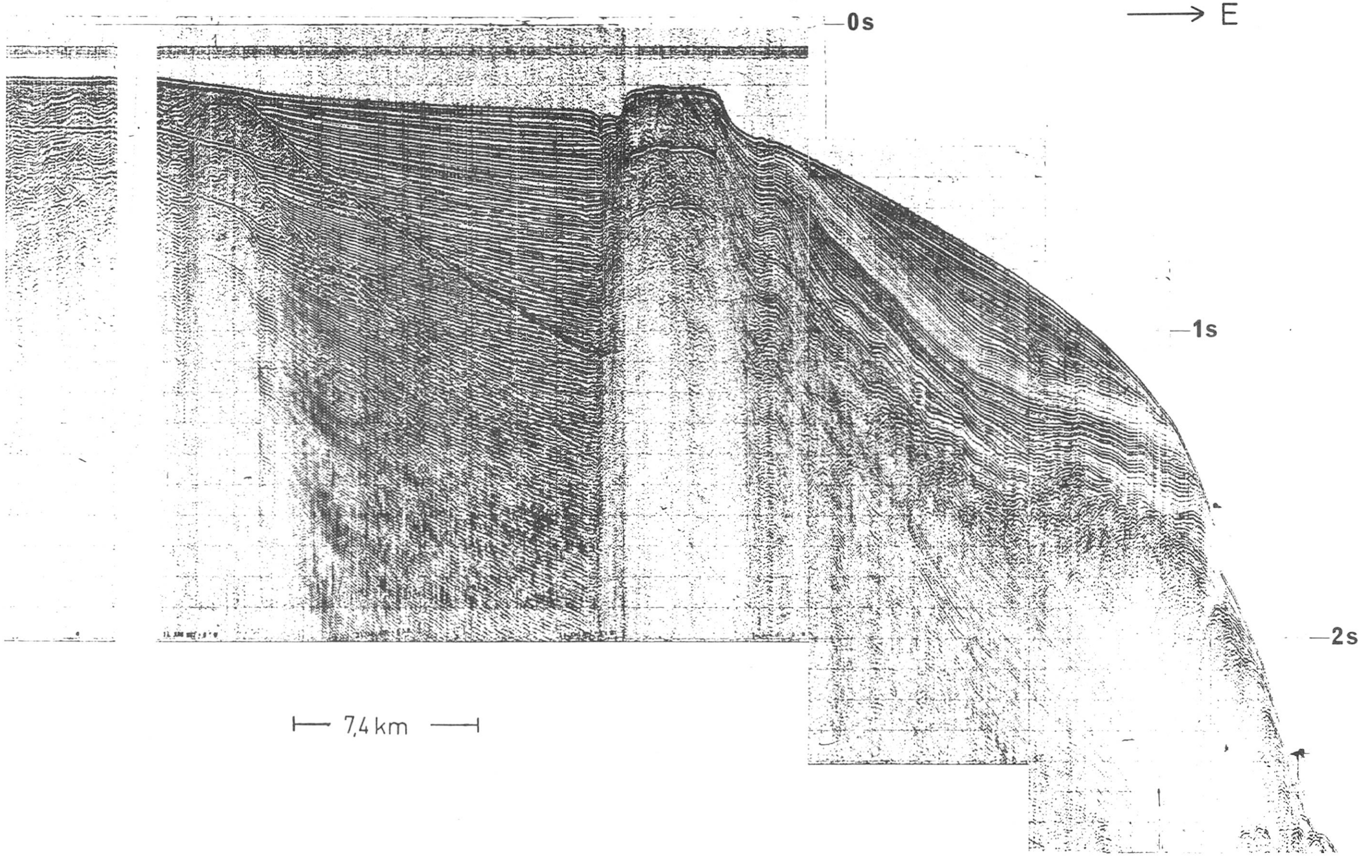

Figure I–7. Seismic profiling record for profile 17, off Pohang.

sedimentary basin (the Pohang Basin) extends parallel to the coast from the seaport of Pohang in the south to offshore from Ulchin in the north (see *Map I–4*).

The upper surface of the acoustic basement (in the north, presumably composed of granites, in the south presumably consolidated older Tertiary sedimentary strata) dip seawards gradually at about 3 or 4 degrees towards the basin centre. In the seismic reflection profiles the surface appears as a strongly marked reflector (*Fig. I–7*). The Pohang Basin is bordered on the east by a steeply rising surface of the acoustic basement, though here the surface is seen as a rather dark but not always clearly identifiable zone. In the outer shelf area there are further horst-like ridges with sediment-filled troughs between them.

Within the Pohang Basin, the acoustic basement appears to represent rocks varying from place to place. Granites and/or metamorphic rocks may be assumed to underlie the Cenozoic basin sediments in the north, as there are no recognizable reflections within the acoustic basement in the seismic records. Also, Precambrian metamorphic rocks and Cretaceous granites are exposed in the adjacent coastal areas. However, in the southern part of the Pohang Basin, weak reflections which are difficult to correlate were recorded from beneath the top of the acoustic basement; this indicates probable older Tertiary strata.

The Pohang Basin is bordered on the east by a ridge which may be traced over a distance of 120 km northwards from the Kuryongpo Peninsula, and which is presumably composed of volcanic rocks, similar to the peninsula. The presumed Cenozoic basin sediments above the acoustic basement appear as successive, partly unconformable reflecting horizons in the airgun recordings, and this layering in the shelf area off Pohang shows the effect of recent tectonic movements.

With a velocity of Vp = 2,000 m/sec assumed for the Cenozoic sediments, a thickness of 850 m was obtained for these in the centre of the Pohang Basin. Indications of the thickness of the underlying older strata at the southern end of the trough could only be obtained in the vicinity of the seismic refraction profiles. Apparently these increase in thickness towards the west and south, reaching their maximum thickness close to the coast (compare profiles 4 and 9 in *Map I–2*).

The greatest sediment thickness in the survey area was found beneath the continental slope east of Ulchin. Here the presumably Cenozoic strata reach a thickness of 2,500 m.

Acoustic basement structure contour map

The results of the seismic reflection survey were compiled as a structure contour map of the upper surface of the acoustic basement, showing depth of the surface below sea level (*Map I–4*). The results, briefly, show that there are two major elongate depressions in the basement surface, now filled with sediments, one offshore between Kangneung and Mukho, the other being the Pohang Basin. The basin infills are presumably Cenozoic in age; east of Kangneung they may be more than 1,400 m in thickness and southeast of Ulchin 850 m. The troughs are separated by a major ridge projecting far to the northeast, which has a thin (50–300 m) sedimentary cover and might well be a continuation of the "Sobaegsan Swell" known on land. Eastward of the shelf basins lies the horst-like ridge which extends north from the Kuryongpo Peninsula, and east of this is the continental slope where the sedimentary cover exceeds 2,500 m.

Tectonic development of the shelf area off Mukho

From the reflection profiles and the sea-bottom morphology, which partly follows the relief of the subsurface acoustic basement ridges (see profiles 27, 28 and 29), conclusions may be drawn about the tectonic development of the shelf off Mukho. Syn-sedimentary tectonic movements, obviously of very young age, led to the formation of mainly north-south trending ridges and basins. The style of the tectonic movements may be visualized in two ways: (i) graben zones may have been formed in the shelf area by subsidence along faults, and then infilled with sediments; or (ii) the present swell areas may have developed as a result of the intrusion of plutonic rocks, resulting in the uplift of the overlying sediments which were subsequently partly eroded. A combination of both concepts is possible.

The arrangement of several horst-like crystalline swells near the mainland, with sediment-filled basins in between, is characteristic of a block-faulted type of shelf as described by Guilcher (1963).

ECONOMIC SIGNIFICANCE

Prospects of economically significant raw materials in the Mukho offshore area

More-consolidated sediments which might be the offshore extension of the coal-bearing Permo-Carboniferous apparently do not exist in the survey area off Mukho. Nor has the general northeasterly strike of the Ogcheon Geosynclinal Zone on the mainland been detected offshore; the seismically observed structures in the shelf area off Mukho strike north or north-northwest. This marked difference in the strike of structures on the mainland and those on the shelf suggests that the seaward continuation of the Ogcheon Zone is restricted to a narrow strip along the coast, an area that could not be surveyed because of the deep draft of the R/V *Tam Yang*. Following this deduction, it may be stated that coal-bearing Palaeozoic rocks would only occur off Mukho in areas close to the coast. The greatly reduced sedimentary section directly offshore from Mukho also suggests that there is no major extension of the coal-bearing rocks onto the shelf. The sediments in the western part of the survey area are a maximum of 250 m thick, in contrast to the up-to-2,800 m-thick Palaeozoic sequence overlying the crystalline basement on the mainland. The coal-bearing Palaeozoic is therefore thought to have been uplifted by intrusion of granite during the Daebo Orogeny (Jurassic), and largely eroded before the Cenozoic sediments were deposited.

As the seismic refraction and reflection records do not indicate Mesozoic or Palaeozoic strata, occurrence of economically interesting anthracite and/or hydrocarbons off Mukho are improbable. Hydrocarbons are particularly unlikely since the Cenozoic strata are thin in this area and lack interesting structures.

Possible hydrocarbon reservoirs in the older Tertiary of the Pohang Basin

Economically important hydrocarbon accumulations within the upper Cenozoic strata in the Pohang Basin are unlikely, because of the generally horizontal stratification and the thinness of the section. Structures exist in the underlying older strata but, according to the drilling on the land, the older Tertiary is probably not more than about 750 m thick even in the southern part of the basin. No conclusions can be reached concerning the occurrence, thickness and distribution of pre-Tertiary strata in this area.

In the southern part of the Pohang Basin, the acoustic basement probably includes the top of the more-consolidated older Tertiary strata. Miocene strata are exposed near Pohang and have been recorded in the literature. These were proved by seismic refraction measurements made by Huntec, Ltd. (1966) offshore within the 100 m isobath. However, this survey has shown that Tertiary strata are overlain unconformably by younger sediments; therefore, the main sedimentation axis has shifted from west to east since the Miocene.

REFERENCES

Beloussov, V. V., and E. M. Ruditch, 1971, Genesis and age of the abyssal depression of the Sea of Japan: *Abstracts of Symposium papers, 10th Pacific Science Congress*, Honolulu, p. 345–356.

Bosum, W., E. G. Kind and J. H. Koo, 1970, Aeromagnetic survey of offshore areas adjoining the Korean Peninsula: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 4, p. 1–21.

Emery, K. O., Y. Hayashi, T. W. C. Hilde, K. Kobayashi, J. H. Koo, C. Y. Meng, H. Niino, J. H. Osterhagen, L. M. Reynolds, J. M. Wageman, C. S. Wang and S. J. Yang, 1969, Geological structure and some water characteristics of the East China Sea and the Yellow Sea: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 2, p. 3–43.

Gabert, G., and R. Virken, 1967, Steinkohlenlagerstätten im Taeback-Gebeit (Südkorea): *Geol. Jahrb.*, vol. 84, p. 463–484.

Geological Survey of Korea, 1967, *An outline of the geology of Korea*: Seoul, 29pp.

———, 1968, Summary report on natural gas exploration in the Pohang area, east coast of Korea: United Nations ECAFE, *Report of the fifth session of CCOP*, Tokyo, 1968, p. 69–71.

———, 1969, Progress on projects of offshore geophysical exploration in the Republic of Korea: United Nations ECAFE, *Report of the sixth session of CCOP*, Bangkok, 1969, p. 80–87.

———, 1970, Geology of islands off the south coast of Korea: United Nations ECAFE, *Report of the seventh session of CCOP*, Saigon, 1970, p. 102.

Gnibidenko, H., and P. Sychev, 1972, Crustal structure and evolution of the Bering, Okhotsk and Japan Seas: *24th Int. Geol. Congr.*, Montreal, sec. 8, p. 43–46.

Guilcher, A., 1963, Continental shelf and slope, *The Sea*, vol. 3, p. 281–311.

Huntec, Ltd., 1968, Report on the offshore geophysical survey in the Pohang area, Republic of Korea: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 1, p. 1–12.

Kaseno, Y., 1972, Geological features of the Japan Sea floor: a review of recent studies: *Pacific Geol.*, vol. 4, p. 91–111.

Kim, O. J., 1970, Geology and tectonics of the mid-central region of South Korea: *Jour. Kor. Inst. Min. Geol.*, vol. 2, no. 4, p. 73–90.

———, 1971, Study on the intrusion epochs of younger granite and their bearing on orogenesis in South Korea: *Jour. Kor. Inst. Min. Geol.*, vol. 4, no. 1, p. 1–10.

———, 1974, Geology and tectonics of southern Korea: United Nations ESCAP, *CCOP Tech. Bull.*, vol. 8 (*this volume*).

Kobayashi, T., 1953, *Geology of South Korea, with special reference to the limestone* *plateau of Kogendo*, University of Tokyo Press, 293pp.

———, 1954, Tectonic development of Korea: *19th Int. Geol. Congr.*, Algèr, sec. 8, fasc. 9, p. 281–291.

Konno, E., 1928, The geological structure of the western marginal region of the Heijo coal field: *Jap. Jour. Geol. Geogr.*, vol. 25, no. 412.

Kovylin, V. M., and E. G. Mirlin, 1971, Crustal structure and tectonics on the southern and southeastern parts of the Sea of Japan (in Russian): *Geotectonika*, vol. 3, p. 95–103.

Lee, S. M., 1972, Metamorphic facies and facies series in relation to tectonics of South Korea: *24th Int. Geol. Congr.*, Montreal, sec. 2, p. 81–87.

———, 1974, The tectonic setting of Korea with relation to plate tectonics: United Nations ESCAP, *CCOP Tech. Bull.*, vol. 8 (*this volume*).

Lee, Y. J., 1966, Geology of the Jeongsum coal field: *Geological report on coal fields of Korea*, no. 6, Geological Survey of Korea, p. 33–66.

Schwind, M., 1967, Das Japanische Inselmeer: *Die Naturlandschaft*, Bd. 1.

Statistisches Bundesamt Wiesbaden, 1972, Allgemeine Statistik des Auslandes, Länderkurzberichte, Süd-Korea: *Kohlhammer Verlag*, Stuttgart, p. 1–33.

Tateiwa, J., 1960, Outline of the geology of Korea: *Int. Geol. Rev.*, vol. 2, p. 1053–1070.

Yasui, M., T. Kishii, T. Watanabe and S. Uyeda, 1968, Heat flow in the Sea of Japan: *The crust and upper mantle of the Pacific Area* (eds. L. Knopoff, C. L. Drake and P. J. Hart), Geophys. Monogr. Ser., no. 12, p. 3–16.

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II. GEOLOGY AND TECTONICS OF SOUTH KOREA

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(with tables II-1 to II-3; and figures II-1 to II-7)

ABSTRACT

South Korea consists of two related Precambrian schist-gneiss units, the Ryongnam and Kyonggi Massifs, separated by the northeast-trending Okchon Geosynclinal Zone of Precambrian to early Mesozoic metamorphic and sedimentary formations. In the southeastern part of the area, the Kyongsang Basin consists mostly of Jurassic-Cretaceous sedimentary and volcanic rocks, and Tertiary sedimentary basins with basalts are found on the east and southwest coasts and offshore islands.

Numerous granitic bodies elongated parallel to the prevailing northeasterly structural trend are intruded into the Precambrian massifs and the Okchon Zone, associated with the Jurassic Daebo Orogeny, and Cretaceous (Bulkusa) granites are scattered throughout the Kyongsang Basin. Two periods of metamorphism and igneous intrusion are represented in the Precambrian by granite gneisses, and other tectonic and/or igneous activity is recognized in the Palaeozoic, the Triassic and the Tertiary. Structures are associated with each major tectonic episode, and most follow the northeasterly (Sinian) trend except for those in the northern part of the area where trends are north-northeasterly.

Metallogenic epochs occurred during the Precambrian, Palaeozoic, Jurassic to early Cretaceous, and late Cretaceous to early Tertiary, and appear to have coincided with orogenic and igneous activity. Minerals of the latter two epochs include gold, silver, lead, zinc, copper, molybdenum, tungsten and magnetite, with also some tin, fluorite and nickel in the Jurassic-Cretaceous period. Mineralization occurred mainly in zones parallel to the prevailing tectonic trends, except in the Kyongsang Basin.

Plate tectonic explanations of the geological and tectonic development of South Korea have been made, but these are speculative as there is at present insufficient knowledge on the various tectonic units and their relationships.

INTRODUCTION

During the last few years, several articles devoted to plate tectonics and the interpretation of geological features and tectonics of the Korean Peninsula have appeared in the Korean geological literature. However, application of plate tectonic theory to Korean geology and tectonics is at present entirely in a state of speculation, because as yet no systematic studies have been made of the problem; hence, there is no undisputed evidence supporting such an application. Therefore, the writer intends in this paper to summarize very briefly the geology, tectonics, and some aspects of metallogeny, and then to offer some remarks which may or may not assist solution of the basic problems of plate tectonics.

GEOLOGICAL SEQUENCE

The geology of South Korea is relatively well understood, except for the stratigraphy of the Precambrian, which is still being studied in a reconnaissance fashion.

Cheong (1956) summarized the geological sequences of Korea from data available in the writings of many earlier geologists and revised it slightly in 1970. The sequences thus assimilated have been taken as standards, and were generally accepted until very recently, apart from the Precambrian and other minor items. The present writer has been working on Precambrian stratigraphy and Mesozoic granites (formerly known in Korea as Younger Granites); this work has established Precambrian stratigraphy on a sounder basis and has also differentiated the Younger Granites into Jurassic and Cretaceous, whereas previously these were all considered to be Cretaceous in age.

It must also be mentioned that the "Granite Gneiss System" cited by Cheong was not differentiated and was misused by previous geologists as a general term to include the granite gneisses known as "Kokurian Granites" and the majority of paragneisses and schists, all of which are of Precambrian age. Recently, two granite gneisses of middle and late Precambrian age have been identified and many Precambrian schist formations have been differentiated which were previously thought to be granite gneiss. These facts formed the basis of establishment of a rough Precambrian stratigraphy.

For reference, the geological sequence of South Korea which was summarized by Cheong and the one supplemented by the present writer are tabulated in *Table II–1*.

The most controversial problem among geological sequences of South Korea has concerned the Okchon System since the mid-1950s. The system originally was thought to be Precambrian (Nakamura, 1923), but later was considered by many workers to be metamorphosed Palaeozoic and/or Mesozoic formations, so Cheong did not even mention the system in the table. Kobayashi (1953) stated that the system was metamorphosed late Palaeozoic to early Mesozoic, so did Son, but he has modified his interpretation several times. This writer (1968) concluded that the Okchon System was Precambrian as originally proposed, but that sequence of the system was reversed compared to that given in previous works; this conclusion was supported by Reedman *et al.* (1973).

TECTONICS AND GEOLOGICAL SETTINGS

The tectonics of South Korea have been described by Kobayashi (1953), with later revisions by the present writer (1970).

To the north, the Chungaryong Rift Valley, which trends north-northeastward, forms a geological connection to North Korea. South Korea is characterized by northeast-

Table II-1. Generalized geological sequence in South Korea.

Age		C.H.Cheong (1956, 1970)			O.J.Kim (1973)				
Age		System	Series		System	Series			
Cenozoic		Quaternary			Quaternary	basalts			
		Tertiary	Yonil		Tertiary	Yonil			
			Janggi			Janggi	granites (Bulkuksa granites)		
Mesozoic	Cretaceous	Kyongsang	Bulkuksa (granite & porphyry) intrusion		Kyongsang	volcanic rocks			
			Silla			Silla			
			Naktong	granites		Naktong	granites (Taebo granites)		
	Jurassic	Daedong	Ryukyong	(in N.Korea)	Daedong	undifferentiated in S.Korea			
			Sonhyon				granite ?		
	Triassic	Pyongan	Nokam		Pyongan	Nokam			
Palaeozoic	Permian		Kobangsan			Kobangsan			
	Carboniferous		Sadong			Sadong			
			Hongjom			Hongjom	granite?		
	Devonian		Chonsongri ?			(hiatus)			
	Silurian								
	Ordovician	Chosun	Great Limestone		Chosun	Great Limestone			
	Cambrian		Yangduk			Yangduk	granite?		
Precambrian	Proterozoic	Sangwon	Kuhyon	(in N.Korea)	Okchon	Kunjasan			Late-Precambrian
			Sadangwu			Hwanggangri			
			Jikhyon			Changri			
						Munjuri			
						Hyangsanri			
						Kemyongsan	granite gneiss		
		granite gneiss			Yulri	Taebaeksan			
	Archeozoic					Kosonri	Chunchon	Chunsong	Middle-Precambrian
						Kakhwasa		Jangraksan	
						granite gneiss			
		Yonchon			Ryongnam	Wonnam	Yonchon	Yangpyong	Early-Precambrian
						Kisong		Sihung	
						Pyonghae		Puchon	

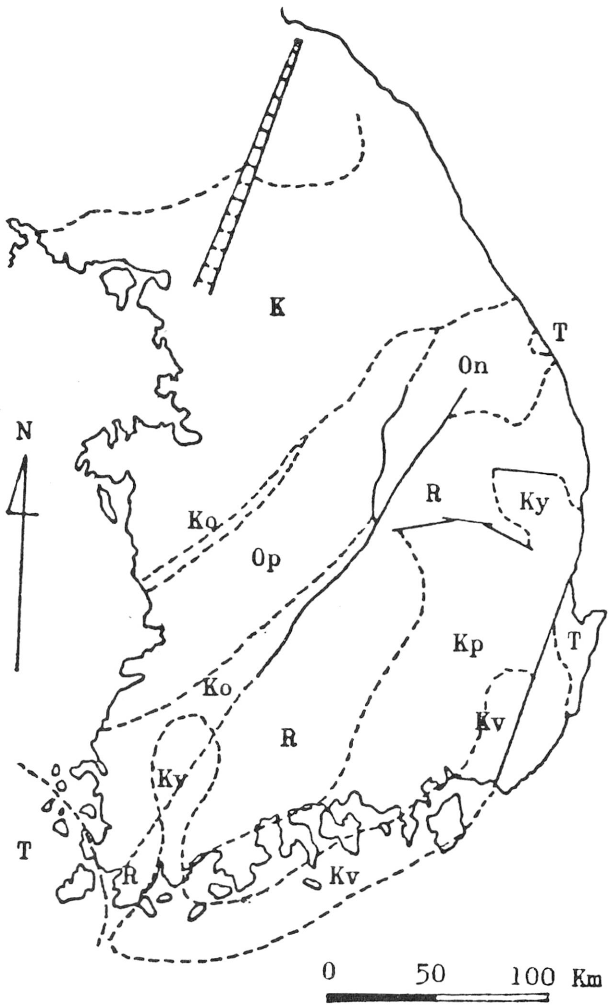
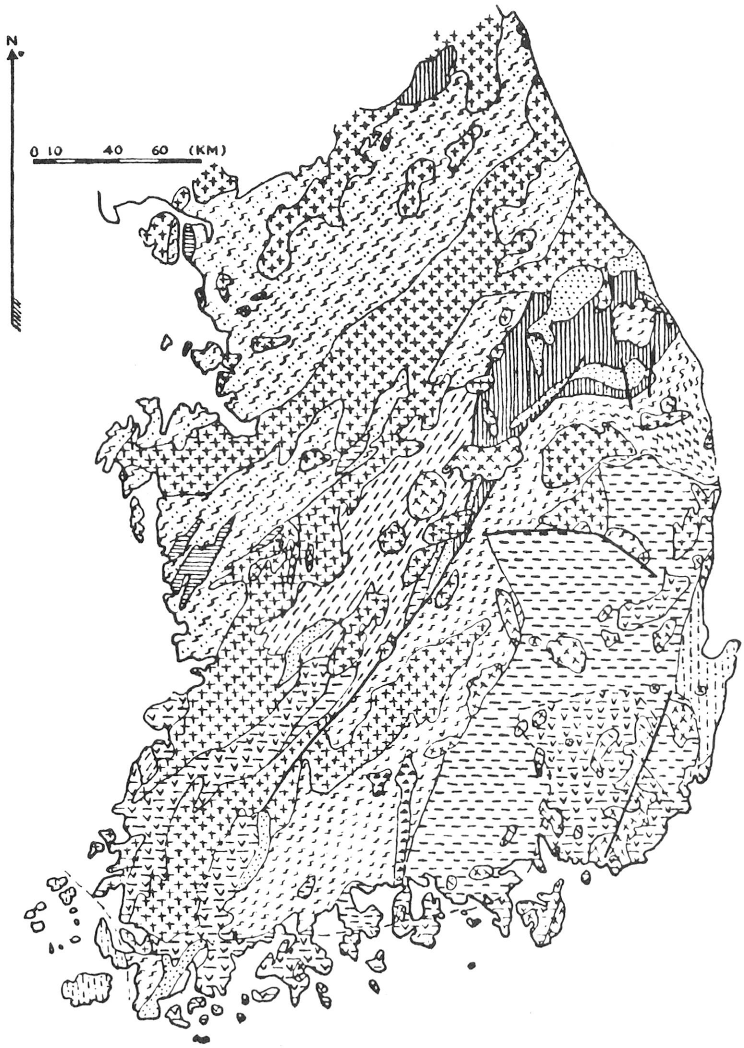


Figure II–1. Geological provinces and subdivisions of South Korea. 1. Kyonggi-Ryongnam Province: Kyonggi Massif (K) and Ryongnam Massif (R). 2. Okchon Geosynclinal Province: Okchon Palaeogeosynclinal Zone (Op) and Okchon Neogeosynclinal Zone (On). 3. Kyongsang Basin Province: Kyongsang Basin proper (Kp), Yongyang Basin (Ky), Kyongsang Volcanic Zone (Kv) and Kyongsang Trough in the Okchon Zone (Ko). 4. Tertiary Basins (T).

southwest structural trends, the Sinian trend. The Kyonggi and Ryongnam Massifs are oriented in this direction, lying northwest and southeast respectively of the Okchon Geosynclinal Zone. To the southeast of the Ryongnam Massif lies the Kyongsang Basin which connects to the southwestern parts of the Okchon Zone around the southwestern tip of the Korean Peninsula.

Both the Kyonggi and the Ryongnam Massifs are composed of Precambrian formations, and the Okchon Zone is composed of Precambrian to Mesozoic formations. South



Cenozoic — Tertiary

Mesozoic
- Cretaceous: Bulkuksa granites; Kyongsang volcanic rocks; Kyongsang system
- Jurassic: Daebo granites; Daedong system

Paleozoic: Pyongan system; Chosun system

Precambrian: Basic Rock, unknown age; Okchon system; Yonchon system, its associated schists and granite gneisses.; Ryongnam system, its associated schists and granite gneisses.

Figure II-2. Geological map of South Korea.

Korea can thus be divided into four geological provinces, the geological characteristics of which are summarized below:

Provinces	Geological characteristics
1. Kyonggi-Ryongnam Province	Precambrian systems and Jurassic granites
2. Okchon Geosynclinal Province:	
Okchon Neogeosynclinal Zone	Palaeozoic to Mesozoic formations and Jurassic granites
Okchon Palaeogeosynclinal Zone	Precambrian Okchon System, Jurassic and Cretaceous granites
3. Kyongsang Basin Province:	
Kyongsang Basin proper	Cretaceous formations, granites and volcanic rocks
Yongyang Basin	Cretaceous formations, granites and volcanic rocks
Volcanic Zone	Cretaceous volcanic rocks
4. Tertiary Province	Tertiary formations and volcanic rocks

Kyonggi-Ryongnam Province

This province was previously separated into Kyonggi and Ryongnam Lands, the former correlated to Shantung Land and the latter to Fukien Land in China. However, in Korea it is desirable to group them together because: (a) the Kyonggi and Ryongnam Massifs are located respectively northwest and southeast of the Okchon Geosynclinal Zone; (b) the geology and structure of these massifs are similar to each other and can be correlated roughly; and (c) the province as a whole acted as a basement for the Okchon Geosyncline. In the northern half of the province (the Kyonggi Massif), the Yonchon System, composed of Precambrian schists, is found in the northwestern part of the province and its schistosity has a north-northeasterly strike. The Jangrak and Chungsong Groups, which comprise the Chunchon System of mid to late Precambrian age, unconformably overlie the Yonchon System in a small area in the north-central part of the province. The geological sequence of the Kyonggi Massif is shown below:

Precambrian	mid to late	Chunchon System	~~~ granite gneiss
			Chungsong Group
			~~
			Jangrak Group
			~~ granite gneiss
	early	Yonchon System	Yangpyong Complex
			Shihung Complex
			Puchon Complex

In the southern half of the province (the Ryongnam Massif), the Ryongnam System and the unconformably overlying Yulri System were established as shown below:

Precambrian	late	Yulri System	~~~~ granite gneiss
			Taebaeksan Series
			Kosonri Series
			Kakwhasa Series
			~~ granite gneiss
	early	Ryongnam System	Wonnam Series
			Kisong Series
			Pyonghae Series

Granite gneisses of both post-Ryongnam and post-Yulri ages were detected. The Yongchon System and accompanying schists in the Kyonggi area are roughly correlated to the Ryongnam and Yulri Systems of the Ryongnam area, and their ages range from 1,100 to 2,900 m.y. The controversial Okchon System is probably later than these systems in age, but the lower part of the Okchon System probably could be correlated with the top of Yurli System. Jurassic granites are predominant in both the Kyonggi and Ryongnam areas, whereas Cretaceous (Bulkuksa) granites appear in only a few localities as small stocks.

Okchon Geosynclinal Province

Kobayashi (1953) divided the Okchon Geosynclinal Zone into metamorphosed and non-metamorphosed zones. These zones originally consisted of the same sedimentary formations, being metamorphosed in the southwestern part but remaining unmetamorphosed in the northeastern part, so that the boundary between them must be gradational. This writer (1969) has clearly demonstrated that the boundary between them was upthrust and shear faulted, the metamorphosed part being thrust over the non-metamorphosed part. The so-called metamorphosed part consists of Okchon System rocks, of Precambrian age, and the so-called non-metamorphosed part of sedimentary formations of Palaeozoic to Cretaceous age. The differences of geology and structure in both areas are due to the fact that the Okchon Geosyncline migrated or was shifted, and was affected by successive orogenies from time to time so as to show different sediments and tectonic relations. Thus the writer designates the so-called metamorphosed part the "Palaeogeosynclinal Zone" and the so-called non-metamorphosed part the "Neogeosynclinal Zone."

The Palaeogeosynclinal Zone is composed mainly of the Okchon System, various schists of Precambrian age, accompanied by the Permian Pyongan System and Cretaceous Kyongsang System in a few separated localities. The first two systems are intruded by Jurassic granites and associated plutons which are aligned parallel to the trend of the Okchon Geosyncline axis. The Cretaceous granites also intruded the zone in border areas. The Hwanggangri Series, an upper member of the Okchon System, is composed of pebble-bearing phyllitic to slaty rock interstratified locally with a few thin layers of limestone. The pebbles are composed of many varieties of rock fragments but mainly granite-gneiss, quartzite, limestone and phyllite, and in rare occurrences, granite. The scattering of various sizes of pebble in a fine-grained matrix is suggestive of tillite deposits; this idea was supported by Reedman *et al.* (1973), although many geologists still believe the Hwanggangri Series to be of post-Chosun age (post-Ordovician).

The Okchon System in the Okchon Palaeogeosynclinal Zone trends northeasterly parallel to the general trend of the geosyncline and is isoclinally folded and thrust so as to repeat the same sequences several times. These structural features were developed in Daebo Orogeny of the Jurassic period.

The Neogeosynclinal Zone forms northeastern parts of the Okchon Geosynclinal Zone and is mostly composed of limestones of the Chosun System (Cambro-Ordovician), and terrestrial sediments of the Pyongan System (Late Carboniferous to Triassic age); but in a few narrow strips there are also terrestrial sediments of the Daedong (Jurassic) and Kyungsang (Cretaceous) Systems. Granite and granodiorite stocks of Jurassic and Cretaceous age are found in a few scattered places. Sedimentary formations in the area are not metamorphosed; and it must be mentioned that all limestone for cement manufacture and other uses, with one exception, and over 80 percent of the anthracite coal produced in the Republic of Korea come from this area.

Precambrian systems described above can be correlated as shown in *Table II-2*.

Kyongsang Basin Province

This province is located in the southeastern part of the Korean Peninsula. The geology of the province is composed of the Naktong and Silla Series, both of which are of Cretaceous age and believed to be terrestrial sediments. Both series consist of sandstones, shales, conglomerates and red beds, but thin cherty layers are intercalated in a black slate bed in the upper part of Silla Series which the writer believes to be of marine origin. Volcanic rocks of

Table II-2. Correlation chart of Precambrian systems in South Korea.

age \ area	Kyonggi massif		Okchon palaeogeosynclinal zone		Ryongnam massif	
Late Precambrian	Sangwon system (in North Korea)		Okchon system	Kunjasan Hwanggangri Changri Munjuri Hyangsanri ?		
Mid to Late Precambrian	Chunchon system	granite gneiss Chungsung group Jangraksan group		Kemyongsan	Yulri system	granite gneiss Taebaeksan Kosonri Kakhwasa
Early Precambrian	Yonchon system	granite gneiss Yangpyong complex Shihung complex Puchon complex			Ryongnam system	granite gneiss Wonnam Kisong Pyonghae

andesite and rhyolite are predominant at the upper horizons of the Silla Series. Granites and masanites of Cretaceous age are scattered as stocks in many places in the basin without disturbing the adjacent sedimentary formations except for induration.

The Kyongsang Basin proper and the Yongyang Basin (the northeastern part of the Kyongsang Basin) are separated by a narrow belt of schists and gneisses, but sedimentary formations are connected to each other in an area having a width of only a few kilometers. Cretaceous volcanic rocks are distributed in a wide belt in the middle of the basin and in the southwestern part of the Okchon Geosynclinal Zone. The structure of the province is rather simple, showing a north-northeasterly strike, and gentle homoclinal and southeasterly dip, although gentle folds are observed in a few localities.

Tertiary Province

Tertiary sediments are found in three places in South Korea: on the central east coast (Samchok), in the southeastern coastal area (Ulsan-Pohang area), and in archipelagos in the southwestern part of the peninsula. The former two occurrences are definitely of Tertiary age, but the latter is still uncertain, although this writer believes it to be Palaeogene.

The lower Janggi Series is generally a terrestrial deposit and is composed of conglomerate, shale, mudstone and sandstone intercalated by a few thin lignite coal seems and basalt and rhyolite flows. The upper Yonil Series is a marine deposit and is composed of shale, mudstone, sandstone and conglomerate. Both series are believed to be of Miocene age.

Structure is rather simple and characterized by a shallow dip. However, in the lower series, tight folds are observed in some places. This led to the idea that folding took place after deposition of the Janggi Series but before deposition of the Yonil Series. The structural relationship between the Janggi and Yonil Series is believed to be unconformable.

GEOLOGICAL STRUCTURE

There were two periods of deformation and metamorphism which affected the Precambrian of the Kyonggi and Ryongnam Massifs: (i) the post-Yonchon/Ryongnam period, and (ii) the post-Chunchon/Yulri period. There are also movements younger than the Sangwon and Okchon Systems (Sinian), but their exact nature is still uncertain. Thus, the geological structure of the Precambrian massifs is grouped together as pre-Triassic in age, because structural breaks are known definitely to have occurred in Korea in the Triassic as well as in Jurassic-early Cretaceous and late Cretaceous times. The geological structure of the region is shown in *Figure II-3*.

Pre-Triassic deformation

In the Kyonggi Massif NNE-SSW foliation trends prevail in the Yonchon and Chunchon Systems although some diversity exists. Paralleling this direction there are one major rift valley and four fault-line valleys in the area, shown in *Figure II-3*; these features characterize the physiography of the north-central parts of South Korea. Pleistocene basalt flows were extruded along the Chugaryong Rift Valley. Along other faults the Jurassic Daebo granites were intruded into Precambrian formations, and some Cretaceous sedimentary

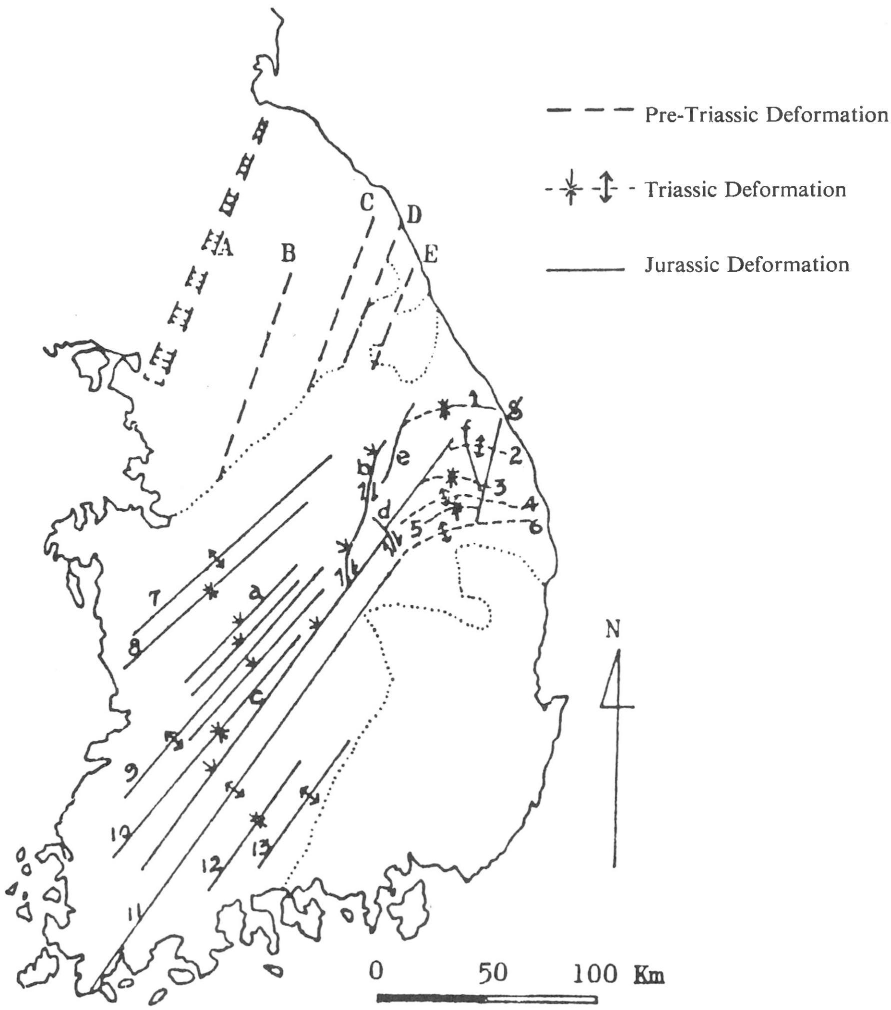


Figure II–3. Pre-Tertiary structural features of South Korea. **Pre-Triassic Deformation** A. Chungaryong Rift B. Kyonggang Fault C. Inje Fault D. Hyonri Fault E. Changchon Fault. **Triassic Deformation** 1. Jongson Syncline 2. Jungbongsan Anticline 3. Hambaek Syncline 4. Sobaeksan Anticline 5. Yulri Syncline 6. Andong Anticline. **Jurassic-early Cretaceous Deformation** 7. Charyong Anticline 8. Kongju Syncline 9. Okchon Anticline 10. Yongdong Syncline 11. Dukyusan Anticline 12. Kure Syncline 13. Jirisan Anticline a. Okchon Thrust b. Hwanggangri Thrust c. Jomchon Thrust d. Danyang Fault e. Pyongchang Fault f. Samchok Fault g. Osipchon Fault.

and/or volcanic rocks also crop out in the area. It is known conclusively that these faults were cut by the Jurassic Daebo granites at the southeastern end, and differ in direction from Triassic and Jurassic deformation trends.

In the Ryongnam Massif, the foliation in Precambrian systems is diverse, but mostly shows an east-northeast trend which is cut by both Triassic and Jurassic deformational lineaments.

Triassic deformation (Songrim Disturbance)

In the Okchon Neogeosynclinal Zone in the east-central region of southern Korea, Palaeozoic and Triassic sedimentary formations are folded and the axes of the folds trend west-northwesterly. The deformation was caused by the Songrim Disturbance at the end of the Triassic period. Jurassic deposits, however, have not been affected by this deformational movement. The western ends of the folds are bent in the Sinian direction of Jurassic structures. The northeastern part of the Ryongnam Massif also reveals west-northwest foliation trends, but it is uncertain whether this foliation is contemporaneous although it has been grouped in the Triassic deformation in *Figure II-3*.

Jurassic deformation (Daebo Orogeny)

Jurassic deformation, known as the Daebo Orogeny, continued from early Jurassic to early Cretaceous (as shown by radiometric dating of the Daebo granites). This orogeny was the most intensive in Korea and all previous formations in the Okchon Geosynclinal Zone were severely folded and faulted. The nature of the Daebo Orogeny is shown by two sets of data, the distribution of the Jurassic Daedong System sedimentary formations and the alignment of the Daebo granites.

Daedong sedimentary rocks are scattered both in the Okchon Palaeogeosynclinal and Neogeosynclinal Zones, and are aligned in a northeast-southwest direction, whereas the Cretaceous Kyongsang sedimentary formations in these zones are aligned and deformed in different directions. The trend of the Daebo granites is also northeast-southwest, parallel to the axis of the Okchon Geosynclinal Zone. These granites are regarded as syntectonic, and their ages range from early Jurassic to early Cretaceous. Thus, the age of tectonic activity in the area is definitely of early Jurassic to early Cretaceous age, and in connexion with this it must be mentioned that Daebo granites were considered to be late Cretaceous in age and so described in all previous papers before about 1968.

Foliation of the Okchon System strikes northeasterly (the Sinian direction), coincides with the axis of the Okchon Geosynclinal Zone, and mostly dips to the northwest. There are mostly overturned isoclinal folds in which at least three overthrusts are apparent. Consequently the same formations appear repeatedly in narrow strips in the Okchon Zone.

As shown in *Figure II-3*, four anticlinoria and three synclinoria run alternately from the southern border of the Kyonggi Massif to the Ryongnam Massif through the Okchon Zone. The Okchon Thrusts are in the Okchon Zone, the Hwanggangri Thrust (combination of upthrusts and shear faults) bounds the Okchon Palaeogeosynclinal and Neogeosynclinal Zones, and the Jomchon Thrust joining the Hwanggangri Thrust separates the Okchon Zone from the Ryongnam Massif to the southeast. These anticlinoria constitute major mountain ranges, and younger deposits of Jurassic and Cretaceous age are found in a few isolated locations in the synclinorium areas. As already mentioned, the western ends of Triassic deformation swing towards the Sinian direction, which means that Triassic deformation was modified by the Jurassic Daebo Orogeny. All major structures are shown in *Figure II-3*, classified by age and manner of formation.

GRANITES: AGES AND RELATION TO OROGENESIS

As mentioned in the preceding section, four sets of granitic intrusions have been recognized in South Korea, that is, two in the Precambrian, the Daebo granites in the Jurassic and the Bulkuksa granites in the Cretaceous. These granites are closely associated with the major orogenies which have affected the peninsula. Intrusion of mid-Precambrian granites took place during a disturbance after the formation of the Yonchon and Ryongnam Systems, and early late-Precambrian granites were intruded the Taebaek Orogeny after the Yulri and Chunchon Systems were formed. Granite intrusion accompanied the Jurassic Daebo Orogeny, and intruded the core of the Okchon fold-belt and into the Ryongnam and Kyonggi Massifs.

The Daebo Orogeny, the greatest tectonic disturbance in Korea, took place during the Jurassic and probably continued into early Cretaceous. All pre-Kyongsang formations were deformed such that the schistosity and fold axes of the Okchon System and pre-Kyongsang formations in southwestern parts of the Okchong Neogeosynclinal Zone were realigned in a northeast-southwest direction parallel to the trend of the Okchon Geosynclinal Zone. The uplift of the Okchon Zone and the Ryongnam and Kyonggi Massifs resulted in depression of the adjacent southeastern parts, thus forming the Kyongsang Basin, and small inter-mountain basins formed within the massifs themselves.

At the end of the Cretaceous, after the deposition of the Kyongsang System in the Kyongsang Basin and the intermountain basins, andesitic volcanic rocks were extruded in an early igneous phase. Small stocks of granite and associated acidic rocks were intruded into the Kyongsang Basin in a later phase of igneous activity, as well as in the adjacent part of the Okchon Basin, without any pronounced deformation. This mode occurrence is a characteristic feature of the Cretaceous granite. This disturbance is named the Bulkuksa Disturbance and the granite intrusion probably continued into the early Tertiary, but no age of granite younger than Cretaceous has been determined so far.

It is natural to deduce that more granites of different ages are present in Korea, if the assumption is valid that granite intrusion accompanies orogenesis and tectonic disturbance. Granite of the post-Sangwon and pre-Chosun period has been described in North Korea, but no data are available in South Korea so far. A lack of formations between late Ordovician and early Carboniferous in Korea was thought to be due to eustatic uplift of the land during that period, so that the relationship between the Great Limestone Series and the overlying Hongjom Series, a base member of the Pyongan System, was believed to be a disconformity (parallel unconformity). However, this is not valid, as an angular unconformity between them has been described in many places. Thus it may be expected that granite representing this time gap might exist. Unfortunately it has not yet been discovered in South Korea, though such a granite was recently reported in North Korea. There was minor tectonic activity, following the formation of the late Triassic Nokam Series, the uppermost formation of the Pyongan System and prior to overlying the Daedong System. This was previously named the Songrim Disturbance. Granite representing this age is also expected, but has not been discovered so far.

As for the Tertiary System, the Janggi Series has been deformed and has associated basaltic and rhyolitic rocks, whereas the Yonil Series has not. This is suggestive of the occurrence of a minor disturbance in Miocene time, which is called the Yonil Disturbance. There is, however, no direct evidence for Tertiary granite, but it was recently discovered that mineralization had affected Tertiary sediments. Consequently it is expected that granite of Miocene age might exist.

As described very briefly above, the granite problem in regard to age and relationship to orogenesis is, thus far, ambiguous in most cases. Further insight into the problem must await completion of more intensive study on the granites.

METALLOGENIC EPOCHS AND PROVINCES

Genesis of mineral deposits associated with igneous rocks is naturally related to igneous activity accompanying orogenesis and other tectonic disturbances. These events were fully discussed in the preceding section, and the results are tabulated in *Table II-3*. Both metallic and non-metallic minerals were formed in these epochs, and in this paper the formation of both is included within the term metallogenesis.

Metallogenic epochs may coincide with periods of syntectonic or subsequent igneous activity accompanying orogenies and other tectonic disturbances. However, as indicated by *Table II-3*, there are thought to be igneous intrusions associated with certain disturbances which have not yet been discovered, since a study on granites as well as age determination have not been dully completed in Korea. Thus far, metallogenic epochs that have certainly occurred in Korea are: (i) Precambrian, (ii) Palaeozoic, (iii) Jurassic to early Cretaceous, and (iv) late Cretaceous to early Tertiary.

The majority of hydrothermal deposits are embedded in Precambrian schists and gneisses and in younger sedimentary formations up to the Kyongsang formation. Nearly all contact replacement deposits are occurred in limestone layers in Precambrian formations

Table II–3. Tectonic events and associated igneous activity in South Korea

Tectonic event	Date	Granitic rocks	Associated Volcanics
Yonil Disturbance	mid-Tertiary	unknown	basalt, rhyolite
Bulkuksa Disturbance	late Cretaceous-early Tertiary	Bulkuksa granites	rhyolite, andesite
Daebo Orogeny	Jurassic-early Cretaceous	Daebo granites	hornblendite
Songrim Disturbance	late Triassic	unknown	unknown
Post-Chosun Disturbance	late Ordovician-early Carboniferous	unknown	unknown
Post-Sangwon Disturbance	end of Precambrian	unknown	unknown
Taebaek-Chunsong Disturbance	early-late Precambrian	granite gneisses	amphibolite (?)
Ryongnam-Kyonggi Orogeny	middle Precambrian	granite gneisses	serpentine (?)

and in the Great Limestone Series of Cambro-Ordovician age. In spite of the wide range of occurrence, no detailed study on these mineral deposits has been able to differentiate them into their metallogenic epochs; hence, it is impossible at this time to discriminate a Precambrian epoch from a Jurassic one in Korea. Thus, most of the mineral deposits of the kinds mentioned above are classified into metallogenic epochs of Jurassic to early Cretaceous age, except for one which can definitely be identified as a Precambrian epoch. Thus, the spatial distribution of mineral deposits of Jurassic to early Cretaceous age is widespread all over Korea, with the exception of the Kyongsang Basin.

Mineral deposits belonging to late Cretaceous to early Tertiary age are usually of mesothermal to epithermal fissure-filling vein types and occur in the Kyongsang Basin and partly in the Okchon Geosynclinal Zone where some of the Bulkuksa granites outcrop.

Minerals which belong to the Precambrian mineralization epochs are asbestos, talc, scheelite, hematite and graphite. Asbestos and talc are associated with Precambrian serpentines, and scheelite with Precambrian amphibolite; to which epoch they relate is uncertain, although they are grouped into the Precambrian epoch. Graphite occurs in graphite schist formations and hematite in quartzite beds of Precambrian age. Beds of hematite are known to occur in the Dongjom Quartzite of early Ordovician age, and at the base of the Hongjom Series of late Carboniferous age. Beds of limonite are known to occur in the Sadong Formation of Permian age. These together constitute a Palaeozoic metallogenic epoch. Major mineral commodities that are associated with the Jurassic to early Cretaceous metallogenic epoch are gold, silver, lead, zinc, molybdenum, tungsten, tin, iron (magnetite), fluorite and manganese, although the metallogenic epochs of some fluorite and magnetite occurrences are uncertain.

The minerals formed during the late Cretaceous to early Tertiary metallogenic epoch are identical with those associated with the Jurassic epoch, except that copper and pyrophyllite are prominent, whereas fluorite and tin are entirely or nearly lacking in this epoch. The mineral deposits of this epoch are of the fissure-filling vein type in the upper Silla Series of the Kyongsang sedimentary and andesitic rocks.

In general, both the abundance and scarcity of mineral commodities are well reflected by the geology of Korea. Abundance of gold, silver, molybdenum, tungsten and fluorite results from a predominance of granitic rocks and gneisses. Scarcity of chromite, nickel and cobalt is due to a lack of basic to ultrabasic intrusions. Sedimentary formations of post-Ordovician age are mostly terrigenous deposits, with the result that no petroleum or natural gas deposits have so far been found, except that oil prospecting is currently under way on the continental shelf.

Metallogenic epochs and accompanied mineral commodities are tabulated as follows:

Metallogenic epoch	**Mineral commodities**
Precambrian epoch	hematite
	graphite
	talc, asbestos
	scheelite
Palaeozoic epoch	hematite
	limonite

Jurassic-early Cretaceous epoch	gold, silver
	lead, zinc
	molybdenum, tungsten, tin
	magnetite
	fluorite
	manganese
	nickel
Late Cretaceous-early Tertiary epoch	gold, silver
	lead, zinc
	copper
	tungsten, molybdenum
	magnetite
	pyrophyllite
Unknown epoch	kaolin

Figure II–4. Jurassic to early Cretaceous metallogenic provinces: **gold-silver**. 1. Pochon 2. Hongchon 3. Haemi 4. Chonan 5. Hwaamri 6. Chunyang 7. Solchon 8. Hapchon 9. Sunchon 10. Kwangyang.

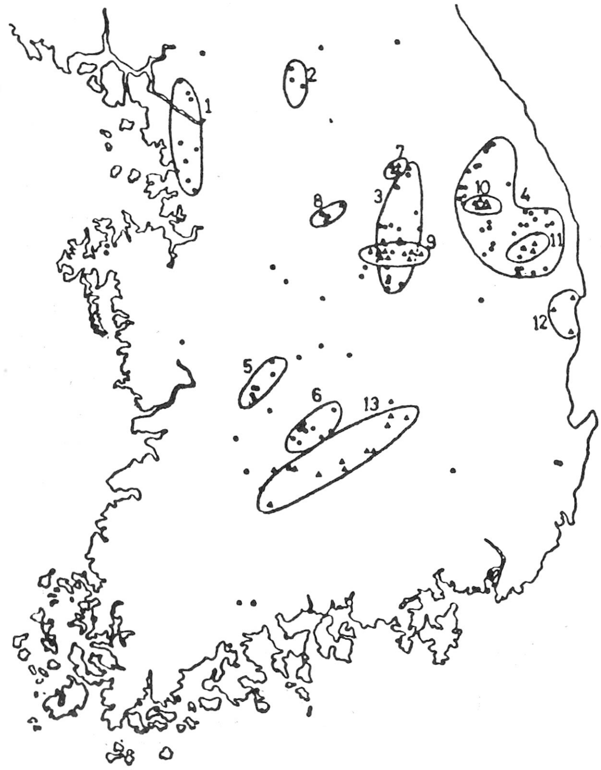


Figure II–5. Jurassic to early Cretaceous metallogenic provinces: lead-zinc (closed circle) and tungsten-molybdenum-tin (triangle). **lead-zinc** 1. Shihung 2. Kapyong 3. Hwanggangri 4. Taebaeksan 5. Kumsan 6. Muju. **tungsten-molybdenum-tin** 7. Junchon 8. Daehwa 9. Danyang 10. Sangdong 11. Ulchin 12. Pyonghae 13. Kochang.

Of 952 mineral deposits studied in South Korea, 40 were definitely of sedimentary origin, of which 12 were Precambrian hematite-magnetite deposits, 17 were Palaeozoic hematite and limonite deposits, and 11 were Precambrian graphite deposits; most of these deposits had been deformed and/or metamorphosed.

Most of the deposits were closely located within areal limits and along certain trends. Of these metallogenic provinces, the two most common types were of Jurassic to early Cretaceous and late Cretaceous to early Tertiary ages, respectively, and their characteristics are briefly described below.

Jurassic to early Cretaceous Metallogenic Provinces

The majority of mineral deposits of various kinds in South Korea are associated with the Daebo granites of Jurassic to early Cretaceous age. In general, the deposits are emplaced in the granites as well as in the surrounding Precambrian schists and para-gneisses, and are aligned parallel to the northeasterly Sinian trend as shown in *Figures II–4* and *II–5*.

Figure II–6. Late Cretaceous to early Tertiary metallogenic provinces: copper (closed circle) and tungsten-molybdenum (triangle). **copper** 1. Jungwon 2. Kyongnam 3. Ilkwang. **tungsten-molybdenum** 4. Yonil.

Late Cretaceous to early Tertiary Metallogenic Provinces

With few exceptions, metallogenic provinces of late Cretaceous to early Tertiary age are restricted in distribution to the Kyongsang Basin, which consists exclusively of Cretaceous sedimentary, volcanic and plutonic rocks. Mineral deposits in the area show no definite trends, but occur rather irregularly, as shown in *Figures II–6* and *II–7*. These deposits are mainly mesothermal to epithermal vein types. Occurrence of deposits are also limited to fissures and cracks in either andesitic rocks or black, indurated slate of the upper member of the Silla Series, both of which are late Cretaceous age. Thus, from this viewpoint, it is evident that lithological control is subordinate to structural control in the basin area. One of the few exceptions mentioned above is probably the Jungwon area where late Cretaceous granite crops out, and copper and magnetite deposits are known to occur as shown in *Figure II–6*.

As shown in *Figures II–6* and *II–7*, a rough alignment of mineral zones can be deduced. Copper deposits occur in the southernmost part of the area, and lead-zinc deposits occur in the surrounding inland areas of the basin. It is the writer's opinion that younger metallogenic epochs occurred progressively further to the southeast of the Korean Peninsula, and this is very apparent in the Kyongsang Basin area.

Figure II–7. Late Cretaceous to early Tertiary metallogenic provinces: **lead-zinc**. 1. Yongdok 2. Kusandong 3. Taeku 4. Masan-Milyang.

SOME FEATURES RELATING TO PLATE TECTONICS

Among geologists in Korea, two schools of thought exist in regard to the application of plate tectonics to the explanation of the geology and tectonics of Korea. One school postulates subduction at the continental margin of the peninsula, while the other visualizes obduction beneath it. These ideas are summarized below.

Park and Kim (1971) postulated that subduction along the margin of the Pacific Plate might have accelerated the compressional strain on the peninsula along its east coast, and uplift of the east coast might have been the result. Park and So (1972) illustrated the numerous similarities between the Okchon System and recent island arcs, and insisted that lithology, metamorphic facies, geological structure, genesis of ore deposits, and the general elongated distribution of the component rocks of the Okchon System all pointed to an island arc origin. Lee (1972 and 1974) also discussed some characteristic features such as metamorphism, heat flow and magnetism and then postulated that these features might be related to plate tectonic processes.

Contrary to the ideas described above, Workman (1972) proposed that the Mesozoic granites of Korea might lie along a Mesozoic thermal rise which might be a lithospheric plate source.

It is possible to examine the same features to judge whether or not they are related to the basic features of plate tectonic regimes. The answer will not be reached until further study on them has been thoroughly pursued, but this writer can state with certainty that all ideas at present are based on speculation, because no detailed and careful studies of these features have so far been undertaken, even by the authors quoted.

Metamorphic facies

The Korean Peninsula is a part of the Asian continent and consists of Precambrian metamorphic basement rocks over more than half of the land. Lee (1972) stated that the basement is marked by low-pressure/high-temperature metamorphic facies and is overlain by metamorphic rocks of high-pressure/low-temperature facies (the latter presumably representing the rocks of the Okchon System). Park and So (1972) applied the paired metamorphic belt concept, postulated for Japan by Miyashiro (1973), to the Korean Peninsula, but this may not be a valid comparison.

In most cases the age of deformation and metamorphism of the Precambrian basement dates from Precambrian times, having occurred on several different occasions within those times; hence, the paired metamorphic belt idea is not applicable to the metamorphic complexes of Korea. The metamorphic facies are so diverse that it is too early to generalize the facies series, as was done by Lee (1974). This writer does not hesitate to state that the difference in metamorphic facies is not related to plate tectonic processes, because study of the Precambrian metamorphic complex in Korea is in an early stage, and its evolution with regard to deformation and metamorphism is presently beyond our capability to visualize.

Heat flow

Eighteen heat flow values measured by the Geological Survey of Korea showed an overall average of 1.7 HFU (Chang *et al.* 1970). Anomalously high heat flow values of over 2 units appear in the southeastern parts of the peninsula, to the east of the Yangsang Fault (*Fig. II–3*). Uyeda and Horai (1964) reported high values of 2 to 3 HFU on the east coast of Korea. All these high values seem to be western extension of heat flow values in the Japan Sea.

The data accumulated so far are not sufficient to conclude whether or not the heat flow values are the result of a submerging oceanic slab, as advocated by Lee (1974), or the result of the southward drift of the Japan island arc from the Asian continent, as advocated by Sugimura and Uyeda (1973). A north-northwest trending (Korean direction) fault has been detected in the Japan Sea off the Korean coast. The high heat flow is probably related to faults, but the origin of such faults is not known so far.

Magmatism and volcanism

It has been observed that the ages of granites in Korea get progressively younger toward the south. Triassic and older granites are known to occur in a few places in North Korea, Jurassic to early Cretaceous granites in mid-peninsula, and late Cretaceous granites in the south. The exact explanation of this arrangement of granites has not been determined, but it might be assumed to be related to plate tectonic activity where a descending oceanic plate (the Pacific Plate) dips very gently northwards, with the hot-spot suggested by Uyeda and Miyashiro (1973) located beneath the Korean Peninsula.

As shown in *Figure II–2*, andesitic volcanic rocks are distributed throughout the southern part of the Kyongsang Basin. Basaltic volcanic rocks are found on Cheju and Ulnung islands which lie some distance off the south and east coasts of the peninsula respectively. Petrochemical study of these volcanic rocks has not been fully done, so it is not yet possible to relate them to the mechanics of plate tectonics; but the disposition of the volcanic rocks may relate to such activity.

Some basic rocks are distributed in the Okchon Palaeogeosynclinal Zone and in southern parts of the Ryongnam Massif. This writer's recent study revealed that most of the basic rocks are hornblendite but more careful study is needed to decided whether or not they are ophiolite; however, it is this writer's opinion that they do not look like ophiolite in either lithology or occurence.

REFERENCES

Chang C. C., H. K. Kim and Y. S. Kang, 1970, Heat flow in Korea (in Korean): *Rept. Geophysical and Geochemical Exploration, Geological Survey of Korea*, vol. 4, no. 1, p. 30–37.

Cheong, C. H., 1956, Outline of the Geology of Korea (in Korean): *Geological Survey of Korea, Bull.*, vol. 1.

Kim, O. J., 1968, Stratigraphy and tectonics of the Okcheon System in the area between Chungju and Munkyeong (in Korean): *Jour. Korean Inst. Mining Geology*, vol. 1, no. 1.

———, 1969, Geology and tectonics of the mid-central region of South Korea: *Jour. Korean Inst. Mining Geology*, vol. 2, no. 4.

———, 1971a, Metallogenic epochs and provinces of South Korea: *Jour. Geol. Soc. Korea*, vol. 7, no. 1, p. 37–59.

———, 1971b, Study of the intrusion epochs of Younger Granites and their bearing on orogenesis in South Korea (in Korean): *Jour. Korean Inst. Mining Geology*, vol. 4, no. 1, p. 1–10.

———, 1972, Precambrian geology and structure of the Central Region of South Korea (in Korean): *Jour. Korean Inst. Mining Geology*, vol. 5, no. 4, p. 231–240.

———, 1973, The stratigraphy and geological structure of the metamorphic complex in the northwestern area of the Kyonggi Massif (in Korean): *Jour. Korean Inst. Mining Geology*, vol. 6, no. 4.

Kobayashi, T., 1953, Geology of South Korea: University of Tokyo Press, Tokyo.

Lee, S. M., 1972, Metamorphic facies and facies series in relation to the tectonics of South Korea: *24th Int. Geo. Congr.*, sec. 2, p. 81–87.

———, 1974, The tectonic setting of Korea with relation to plate tectonics: United Nations ESCAP, *CCOP Tech. Bull.*, vol. 8 (this volume).

Miyashiro, A., 1973, Paired and unpaired metamorphic belts: *Tectonophysics*, vol. 13, p. 241–254.

Nakamura, S., 1923, *Mineral Resources of Chosun (Korea), Volume VIII (N. Chuseido)* (in Japanese): Geological Survey, Chosun, pp. 261.

Park, B. K. and S. W. Kim, 1971, Recent tectonism in the Korean Peninsula and sea floor spreading: *Jour. Korean Inst. Mining Geology*, vol. 4, no. 1, p. 39–43.

Park, B. K. and C. S. So, 1972, The Ogchon System in the central part of southern Korean Peninsula as an ancient island arc (in Korean): *Jour. Geol. Soc. Korea*, vol. 8, no. 4.

Reedman, A. J., W. N. Fletcher, R. B. Evans, D. R. Workman, K. S. Yoon, H. J. Rhyn, S. H. Jeong and J. N. Park, 1974, Geology of the Hwanggangri Mining District, Republic of Korea: *Anglo-Korean Mineral Exploration Group report, Geological and Mineral Institute of Korea*, pp. 118.

Sugimura, A. and S. Uyeda, 1973, *Island arcs, Japan and its environs*: Elsevier, Amsterdam, pp. 247.

Uyeda, S. and K. Horai, 1964, Terrestrial heat flow in Japan: *Jour. Geophys. Res.*, vol. 69, p. 2121–2141.

Workman, D. R., 1972, The tectonic setting of the Mesozoic granites of Korea: *Jour. Geol. Soc. Korea*, vol. 8, no. 2, p. 969–976.

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III. THE TECTONIC SETTING OF KOREA WITH RELATION TO PLATE TECTONICS[1]

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(with figures III-1 to III-6)

ABSTRACT

Physiographic and tectonic features of the Korean Peninsula show that a NE-SW structural trend (the Sininan direction) is prominent throughout and has influenced its tectonic development during most of its geological history. A subsidiary trend, the NNW-SSE Korean direction, has influenced the trend of the east coast. The peninsula forms a marginal portion of the Korea-China Heterogen, a microcraton of Precambrian to Mesozoic age, and rocks on the southeast margin may represent a former island arc accreted to the continent.

Metamorphism of the Precambrian rocks of the peninsula is predominantly of low-pressure/high temperature facies, with much granitization, while the overlying Palaeozoic rocks show low-temperature/high-pressure effects and less granitization.

Anomalously high heat flow measured in the southeastern part of the peninsula appears to be associated with volcanoes and andesite lavas on nearby islands, which lie along a postulated NE-SW submarine fault. The presence of a basic rock complex and other features suggests that this marks the Mesozoic continental margin, now seen as a collision zone between the continent and an island arc along a pre-existing plate boundary.

Granite magmatism decreases in age from Triassic in the north to Cretaceous in the south, resulting from a migrating magmatic source. This is considered to be the result of partial fusion at depth on north-dipping subduction zones which migrated southwards with the Japanese island arcs during the Mesozoic.

INTRODUCTION

Recently much discussion has focussed on the new global tectonics (Isacks *et al.*, 1968). The hypothesis of sea-floor spreading of Dietz (1961) and Hess (1962) was expanded to plate tectonics by Morgan (1968), and is now commonly regarded as synonymous with the new global tectonics.

1: This paper was presented at the Second Intra-Congress of the 13th Pacific Science Congress, held in Guam, May 1973.

Favourable evidence supporting the theory has been presented by many writers, such as Vine and Matthews (1963) and Pitman and Heirtzler (1966), concerning linear magnetic anomalies in the oceans; Menard (1965) concerning the topography of the ocean floors; Bullard (1964), Bullard *et al.* (1965) and Wilson (1965) for physiographic features of continental margins; Ewing and Ewing (1967) on the characteristics of deep-sea sediments; Wilson (1965) and Oliver and Isacks (1967) on some seismic evidence of transform faults; and so forth.

However, many tectonic features of the oceans and adjacent land areas have not been fully explained by plate tectonics, for example the features described by Beloussov (1968), Kent (1969), Bartlett (1971), Trümpy (1971), Hill (1971), Martin (1972) and others. Martin (1972) also pointed out that global tectonics involves several sets of mechanisms, of which plate tectonics is only one.

Inasmuch, however, as the theory of plate tectonics provides a useful conceptional framework for the interpretation of certain global tectonic features, this paper will describe some characteristic features of the continental margin of southern Korea, adjacent to the Japanese island arcs, in the light of the interpretation of this theory.

The writer wishes to acknowledge his indebtedness to Mr. S. Frazier, Manager of Gulf Oil Company of Korea, and to Mr. C. S. Kim, Director of the Marine Geology Division, Geological and Mineral Institute of Korea, for providing information for this paper. He is also indebted to Dr. C. Nishiwaki of the Institute for International Mineral Resources Development, Japan and Dr. J.D.C. Laming of UNDP/CCOP for many valuable comments on the manuscript.

OUTLINE OF THE TECTONICS OF THE KOREAN PENINSULA

The Korean Peninsula forms part of the Korea-China Heterogen, a microcraton of Precambrian to Mesozoic mainly crystalline rocks extending from China through Manchuria to Korea. The Precambrian basement of the peninsula, which forms more than half of the land area, is tectonically related to that of Manchuria and China; the various parts of the basement are shown in *Figure III–1.*

The Pyeongbuk-Gyema Massif forms the southern part of the Liao-Gyema (Lias-Gaema)[1] Massif of southern Manchuria (*Fig. III–1*). The Gyeonggi (Kyonggi) and Sobaeksan (Ryongnam, Reinan) Massifs of southern Korea can be correlated respectively to the Shantung and Fukien Massifs of China. The Pyeongan (Pyongyang) Basin and Okcheon (Okchon) Geosynclinal Zone of Palaeozoic sedimentary rocks, resting on the Precambrian basement massifs, can be correlated with the Hwangho and Yangtze Basins respectively. On the other hand, Mesozoic rocks of the Gyeongsang (Kyongsang) Basin in the southeastern part of the peninsula appears to relate instead to the Japanese islands, as they may extend through the Korea Strait to the Kwanmon Basin off the southwestern tip of Honshu. Hence, in a tectonic sense, Korea is situated on the margin of the Korea-China Heterogen adjacent to the Japanese islands.

1: Alternative terms or spellings are shown in brackets to confirm the identity of the various units in relation to other published work (such as the preceding article in this volume). The spellings used in this paper confirm to the recommended orthography for the Korean language.

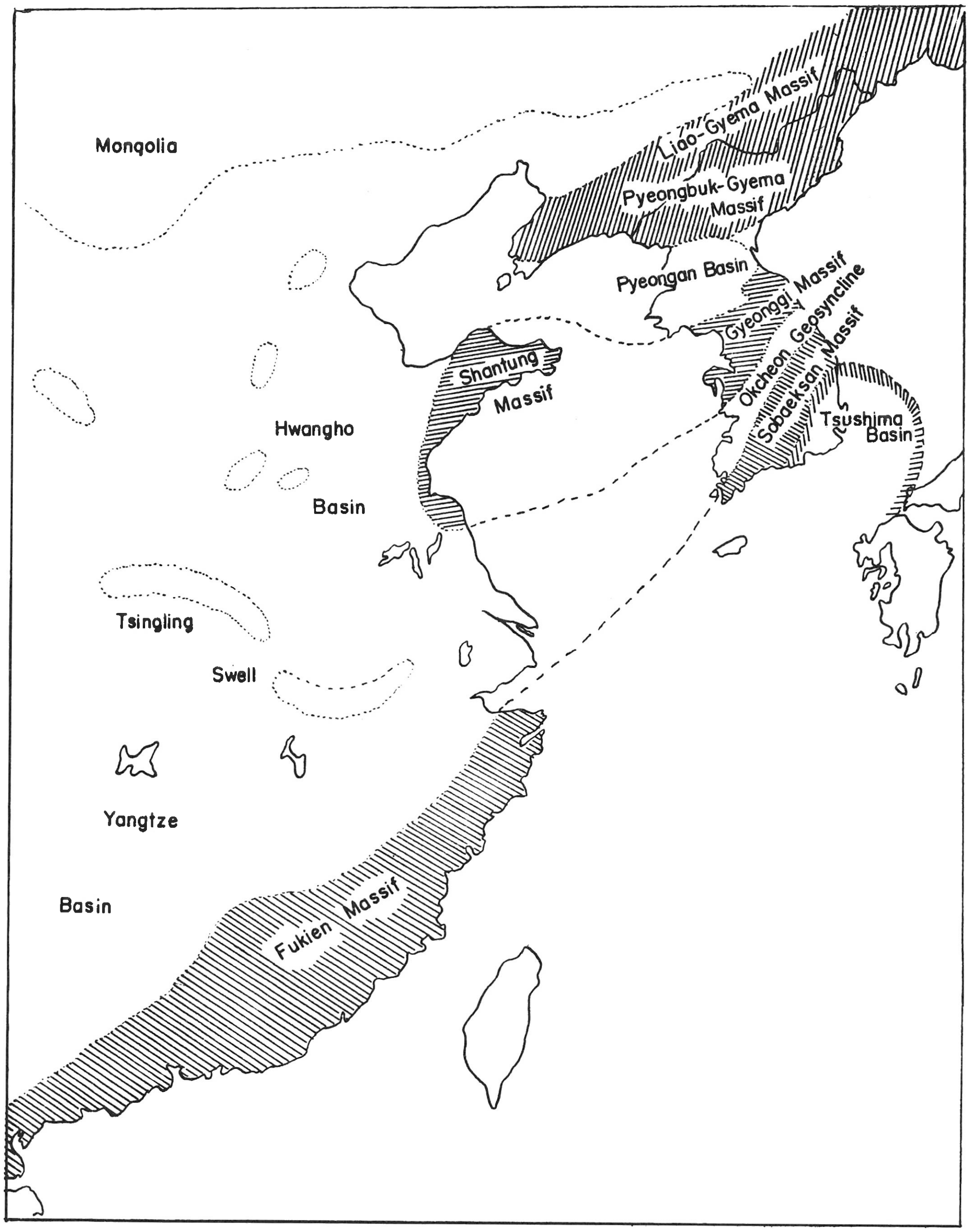

Figure III-1. The Korea-China Heterogen, after Kobayashi (1953, 1957) and S. M. Lee (1972).

Tectonic characteristics

Distinct tectonic configurations in the Korean Peninsula are defined by NNW-SSE and NE-SW structural trends. The former, known as the Korean direction, is found in some parts of the Gyeonggi Massif and is also seen as the prevailing physiographic trend of the east coast of the peninsula and the mountain range which lies close to it (*Fig. III–4*); the latter trend, known as the Sinian direction, prevails over most of the area west of the continental divide. The east coast is uplifted, while west and south coasts show evidence of submergence such as numerous islands and drowned valley inlets; hence the Korean Peninsula has been recognized as a tilted continental block.

The Okcheon Geosynclinal Zone of Palaeozoic age shows the most prominent structures with the northeasterly Sinian direction. This zone divides the Precambrian areas of southern Korea into the Gyeonggi and Sobaeksan Massifs, northwest and southeast of the zone respectively. The zone also shows distinct signs of tilting, since the northeastern portion includes an almost unmetamorphosed zone with a partially intrazonal Precambrian basement uplift, while the more downwarped central and southwestern portions underwent progressive metamorphism under low and intermediate temperature conditions, respectively. After an erosion period, and as the downwarping proceeded in the southwest, troughs filling with Mesozoic sediments were formed such as the Okmasan and Yeongsanggang Troughs (Lee, 1972).

Extensive epeirogenic movement of the land took place during Silurian to early Carboniferous time. Several tectonic events have been recognized in the Mesozoic, such as the Songlim Disturbance (Triassic to early Jurassic), the Daebo Orogeny (Jurassic), and the Bulguksa (Bulkuksa) Disturbance (early to middle Cretaceous). The Songlim and Bulguksa Disturbances were accompanied by minor folding and some granite intrusion, whereas the Daebo Orogeny, which was the most extensive, led to severe folding and faulting. Many granite intrusions of this age are of synkinematic origin (called the Daebo Granites), and lie more or less along the anticlinal axis of the regional structure; they show a long linear outcrop from northeast to southwest across the peninsula.

During the Cenozoic (Miocene to Pleistocene) some alkaline volcanic rocks were extruded along the Chugaryeong Graben Zone in the central part of the peninsula, as well as on islands such as Cheju and Ulryeung (Ulnung) located southwest and east of the peninsula respectively.

SOME FEATURES RELATED TO PLATE TECTONICS

The Korean Peninsula lies at the southwestern tip of a stable continental craton, which borders the oceanic-type Pacific Plate. Writers such as Le Pichon (1968), Isacks *et al.* (1968) and Hill (1971) have categorized this craton as part of the Eurasian Plate; whereas Morgan (1968), Mitchell and Reading (1969) and Dewey and Bird (1970) included it in the southeast Asian continental craton. However, all writers considered the Japanese islands to be the margin of the plate. There are, nevertheless, some problems remaining to be clarified: for example, where does the actual continental edge lie, and what was the mechanism which formed the East Sea (Japan Sea)? In this paper the writer proposes some interpretations which may help resolve these problems.

Metamorphic facies series

A classification of the metamorphic facies and facies series in southern Korea (S. M. Lee, 1972) shows that low-pressure and intermediate- to high-temperature metamorphic rocks form the Precambrian basement of the land, whereas intermediate- and low-temperature rocks overlie the basement. The former facies series ranges from greenschist to granulite facies, consisting of typical mineral assemblages of cordierite and sillimanite without kyanite or staurolite, while the latter facies series, consisting mainly of greenschist and minor amphibolite facies, contains diagnostic mineral assemblages such as kyanite, sillimanite and staurolite.

The temperature conditions between the basement and the overlying rocks were the inverse of the pressure. Much granitization accompanied the high temperature assemblages in the basement, but granites are absent from the overlying rocks except as a local phenomenon of migmatitization.

Radiometric dating of the Precambrian basement rocks has yielded ages of 1,000 to 2,900 m.y., based on 17 analyses made by J. H. Lee *et al.* (1972). Because of insufficient data, the upper and lower age limits cannot be determined. However, judging from the characteristics of the metamorphic facies and nature of granitization, the rocks of the basement are similar to the "primary crust," as described by Mouratov (1972), who indicated that when hypersthene, amphibole and other gneisses and crystalline schists were subjected to intense metamorphism, granitization resulted not only in the amphibolite facies but also partly in the granulite facies where more intense metamorphism took place. Furthermore, with respect to the age of the metamorphic rocks in relation to a metamorphic facies series, Saggerson and Turner (1972) pointed out that a progressively increased pressure condition, from low through intermediate to high pressure metamorphism, characterized progressively younger Precambrian rocks in an evolutionary sequence. Because of this, it can be said that the Precambrian basement of the peninsula forms part of an ancient continent.

The Precambrian basement of the Korean Peninsula is characterized by low-pressure/high-temperature metamorphism, whereas the Japanese island arcs show characteristics of blueschist metamorphism. Miyashiro (1961) described the paired metamorphic belts of Japan, characterized by blueschist metamorphism of the jadeite-glaucophane type on the oceanic side, and the high-temperature/low-pressure facies metamorphism of the andalusite-sillimanite type on the continental side. The pressure-temperature conditions between the continents and the Japanese islands are illustrated in *Figure III–2*. The Sanbagawa Zone of blueschist metamorphism is mainly on the high-pressure side, whereas the Ryoke Zone lies on the low-pressure side. However, the Sobaeksan and Gyeonggi metamorphic belts of the Korean Precambrian basement represent low-pressure/high-temperature conditions.

The low-pressure metamorphism in the basement of the continent may be due to minor downbuckling, which could have resulted in a low-pressure condition at the continental margin, while the high-pressure type of blueschist metamorphism developed within a subduction zone adjacent to the downgoing oceanic plate.

Heat flow

Terrestrial heat flow values in Korea were measured by the Geological Survey of Korea (Chang, 1970). The average value among 18 measurements was 1.70 HFU (10^{-6} cal/cm^2 sec), which is somewhat higher than the world average of 1.5 HFU (W.H.K. Lee, 1963).

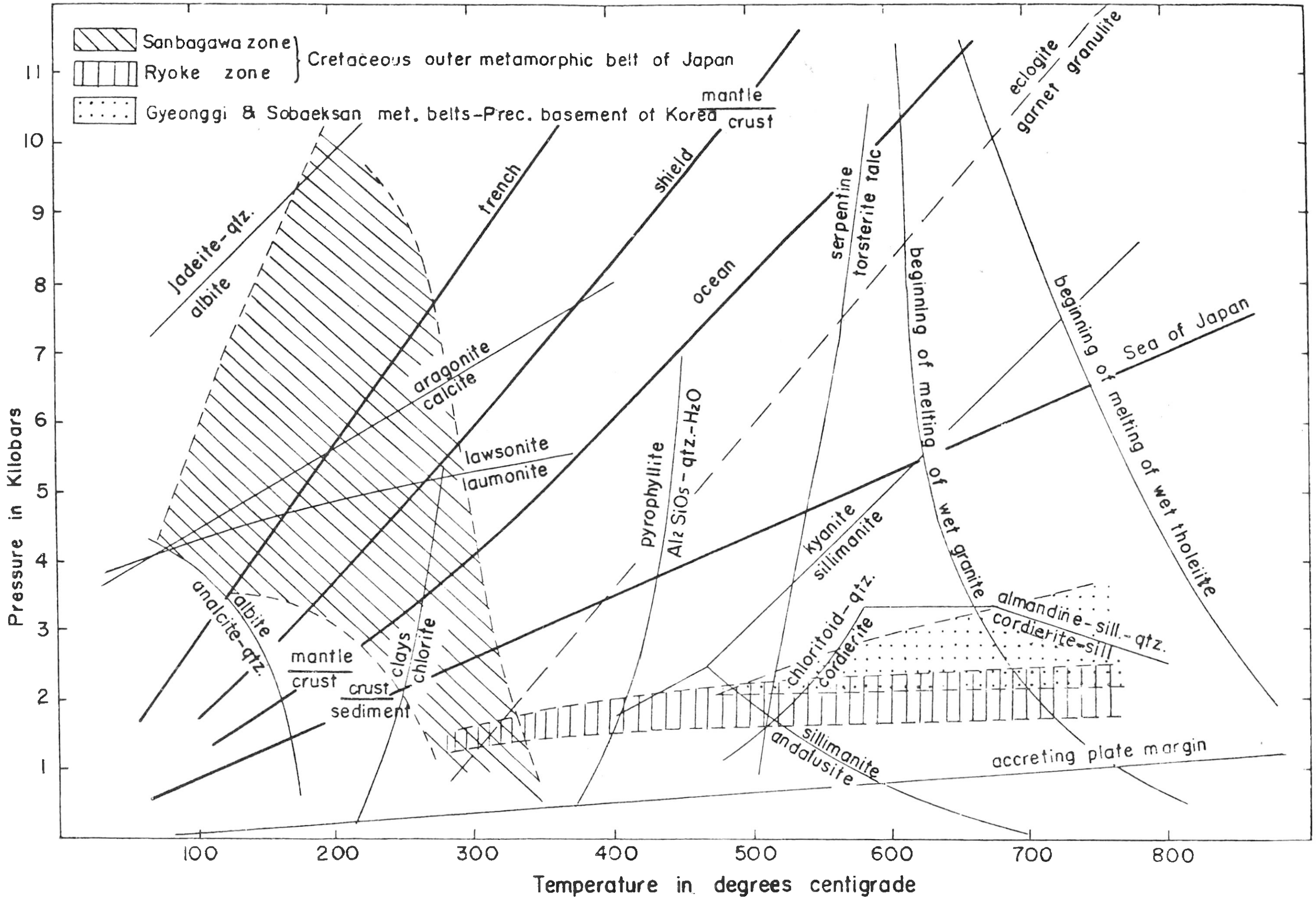

Figure III-2. Pressure-temperature plot of metamorphic facies series comparing the Japanese paired metamorphic belts and the Precambrian basement of Korea, with various metamorphic reaction data (Miyashiro, 1961, 1967; Ernst and Seki, 1967; Turner, 1968; Dewey and Bird, 1970; and S. M. Lee, 1972). Heavy lines labelled trench, shield, *etc.* show increasing of pressure and temperature with depth for each domain; boundaries mantle, *etc.* show pressure level at these boundaries.

This higher value implies that the anomalously high heat flow values in the southeastern corner of the peninsula, greater than 2.0 HFU, were taken into account in determining the average. On the other hand, values in the Precambrian basement lie within the range 1.3 to 2.3 HFU, which is also relatively higher than the average for Precambrian shields (Lee and Uyeda, 1965), although somewhat lower values of 1.0 to 1.3 HFU were found in the overlying Palaeozoic rocks of the Okcheon metamorphic belt. Furthermore, unusually high values of 2.0 to 3.0 HFU were reported on the east coast of the peninsula by Uyeda and Vacquier (1968).

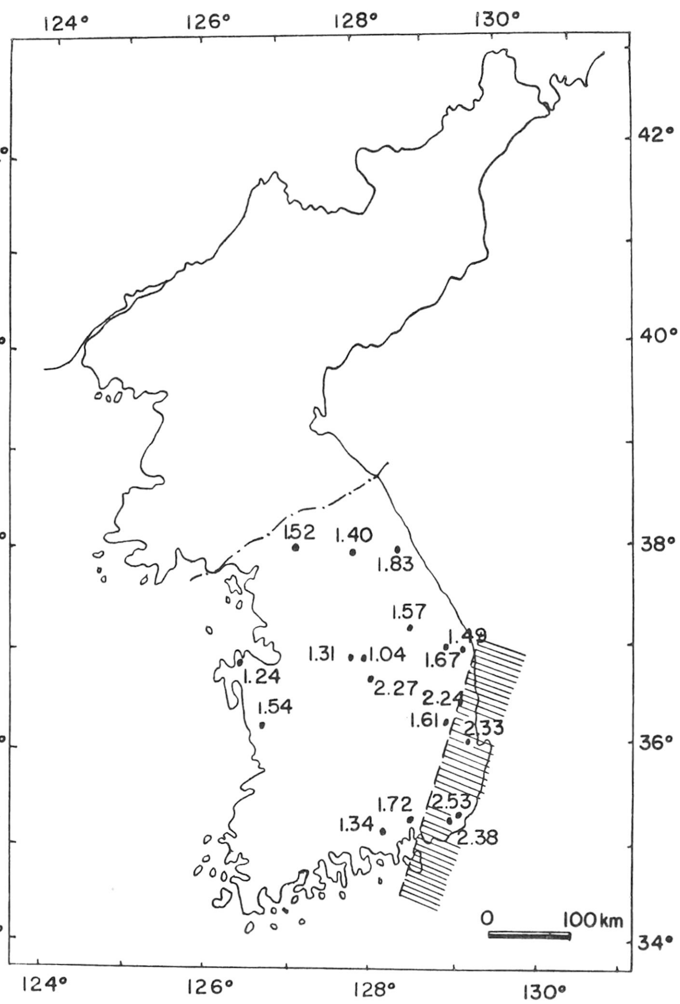

Figure III–3. Terrestrial heat flow values in Korea given in HFUs (10^{-6} cal/cm^2 sec) after Chang (1970). Shading indicates the area of heat flow greater than 2.0 HFU.

These anomalously high values of heat flow in the southeast corner of the land as well as on the east coast may be due to thermal energy produced at the continental margin, where descending oceanic slabs may result in high heat generation which would be transmitted upwards to the surface. Along this zone of high heat flow are some associated characteristic features, such as the uplifted Taebaeksan mountain range running parallel to it, a great fault on the ocean side (Huntec Ltd., 1967), and much andesite and dacite accumulated on the land. It may also be noted that the islands of the Aleutian arc consist dominantly of andesitic rocks. As Menard (1969) pointed out, island arcs are characterized by volcanoes and andesitic lavas, due to the partial melting of the oceanic crust of the descending plate, forming a calc-alkaline magma which is erupted as andesite and dacite in the arc (Dewey and Bird, 1970). These facts may imply that the peninsula margin, as described above, may have been associated with an ancient island arc.

Figure III–4 shows an inferred continental (cratonic) margin of Mesozoic date, which can be traced from the southeastern margin of the mainly pre-Mesozoic Fukien Massif of southern China (Cathaysia), through the high heat-flow zone associated with the Gyeongsang Basin, to the Sikhote, Verkhoyansk and Chukhotsk regions of eastern Siberia. This 7500-km long belt is broadly characterized by numerous Mesozoic granites intruded into Mesozoic and earlier rocks. A Mesozoic sedimentary basin with associated andesitic volcanic and pyroclastic rocks lies to the southeast of this margin, and presents a picture of a series of molasse basins of intermontane and continent-margin type which had developed comtemporaneously with tectonic uplift and volcanicity along the edge of the continent. Unlike the Cenozoic fold belts along the present-day Pacific margin, most of the Mesozoic basins are not strongly folded, and the granites intruding them show post-orogenic features (Workman, 1972).

A major fault can be traced parallel to this inferred cratonic margin. The Yangsan Fault in the southeastern corner of the Korean Peninsula can be correlated with the extensive right-lateral fault postulated by Emery *et al.* (1969) to lie off the east coast of Taiwan and extend northeastwards across the East China Sea to the volcanic island of Cheju. Lying along this inferred major fault and its extension into the East Sea (*Fig. III–4*) are volcanoes such as those on Cheju and Ulryeung islands, and a submerged volcano recently discovered by a seismic reflection survey run by Gulf Oil Company of Korea. This was found two kilometres east of Socotra Rock (situated at 32°07′N and 125°11′E), which consists of a coral patch on volcanic rock at depths of 17 to 30 fathoms (31–55 m).

Continuing the speculation on the nature of the continental margin, it is possible that an ancient trench developed along the east coast of Korea, in which case the East Sea basin could have been developed as a rift within the Pacific Plate, and the Japanese islands could have reached their present position by separation and some form of sea-floor spreading (Uyeda and Vacquier, 1968; and Park and Kim, 1971).

Magmatism

Granite intrusions which accompanied the orogenies in the Korean Peninsula are recognized to be of early to middle Precambrian, Triassic, Jurassic, and middle Cretaceous to early Tertiary ages. The Precambrian granites, known as the Kokurian Granites, are widely distributed throughout the country and are intruded into the early Precambrian metamorphic basement complex. These granites are now of gneissic character due to sub-

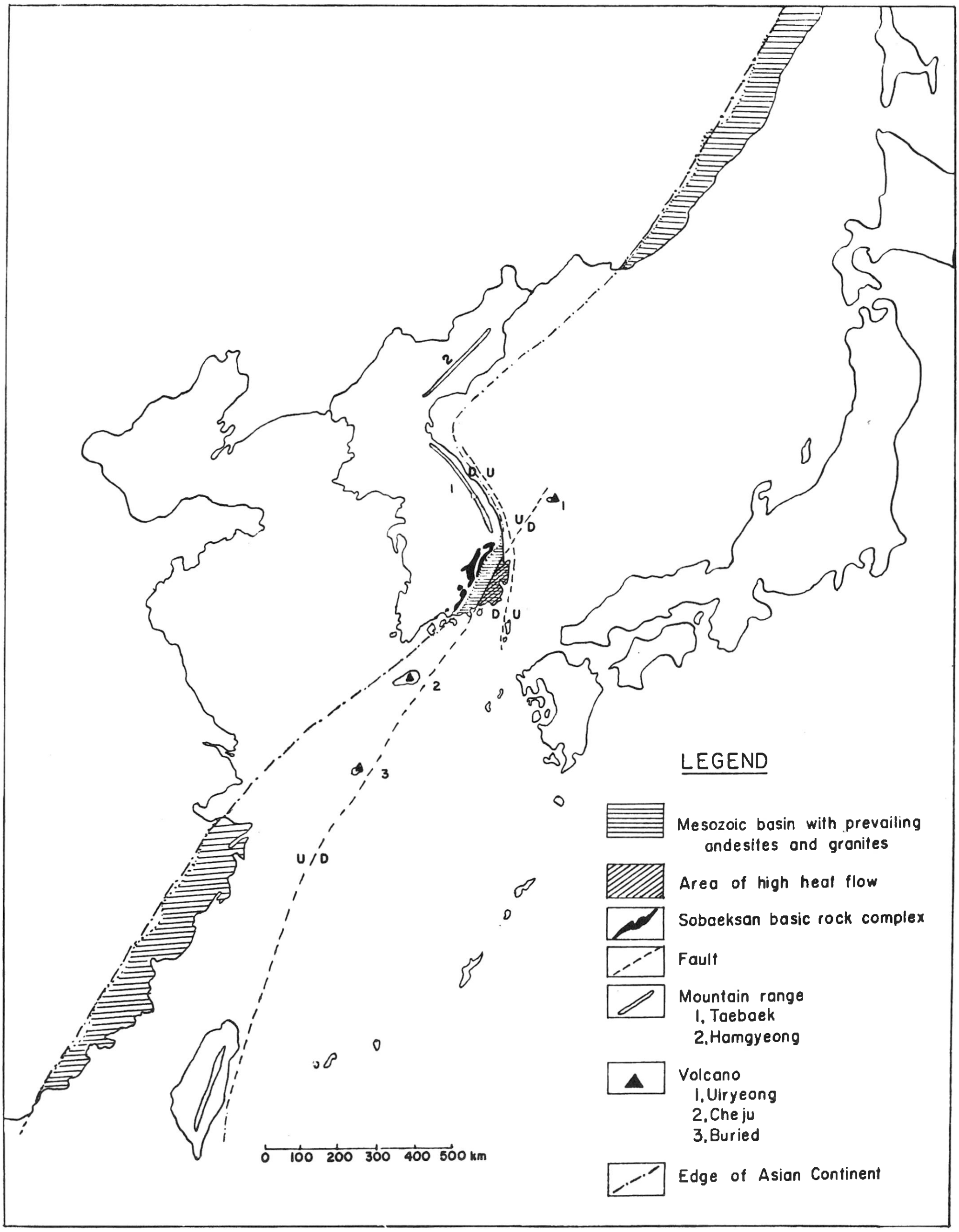

Figure III–4. Inferred edge of Asian continent during the Mesozoic, and related features.

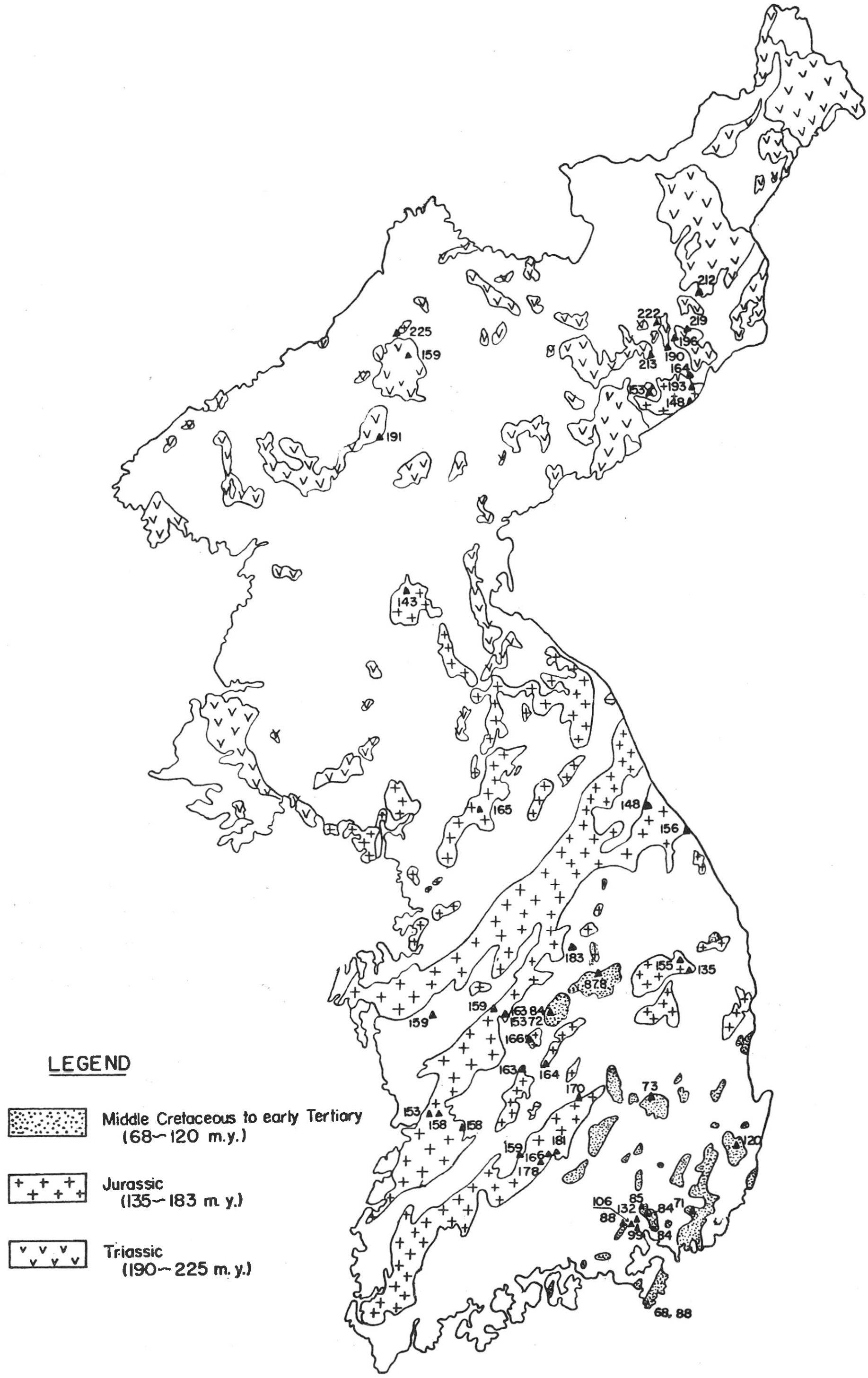

Figure III–5. Distribution of radiometric ages of granites (Compiled by Geological Survey of Korea, 1972). Figures beside triangles indicate radiometric dates of granites in million years.

sequent regional metamorphism.

The so-called Younger Granite is a group of intrusions including all granites exclusive of the Kokurian Granite, but three different types and ages of these intrusions have been recognized within the Younger Granite so far: these are Triassic, Jurassic and Cretaceous. These granites occur along the Chukhotsk-Cathaysia Zone which extends from southern China to the northeastern tip of Siberia.

Triassic granites are mainly restricted to the northern part of the peninsula, whereas Cretaceous granites occur in the southeastern portion of the land: these are principally in the Gyeongsang Basin, except for occurrences in the Hwanggangri and Sokrisan areas (*Fig. III–5*). The Jurassic and Cretaceous granites are mostly long linear bodies with a general northeast trend across the peninsula, and were probably emplaced along the anticlinal axis of the regional structure. The gradational contact with the gneisses is noticeable. These facts may indicate that the Jurassic granite is of synkinematic origin and therefore different from the Triassic and Cretaceous granites in occurrence and genesis.

The granitic magmatism of the peninsula shows a general tendency of having migrated laterally from north to south along the peninsula, as indicated by the distribution of radiometric ages for granites shown in *Figure III–5*. These range from Triassic in the north to Cretaceous in the south. Furthermore, to the southeast, in Japan, there are granites of late Cretaceous and Miocene age in parts of Kyushu and Honshu (Workman, 1972).

This lateral migration of granites may be related to plate tectonics. When descending plates of basaltic oceanic crust reach a depth greater than 100 km, amphibolite and quartz-eclogite crust begins partially to melt, resulting in calc-alkaline magmas which undergo fractional crystallization as they rise (Dewey and Bird, 1970). This fractional crystallization may result in granite intrusion at the continental margin. Also, Ueda (1969) indicated that certain Triassic-Jurassic granites of Korea could have originated in the mantle. The locus of

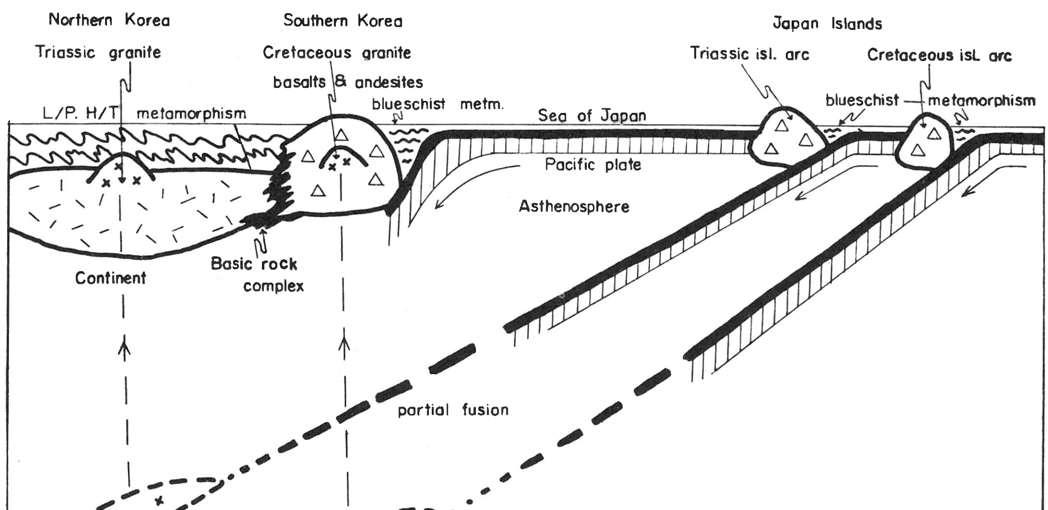

Figure III–6. Schematic section illustrating migration of granite intrusion from northern to southern Korea as the island arcs of Japan migrate.

emplacement of the magma moved in response to migration of the source zone if the source was the partial fusion of a downgoing lithospheric plate. The paired island arcs of Honshu, the older Triassic pair and the younger Cretaceous pair, seem to be related genetically to the intrusion of Triassic and Cretaceous granites in Korea, respectively, as a result of northward subduction of the Pacific Plate (*Fig. III–6*); nevertheless, the mechanism of the magma generation is not fully understood.

A plutonic complex of ultrabasic to basic rocks occurs adjacent to the inferred continental edge along the Mesozoic Gyeongsang Basin. This complex was first recognized by this writer and named the Sobaeksan Basic Rock Complex (S. M. Lee, 1972); it includes anorthosite bodies with which gradational gabbroic to dioritic rocks and a few peridotite dykes are associated (Lee and Kim, 1966). Most of these rocks are metamorphosed into various gneisses. The question of whether these basic rocks represent ophiolites, which could have been derived from former oceanic crust subducted beneath the peninsula, is worth considering: the definition of an ophiolite given by the Conference on Ophiolites (Geological Society of America, reported in *Geotimes*, December 1972) was of a distinctive assemblage of mafic to ultramafic rocks which may display a complete sequence from the bottom upwards of ultramafic complex, gabbroic complex, mafic sheeted dyke complex and mafic volcanic complex. The mineral assemblage of the Sobaeksan Complex is somewhat different from normal ophiolites, however; it may have been derived from basic magma formed by anatexis of the remnants of ancient oceanic crust contaminated by supracrustal rocks of sedimentary origin.

CONCLUSIONS

The Korean Peninsula forms a part of the Korea-China Heterogen, a microcraton of early Precambrian to Mesozoic metamorphic and granitic rock composition, and lies adjacent to the tectonically active Japan island arc, the marginal basin of the East Sea (Japan Sea) and the intracratonic Tertiary basin of the East China and Yellow Seas. The edge of this craton lies at the southeast corner of the peninsula, and extends southwestward along the margin of Cathaysia in southern China, and northeastward along the coastal regions of eastern Siberia. Mesozoic sedimentary and volcanic rocks demonstrate that this continental margin was tectonically active at that time, though in a mode different from the island arc-oceanic trough regime widespread along the Pacific margin today.

In the southeastern part of the peninsula the margin is marked at present by unusually high heat flow, thought to result from energy released by the collision of continental and oceanic crustal elements in the vicinity. Uplifted mountain ranges are located along the margin on the continental side, and a great fault with associated volcanoes and andesitic extrusions is thought to be present on the oceanic side. This may suggest that at least part of Korea is the site of a collision between the continent and an island arc.

The metamorphic facies series divide the low-pressure metamorphism with much granitization, prevalent in the Precambrian basement on the continental side, from the anomalously high-pressure metamorphism of post-Triassic age in the Japan island arcs on the oceanic side.

The Sobaeksan Basic Rock Complex, consisting of anorthosite with gradational gabbroic to dioritic rocks adjacent to its margin, seems to be genetically related to plate tectonic activity. It was probably derived by anatexis of remnants of basic oceanic crust contaminated by supracrustal rocks of sedimentary origin, during the collision of the continent with an oceanic plate.

The granitic magmatism in the peninsula shows a general lateral migration of the magma source from north to south along the peninsula, as indicated by the decreasing age of granite intrusions in that direction from Triassic in the north to mainly Cretaceous in the south. The paired metamorphic belts of the ancient island arcs of Japan, an older Triassic pair and a younger Cretaceous pair, are possibly related genetically to the magmatism of Triassic and Cretaceous age in Korea, respectively.

REFERENCES

Bartlett, G. A., 1971, *The Canadian Atlantic continental margin-paleogeography, paleoclimatology and sea-floor spreading*: Geological Survey of Canda, Paper 71–23.

Beloussov, V. V., 1968, Debate about the earth: *Geotimes*, vol. 13, p. 17–19.

Bullard, E. C., 1968, Continental drift: *Quart. Jour. Geol. Soc. London*, vol. 120, p. 1–33.

———, J. E. Everett and A. G. Smith, 1965, The fit of the continents around the Atlantic, *in* Symposium on continental drift: *Phil. Trans. Royal Soc. London*, ser. A, vol. 258, p. 41–57.

Chang, C. H., 1970, Heat flow in Korea: *Ann. Rev. Korean National Comm. IUGG (1970)*, p. 1–7.

Dewey, J. F., and J. M. Bird, 1970, Mountain belts and the new global tectonics: *Jour. Geophys. Research*, vol. 75, p. 2625–2647.

Dietz, R., 1961, Continent and ocean basin evolution by spreading of the sea floor: *Nature*, vol. 190, p. 854–857.

Emery, K. O., Yoshikazu Hayashi, T. W. C. Hilde, Kazuo Kobayashi, Ja Hak Koo, C. Y. Meng, Hiroshi Niino, J. H. Osterhagen, L. M. Reynolds, J. M. Wageman, C. S. Wang and Sung Jin Yang, 1969, Geological structure and some water characteristics of the East China Sea and the Yellow Sea: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 2, p. 3–43.

Ernst W. G., and Y. Seki, 1967, Petrologic comparison of the Franciscan and Sanbagawa metamorphic terrains: *Tectonophysics*, vol. 4, p. 463–478.

Ewing, J. and M. Ewing, 1967, Sediment distribution on the mid-ocean ridges with respect to the spreading of the sea floor: *Science*, vol. 156, p. 1590–1592.

Hess, H. H., 1962, History of ocean basins, *in Petrologic studies—a volume in honor of A. F. Buddington*: Geological Society of America, New York, p. 599–620.

Hill, M. L., 1971, A test of the new global tectonics: comparisons of the northwest Pacific and California structures: *Bull. Amer. Assoc. Petroleum Geologists*, vol. 55, p. 3–9.

Huntec, Ltd., 1968, Report on the offshore geophysical survey in the Pohang area, Republic of Korea: United Nations ECAFE, *CCOP Tech. Bull.*, vol. 1, p. 1–12.

Isacks, B., J. Oliver and L. R. Sykes, 1968, Seismology and the new global tectonics: *Jour. Geophys. Research*, vol. 73, p. 5855–5899.

Kent, P. E., 1969, The geological framework of petroleum exploration in Europe and

North Africa and the implications of continental drift hypotheses: *in Inst. Petrol., The exploration for petroleum in Europe and North Africa*, p. 3–17.

Kobayashi, T., 1953, *Geology of South Korea, with special reference to the limestone plateau of Kogendo, The Cambro-Ordovician Formations and the Faunas of South Chosen*: University of Tokyo Press, Tokyo, 293pp.

———, 1957, *Geology of Asia* (in Japanese): Asakura Shoten, Tokyo, 253pp.

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

Lee, J. H., P. M. Hurley and W. H. Pirson, Jr., 1971, Radiometric dating of Precambrian rocks in Korea: *Geol. and Ore Deposits*, no. 13, Geological Survey of Korea, p. 12–20.

———, P. M. Hurley, H. W. Fairbairn and W. H. Pirson, Jr., 1972, Middle or older Precambrian apparent age values in basement gneisses of Korea, as affected by Mesozoic plutonism: *Geol. and Ore Deposits*, no. 17, Geological Survey of Korea, p. 15–21.

Lee, S. M., 1972, Metamorphic facies and facies series in relation to tectonics of South Korea: *24th Int. Geol. Congr.*, sec. 2, p. 81–87.

———, and H. S. Kim, 1966, *Explanatory text of the Geological Map of Bongnae*: Geological Survey of Korea, 11pp.

Lee, W. H. K., 1963, Heat flow data analysis: *Jour. Geophys. Research*, vol. 68.

———, and S. Uyeda, 1965, Review of heat flow data: *in Terrestrial heat flow*: Am. Geophys. Union, Geophys. Monograph Series no. 8, p. 87–190.

Martin, R., 1972, Sixty years of global tectonics—pros and cons of some modern concepts: *24th Int. Geol. Congr.*, sec. 3, p. 143–152.

Menard, H. W., 1965, Sea floor relief and mantle convection: *Phys. Chem. Earth*, vol. 6, p. 315–364.

———, 1969, The deep ocean floor: Sci. American, vol. 221, p. 127–142.

Mitchell, A. H. G., and H. G. Reading, 1969, Continental margins, geosynclines, and ocean floor spreading: *Jour. Geol.*, vol. 77, p. 629–646.

Miyashiro, A., 1961, Evolution of metamorphic belts: *Jour. Petrol.*, vol. 2, p. 277–311.

———, 1967, Orogeny, regional metamorphism, and magmatism in the Japanese islands: *Medd. Dan. Geol. Foren.*, vol. 17, p. 390.

Morgan, W. J., 1968, Rises, trenches, great faults and crustal blocks: *Jour. Geophys. Research*, vol. 73, p. 1959–1982.

Mouratov, M. V., 1972, Main structural elements of the crust on continents, their interpretations and age: *24th Int. Geol. Congr.*, sec. 3, p. 71–78.

Oliver, J., and B. Isacks, 1967, Deep earthquake zones, anomalous structures in the upper mantle and the lithosphere: *Jour. Geophys. Research*, vol. 72, p. 4259–4275.

Park, B. K., and S. W. Kim, 1971, Recent tectonism in the Korean Peninsula and sea-floor spreading: *Jour. Korean Inst. Mining Geology*, vol. 4, p. 39–43.

Pitman, W. C., III, and J. Heirtzler, 1966, Magnetic anomalies over the Pacific-Antarctic Ridge: *Science*, vol. 154, p. 1164–1166.

Saggerson, E. P., and L. M. Turner, 1972, Some evidence for the evolution of regional metamorphism in Africa: *24th Int. Geol. Congr.*, sec. 1, p. 153–161.

Trümpy, R., 1971, Stratigraphy in mountain belts: *Quart. Jour. Geol. Soc. London*, vol. 126, p. 293–318.

Turner, F. J., 1968, *Metamorphic Petrology*: McGraw-Hill, New York, 403pp.

Ueda, N., 1969, Evolution of the continent in northeastern Asia: reconnaissance survey of the geochronology of the Korean Peninsula (summary): *Jour. Korean Inst. Mining Geology*, vol. 2, p. 96–97.

Uyeda, S., and V. Vacquire, 1968, Geothermal and geomagnetic data in and around the island arc of Japan, *in The crust and upper mantle of the Pacific area*: Am. Geophys. Union Geophys. Monograph Series no. 12, p. 349–366.

Vine, F. J., and D. H. Matthews, 1963, Magnetic anomalies over oceanic ridges: *Nature*, vol. 199, p. 947–949.

Wilson, J. T., 1965, A new class of faults and their bearing on continental drift: *Nature*, vol. 207, p. 343–347.

———, 1965b, Transform faults, oceanic ridges, and magnetic anomalies, southwest of Vancouver Island: *Science*, vol. 150, p. 482–485.

Workman, D. R., 1972, The tectonic setting of the Mesozoic granites of Korea: *Jour. Geol. Soc. Korea*, vol. 8, p. 967–976.

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IV. PETROLEUM PROSPECTS OF THE SOUTHERN PART OF THE BANDA ARCS, EASTERN INDONESIA[1]

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(with figures IV-1 to IV-8)

ABSTRACT

The southern part of the Banda Arcs consists of an outer, non-volcanic, island arc extending from Sumba through Timor to the Kai Islands, and an inner, mainly volcanic, arc which diminishes eastwards from Flores through Wetar to the tiny island of Manuk. The location of the Eurasian-Australian plate boundary in this area is under debate.

The Outer Banda Arc islands contain rocks of both Asian and Australian affinities. The oldest rocks are metamorphic, probably Precambrian, and the oldest unmetamorphosed rocks are Early Permian marine sediments in Timor and Leti. Triassic, Jurassic and Cretaceous marine strata are found throughout most of the islands of the Outer Arc. According to different tectonic interpretations, these strongly folded and faulted rocks of Australian facies (Permian to Jurassic) are regarded as (i) entirely allochthonous, derived from an uncertain northern location; (ii) allochthonous, part of a tectonic mélange separated from the Australian shelf by a subduction zone in the Timor Trough and its eastward extension; or (iii) autochthonous or paraautochthonous Australian shelf and slope deposits forming an imbricate zone underlain by Australian crystalline continental basement.

These different tectonic interpretations have a direct bearing on the view taken of the petroleum prospects. Only if the pre-Cenozoic strata of Australian facies are regarded as autochthonous or paraautochthonous can they be considered to have petroleum prospects. In the Outer Arc islands, the Palaeogene rocks are mainly carbonate reef facies, and where they have been preserved below Neogene basin margins they could be prospective. Above the widespread Bobonaro Scaly Clay Formation, interpreted as a mid-Miocene olistostrome, there are Neogene marine molasse rocks which accumulated in downfaulted basins both on and offshore the Outer Arc islands. Some of the larger fold and fault structures in these basins could be prospective. Oil and gas seepages occur in three main structural elements of the arc: (i) the Neogene molasse, (ii) the Bobonaro mid-Miocene olistostrome, and (iii) the Mesozoic-Permian strata of Australian slope and shelf facies.

The inner volcanic arc is not considered prospective for hydrocarbons because

1: This contribution was invited as a background paper to one of the multidisciplinary transect studies recommended by the IDOE Workshop on Metallogenesis and Tectonic Patterns in East and Southeast Asia, held in Bangkok, 24-29 September 1973.

of their volcanic history, the smallness of the islands, and the steepness and depth of the surrounding sea floors.

INTRODUCTION

The Outer and Inner Banda Arcs form a segment of the strongly-curved double island arc of Eastern Indonesia. The Inner Arc is the eastward continuation of the volcanic Sunda Arc (Sumatra, Java and the Lesser Sunda Island), and consists of islands diminishing in size eastward from Flores through Wetar to the tiny island of Manuk in the Banda Sea. The Outer Arc consists largely of sedimentary rocks, of both Asian and Australian affinities, comprising Sumba, Timor and smaller islands as far as the Kai Islands, with apparent continuity round the north side of the Banda Sea with Seram and Buru (*Fig. IV–1*).

The southern part of the Outer Banda Arc is separated from the present edge of the Australian continental shelf by the narrow Timor Trough between 1,000 and 3,000 m deep. The location of the plate boundary between the Indo-Australian and Eurasian Plates in this area is under debate, but there is some evidence that it lies north of Timor; seismic and other

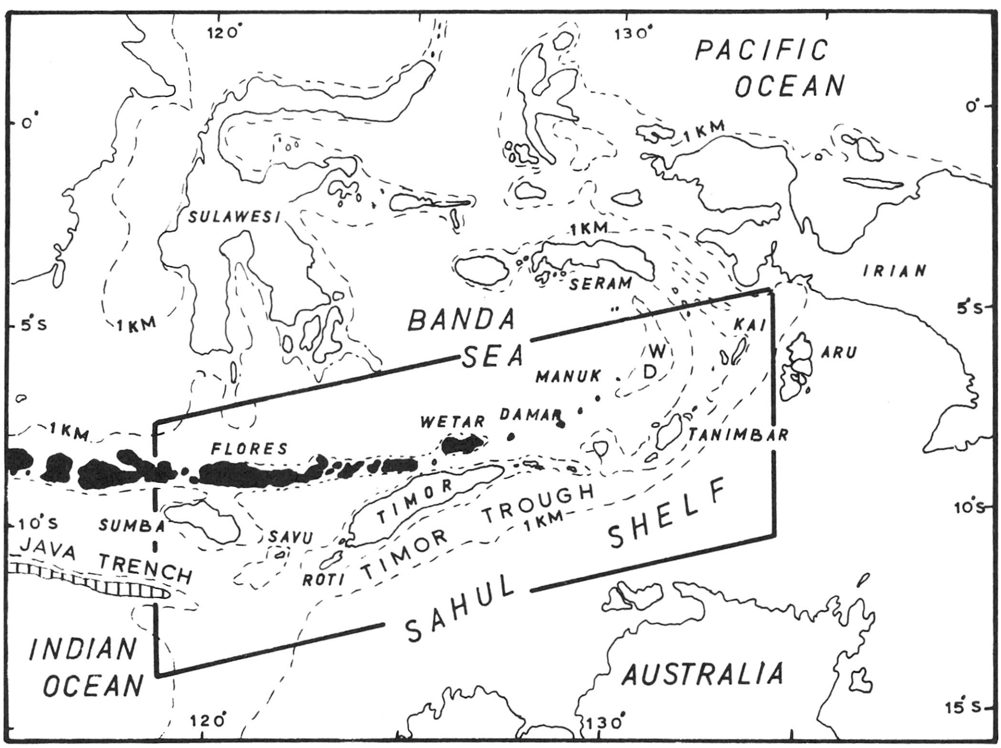

Figure IV–1. Eastern Indonesia with the area of the southern Banda Arcs enclosed within the thick line. The volcanic Inner Banda Arc islands are shown in black; Sumba is included in the Outer Banda Arc. WD = Weber Deep, 7,440 m.

evidence suggests that the arcs were formed in response to northward underthrusting of the Indo-Australian Plate. Along this segment of the boundary, the underthrusting element was the Australian craton, which produced significantly different results compared to the arc segment to the westward, where only oceanic crust was involved in the underthrusting.

Recently-published seismic profile across the Timor Trough (Beck and Lehner, 1974; CCOP-IOC, 1974) indicate that the Mesozoic and Permian strata underlying the Australian shelf extend northwards beneath the trough and, on the north side adjacent to the Outer Arc islands, appear in the reflection profiles to be imbricated (*Fig. IV–2*). Australian-type Mesozoic facies rocks crop out on Timor, Leti, Moa, Babar and Tanimbar, while the Australian-type Permian facies are found on Timor and Leti. In outcrop, these strata display compressional folding and faulting characteristic of an imbricate zone; similar imbricate structure is seen in the seismic profiles mentioned, on the north side of the Timor Trough.

Also present in Timor, Leti, Moa and Babar are Permian and Mesozoic Asian-type facies which rest on thrusts by which they were emplaced from the north (van Bemmelen, 1949; Audley-Charles, 1968).

Fitch (1972), Hamilton (1973), Katili (1973) and Warris (1973) interpreted the Timor Trough and its eastern extension as a subduction zone. More recently on the basis of a seismic reflection survey Beck and Lehner (1974) have supported this interpretation and claimed that the Timor Trough is the continuation of the Java Trench. However, it was argued by Audley-Charles, Carter and Milson (1972) that the spatial relationship between

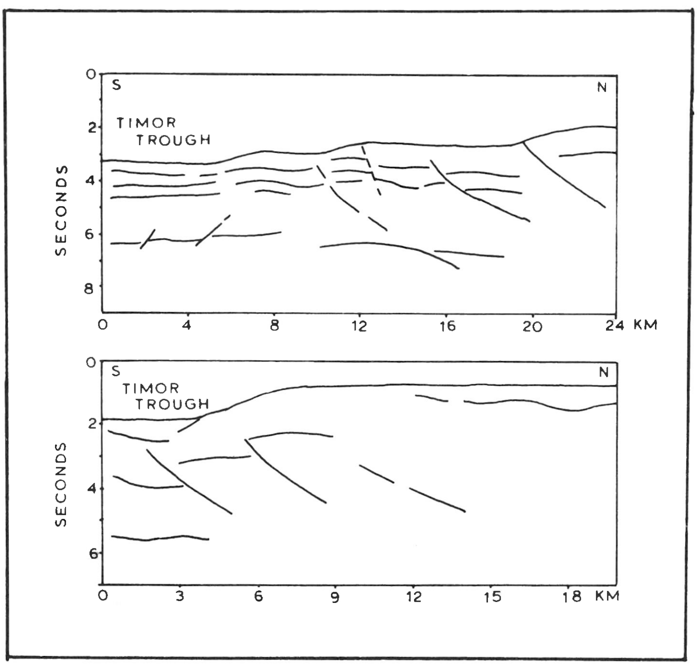

Figure IV–2. Tracing of the principal seismic reflectors encountered in seismic profiling across the Timor Trough (from Beck and Lehner, 1974). Water depths vary between 600 and 2,000 m in these profiles; the vertical exaggeration is about x2. Evidence of compressional folding and imbrication is seen on the north side of the Trough.

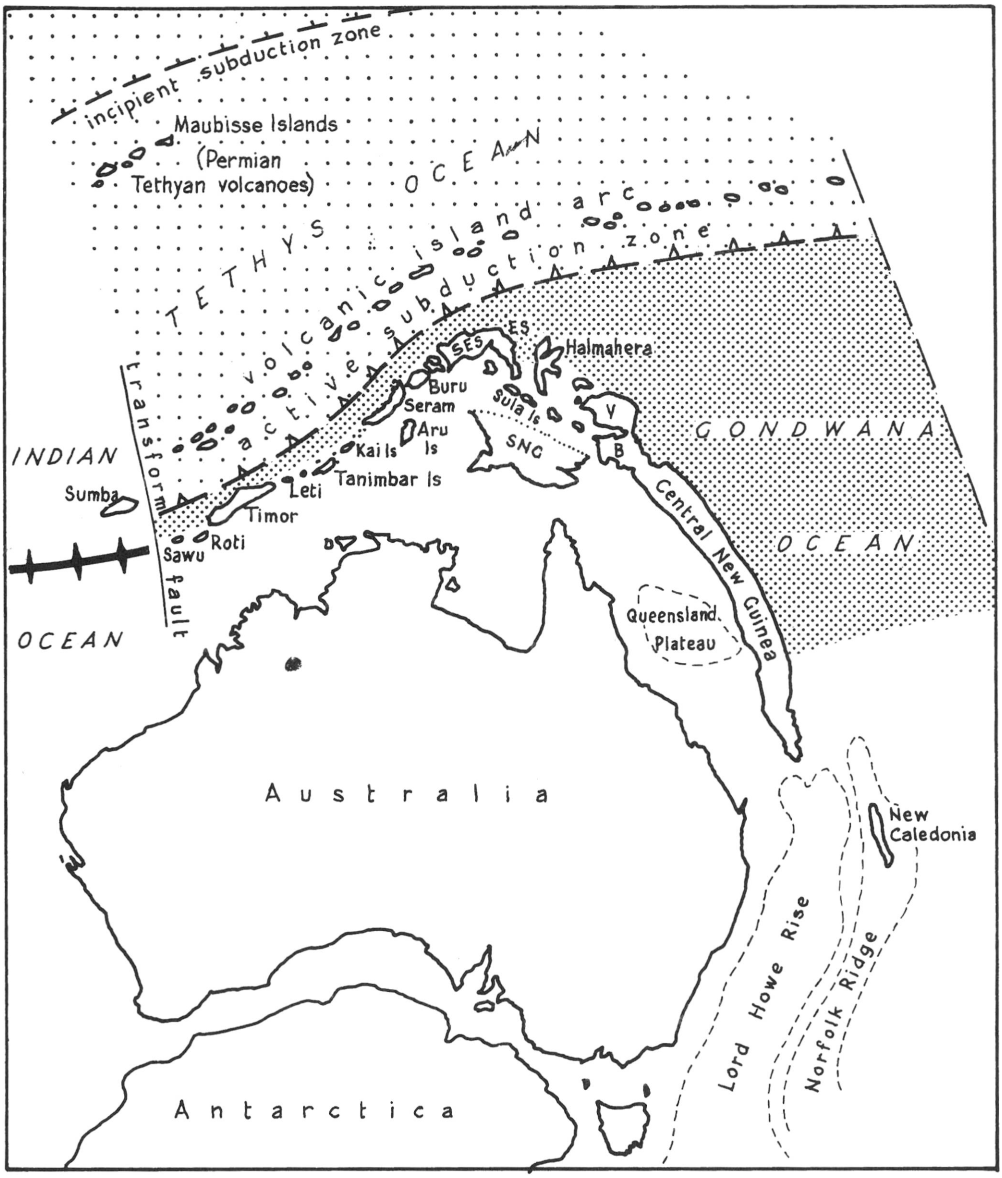

Figure IV–3. Palaeogeographic map of the first of the series of collisions between the northern Australian shelf and a subduction zone, which probably took place in Late Jurassic-Early Cretaceous. The volcanic island arc was formed above a northward-dipping Benioff zone, and was subsequently carried down a later subduction zone during a Middle Miocene collision. Note the position of Sumba, which was rifted away from the Australian continental margin by spreading of the Indian Ocean floor (spreading axis shown by thick spiked line), and which became separated from the Australian margin by a transform fault. SES = southeast arm of Sulawesi, ES = east arm, SNG = southern New Guinea, V = Vogelkop (Cenderawasih), B = Bomberai. The Maubisse Islands no longer exist as such. (Modified from Audley-Charles, Carter and Milsom, 1972).

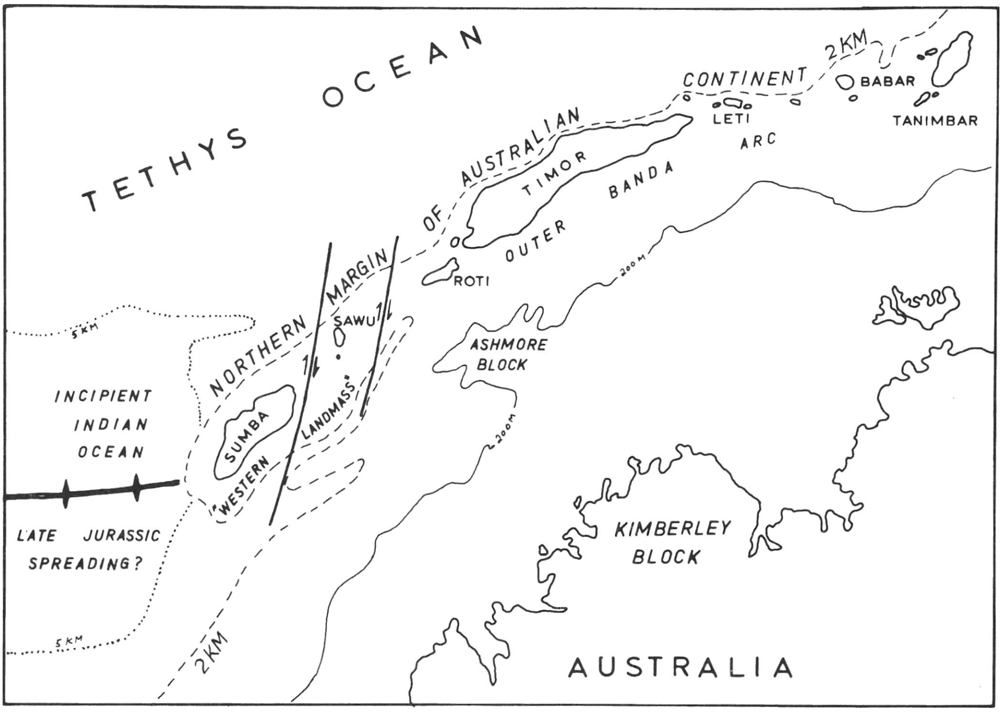

Figure IV–4. Palinspastic interpretation (Late Jurassic) of the early evolution of Sumba as a block detatched from the northern Australia continental margin. The wrench (transcurrent) faults shown represent the initiation of the Sumba fracture as a response to the early spreading of the eastern Indian Ocean floor. The "western Landmass" refers to the recognition in the area of a Late Jurassic-Early Cretaceous palaeogeographic landmass by Warris (1973).

Note that all submarine contours, 200, 2,000 and 5,000 m, are shown in their present positions except that the Sumba 2,000 m ridge has been rotated anticlockwise to bring it adjacent to the 2,000 m contour at the Australian shelf margin. Similarly, all islands are shown in their present-day positions except Sumba and Sawu, which have been rotated anticlockwise with the ridge. (After Audley-Charles, submitted).

the southern Outer Banda Arc islands and Australia has not altered significantly since at least the beginning of the Permian, putting forward evidence in support of their view that no subduction has occurred between Australia and the Outer Banda Arc islands from Timor to Tanimbar. More recently it has been argued that a major transcurrent fault separates eastern and western Indonesia (Audley-Charles, submitted); it was suggested that the Java Trench developed marginal to southeast Asia while the Banda Arcs developed marginal to the Australian continent as it drifted about 3,000 km northwards during the Cenozoic (*Fig. IV–3*). It was also argued by Audley-Charles (submitted) that Sumba represents a portion of the Australian continental margin rifted away from the continent by sea-floor spreading in the eastern Indian Ocean during the late Mesozoic (*Fig. IV–4*). Sumba then became separated from the Outer Banda Arc islands by the transcurrent Sumba fracture. This protected Sumba from involvement in the series of collisions between the Outer Banda Arc and a succession of subduction zones associated with the Cenozoic northward drift of Australia.

It may therefore be postulated that the pre-Cretaceous history of Sumba should be like that of the islands of the Outer Banda Arc, for during that time it formed part of the margin of the Australian continent where shelf and slope facies accumulated. It is expected that the Cenozoic history of Sumba will be found to be very different from that of the Outer Banda Arc.

STRATIGRAPHIC FRAMEWORK OF THE SOUTHERN PART OF THE BANDA ARCS

Precambrian

The oldest exposed rocks in the Banda Arcs are probably the meta-anorthosites of granulite facies that have been overthrust southwards onto Timor (Barber and Audley-Charles, in preparation). They are associated with amphibolite and greenschist facies metamorphic rocks that have also been found in Leti, Moa and other islands of the Outer Banda Arc. The presence of these high grade meta-anorthosites in Timor (*Fig. IV–5*), which elsewhere are only known to represent Precambrian terrains, strongly suggests that these rocks are Precambrian. The pressure-temperature conditions implied by this facies indicate that they were formed near the crust-mantle boundary beneath a continent.

Pre-Permian Palaeozoic

No Palaeozoic rocks older than Early Permian have been found in these islands, rocks of this age being the oldest unmetamorphosed rocks exposed. The history of the Outer Banda Arc and the Timor Sea between the Precambrian and the Permian remains entirely

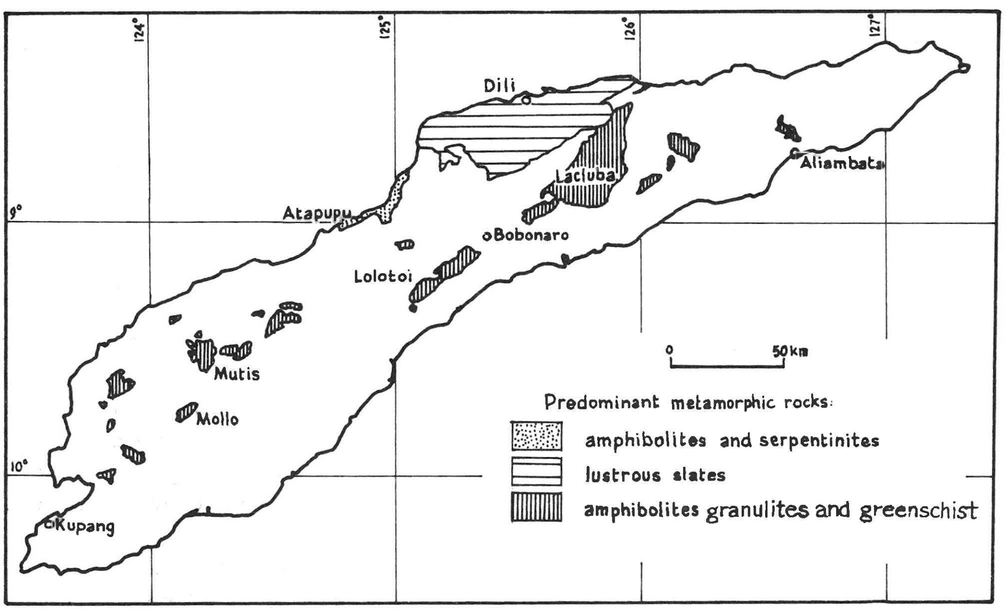

Figure IV–5. Outcrop of metamorphic rocks in Timor (after Barber and Audley-Charles, in preparation).

speculative because of the lack of exposure and well data. South and southeast of Timor lies the Bonaparte Gulf Basin (*Fig. IV–6*) where considerable thickness of Devonian and Carboniferous sediments accumulated (Warris, 1973; Willams, Forman and Hawkins, 1973); it has already been argued that the Outer Banda Arc region formed part of the margin of the Australian continent since the Early Permian, so it follows that the Outer Banda Arc area, lying on the Tethyan (oceanward) side of the Bonaparte Gulf Basin, was probably the site of marine sedimentation during the Carboniferous and Devonian. There is no evidence available to indicate whether such deposits are present at depth in the Outer Banda Arc or whether they were eroded before the Permian.

It has been suggested elsewhere (Barber and Audley-Charles, in preparation) that part of the greenschist facies of the Lolotoi metamorphic overthrusts in Timor may have been produced from continental slope and rise sediments formed during the Palaeozoic.

Permian and Mesozoic: autochthonous/para-autochthonous and allochthonous elements

In Timor and Leti there are two very different facies ranging from Early to Late Permian in age (Audley-Charles, 1968). One facies, represented by the Maubisse Formation, if fundamentally a group of highly fossiliferous limestones associated with volcanic rocks,

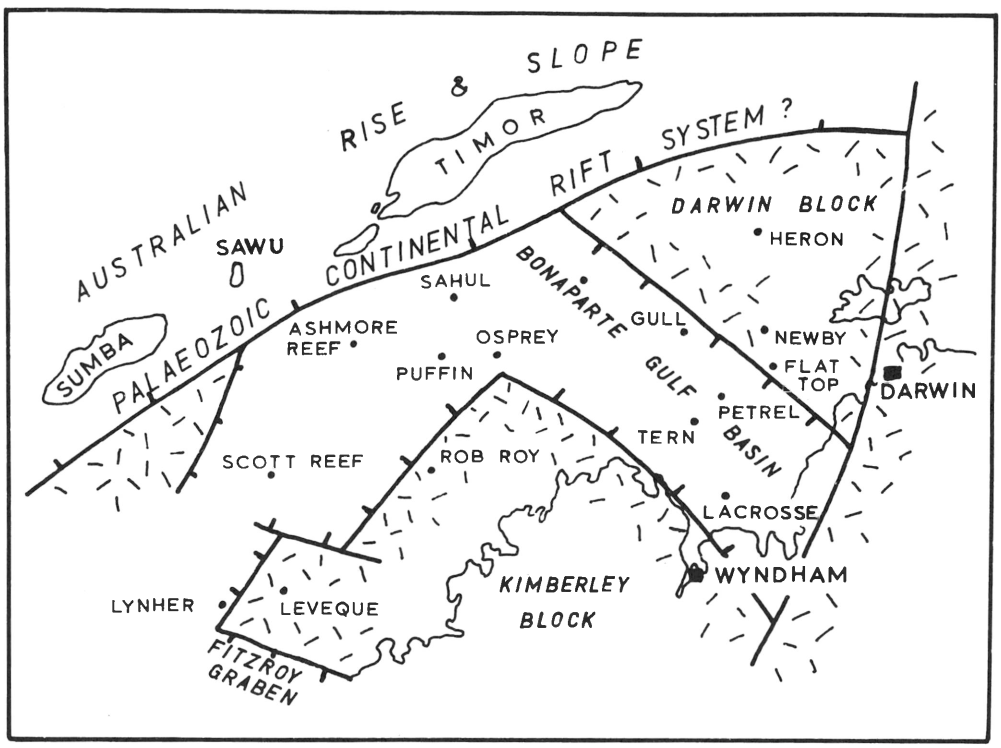

Figure IV–6. Speculative Devonian-Carboniferous palaeogeological map (modified from Warris, 1973). The postulated Palaeozoic continental rift system may mark an old junction with Laurasia. Offshore wells are shown by name.

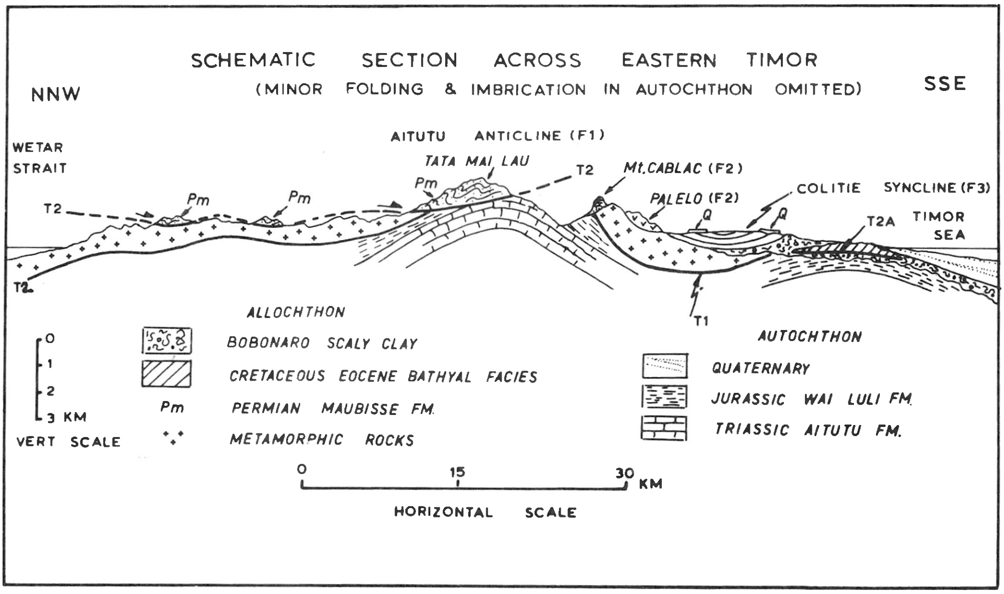

Figure IV–7. Schematic section across eastern Timor showing the relative positions of the various thrust sheets emplaced during the first and second orogenic phases of the Mesozoic-Cenozoic, and their relation to underlying Mesozoic strata, and the overlying Neogene Bobonaro olistostrome and Viqueque molasse. F1 and T1 represent folds and thrusts developed during the first Mesozoic-Cenozoic orogenic phase, F2 and T2 during the second phase, and T2A a thrust sheet emplaced in the second phase but involved in younger movements which displaced it. The F3 Colitie Syncline consists of Viqueque molasse (Plio-Pleistocene) folded by the third and fourth orogenic phases. These rocks are unconformably overlain by Quaternary reefs (Q). (After Audley-Charles, Carter and Barber, in the press).

the fauna indicating that they accumulated in tropical latitudes. The other facies is flysch (the Atahoc and Cribas Formations), lacking a warm water fauna; this appears to be the marine equivalent of the paralic facies developed on the Australian shelf south of Timor (Warris, 1973). The Permian Maubisse Formation and the Aileu Formation always rest with tectonic discordance on the underlying rocks, having been emplaced in their present position on Timor by overthrusting or gravity gliding from the north (*Fig. IV–7*).

The base of the flysch facies is not exposed and no direct information about its basal contact is available. It was described as autochthonous by Audley-Charles (1968), but in view of its strongly folded condition and because it forms part of a major imbricate zone it might be better to apply the term para-autochthonous until the structural relation of these strata to the crystalline basement is known from geophysical work or drilling.

The same strong contrast, in facies of early Mesozoic is found in the older Outer Banda Arc islands. Reef limestones of Triassic age are always found with tectonic discontinuity on younger strata in western Timor, whereas the Triassic calcilutites and shales containing radiolarians and pelagic pelecypods, but with no shelly benthos, are found folded with the underlying Permian flysch and have not been found thrust over younger strata. These deeper-water calcilutites called the Aitutu Formation (Audley-Charles, 1968) resemble the

Triassic limestones found in wells drilled in the Australian shelf south of Timor (Warris, 1973). The Triassic reef limestones that are only found as allochthonous units in Timor must have originated in the tropics, while the other Triassic facies composed of Aitutu radiolarian calcilutites appear to be related to facies deposited on the margin of the Australian craton when it was attached to Antactica and in high southern latitude (Smith, Briden and Drewry, 1973). They pass up without apparent break into the Jurassic Wai Luli Formation which consists mainly of marls, shales, siltstones and sandstones. The top of the sequence is marked by evidence in Middle to Late Jurassic time (Audley-Charles, 1968).

There appears to have been an important break at the end of the Middle Jurassic, represented in subsurface sections of the Ashmore-Sahul Block by evidence of emergence and erosion (Warris, 1973). A contemporaneous break appears to be present in Timor and other islands of the Outer Banda Arc where the Late Jurassic and Early Cretaceous strata seem to be missing. The Cretaceous strata of Timor had been thought of as autochthonous, but they are now known to be allochthonous in western Timor (Audley-Charles, Carter and Barber, in the press), and there are good grounds for suspecting they are allochthonous in eastern Timor, although this needs reinvestigating in the field. The Cretaceous rocks of western Timor can be shown to have been emplaced by overthrusting or gravity sliding from the north. These were described by Audley-Charles, Carter and Barber (in the press), who suggested they were continental slope and rise deposits, but further study is required before their palaeogeography can be interpreted with confidence. These bathyl-type Cretaceous rocks pass up into Palaeogene strata of similar facies.

No shallow-water Cretaceous deposits have found in Timor or other islands of the Outer Banda Arc, including Sumba, although the origin of what are described in Tanimbar as Globigerina-marls (van Bemmelen, 1949) is uncertain in the absence of more detailed information.

Cenozoic: Palaeogene

In Timor there are two distinct Palaeogene facies: an allochthonous bathyal facies associated with allochthonous bathyal Cretaceous strata, and a neritic-littoral facies, including reef developments at several stratigraphic levels, which sit with stratigraphic contact upon overthrust metamorphic rocks of the Lolotoi Complex. In the other islands of the southern Outer Banda Arc all the Palaeogene strata have been described as either of neritic or littoral facies (van Bemmelen, 1949). In all these islands the Palaeogene sediments have been described as overlying the pre-Cenozoic strata unconformably, although in Jamdena of the Tanimbar Islands there seems to be some doubt about the nature of the basal contact of the Eocene.

Recent detailed studies in Timor have shown that, although the basal contacts of the Palaeogene sediments are sedimentary unconformities, there are some situations where it is not possible to be certain that Palaeogene strata have not been carried to their present position on the back of the metamorphic thrust sheets. It is hoped that further field studies will resolve this ambiguity.

Middle Miocene

This was the time of a major orogenic phase throughout the Outer Banda Arc for which there is abundant field evidence which has been reviewed recently (Audley-Charles, Carter and Barber, in the press). This orogenic phase resulted in compressional folding and the emplacement of large thrust sheets with a major olistostrome called the Bobonaro Scaly Clay, that extends from Raijua (between Sawu and Sumba) eastwards as far as the Kai Islands (Higgins and Saunders, 1974).

Sumba differs from the Outer Banda Arc islands in lacking any evidence for this Mid-Miocene orogenic phase, but there is evidence of two Palaeogene folding phases.

Late Miocene to Pleistocene

Above these allochthonous units emplaced by the Mid-Miocene tectonic activity the younger Cenozoic strata are autochthonous. Three principal facies are developed in the Outer Banda Arc: (i) a tuffaceous marly basinal marine deposit, (ii) a molasse which is largely marine and (iii) raised reef terraces. In Timor these deposits amount to about 2,000 m thickness while in the offshore basins they may be about 3,000 m thick.

STRUCTURAL FRAMEWORK AND TECTONIC HISTORY

Metamorphic rocks

The metamorphic rocks of Timor are found lying on folded thrust planes above unmetamorphosed Permian and Mesozoic strata of Australian facies (*Fig. IV–7*). In most of the other islands in the southern Outer Banda Arc, the base of the metamorphic elements has not been seen, so in these islands there is no direct evidence for the structural position of the metamorphic rocks, except in Leti where they were described as imbricated by van Bemmelen (1949). The apparent similarity of the metamorphic rocks throughout these islands may suggest they are all allochthonous like those of Timor.

In Sumba the oldest dated rocks are Jurassic sedimentary and volcanic rocks which have been slightly metamorphosed to hornfels in places (van Bemmelen, 1949). The apparent absence of metamorphic rocks, of the type found in the other Outer Arc islands, and the absence of other overthrust sheets in Sumba, together with the presence of calc-alkaline intrusive igneous rocks of either Cretaceous or late Jurassic age, indicates that it had a very different post-Jurassic tectonic history from the southern Outer Arc islands, which received the various allochthonous units during the Cenozoic and which lack calc-alkaline intrusions in the young Mesozoic autochthon.

Late Jurassic to Early Cretaceous movements

The apparent absence of Late Jurassic and Early Cretaceous sediments from the autochthonous or para-autochthonous units in all these islands may be related to the uplift and erosion of the Ashmore-Sahul Block at this time (Warris, 1973). Warris suggested that large transcurrent movements occurred associated with the Cretaceous development of the Wharton Basin (the eastern Indian Ocean). Audley-Charles (in the press) argued that these developments were also associated with the rifting away of Sumba from the margin of the Australian continent (*Fig. IV–3*).

Late Cretaceous-Early Eocene orogenic phase

The evidence for this orogenic phase, involving compressional folding and large-scale overthrusting of metamorphic rocks, has been discussed in detail elsewhere (Audley-Charles, Carter and Barber, in the press). It was concluded that although the evidence for this phase in Timor is strong, there remains some doubt as to its having happened because it is possible that the Palaeogene strata, whose position is critical to the dating of the thrust sheet emplacement, were carried to their present position on the back of the metamorphic thrust sheets during the later Mid-Miocene orogenic phase. More recent work in Timor suggests a late Jurassic-Early Cretaceous date for this phase rather than Late Cretaceous-Early Eocene, but the ambiguity associated with the Palaeogene strata remains.

In Tanimbar the folded Jurassic strata are overlain unconformably by Eocene sediments, providing evidence for a post-Jurassic and pre-Eocene folding phase (van Bemmelen, 1949). In Sumba there is also evidence of a post-Jurassic and pre-Eocene folding phase.

Palaeogene tectonics

The persistence of littoral and neritic Paleogene facies in the southern part of the Outer Banda Arc suggests a relatively stable period during which Australia and, it has been argued (Audley-Charles, Carter and Milson, 1972), the Outer Banda Arc region drifted northwards.

The Palaeogene history of Sumba is in marked contrast to this, for here two separate phases of moderately strong folding are recorded, one at the Eocene/Oligocene boundary and the other at the Oligocene/Early Miocene boundary (van Bemmelen, 1949).

Mid-Miocene orogenic phase

There is overwhelming evidence from Timor for a major orogenic phase involving the emplacement of large-scale overthrust sheets of Permian limestones and volcanic rocks (the Maubisse Formation) associated with lustrous slates (the Aileu Formation) as well as the emplacement of the large-scale Bobonaro olistostrome.

There is evidence for a Middle to Late Miocene orogenic phase involving overthrusts and/or emplacement of the Bobonaro olistostrome on Leti, and in the Tanimbar and Kai Islands. Sumba is anomalous in apparently not having been involved in this orogenic phase.

Plio-Pleistocene orogenic phases

Two folding phases in Timor have been dated as Early Pliocene and Early Pleistocene. In the Kai and Tanimbar Islands there is evidence for at least one Plio-Pleistocene folding phase.

Late Cenozoic faulting

There is abundant evidence in the form of raised reefs and alluvial terraces for the Plio-Pleistocene uplift of the islands of the Inner and Outer Banda Arcs. It has been argued recently that the inter-arc trough extending from the Sawu Sea through the Wetar Strait eastwards has been downfaulted about 3,000 m since the Middle Pleistocene (Audley-Charles and Hooijer, 1973). There is also evidence for the downfaulting of the southern margin of the Outer Banda Arc islands between Timor and the Kai Islands that has been associated with the development of the marginal offshore Neogene basins. These basins have become filled with marine molasse as a result of the uplift of the islands. Boutakoff (1968) reported about 3,000 m of Neogene sediments in the marginal offshore basins off the southern coast of Timor.

TECTONIC INTERPRETATIONS

There are two main interpretations of tectonic origins of the islands of the Outer Banda Arc:

1. Tectonic mélange: this interpretation is favoured by Hamilton (1972 and 1973) who regarded these islands as a wedge of chaotically-mixed slices of Asian and Australian elements riding above a northward dipping Benioff zone. He considered that the Timor Trough and its eastern extension was a continuation of the Java Trench, a view supported by Beck and Lehner (1974). According to Hamilton (1973), Katili (1973) and Warris (1973) the Timor Trough marks the plate suture between Asia and Australia in which subduction has occurred during the late Cenozoic.

2. Outer Banda Arc is the deformed margin of the Australian continent: This interpretation was put forward by Audley-Charles, Carter and Milsom (1972), who considered the Outer Banda Arc islands to have a crystalline basement of Australian continental crust, which extends below the Timor Trough and the Sahul Shelf (*Fig. IV–8*). This interpretation views the Asian elements as having been emplaced on these islands by overthrusting on gravity gliding from the north. It considers the Permian and Mesozoic Australian facies in these islands as having been originally deposited on Australian continental crust above the shelf, slope and rise of the margin (*Fig. IV–6*); they are therefore regarded as autochthonous although the compressional folding and imbrication they display might have detached them from the crystalline basement, so that they may be better termed para-autochthonous. No direct geophysical or well evidence is available to resolve this uncertainty. The compressional folds and overthrusts are considered to be the products of repeated Cenozoic collisions between the northward drifting Australian continent and a series of subduction trenches in

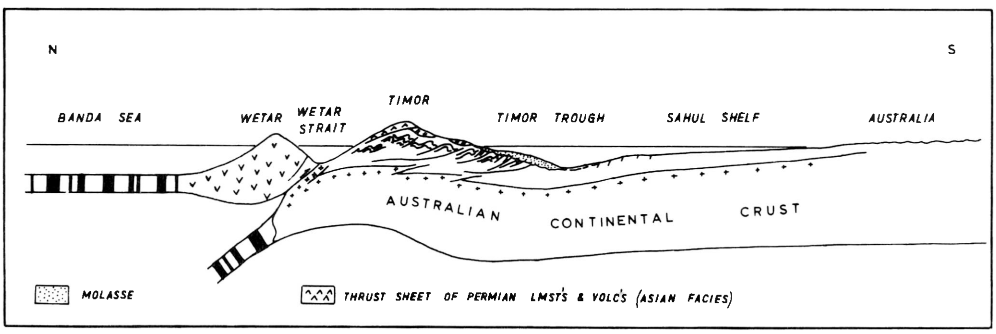

Figure IV–8. Schematic speculative cross section through the southern part of the Banda Arcs, the Timor Trough and the Australian shelf, to show an interpretation of the present crustal structure. The subduction zone is interpreted to be sited north of the Outer Arc (Timor) and to dip northwards, but subduction is no longer active here because the continental crust of Australia has reached the trench zone (Wetar Strait). The volcanic arc immediately north of Timor shows no present-day volcanicity, subduction having ceased.

Timor is interpreted as an imbricate zone of Australian Permian and Mesozoic shelf and slope facies rocks, overlain by various thrust sheets and Cenozoic deposits. The lowest overthrust sheets in Timor are thought to consist of crystalline continental basement (indicated by $^{+++}$; see *Fig. V–7*). Oceanic crust is shown by black and white bands.

which the Benioff zone consistently dipped north away from the Australian continent.

It is hoped that seismic refraction studies will eventually be made in this region of the Outer Banda Arc islands and Australian Shelf so that critical evidence will be obtained to indicate whether the Outer Banda Arc islands are underlain by continental crust connecting them to Australia (*Fig. IV–8*) or whether, as Hamilton (1973), Katili (1973), Beck and Lehner (1974) and Warris (1973) have suggested, the islands are separated from Australia by a zone of major crustal underthrusting below the Timor Trough.

These two different interpretations of the tectonics of the region bear directly on the view taken of the petroleum prospects of the Outer Banda Arc. Hamilton's (1973) interpretation of the islands as a wedge of tectonic mélange above a Benioff zone excludes the prospect of economic hydrocarbon traps in the pre-Miocene rocks because their chaotic and rootless condition would rule out scientific exploration techniques even if reservoirs could have survived such deformation. Only the autochthonous Plio-Pleistocene marine molasse would be prospective.

The second interpretation, favoured by the present authors, is that the Alberta-foothills-type structure of the autochthonous or para-autochthonous Permian and Mesozoic Australian facies (*Figs. IV–7 and IV–8*) could be economically prospective. This interpretation also allows for prospects in the Palaeogene and Neogene deposits as discussed below.

PETROLEUM PROSPECTS

The Inner Banda Arc is a volcanic island arc that available evidence seems to indicate was initiated in the Middle Miocene (Audley-Charles, Carter and Milsom, 1972). That part of the volcanic arc opposite Timor, the islands of Alor, Wetar, etc., lacks active volcanoes and may have been extinct since the Middle Pliocene. The petroleum prospects of this volcanic arc appear to be poor owing to the young volcanism and the rapid deepening of the sea floor (to 3,000 m) close to the islands.

The larger islands of the Outer Banda Arc (Timor and Seram) have long attracted the attention of explorers for petroleum because of the presence of oil and petroliferous gas seepages (Gribi, 1973).

The oil and gas seepages of Timor (Audley-Charles, 1968) occur in three quite distinct structural elements: (i) the Permian and Mesozoic strata of the autochthon/para-autochthon, (ii) the Bobonaro Scaly Clay mid-Miocene olistostrome which has gas seepages only, and (iii) the Viqueque Group of Neogene molasse. The type of oil found in these seepages varies according to the host rock. The oil found in the Permian and Mesozoic strata is either 39°–40° A.P.I. gravity with a mixed base, or a 22° A.P.I. gravity, asphaltic base with 4 percent sulpher content. In contrast the oil seeping from the Cenozoic rocks is 34° A.P.I. gravity with a mixed base (Boutakoff, 1968). It should be noted that in the north-east part of the Outer Banda Arc oil has been obtained from 18 wells in Seram at a rate of 2,000 barrels of 21°–25° oil per day in 1971. The oil is obtained from Pleistocene bar sands, according to Gribi (1973).

Petroleum prospects in the pre-Cenozoic strata

Based on the interpretation favoured here, that the Permian and Mesozoic strata of

Australian facies in the Outer Banda Arc represent a large imbricate zone (*Fig. IV–8*) comparable with the type of structure reported from the southern foothills and front ranges of the Rocky Mountains of western Canada (Fox, 1969), these strata in the Banda Arcs could be prospective. In the Rocky Mountains foothills drilling confirmed repeated large thrust slices amounting to more than 3,000 m thickness. If this foothills tectonic model applies to the pre-Cenozoic strata of the Outer Banda Arc then, in view of the oil and gas seepages, there could be traps for petroleum if sufficient reservoir characteristics are present in the thick Permian quartz arenites, the much less common calcirudites and calcarenites of the Trias and the quartz arenites of the Jurassic. The obstacles to exploring for these prospects are the complex geometry of the structures, and the difficulty of obtaining subsurface data of these strata below the cover of Cenozoic deposits and allochthonous elements. Other discouraging factors include the possibility that these strata have been too deeply buried and the high degree of fracturing they may have suffered, which may have reduced their reservoir potential.

Petroleum prospects in the Palaeogene

The presence of reef limestones of Eocene, Oligocene and Early Miocene age throughout these islands suggests that it could be worthwhile seeking them at depth, where they are covered by the Bobonaro olistostrome and Neogene deposits. Attention could be directed to the southern side of the islands east of Roti where the thrust sheets of the Lolotoi Metamorphic Complex, on which the Palaeogene reefs accumulated, have been faulted or folded below the younger cover.

The discouraging factors here would be the possible small size of the targets and the difficulty of locating them.

Petroleum prospects in the Neogene

The thickness and porosity of some sand bodies in the marine molasse sequence encourages exploration, especially since relatively gentle folds are known to have developed during the Plio-Pleistocene. The offshore basins south of Timor and those associated with the Tanimbar and Kai Islands would appear worthy of attention in the present state of knowledge. If the tectonic model for Sumba proposed by Audley-Charles (submitted) is correct, in regarding Sumba as having been rifted away from the Australian margin during the Late Jurassic and Cretaceous, then there might be a prograding wedge of Cenozoic sediments developed in basins on the south side of Sumba. The southeastern part of Sumba, furthest from the volcanic arc, could be worthy of attention both onshore and offshore.

It should be pointed out that there are indications in the Timor area of an Early Pliocene folding phase, which in places was followed by erosion of the anticlines sometimes associated with diapiric intrusion of the Bobonaro olistostrome from below. Much of the sediment filling these offshore basins may be Pleistocene turbidites, the Pliocene sediments which from land-based studies tend to be predominantly lutites, may have been eroded or never deposited in some parts of these basins. However the presence of oil seepages in at least one Neogene anticline at Suai in eastern Timor is an encouragement to exploration of the offshore basins.

ACKNOWLEDGEMENTS

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REFERENCES

Audley-Charles, M. G., 1968, The geology of Portugues Timor: *Memoir Geol. Soc. London*, no. 4, p. 1–76.

———, (submitted), The Sumba fracture: A major discontinuity between eastern and western Indonesia: submitted to *Tectonophysics*.

———, 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.

———, and D. A. Hooijer, 1973, Relation of Pleistocene migration of pygmy stegodonts to island arc tectonics in eastern Indonesia: *Nature*, vol. 241, p. 197– 198.

———, D. J. Carter and A. J. Barber, (in the press) Stratigraphic basis for tectonic interpretations of the Outer Banda Arc, eastern Indonesia: *Proc. Indonesian Petroleum Assoc.*, 3rd Convention.

Barber, A. J., and M. G. Audley-Charles, (in preparation), Significance of the metamorphic rocks of Timor in the development of the Outer Banda Arc, eastern Indonesia.

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

Boutakoff, N. A., 1968, Oil prospects of Timor and the Outer Banda Arc, S. E. Asia: *Austral. Oil Gas Review*, vol. 14, p. 44–55.

CCOP-IOC, 1974, *Metallogenesis, hydrocarbons and tectonic patterns in Eastern Asia*: United Nations Development Programme (CCOP), Bangkok, 158p.

Fitch, T. J., 1972, Plate convergence, transcurrent faults, and internal deformation adjacent to south-east Asia and the western Pacific: *Jour. Geophys. Research*, vol. 77, p. 4432–4460.

Fox, G. F., 1969, Some principles governing interpretation of structure in the Rocky Mountain orogenic belt: *Time and Place in Orogeny*, Geol. Soc. London, p. 23–41.

Gribi, E. A., 1973, Tectonics and oil prospects of the Moluccas, Eastern Indonesia: *Geol. Soc. Malaysia Bull.*, no. 6, p. 11–16.

Hamilton, W., 1972, Preliminary tectonic map of the Indonesian region, 1 : 5,000,000: Open File Report, United States Geological Survey.

———, 1973, Tectonics of the Indonesian region: *Geol. Soc. Malaysia Bull.*, no. 6, p. 3–10.

Higgins, G. E., and J. B. Saunders, 1974, Mud volcanoes—their nature and origin: *Verh. Naturf. Ges. Basel*, vol. 84, p. 101–152.

Katili, J. A., 1973, On fitting certain geological and geophysical features of the Indonesian Island Arc to the new global tectonics: *The Western Pacific: Island Arcs, Marginal Seas, Geochemistry* (ed. Coleman, P. J.), p. 287–305.

Smith, A. G., J. C. Briden and G. E. Drewry, 1973, Phanerozoic World Maps: *Special Papers in Palaeontology*, vol. 12, p. 1–42.

Van Bemmelen, R. W., 1949, *The Geology of Indonesia*: Government Printing Office, The Hague, 732p.

Warris, B. J., 1973, Plate tectonics and the evolution of the Timor Sea, northwest Australia: *Austr. Petroleum Expl. Assoc. Jour.*, vol. 13, p. 13–18.

Williams, L. W., D. J. Forman and P. J. Hawkins, 1973, Sedimentary basins of the Sahul Shelf: *Proc. Indonesian Petroleum Assoc. 2nd Convention*, p. 279–289.

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V. TERTIARY BASINS IN INDONESIA

By

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(with figure V-1, in envelope on back cover)

ABSTRACT

A map of Tertiary basins and important oil fields in Indonesia was prepared to summarize the present state of knowledge. Structural framework is presented by basins and arches, but no fault zones are indicated. At the scale of the present map, any additional detail may not be satisfactorily represented. Petroleum occurrence is expressed by depicting oilfield areas and main oilfields.

INTRODUCTION

Regional maps depicting outlines of Tertiary basins were occasionally published since World War II. Emphasis was usually put on petroleum occurrences within these basins. A large number of papers outlining individual basins were presented at regional or national conferences recently held and they provided additional data. An effort is presently being made by PERTAMINA, the Indonesian State Oil and Gas Enterprise, to compile and publish data on outlines of Tertiary basins from own and other sources. The preliminary sketch map of Tertiary Basins in Indonesia presented as *Figure V-1*[1] tries to summarize the present state of knowledge. It is the intention of PERTAMINA to publish the final outline map in future.

Acknowledgement is respectfully given to the Board of Directors of PERTAMINA to contribute the present map.

EXPLANATORY NOTE TO TERTIARY BASINS MAP

The structural framework is presented as trends defined by thickening, thinning or absence of Tertiary strata. Thickening is represented by basins (more than 1,000 m thick). Thinning covers "arches". At present no effort is made to present faulted zones or regional tectonics. It seems certain that the present knowledge of regional tectonics is strongly influenced by the proven occurrences of very young Quaternary vertical movements. These

1: The original scale of the map is reduced to a half (1: 10,000,000).

forces may have subdued the main Tertiary structural unit. Furthermore, lack of published systematic onshore geology may add to schematic structural knowledge, leading to all too often misrepresentation of Tertiary regional tectonics in this area.

Quaternary and Middle to Lower Tertiary volcanic rocks are included within the Tertiary amongst others. Within Quaternary volcanic rocks all pyroclastics and effusive activities during that time are defined. It is postulated that these extensive deposits cover mainly Tertiary strata. The Middle to Lower Tertiary volcanic rocks, locally important as metallogenic bodies and petroliferous reservoir rocks, were found at places definitely intercalating with thin marine sediments of Tertiary age. Appropriately such stratigraphical phenomena may also represent basinal deposition.

The basins should be thought of as basins at present time. Any conclusion regarding strandline or palaeogeographic boundaries should be made only with complete and sufficient geological evidence. Some subsea contours on basement are given. However, at the scale of the present map other additional details may not be sufficiently expressed. Amongst noteworthy basinal aspects is the phenomenon of small Tertiary basins ("sub-basins" by some authors) within vast irregular pre-Tertiary complexes. This may point out to evidences of dominating Quaternary vertical movements leading to differential erosion of the Tertiary succession.

Emphasis on petroleum occurrence is expressed by depicting oilfield areas and main oilfields. Published data on cumulative production of areas and individual fields, which should be a help to obtaining first impressions on oil potential of the area, are incorporated in *Figure V–1*.

(Paper delivered to the ninth session of the Technical Advisory Group of CCOP held in Bangkok, Thailand from 10 to 18 September 1973.)

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VI. A DECADE AND A HALF OF GEOPHYSICAL EXPLORATION FOR HYDROCARBONS IN INDIA

By

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(with table VI-1; and figures VI-1 to VI-7)

ABSTRACT

Development of the organization and capabilities for geophysical exploration for hydrocarbons in India since independence in 1947 is outlined. At present the organization is staffed with very experienced geophysicists and is equipped with modern data aquisition and digital processing equipment. A few examples showing improvements in seismic data obtained by using sophisticated digital processing techniques are presented. Discussion of marine seismic surveys in Indian offshore areas indicates a substantial thickness of sediments below the Indian continental shelf. Many of the offshore sedimentary basins are continuations of basins outlined on adjacent coastal areas. Structural patterns suggest that basement block tectonics play a significant role in the formation of structures in the overlying sediments. The strikes of the structural deformations generally are controlled by ancient tectonic lineaments.

INTRODUCTION

The occurrence of oil in India was established only about a decade after the drilling of the celebrated Drake well in America. However, at the dawn of independence of the nation in 1947, the country still had very meagre known resources of oil. These were situated on the eastern wing of the country in Assam. The exploitation of these fields was in the hands of a private oil company. The reason that despite the presence of vast sedimentary areas (including offshore) totalling about 1 million sq km the oil potential of the country remained untapped until independence, was a lack of an aggressive exploration policy and a total neglect in this direction at that time.

In order to speed up economic development and industrialization of the nation, it was soon realized that all the available energy resources would have to be rapidly harnessed. Oil being an indispensable source of energy, the Government of India decided in 1956 to form a department for launching a vigorous programme to search and exploit the nation's oil

1: Now with the Geology and Geophysics Department, University of Roorkee, Roorkee 247667, India.

resources. This department was later designated as the Oil and Natural Gas Commission of the Government of India.

Geophysical surveys had been playing an important role in the hunt for hydrocarbons throughout the world since the early part of this century. In recognition of the importance of such surveys in locating hydrocarbons the Oil and Natural Gas Commission (ONGC) established the Directorate of Geophysics as one of its cardinal arms.

GROWTH OF GEOPHYSICAL ACTIVITIES

At the time of inception of the Directorate of Geophysics, there was only a handle of trained and experienced geophysicists in the country to undertake the task of exploring the large sedimentary areas. The instruments available also were meagre. A programme for training the geophysicists in exploration for oil was launched in 1956. The trained personnel formed the core of the crews and geophysical exploration was started in right earnest in 1957. Over the years the number of geophysicist rose and now there are three hundred and eighty geophysicists in various cadres.

The geophysicists have been highly specialized in various disciplines, viz., land seismic, marine seismic, gravity, magnetic, electrical, electrologging, digital data processing, electronics, instrumentation, interpretation and synthesis of geophysical and geological data.

The activities of the Directorate of Geophysics have been carried out on a broad and comprehensive basis. Gravity, magnetic, electrical, seismic surveys and electrologging operations have been organized in keeping with the needs of exploration. The number of land seismic parties has progressively increased from one hired crew in 1957 to the present twenty-six Indian crews belonging to the ONGC. The Commission also operated a marine seismic crew in an Indian Offshore area during the period 1963–1968. It has plans to launch an ultramodern seismic ship in the near future.

There were four gravity-magnetic crews to start with in 1957. Their number rose to a maximum of twelve during 1962 and 1965 but thereafter was reduced as the areas to be surveyed by these methods were covered. The electrologging operations expanded in keeping with the drilling metrage. The growth of geophysical parties is shown in *Figure VI–1*. *Figure VI–2* illustrates the relative percentage of the exploration activity amongst the various techniques.

Basin explored

The country has twenty-seven recognized basins on land. On the basis of geological considerations, however, only fifteen of the basins are considered as moderately to highly prospective for the accumulation of hydrocarbons. These prospective basins have been subjected to systematic geophysical exploration. All the basins now have reconnaissance coverage by gravity and ground magnetic surveys. Five basins have been covered by aeromagnetic surveys. The intensity of seismic surveys has been in keeping with the status of exploration in various basins, being most concentrated in the two petroliferous basins, namely Cambay and Assam-Arakan.

These investigations have taken the geophysical crews over difficult terrain such as desert, marshy, hilly and afforested areas. The marine investigations encountered difficult

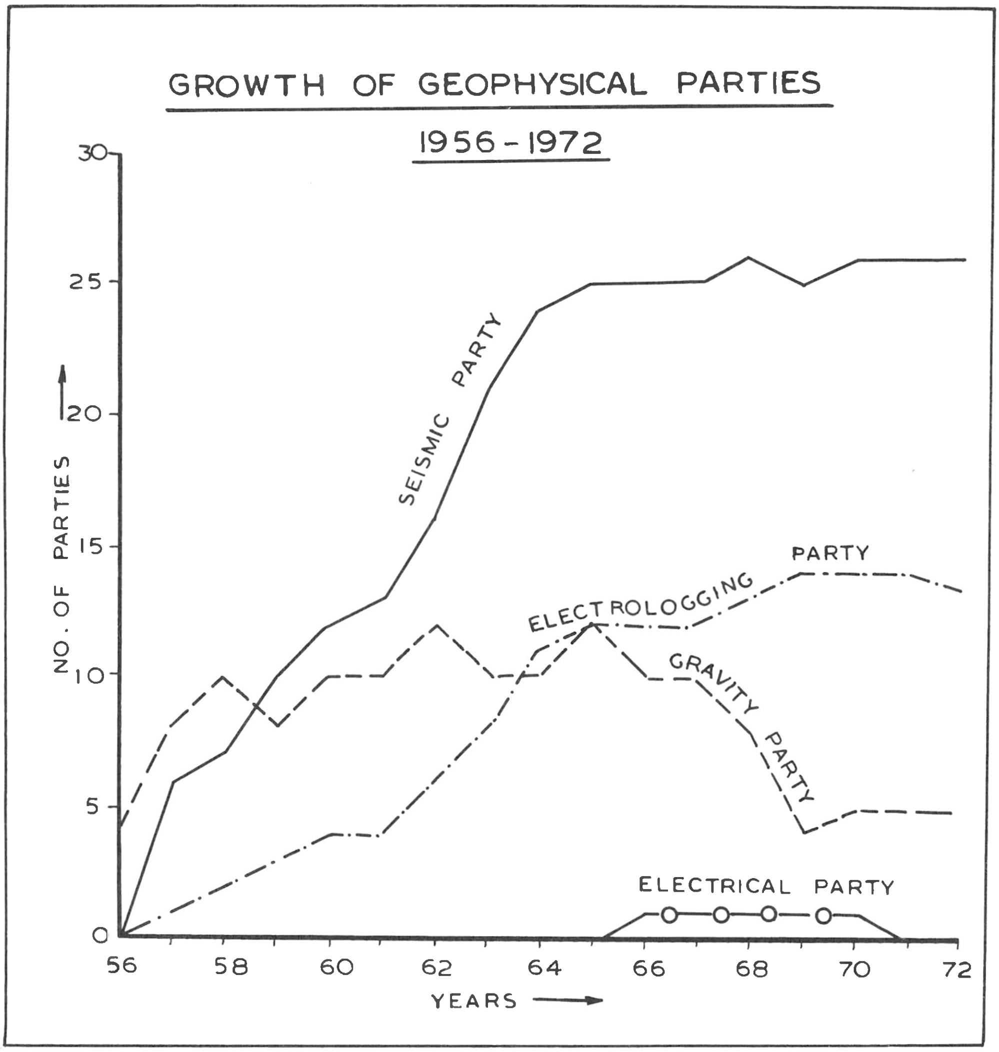

Figure VI-1. Growth of geophysical parties in India, 1956–1972.

conditions including high tides, fast currents and frequent sand bars.

The depth of investigations by seismic techniques has been quite large and horizons have been mapped at depth of around 5 to 6 km in some areas. The survey techniques that have been used include split spread, end on configurations and the common depth point techniques for reflection. The choice depends on the requirement and objectives of the investigations. High resolution seismic investigations have also been done in an attempt to map thin beds. Broad-side offset configurations were found very effective in desert areas where surface noise poses a serious problem. For hill work special data acquisition and interpretation techniques have been developed.

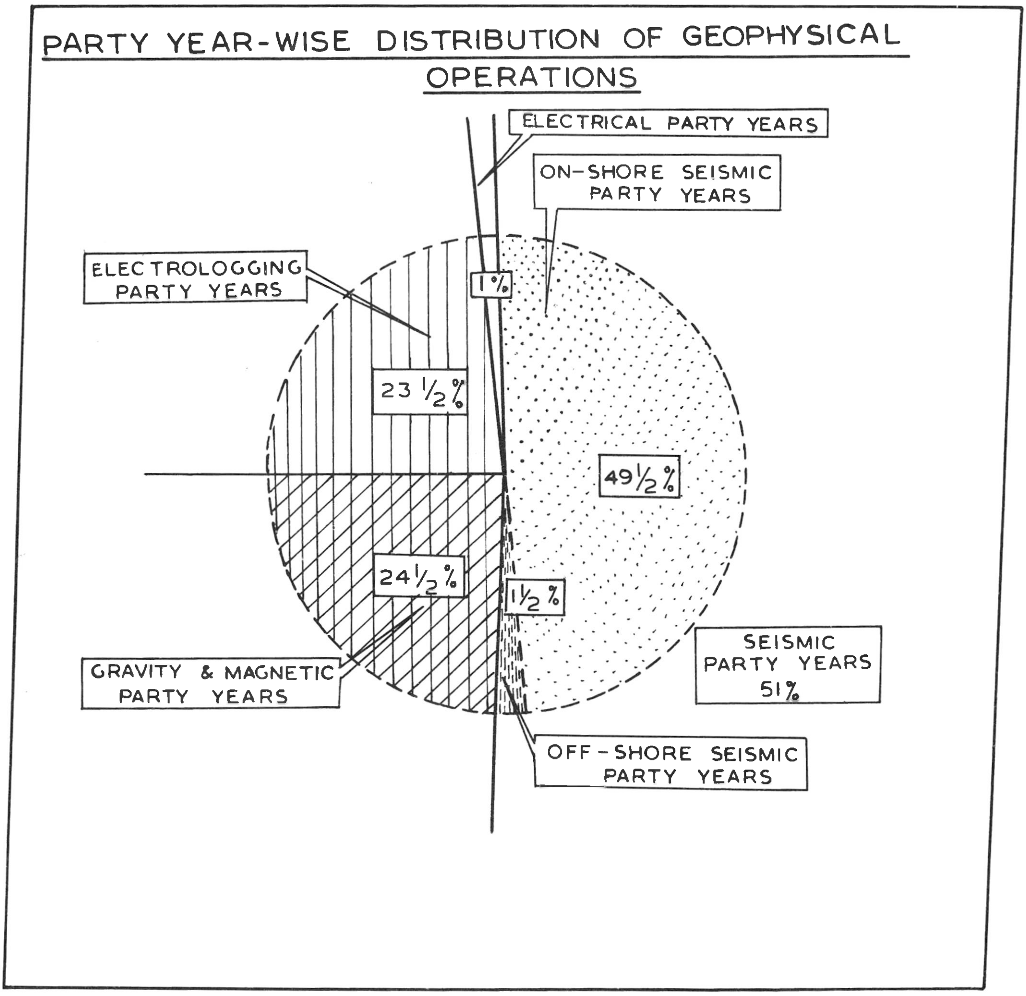

Figure VI–2. Party year-wise distribution of geophysical operations in India.

The electrologging operations have been conducted in deep wells touching 3.2 km routinely. The deepest well logged was a little over 4 km deep. The well log survey consists of SP, lateral and normal resistivity, natural gamma ray, caliper, thermal, neutron-gamma, micro, latero and velocity logs. It is planned to add in near future to the above complement induction, pulsed neutron, micro-latero, CBL, CVL and density logs.

Geophysical equipment

For gravity surveys Worden and Worldwide gravimeters are available. Magnetometers of the Askania vertical force balance type and Askania torsion balance type are provided for ground magnetic observations. Seismic data acquisition until 1970 made use of analog magnetic recording seismic units. A modernization of the seismic crews is underway and already four binary gain digital seismographs have been in operation for the last two years. Four more new digital seismic units will be pressed into operations very shortly.

A comprehensive programme is underway to manufacture geophysical equipment indigenously. Already several seismic amplifiers, control units, well logging units, blasters, cables, well logging devices, portable drilling rigs etc. have been produced.

Digital processing of data

ONGC has a well established seismic data processing centre manned by geophysicists each having over ten years experience in data acquisition and interpretation.

A third generation fast computer with half-inch nine-track tape transports, large fast access disc memory, a fast fourier transform box capable of transforming data into frequency domain and back to time domain using the Cooley-Tuckey algorithm, high speed time domain convolutions, complex multiplications and filtering, analog to digital and digital to analog converters, on-line data monitoring scope etc., are the hardware used for data processing.

Two trace-sequential plotters are available for processed data display and quality control purposes.

With the existing hardware any nine track NRZI recorded data as well as analog recordings on SIE standard tape format can be processed at this centre.

The hardware is being updated by addition of 1,600 bpi tape transports, increase of core and disc memory and addition of a very fast off-line plotter.

The vast repertoire of the software available at present includes the following:

(a) Preprocessing:

1. Demultiplex
2. Binary gain recovery
3. Vertical stack
4. Amplitude recovery
5. Resampling
6. EDIT.

The preprocessing package, as the name implies, is designed for preparing the data for further sophisticated processing. This package provides sequential traces of the seismic record. The signals in these traces have their corrected amplitudes as arriving at the surface. Vertical stacking can be achieved at this stage to reduce the volume of data processing. Similarly, editing of noisy traces or poor quality records is accomplished in the preprocessing stage. The data can be resampled if so desired.

(b) Processing:

1. Minimum phase deconvolution
2. Zero phase deconvolution
3. Statics
4. S.V. normal moveout corrections
5. T.V. band pass filter
6. CDP stack
7. Trace equalization
8. Phase equalization
9. Automatic section migration

10. Automatic residual statics
11. Fan filtering
12. Coherent energy enhancement
13. Reflection picking
14. Trace gather
15. CDP trace sort.

The processing package has options for alternative deconvolution of traces. One may do either the standard minimum phase deconvolution using the concept of minimum delay wavelet or zerophase deconvolution in which the phase is held at zero value.

Removal of residual static correction prior to CDP stack plays an important role in improving data quality. When dealing with large volume of data, an automated process for removal of residual statics becomes very essential. A programme to deal with this source of noise has been developed in which the residual corrections are statistically estimated and are optimized for a specified time gate having maximum interest. The improvement brought about by this process is illustrated in *Figures VI–3* to *5*. *Figure VI–3*(*a*) is a section in which stacking was done without using the automatic residual statics program and *Figure VI–3*(*b*) is the same section in which stacking was done after applying automatic residual statics. Note the improvement in data quality in the latter within the boxed area.

A new technique has been developed for data quality improvement which searches for coherency or reflections laterally. Both the intrinsic reflection character and lateral extent of the reflections are taken into account for enhancing the reflection quality. Improvement in data quality by the application of coherency enhancement technique is illustrated in *Figure VI–4* where *4*(*a*) is without the coherency technique and *4*(*b*) is with the use of the same.

Phase equalization is useful in standardizing the waveform prior to the stacking process. The amplitude spectrum is kept the same as observed whereas the phase is equalized to an optimized standard in each case. This enable considerable enhancement of signal in the CDP stack process output. *Figure VI–5*(*a*) shows a section without using the phase equalization program. *Figure VI–5*(*b*) shows the same data after the application of the phase equalization process. A comparison of the two clearly shows the effectiveness of the process in this case.

(c) Data analysis:

1. Automatic velocity analysis I
2. Automatic velocity analysis II
3. Automatic velocity analysis III
4. Automatic velocity analysis IV
5. Autocorrelation and frequency spectra
6. Sectional correlograms and power spectra
7. Frequency tests.

In modern geophysical exploration a considerable weight is given to data analysis in order to extract as much information as possible regarding the geologic model. Analysis of interval velocity of the subsurface section plays a key role in this task. A number of automatic velocity analysis programmes have been evolved to meet a wide range of situations of data quality etc. The output of one such process which uses the principle of maximization of coherency is displayed in *Figure VI–6*.

The analysis of data regarding the presence of multiples, ringing etc. are done by computing the correlograms and frequency tests. These analyses go a long way in helping to design a proper processing package.

Processing software was designed for ease of operation and enables monitoring of data at each stage of processing if required.

Software is being constantly improved upon by modifications and by addition of new capabilities.

The processing of seismic data is carried out under direct supervision of qualified geophysicists who follow through a job from A to Z.

Success of geophysical exploration

The geophysical exploration has been very successful in determining the thickness of the sedimentary formations and the regional tectonic architecture of the basins (Aithal *et al.*, 1964; Avasthi *et al.*, 1971; Datta *et al.*, 1964; Khattri *et al.*, 1964; Mool Chand *et al.*, 1964; Ray *et al.*, 1964; Sastry *et al.*, 1964; Sengupta and Khattri, 1972). Individual structural features in the sedimentary layers have been reliably mapped. The identification of pay horizons was successfully carried out by ONGC's electrologging crews. All this data has permitted the drawing up of sound exploration policies. Over one hundred and seventy structures have been delineated using geophysical techniques and all the oil and gas discoveries by the ONGC originated from the geophysical investigations.

MARINE EXPLORATION

The shelf area out to the 200 m isobath belonging to India covers a sizable 391,000 sq km. A number of pericratonic basins continue into the shelf areas (Sengupta and Khattri, 1972; Kohli and Raghavendra Rao, 1965). *Table VI–1* lists the various offshore basins and their respective areas. These areas are shown in *Figure VI–7*. Offshore seismic explorations have covered a large proportion of this area in a reconnaissance manner. The total line kilometre shot to date is approximately 28,000. The main concentration of activity has been in the Gulf of Cambay and the adjacent Arabian shelf where the "Bombay High" structure was discovered.

Table VI–1. The areas of various offshore basins.

Basin	Area in sq km out to 200 m isobath
Kutch Offshore	27,600
Saurashtra Offshore	36,400
Cambay Offshore	126,700
Kerala Offshore	67,000
Cauveri Offshore	33,300
Godavari-Krishna Offshore	22,600
Mahanadi Offshore	10,700
Bengal Offshore	35,500
Andaman-Nicobar Offshore	31,000

Initial operations were of conventional type. However, as the time progressed the latest techniques and instrumentation were used. The main results of these surveys are as follows:

Kutch offshore area

The Kutch shelf is about 120 km wide. The offshore region covers both the shelf and the Gulf of Kutch. On land the formations of middle Jurassic to Recent age are exposed with flows of Decan Trap basalts interspersed in the formations of Tertiary and Mesozoic age. The main tectonic trend is E-W along which Mesozoic rocks have been deformed into regional folds. Marine seismic survey has revealed that the sediments thicken towards west in the shelf and reflection times as long as 4.5 sec have been recorded. There is also evidence that Decan Trap flows continue in the offshore areas. The E-W trend has been picked up in the shelf also.

The Saurashtra shelf area has not been explored as yet.

Cambay offshore area

The Cambay offshore region covers the areas of the Gulf of Cambay and the adjoining shelf of the Arabian Sea and constitutes the geological extension of the petroliferous Cambay Basin on land. Seismic surveys have recorded a good number of reflections among which four persistent ones have been mapped over wide areas of the basin. A correlation of the marine geophysical data with geophysical and geological data on land suggests that seismic reflections arises from sediments of Tertiary age. At places the sediments attain a thickness exceeding 5,500 m.

The structural architecture of the basin has been revealed in considerable detail by seismic structural maps. A series of marginal down-to-the-basin step faults characterize the basin flanks on the east. The structural pattern of the basin is dominated by two well known ancient tectonic trends. First, the ENE-WSW Satpura trend characterizes the structural elements in the offshore area adjacent to the coast between Narmada and Tapti rivers. Second, the NWN-ESE trending Dharwar lineament is the controlling factor governing the structures present in the shelf area. The well known "Bombay High" is typical of the Dharwar axis. The structures with Satpura trend appear to have been formed later than those with Dharwar axis.

Although the onshore Cambay Basin contains several oil and gas fields, a commercial offshore oil/gas field in this area is yet to be established. However, a milestone in the history of oil exploration in India was recorded with the oil strike in the offshore Aliabet structure. Whereas the oil deposits in land part of the Cambay basin are of Eocene age the offshore oil strike is probably of Miocene age. This offshore basin acquires a high rating for commercial deposit of hydrocarbons when its large area coupled with large thickness are considered in the light of the oil at Aliabet. Currently the Bombay High structure is under drilling.

Kerala-Laccadive offshore area

The Kerala shelf is about 80 km wide. The Kerala-Laccadive Basin fringes the coast of Kerala where sediments of Miocene age are exposed. These are of marine deltaic origin. The thickness of this sedimentary sheet has been estimated on the basis of gravity and magnetic data to be about 1,000 m.

Reconnaissance reflection profiles have brought to light a westerly monoclinal dip of the formations which are about 800 m thick near the coast. The thickness gradually increases to about 2,000 m near the shelf break. The general westerly dip is intercepted by zones of tectonic disturbance. Fault controlled anticlinal reversals are present. The data suggest the presence of basement blocks.

The reflection horizons follow over the shelf and continental slope and resume a flat dip in the abyssal zone.

Presence of high seismic velocities in Elikalpeni and Kalpeni island areas has been interpreted to be indicative of the presence of carbonate reefs.

Cauveri offshore area

In Cauveri area the shelf has a width of about 40 km. The Mesozoic-Cenozoic Cauveri Basin occupies the coastal area on land. Offshore surveys, which have been of semi-detailed nature, have established the offshore extension of the pericratonic basin. The area is characterised by three dominant reflections, the last of which appears to be arising from the base of the sedimentary layers. The maximum thickness of the sedimentary deposits may be around 4,500 m.

The structural picture based on seismic data shows that horsts and grabens are present, trending in a NE-SW direction. These are offshore continuations of the similar features found on the land. The tops of the ridges are marked by the disappearance of reflections. Numerous faults are present giving rise to the formation of basement blocks.

Godavari-Krishna offshore area

On the Godavari-Krishna coast a pericratonic basin of the same name has been delineated. This basin has sediments of Mesozoic and Cenozoic age which are dominated by the NE-SW tectonic parallel to the ancient Eastern Ghat basement trend. In the reconnaissance offshore seismic surveys four main reflecting horizons have been traced of which the last may be from the basement. This terminating reflector has been recorded a two-way reflection times as long as 4 seconds. The youngest sediments lying above the shallowest mapped horizon record the maximum increase in thickness from about 100 m near the coast to 2,500 m near the shelf edge. The sediments are characterized by gentle homoclinal regional dips of the order of $2°$–$3°$ towards south-east. This background tilt is interrupted by local structural deformations of small amplitude. An important finding is that this basin appears to be confined to within the limits of the continental slope.

Mahanadi offshore area

The Mahanadi Basin as known on land is a pericratonic basin. Gravity and magnetic investigations carried out on the coastal strip indicate that the sedimentary cover is relatively thin but increases rapidly towards the coast in the southeast direction. The structural pattern is dominated by an ENE-WSW strike.

Among the many reflections recorded in seismic profiles two persistent ones have been traced. A structural dip of about $1.5°$ towards southeast is displayed by the lower formations. The deeper of the two reflections is recorded at 1,200 m depth near the coast and drops to about 4,000 m in the south east, whereas the shallower horizon falls from a depth of 350 m to 1,700 m.

Bengal offshore area

A sizable sedimentary basin known by the name of Bengal Basin lies on the eastern margin of the Indian craton. The shelf zone of this basin lies in Indian territory and its subsurface geology is well understood. Sedimentary formations ranging in age from upper Gondwana to Recent are present. The presence of a NE-SW trending hinge zone passing southeast of Calcutta has been established on the basis of seismic data.

The Bengal Basin extends into the Bay of Bengal. The sedimentary thickness exceeds 6,000 m. A number of seismic reflections have been recorded near the land which however, gradually lose character towards south and southeast. The extension of the hinge line established on land has been found in the offshore areas also.

Andaman-Nicobar offshore area

This area has not been surveyed by geophysical method as yet. However, geological investigations on the islands have demonstrated this as a highly promising area for the search of hydrocarbons.

Offshore seismic surveys have shown that the coastal basins have a considerable thickness of sediments. The age of these formations range from upper Gondwana to Recent. The sediments have been deformed and much light has been shed on their tectonic pattern which shows a dominance of block tectonics in the eastern coast basins.

Sediments of Mesozoic and younger ages have proved to be the major producers of all offshore oil and gas. The sediments in Indian shelf areas are largely of this age interval. Geological evidence suggests that the facies of formations is likely to be favourable for generation and accumulation of hydrocarbons and considerable deposits of oil and gas may be discovered in the Indian offshore regions.

CONCLUSIONS

The country has over the years developed a well organized and well equipped modern organization for geophysical exploration. The organization has acquired considerable experience in conducting surveys over difficult terrains of various types. Marine seismic operations in the Gulf of Cambay had been conducted under difficult offshore conditions. The seismic crews are progressively being equipped with "state of the art" field acquisition systems. The digital data processing centre has a vast repertoire of software and continues to develop new and useful processes to improve the subsurface mapping capabilities. Well logging operations have been effective in identifying the pay horizons. A programme is underway for the progressive manufacture of geophysical equipment indigenously. The ONGC has also a well established wing for research and development in the field of geophysics which also undertakes the training of personnel as and when required.

The offshore surveys have revealed the presence of substantial offshore sedimentary basins having formations ranging from upper Gondwana to Recent. These areas hold promise to have large deposits of hydrocarbons.

REFERENCES

Aithal, V. S., G. Gopalakrishnan, Prem Nath, Y. K. Murthy, Brij Nandan and D. Das, 1964, Gravity and magnetic surveys in the plains of Punjab: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Pt. II, Geological Results of Applied Geophysics*, p. 179–188.

Avasthi, D. N., S. Varadarajan, N. D. J. Rao and G. N. Behl, 1971, Study of the Decan Trap of the Cambay Basin by geophysical methods: *Bull. Volcanologique*, vol. 35, no. 3, p. 743–749.

Datta, A. N., T. S. Balakrishnan, A. P. Ghosh, V. C. Mohan and R. Nath, 1964, Seismic survey in the Punjab plain: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Part II, Geological Results of Applied Geophysics*, p. 248–259.

Khattri, K. N., S. K. Verma, Y. B. Rao, S. N. Sharma, N. N. Rao, P. L. Arya, S. K. Choudhury, Prem Nath and H. Chakraborty, 1964, Gravity survey in the Cambay Basin: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Pt. II, Geological Results of Applied Geophysics*, p. 224–235.

Mool Chand, A. N. Datta, R. S. Chellam, A. P. Ghosh, A. M. Awasthi, D. N. Avasthi and V. C. Garg, 1964, Seismic survey in western Uttar Pradesh: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Pt. II, Geological Results of Applied Geophysics*, p. 260–276.

Ray, S., S. Lyngdoh, K. K. Gheeverghese and S. N. Sengupta, 1964, Seismic prospecting for oil in the southwestern part of the Bramhaputra valley of upper Assam: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Pt. II, Geological Results of Applied Geophysics*, p. 277–291.

Sastry, V. L. N., A. M. Awasthi, P. Mahapatra, Mool Chand, S. Ray and K. L. Kaila, 1964, Seismic explorations in Cambay Basin: *Report of the Twenty-Second Session, International Geological Congress, New Delhi, Pt. II, Geological Results of Applied Geophysics*, p. 179–188.

Sengupta, S. N. and K. N. Khattri, 1972, Marine seismic exploration of India's sea-board: *Jour. Indian Geophysical Union*, vol. X, (no. 1–4), p. 47–56.

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VII. ORGANIC METAMORPHISM: ITS RELATIONSHIP TO PETROLEUM GENERATION AND APPLICATION TO STUDIES OF AUTHIGENIC MINERALS[1]

By

A. HOOD[2] and J. R. CASTAÑO[3]

(with figures VII-1 to VII-21)

ABSTRACT

This article is mainly a review of organic metamorphism and its use in studying petroleum generation. In addition it includes an example of applications of organic metamorphism to an understanding of the formation of authigenic minerals.

The review of organic metamorphism considers the thermal process, various techniques of measuring its progress, and its use in studying the main subsurface zones of generation of oil, gas condensate, and gas. Coalification is used as an illustration of the organic metamorphic process. The measuring techniques described are coal rank, vitrinite reflectance, temperature plus time, carbonization, electron spin resonance, kerogen C-H-O composition, and chemical maturity indicators. A scale referred to as "level of organic metamorphism (LOM)" is used as a continuous numerical scale for correlating many of those techniques. The main zones of generation of oil, condensate, and gas are described by LOM ranges of about 8 to 11.5, 11.5 to 13.5, and greater than 13.5, respectively. The specific depths of these zones in any given location can be determined from information on LOM versus depth for that location.

Vitrinite reflectance was used as a measure of organic metamorphism in studying the shallowest depths of occurrence of the post-compaction authigenic mineral laumontite in the Tejon and Cache Creek areas of California. It was found that the shallowest occurrence of laumontite at Tejon is at a burial depth of 2,900 meters and a temperature of 96 °C (LOM 9; equivalent coal rank of high volatile B bituminous). The shallowest occurrence at Cache Creek is at a restored depth of 10,000 m and the estimated paleotemperature is 130 °C (LOM 7; boundary between sub-bituminous B and high volatile bituminous). Because the formation of authigenic minerals is

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2: Shell Development Company, Bellaire Research Center, P. O. Box 481, Houston, Texas, U.S.A.

3: Shell Oil Company, Bellaire Research Center, P. O. Box 481, Houston, Texas, U.S.A.

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governed not only by temperature and time but also by a complex interaction of physical and chemical factors, it appears that measures of organic metamorphism are better measures of thermal history than are authigenic minerals. The concept of organic metamorphism can play an important role in the study of mineral facies during late diagenesis and very-low-stage metamorphism.

INTRODUCTION

In the past few years there has been a renewed interest in the importance of heat in the formation of petroleum. This article is intended primarily as a review of some of the more important thermal aspects of the generation of petroleum during the burial of organic-rich rocks. In addition it includes a detailed study of the formation of laumontite in two locations in California as an example of the application of organic metamorphic concepts to low-grade metamorphism in authigenic minerals. Another reason for submitting this review is to call attention to the availability of methods to determine the burial and temperature history of sedimentary basins. Regional geodynamic models are liable to reflect thermally controlled tectonic processes and therefore have to be compatible with maximum paleotemperature determinations.

The following introductory remarks will include (1) a brief summary of the origin of petroleum in order to indicate where heat fits into the overall process, and (2) the nature of the organic matter which is preserved in organic-rich muds and which will generate petroleum hydrocarbons during burial to sufficiently high temperatures.

Origin of Petroleum

The overall process of petroleum origin can be divided conveniently into four stages:

1. The first stage is the formation of an organic-rich sediment through the photosynthesis of an abundance of organic matter, its subaqueous deposition along with fine-grained clays and/or carbonates, and its preservation in a nonoxidizing environment. Such sediments represent potential (future) source rocks for petroleum. They can be recognized by their high contents of total organic carbon or by a rapid pyrolysis-fluorescence technique (Heacock and Hood, 1970) which measures only the thermally reactive organic matter (*Fig. VII–1*). After lithification these organic-rich sediments can be recognized in thin sections by an abundance of yellow-to-brown-to-red organic matter and often by microlaminations (Heacock, 1972) as a result of sedimentation undisturbed by the activity of aerobic organisms.

2. During the burial of organic-rich sediments to increasing depths and temperatures, conversion of some of the organic matter to hydrocarbons and other petroleum molecules occurs. The generation of petroleum molecules is part of an overall process which may be called "thermal metamorphism of organic matter," or just "organic metamorphism." It has also been called "transformation" (Dobryansky, 1963), "eometamorphism" (Landes, 1966, 1967), "thermal alteration" (Henderson *et al.*, 1968), "incipient metamorphism" (Baker and Claypool, 1970), "katagenesis" (Vassoyevich *et al.*, 1970), and frequently just "maturation."

3. At some point in the organic metamorphic process, sufficient petroleum is gen-

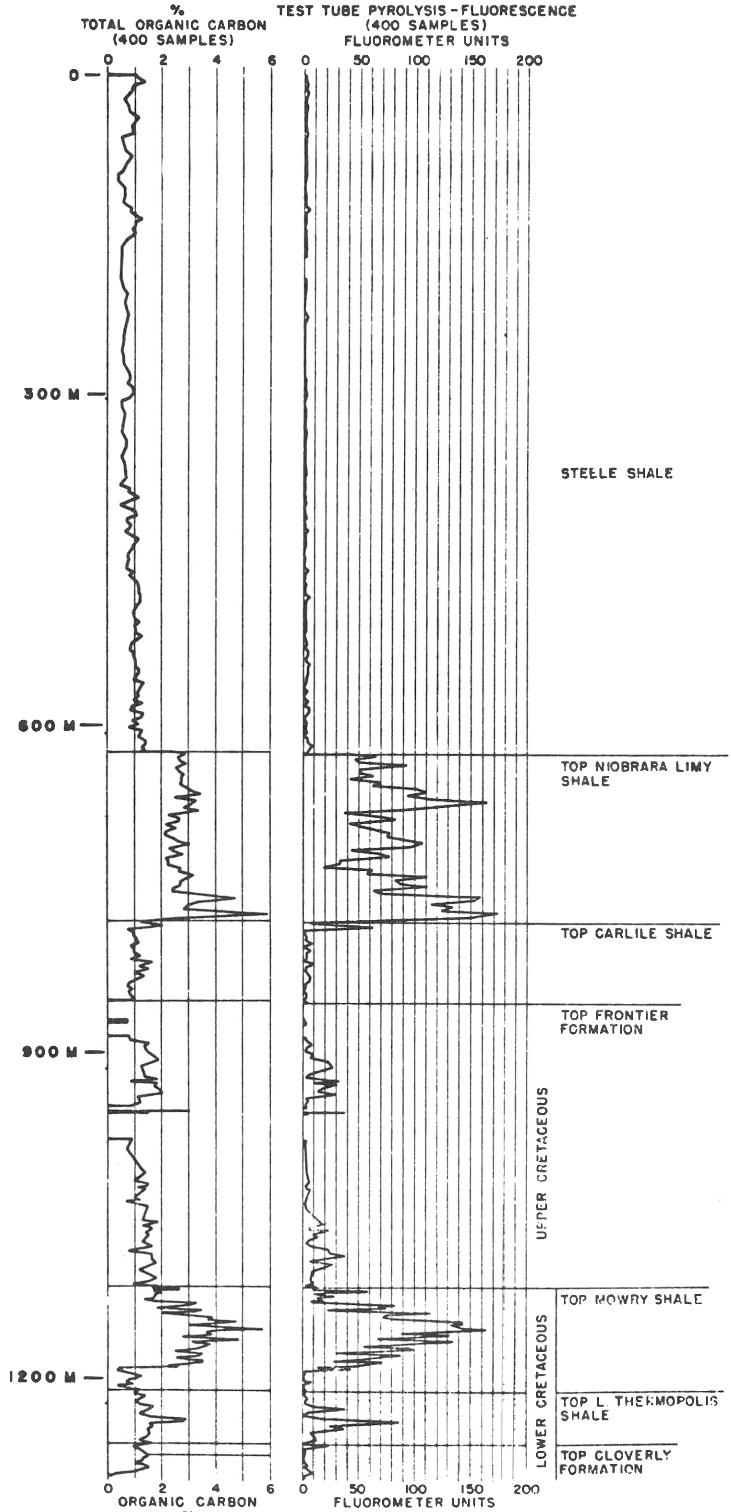

Figure VII-1. Use of organic carbon and pyrolysis-fluorescence to determine the richness of potential petroleum source rocks, Powder River Basin, Wyoming (Heacock and Hood, 1970).

erated to allow oil and/or gas expulsion from the fine-grained source rock into porous, permeable reservoir rock, through which it migrates until it is trapped.

4. One additional stage, alteration, is included here because oil in reservoir rock can be degraded by a variety of processes-physical, thermal and even microbial (Andreev *et al.*, 1968; Winters and Williams, 1969; Evans *et al.*, 1971).

The second stage—the thermal process of organic metamorphism (along with its relationship to low-temperature changes in minerals)—is the main subject of the present paper.

Nature of Preserved Organic Matter

The organic matter preserved in Recent sediments can be classified as "inert" or "reactive" on the basis of its response to heat. Inert organic matter ("dead carbon") occurs in varying proportions and is essentially unaffected by heat. The reactive organic matter, however, can be decomposed by heat and will yield petroleum molecules. The main part of the reactive organic matter is insoluble in typical organic solvents, and it is usually referred to as "kerogen" (Forsman and Hunt, 1958; Forsman, 1963). A relatively small part of the reactive organic matter of Recent sediments is soluble in organic solvents and is often referred to as "soluble bitumen." It includes hydrocarbons (paraffins, naphthenes, and aromatics) and related compounds containing nitrogen, sulfur, and oxygen atoms. It is well known, though, that the hydrocarbon mixtures of Recent sediments are quite different from those of petroleum (Stevens *et al.*, 1956; Erdman *et al.*, 1958; Sokolov, 1959; Hanson, 1959; Erdman, 1961; Bray and Evans, 1961; Dunton and Hunt, 1962; Kvenvolden, 1964; Philippi, 1965). For those mixtures to become petroleum-like in composition requires dilution with additional hydrocarbons generated thermally—mainly from kerogen—during burial to increasing temperatures in the surface. Thus the thermal process of organic metamorphism is essential for petroleum formation.

ORGANIC METAMORPHISM

The following aspects of the thermal process of organic metamorphism will be reviewed:

1. the process,
2. techniques of measuring its progress, and
3. the main zones in the subsurface where oil, condensate, and methane are generated.

The Process of Organic Metamorphism

The subsurface process of thermal metamorphism of organic matter has been described by Dobryansky (1963), Andreev *et al.* (1968), Long *et al.* (1968) and others as a series of catalyzed thermal reaction leading to products of increasing thermal stability—leading disproportionately, on one hand, to smaller molecules of increasing volatility and hydrogen content (with methane as the end product in sedimentary rocks) and, on the other hand, to a carbonaceous residue of decreasing hydrogen content (with graphitic carbon as the end product). The process involves a disproportionation or redistribution of hydrogen which allows the formation of hydrocarbons from reactive organic matter without the need of an

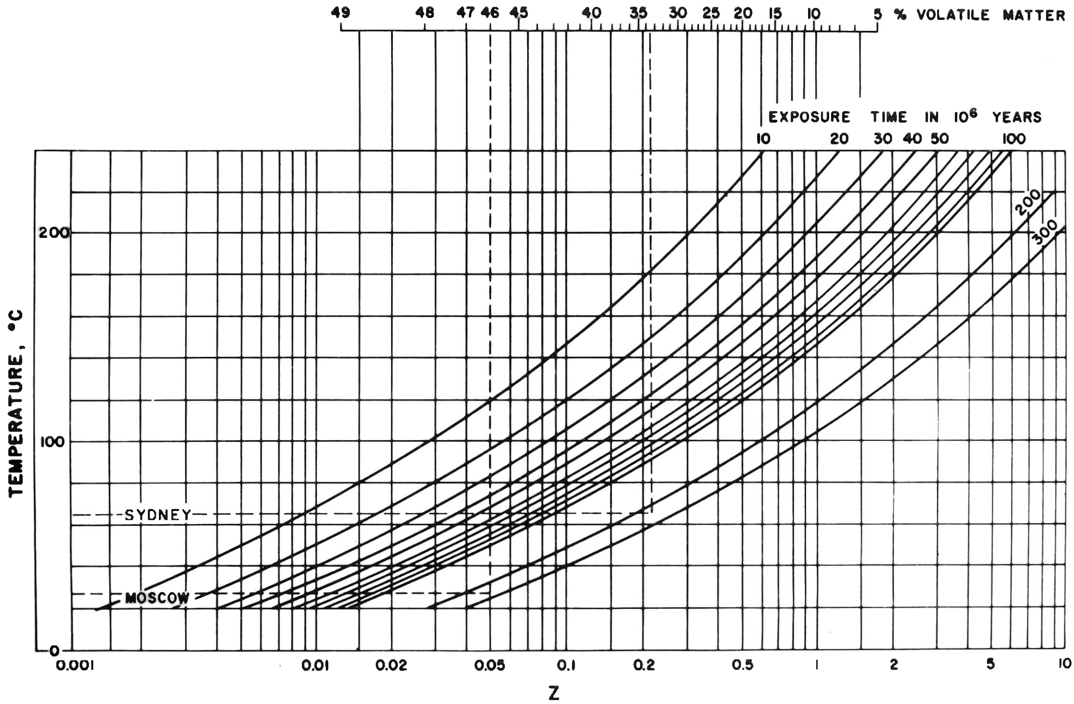

Figure VII–2. The relationship of time and temperature to coal rank (based on Karweil, 1956, and Hacquebard and Donaldson, 1970). The Z-scale of the abscissa is a logarithmic index of conversion which provides a means of summing the increments of coal-rank change for the corresponding intervals of a given burial history.

additional supply of hydrogen. Martin *et al.* (1963) showed evidence that at least the naphtha-generation part of the process follows a free-radical thermal-cracking mechanism.

Probably the best studied type of organic metamorphism is coalification. The conditions controlling the coalification process have been summarized by Teichmüller and Teichmüller (1966 and 1968); they concluded that *temperature* is a critical factor in the chemical reactions involved, while the effect of pressure on the increase of coal rank is only physical, i.e., compression and consolidation accompanied by losses of volume and moisture. For example, they showed that despite the greater tectonic deformation on the southern margins of the Ruhr Basin, the more deeply buried coal-bearing strata farther north exhibit higher coal ranks. Also, Hacquebard and Donaldson (1970) compared the burial history of two lower Carboniferous coals of the same age (about 300 million years old); using Karweil's (1956) chart (*Fig. VII–2*), they concluded that the Moscow, U.S.S.R., brown coal had never been exposed to temperatures higher than 24°C, while the Sydney, Nova Scotia, Canada, high volatile A bituminous coal had been subjected to a temperature of 65°C. Experiments by Huck and Patteisky (1964) have shown that pressure does not advance the chemical coalification process, but actually retards it. In Bostick's (1970, 1973) hydrothermal bomb experiments, no change in vitrinite reflectance was noted in different runs where the pressure was varied from 205 to 1,650 bars while the temperature was kept constant at 250°C.

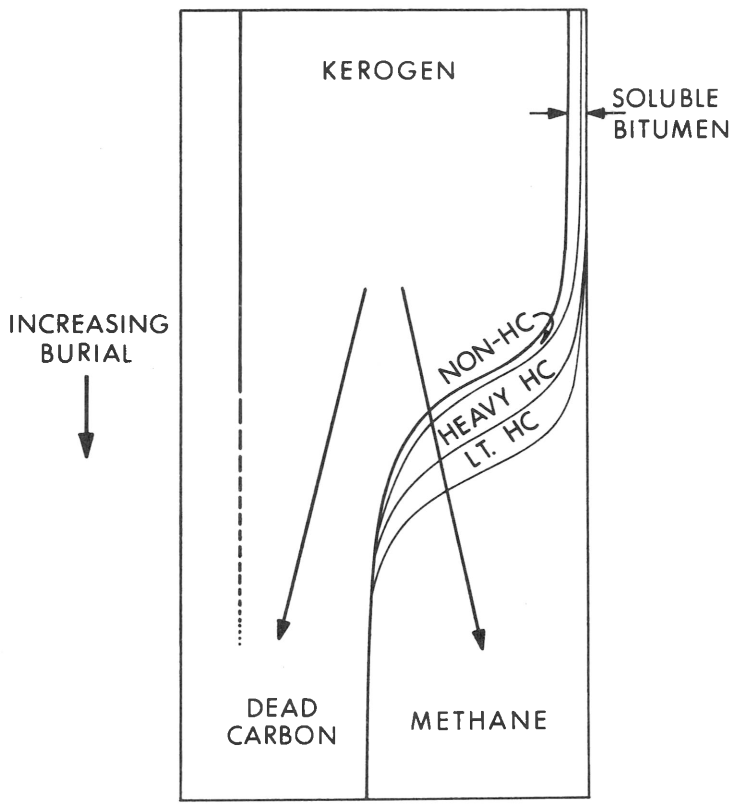

Figure VII–3. Schematic summary of the effects of burying organic matter to increasing depths and temperatures.

The chemical reactions involved in the coalification process are dependent also on *time* (Karweil, 1956; Lopatin, 1971; Bostick, 1973). The data so far tend to support the generalization that the time to attain a given coal rank is cut in half by an increase in temperature of 10 °C.

Pore fluid chemistry does not appear to have any effect on coal rank and, unlike retrogressive mineral reactions, the coalification process is not reversible.

From these and other studies it may be concluded that the most definitive factors in the process of organic metamorphism are temperature and, to a lesser though important extent, time. These factors will be discussed further in the section on techniques of measuring organic metamorphism.

The effect of burying organic matter to increasing temperatures is summarized schematically in *Figure VII–3*. The relative amounts of dead carbon, kerogen, and soluble bitumen do not change much until after considerable burial. Then a rather rapid change occurs, with the generation of hydrocarbons of decreasing molecular weight and with a kerogen composition degrading toward that of dead carbon (see also Tissot, 1969; Tissot *et al.* 1971 and 1974). Subsequent burial produces relatively little change in the organic matter, which is mainly a carbonaceous residue and (in a closed system) methane.

Techniques of Measuring the Level of Organic Metamorphism

Various methods have been employed by the geologist seeking to determine the burial metamorphic history of a particular section. Organic entities such as coal have been proved to be most useful as they are more sensitive than are inorganic minerals to changes in temperature and pressure (Teichmüller and Teichmüller, 1966, 1968; Kisch, 1969, 1971, 1974). Techniques for measuring the level of organic metamorphism must reflect the irreversible effects of temperature and time—therefore, of thermal history. The following useful techniques will be discussed briefly below: coal rank, vitrinite reflectance, the combination of time and temperature, carbonization, electron spin resonance, and kerogen C–H–O composition.

In *Figure VII–4* some of these methods are related through the use of the LOM (level of organic metamorphism) scale reported by Hood *et al.* (in press). The LOM scale is a linear numerical scale which was superimposed on a modification of the New Zealand coal-rank column reported by Suggate (1959). This column appears to be reasonably suitable as a

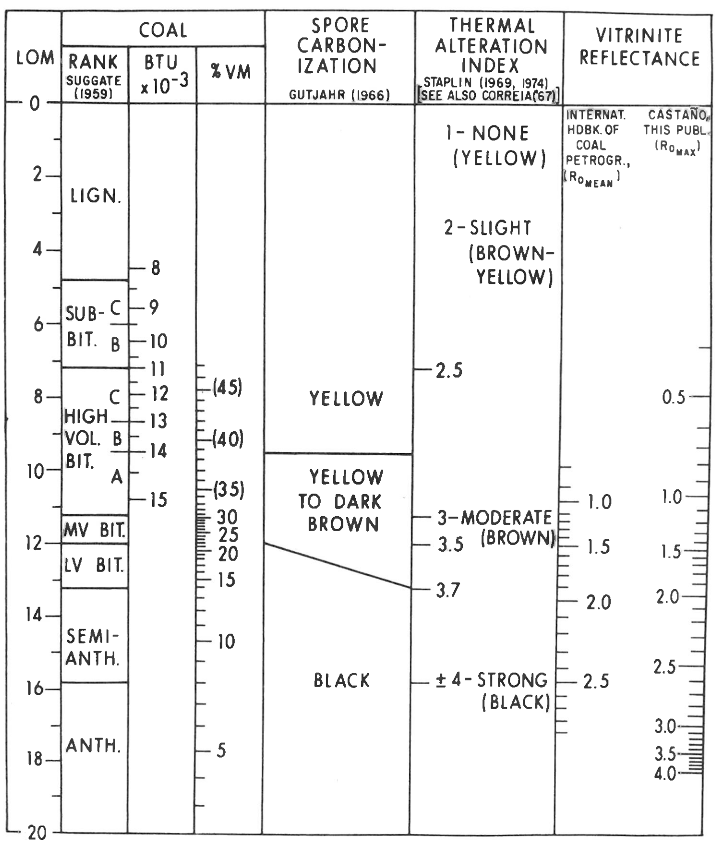

Figure VII–4. Some scales of organic metamorphism (Hood *et al.*, in press).

standard relative-depth column, i.e., a coal-rank column resulting from burial at a constant rate and at a constant temperature gradient. The LOM scale was developed for use by petroleum geologists in correlating organic metamorphism with depth on subsurface cross sections.

a.) Coal rank

Coal rank has for years been the standard for subsurface changes in organic matter during burial. The American Society for Testing Materials (A.S.T.M.) rank classification of humic coals is based on calorific value (moist, mineral-matter-free BTU) for low-rank coals, and on dry, mineral-matter-free fixed carbon (FC = 100—percent volatile matter) for high-rank coals [ASTM Standard D-388-66, (ASTM, 1970)]. Other coal-rank classifications make use of additional coal-ranking properties such as moisture, carbon, and hydrogen contents.

The coal-rank column shown in *Figure VII–4* is that of Suggate (1959), modified to include subdivisions within the sub-bituminous and high-volatile bituminous coals. In that figure the volatile matter (VM) scale has been extended from a value of 31 % to 47 %. This extended portion of the scale is suitable only for humic, vitrinitic coals, and numerical values are shown in parentheses.

The defined relationship of coal rank to LOM (*Fig. VII–4*) is intended as a means of using coal rank as a guide for studying petroleum generation. Others who have emphasized the use of coal rank in petroleum studies include Brooks and Smith (1967, 1969), Brooks (1970), Vassoyevich *et al.* (1970), Hacquebard and Donaldson (1970), Teichmüller (1971), Castaño (1973), Shibaoka *et al.* (1973), and Demaison (1974).

b.) Vitrinite reflectance

For a number of years the reflectance analysis of coal macerals has been utilized as an important technique in the petrographic study and evaluation of coals. The coal macerals are solid, naturally occurring organic substances having distinctive sets of physical properties and chemical compositions. The various macerals are readily distinguished microscopically (*Fig. VII–5*).

McCartney and Teichmüller (1972) consider the reflectance of vitrinite, one of the main macerals of humic coals, to be the best single coal-ranking parameter. They have recommended a set of specific R_0 (% reflectance in oil) values for the various coal-rank boundaries. A comprehensive relationship of vitrinite reflectance to % VM of vitrinite concentrates from coals was published by Teichmüller (1971), and it is reproduced here as *Figure VII–6*. The summary relationship for the R_0 range of 0.8 to 2.9 % appears in the Second Supplement (1971) to the International Handbook of Coal Petrography. That relationship is included in the last column of *Figure VII–4*, along with a previously unpublished relationship of Castaño based on a combination of our own work and literature studies conducted according to A.S.T.M. standards. The standardization of methods and procedures for sample preparation and measurement has led to a very useful and precise coal-ranking scheme.

The same principles and techniques have been applied to macerals in non-coal-bearing sedimentary rocks, as vitrinite is found not only in coals but also as disseminated particles in many shales. Thus vitrinite reflectance provides not only a coal-ranking parameter but also a more general measure of organic metamorphism which is also applicable to petroleum

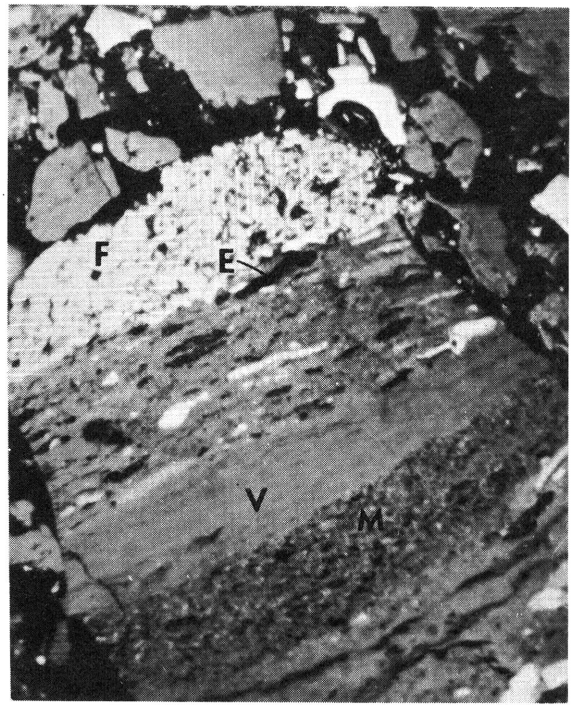

Figure VII–5. Photomicrograph of a polished surface of lignite. A layered coal with highly reflecting fusinite (F), a layer of vitrinite (V), exinite (E), seen as dark elongate bodies in a matrix of vitrinite, and a band of granular micrinite (M). Mean reflectance in oil (R_0) of vitrinite is 0.30%.

source rocks over the LOM range of about 7 to 18.

A detailed discussion of the interpretation of vitrinite-reflectance histograms in non-coal-bearing sequences is given below in the section on the application of vitrinite reflectance to the formation of authigenic minerals.

c.) Temperature and time (thermal history)

As stated earlier, temperature and time appear to be the two most definitive factors in determining the progress of the organic metamorphic process. Numerous geochemists have studied the relationship between these two factors in an effort to predict the level of organic metamorphism (LOM) or coal rank from the reconstructed burial history of a sediment.

Karweil (1956) developed a method of determining the rank of a coal based on the use of a temperature-time-rank nomogram (*Fig. VII–2*) for integrating temperature history. The nomogram was derived mainly from a study of Ruhr coals and has been referred to extensively, but it appears to reflect too great an effect of time relative to temperature. Bostick (1973) has suggested a modification of Karweil's nomogram, and he has presented a good discussion of several aspects of the relationship of temperature to time.

Lopatin (1971) has used a temperature-time index, τ, based on a doubling of the reaction rate for each 10 °C increase in temperature. He has reported a precise linear relationship

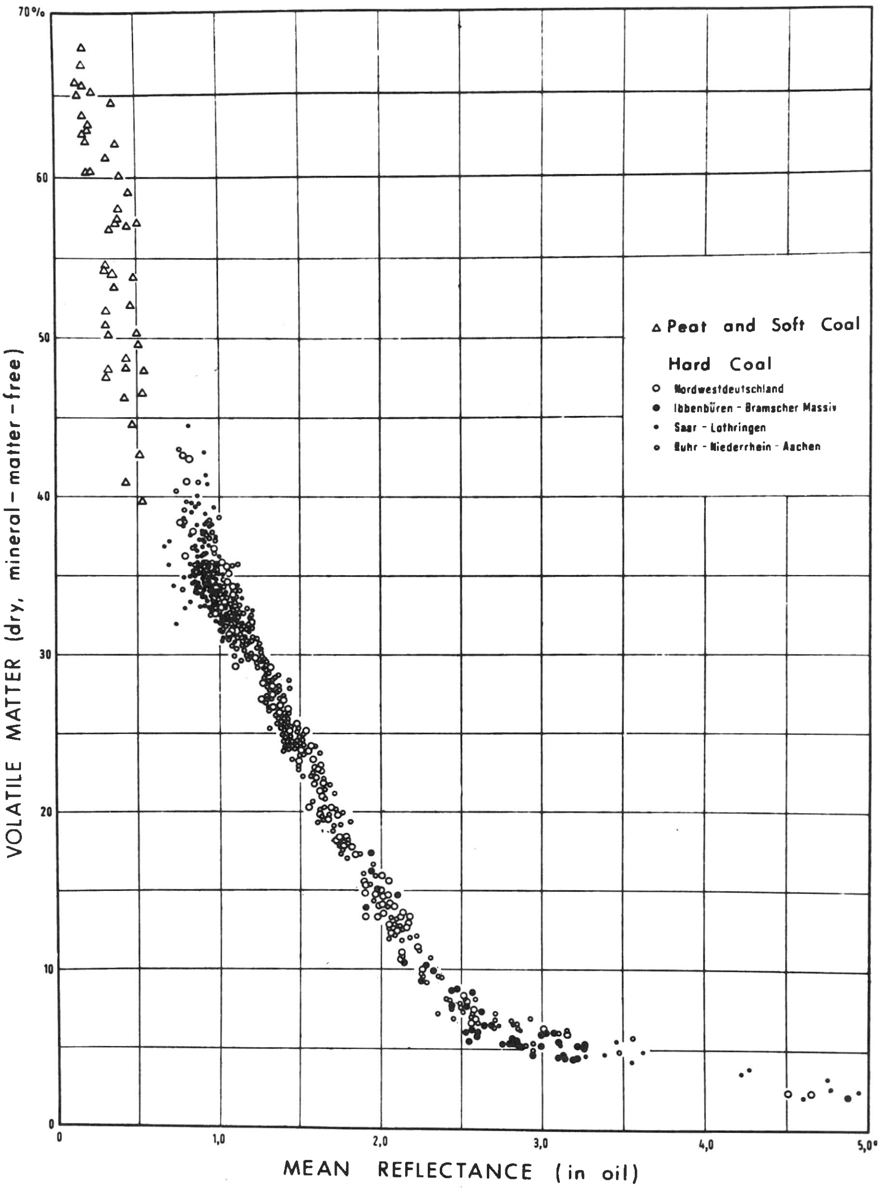

Figure VII–6. Relationship of vitrinite reflectance (R_0 mean) to volatile matter of vitrinite concentrates from various German coals (Teichmüller, 1971).

between log τ and $\% \; R_0$.

Recently Hood *et al.* (in press) have reported the use of maximum burial temperature and effective heating time (the time that the temperature of a given sediment has been within 15 °C of the maximum temperature) for approximating LOM and coal rank. Their temperature-time relationship (*Fig. VII–7*) provides independent support for a doubling of the

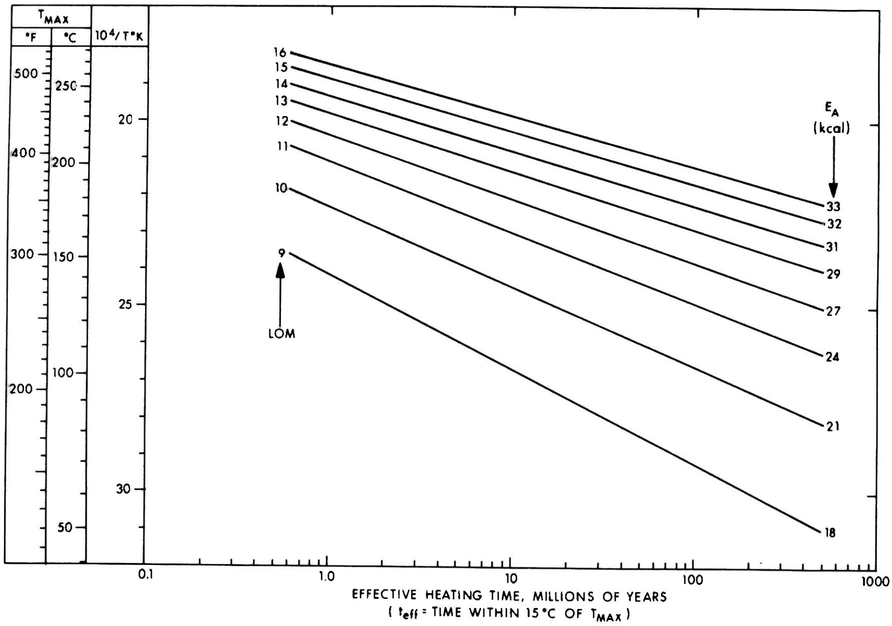

Figure VII–7. The relationship of LOM to maximum temperature and effective heating time (Hood *et al.*, in press).

reaction rate with each 10 °C increase in temperature, on which Lopatin's temperature-time index was based.

d.) Carbonization of structured organic matter

Several methods have been described which are based on microscopic observations of color and/or structure alteration of palynomorphs. Gutjahr (1966) used a color scale (yellow through brown to black) based on the carbonization of spores and pollen. Correia (1967) developed a scale referred to as the "State of Preservation of Palynomorphs" in which both color and structure alteration were used. Possibly the best known of the microscopic methods is the Thermal Alteration Index of Staplin (1969), based on the color and structure alteration of structured organic matter. It has recently been correlated with coal rank (Staplin *et al.*, 1973). These carbonization methods, which are by-products of palynological zonation studies, are useful reconnaissance tools for studying organic metamorphism. The Gutjahr (1966) and Staplin (1973) scales are shown in *Figure VII–4.*

e.) Electron spin resonance

Electron spin resonance (ESR) provides a measure of the number of free radicals per gram of kerogen (Pusey, 1973 a, b, c). Since this value increases with the aromatization of the kerogen, it represents a tool for determining the level of organic metamorphism (LOM) or the equivalent coal rank of kerogen. The spin density, N_g, (the number of free electrons per gram of sample) has been related to the temperatures or thermal histories of coals (Binder, 1965), to vitrinite reflectance of coals adjacent to sills (Crelling and Dutcher, 1968), to coal rank (Retcofsky and Friedel, 1968), and to C/H ratios of kerogen (Marchand *et al.*, 1968, 1969).

ESR has been applied recently by Pusey (1973a) as a technique for estimating maximum paleotemperature. Because both time and temperature are factors in the aromatization process, the estimation of maximum paleotemperature requires a correction for the time factor.

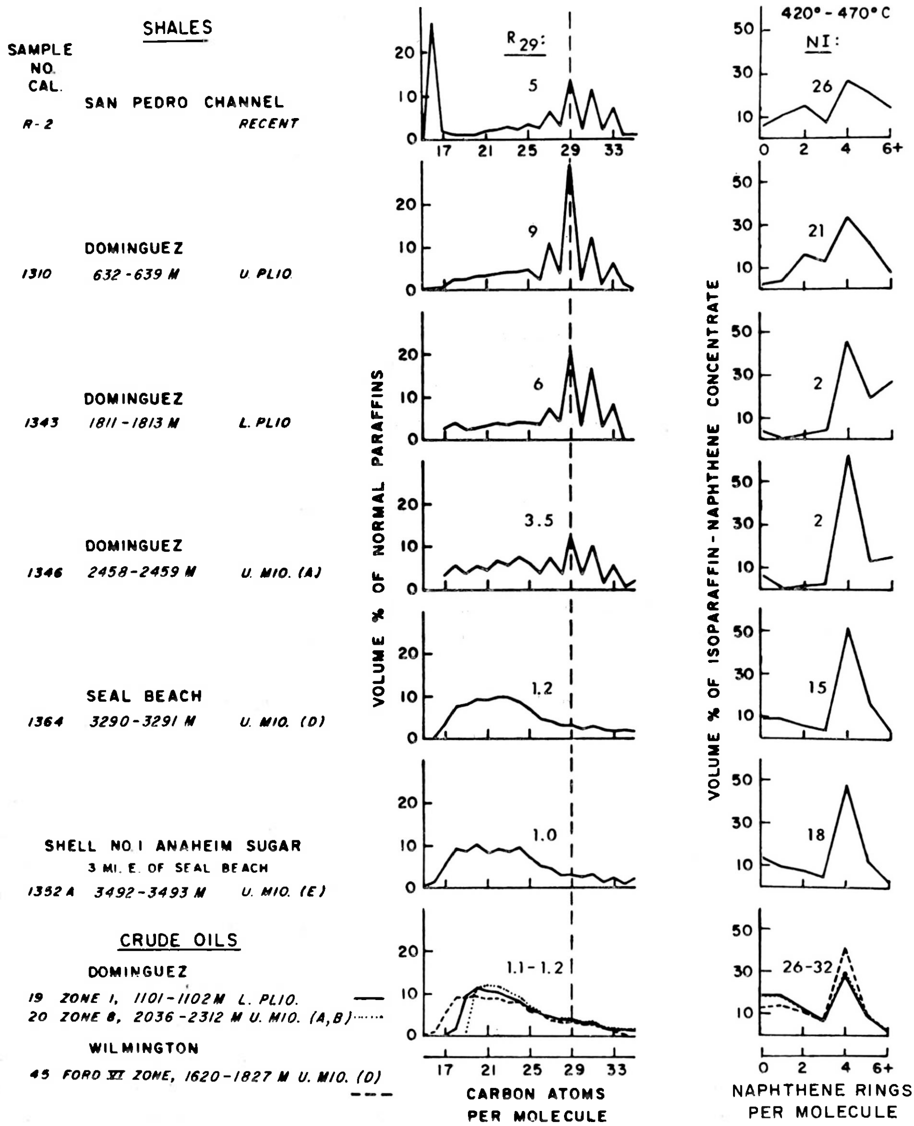

Figure VII-8. Maturity indicators: effect of burial on the compositions of heavy n-paraffins and naphthenes in shales of the Los Angeles Basins, California (based on Philippi, 1965).

f.) Kerogen C–H–O composition

The elemental composition of coals has been used for years as an indicator of humic coal rank (Seyler, 1948; Van Krevelen, 1950; Van Krevelen and Schuyer, 1957). More recently McIver (1967) has applied C–H–O compositions of kerogen to the study of petroleum source rocks in order to indicate how far the organic metamorphism has proceeded and to predict the amount of hydrocarbon generated by cracking. Still more recently Durand and Espitalié (1973) and Tissot *et al.* (1974) have used C–H–O elemental analysis of kerogen in combination with infrared spectroscopy and thermogravimetric analysis to characterize the main stages of organic metamorphism in petroleum source rocks.

g.) Chemical maturity indicators

The compositions of hydrocarbons in potential source rocks for petroleum change during subsurface burial to increasing temperatures. The carbon-number distributions of n-paraffins (Stevens *et al.*, 1956; Bray and Evans, 1961; Philippi, 1965) and the ring-number distribution of high-boiling naphthenes (Philippi, 1965) have been used to indicate, at specific locations, the subsurface depths at which source-rock hydrocarbons become petroleum-like, or thus mature. This is illustrated for sediments of the Los Angeles Basin of California in *Figure VII–8*.

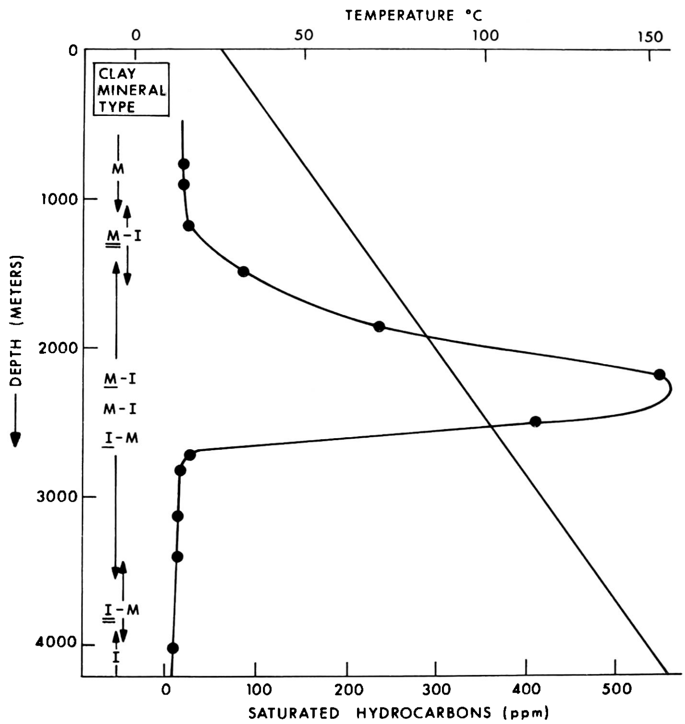

Figure VII–9. Effect of increasing depth of burial and temperature on the concentration of extractable heavy saturated hydrocarbons: Douala (Cretaceous) shales of Cameroun (based on Albrecht and Ourisson, 1969). Variation of the illite-montmorillonite mixed-layers with depth. Illite = I, Montmorillonite = M; from Dunoyer de Segonzac (1970).

Bray and Evans (1961) defined an n-paraffin maturity index (carbon-preference index, CPI) based on molecules with 25 to 34 carbon atoms to indicate an odd-carbon-number predominance of n-paraffins. Philippi (1965) used a simpler odd/even ratio (R_{29}) defined as $2 \times \%nC_{29}/(\%nC_{28} + \%nC_{30})$. Philippi has defined also a naphthene index (NI) as the percentage of 1-ring plus 2-ring naphthenes in the 420–470°C isoparaffin-naphthene fraction. Values of the indices R_{29} and NI are included in *Figure VII–8*.

Generation of Petroleum

One of the important reasons for studying organic metamorphism is the need for knowing, at given locations, the specific subsurface depths in which oil and gas are generated in source rocks. Such information is important because it provides useful limitations on the timing of oil and gas expulsion, on the floor of oil in reservoirs, and on other related questions.

During the burial of kerogen to increasing depths and temperatures, as illustrated in *Figure VII–3*, part of the kerogen is converted to heavy hydrocarbons and other oil-range

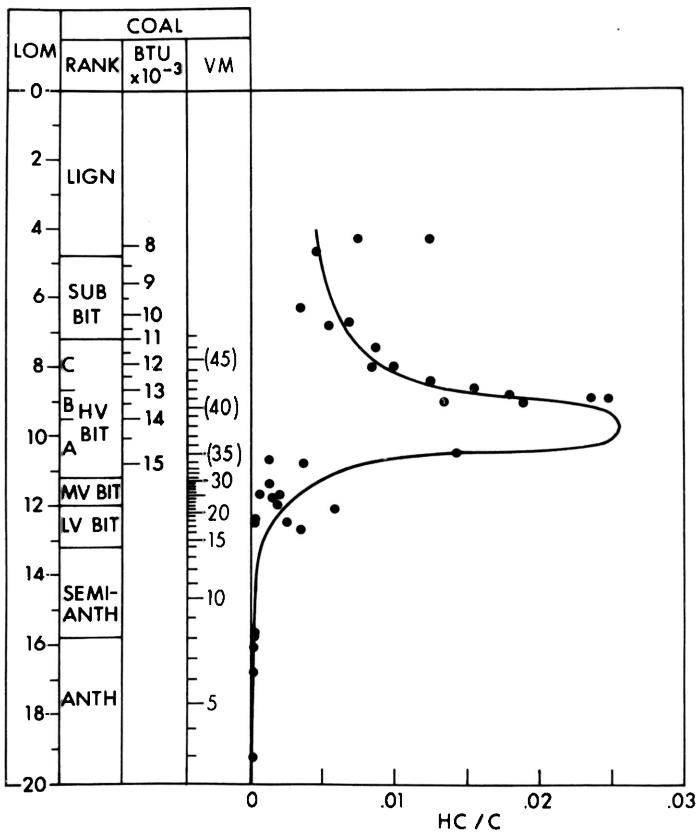

Figure VII–10. Effect of increasing rank and LOM of U.S. humic coals on the ratio of extractable heavy hydrocarbons to carbon (Hood *et al.*, in press). Coal samples were received from U.S. Bureau of Mines.

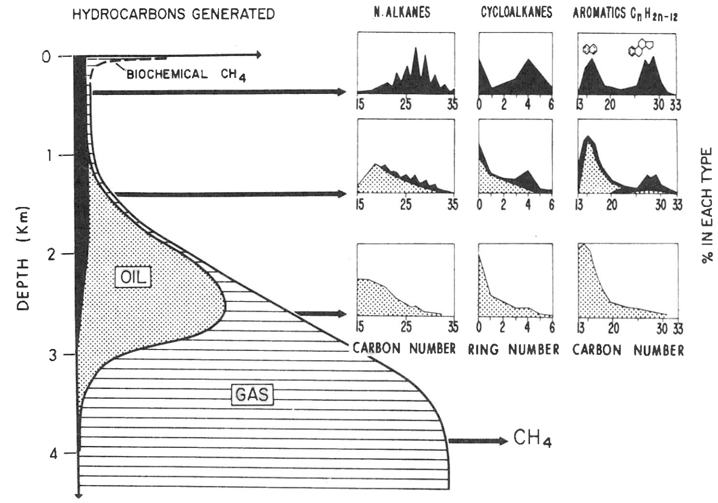

Figure VII–11. Effect of increasing burial on the concentration and composition of oil and gas generated in petroleum source rocks (based on Tissot *et al.*, 1974). The depth scale is based on Mesozoic and Paleozoic source rocks. The scale may vary appreciably with the nature of the original organic matter, with the burial history, and with the geothermal gradient.

molecules. During continued burial, as described in an earlier section, lighter and lighter hydrocarbons are generated at the expense of kerogen and unexpelled heavy hydrocarbons, until dry gas (methane) remains as the only hydrocarbon in the deeply buried source rock. This process applies equally well to humic coal and petroleum source rocks. It is illustrated in *Figure VII–9* for concentrations of extractable heavy saturated hydrocarbons in a thick series of Douala (Cretaceous) shales from Cameroun (Albrecht and Ourisson, 1969); in *Figure VII–10* for heavy hydrocarbon/carbon ratios versus LOM and coal rank for a varied group of U.S. humic coals obtained from the United States Bureau of Mines; and in *Figure VII–11* (along with corresponding changes in hydrocarbon compositions) for concentrations of oil and gas hydrocarbons (Tissot *et al.*, 1974).

By relating data of this type to coal rank, Vassoyevich *et al.* (1970) showed that the specific stage of the organic metamorphic process in which oil is generated in a given source rock may vary with the type of source rock. Those authors, however, were able to define a *principal* stage of oil generation in terms of coal rank—a stage which includes oil generation from a wide variety of source rocks. Similarly, they have indicated principal stages of generation of gas condensate and of late-katagenetic (high-temperature) methane. They refer to the entire stage prior to oil generation as the stage of formation of early diagenetic methane, which includes methane of biological origin. Vassoyevich's stage of formation of early diagenetic methane and his principal stages of generation of oil, condensate plus wet gas, and high-temperature methane are shown in relation to coal rank and the LOM scale in *Figure VII–12*. According to that correlation the four stages fall in LOM ranges of <7.8, 7.8–11.6, 11.6–13.5, and >13.5 respectively.

Recently Shibaoka *et al.* (1973) have reported zones of oil, gas condensate, and gas which are similar to those of Vassoyevich *et al.* (1970). The oil-generation zone, however, is

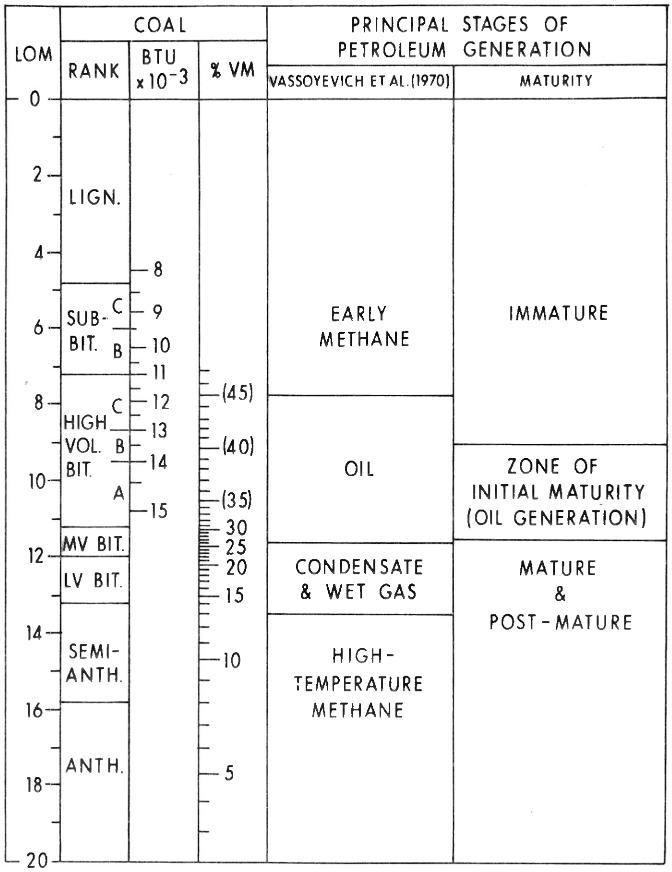

Figure VII–12. Principal organic-metamorphic stages of petroleum generation (Hood *et al.*, in press).

split into three categories: early, main, and late generation. In addition Neruchev *et al.* (1973) have reported a principal stage of gas generation which includes both wet gas and katagenetic methane. This gas-generation stage includes the portion of the coal-rank column with 7 to 26% volatile matter. Neither of these two classifications is included in *Figure VII–12*.

Another indicator of oil generation is the maturation of source-rock hydrocarbons. From our observations of compositions of high-boiling n-paraffins (method of Bray and Evans, 1961) and naphthenes (method of Philippi, 1965) of crude oils and source rocks, initial maturity is usually found to occur in the LOM range of about 9 to 11.5. The immature zone, initial-maturity zone, and mature zone are included in *Figure VII–12*. From the figure it may be seen that the zone of initial maturity occupies essentially the high-LOM two-thirds of Vassoyevich's principal stage of oil generation. Thus the low-LOM one-third of Vassoyevich's oil stage appears to represent oil generation without reaching maturity—and therefore without effective oil expulsion.

An illustration of the relationships of LOM and petroleum generation to depth of burial

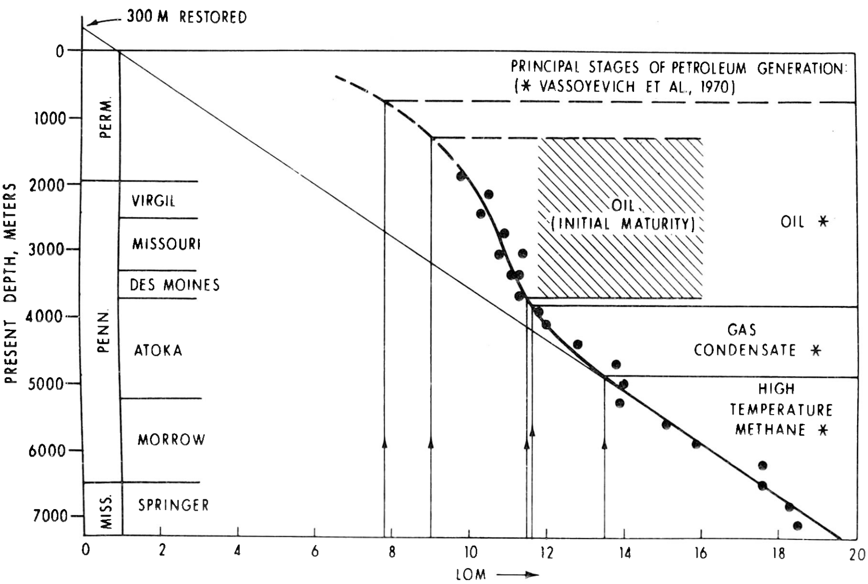

Figure VII–13. Relationships of LOM and petroleum generation to burial depth: Shell *Rumberger No. 5*, Beckham Co., Oklahoma, Anadarko Basin (based on Hood *et al.*, in press).

is given in *Figure VII–13*. It is based on data from a well (Shell *Rumberger No. 5*) from the Anadarko Basin of Oklahoma. LOM data were determined by means of vitrinite reflectance. Vassoyevich's principal stages of petroleum generation, and also the zone of initial maturity, have been superimposed on the LOM graph on the basis of the relationships shown in *Figure VII–4*. From *Figure VII–13* it is seen that Vassoyevich's principal zone of oil generation at the *Rumberger* well is from about 2,000–4,000 to 12,500 feet (about 1,000 to 3,800 meters).

Another illustration—one which emphasizes the great depths and temperatures at which petroleum may be generated in rapidly buried sediments—is given in *Figure VII–14* (Castaño, 1973). Vitrinite reflectance and formation temperature (as well as maturity indices) are shown as a function of burial depth for sediments of the Paloma Field, San Joaquin Basin, California. The present-day depth is the maximum burial depth, for although there is considerable structural relief in the Miocene, the Pleistocene beds are essentially flat-lying. For this field Vassoyevich's principal zone of oil generation occurs in the depth range of about 3,600 to 6,200 meters at temperatures of about 130 to 210 °C. Even at these great depths and temperatures, the sediment hydrocarbons are immature (not petroleum-like) through most of this range, and the high temperatures coincide with an extremely short effective heating time. This illustration provides an interesting comparison with the liquid-window concept reported by Pusey (1973 a, b, c). Pusey pointed out that 99+ percent of the world's oil is found in reservoirs at temperatures less than 300 °F (149 °C) and that liquid-hydrocarbon destruction is dominant at greater temperatures. If the boundary (LOM 11.6) between Vassoyevich's principal zones of oil and condensate generation are used as the beginning of liquid-hydrocarbon destruction, then the destruction of liquid

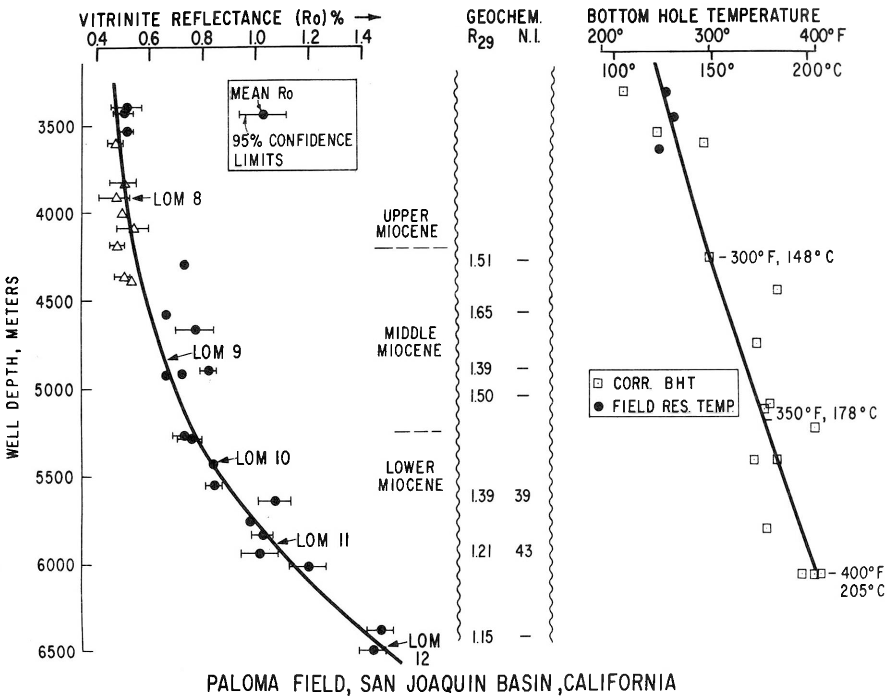

Figure VII-14. Relationships of LOM and temperature to burial depth: Paloma Field, San Joaquin Basin, California (Castaño, 1973). In this field, oil production is obtained from beds of Upper Miocene age between 3,050 and 4,700 meters.

hydrocarbons at Paloma Field (with an effective heating time of only one or two million years) begins at a temperature of 220°C—well outside Pusey's liquid window. By contrast, the corresponding destruction stage in the Shell *Rumberger No. 5* well (with an effective heating time of about 260 million years) is only 130°C—thus within the liquid window. These comparisons illustrate again the importance of time as well as temperature in the organic metamorphic process—including both the thermal generation and destruction of petroleum.

In summary, *Figures VII-13* and *VII-14* illustrate the use of LOM and related measures of organic metamorphism to predict the principal specific depth zones in which oil, gas condensate, and methane would be generated thermally in a source formation at any given location.

APPLICATION TO FORMATION OF AUTHIGENIC MINERALS DURING LATE DIAGENESIS AND VERY-LOW-STAGE METAMORPHIC MINERAL FACIES

In the organic metamorphic process the major defining factors are temperature and time; the process is essentially the effect of burial and incipient metamorphism. Concurrently, there are progressive changes in the texture and mineralogy of the sedimentary rock sequence. These changes take place during late diagenesis and incipient metamorphism, referred to as "burial metamorphism" by Coombs (1961), "anchimetamorphism" by Kubler (1967), and "very-low-stage metamorphism" by Winkler (1970). Generally, those geologists who have been concerned with structural style, basin evolution, and mineral exploration have not fully utilized data which could be obtained from studies of organic metamorphism; i.e., the maximum temperatures to which sediments have been exposed during their history can be reasonably approximated using the techniques which are described in this paper.

As shown by Kisch (1969, 1974) there are two types of burial metamorphic silicate mineral processes to be considered. There are changes in clay mineralogy, particularly the replacement of kaolinite by illite, chlorite, and pyrophyllite, and the transformation of montmorillonite to illite or chlorite. The temperature of transformation of montmorillonite to mixed layer illite-montmorillonite occurs at a temperature of 70–95 °C (Dunoyer de Segonzac, 1970), which is lower than the limits of 120–135 °C established from laboratory experiments. Dunoyer de Segonzac attributed this difference to the reaction rate; it is perhaps noteworthy to mention that the transformation temperature of 70 °C is for the Cretaceous in the Douala Basin, while the examples of Tertiary age ranged from 80° to 90 °C. The Douala Basin study is particularly interesting, for it provides a comparison of the changes in clay mineralogy with depth, temperature, and the amounts of extractable heavy hydrocarbons (*Fig. VII–9*). For further information on clay mineral diagenesis the reader is referred to Powers (1967), Burst (1969), and Perry and Hower (1972).

The second type of silicate mineral process to be considered is the appearance of mineral facies assemblages, especially the following diagnostic groups (Kisch, 1969, 1974):

analcime + quartz	zeolite facies	LATE DIAGENESIS
heulandite (-clinoptilolite) + quartz		
laumontite + quartz (and albite)		
prehnite-pumpellyite		VERY-LOW-STAGE METAMORPHISM
lawsonite-glaucophane		

The formation of authigenic minerals is governed by a complex interaction of physical and chemical factors (Hay, 1966; Kisch, 1969, 1974; and Pusey, 1973c). These mineral facies often do not attain mineral equilibrium and commonly contain mineral relics. Reaction kinetics are important in this low-temperature realm, as is the pore-fluid composition and the partial pressure of CO_2.

In an extensive survey of the relationship of coal rank to burial metamorphic mineral facies, Kisch (1969, 1971, 1974) found that although the ranges of coal rank associated with successive metamorphic mineral stages are not sharply delimited, he concluded that coal-rank studies could become a powerful tool in the study of mineral facies in the range of late diagenesis and incipient metamorphism.

Two areas in California, which contain authigenic laumontite in non-coal-bearing sequences afford a comparison of the use of vitrinite reflectance (as a measure of LOM) and authigenic minerals as indicators of thermal history (Castaño and Sparks, 1974).

The two areas are (1) the Tejon area of the San Joaquin Valley (Miocene to Eocene sediments) and (2) the Cache Creek area west of the Sacramento Valley (Great Valley sequence of late Mesozoic age).

The discussion below will first review the techniques used in sample preparation and some problems of interpretation of vitrinite-reflectance histograms for non-coal-bearing sequences. This will be followed by a comparison of reflectance data with information derived from a study of authigenic laumontite occurrence.

Interpretation of Vitrinite Reflectance Data in Non-Coal-Bearing Sequences

a.) Sample preparation

For preparation of coal specimens, standard A.S.T.M. procedures as provided in ASTM D-297 (A.S.T.M., 1970) are used. For clastic rocks in which carbonaceous macerals are accessory components, however, the vitrinite needs to be concentrated. Various modifications of palynological procedures have been utilized, and experimental data indicate that concentrating vitrinite by non-oxidative acid solution of the inorganic matrix has little effect on the reflectance of the vitrinite. For most clastic sediments an HCl followed by an

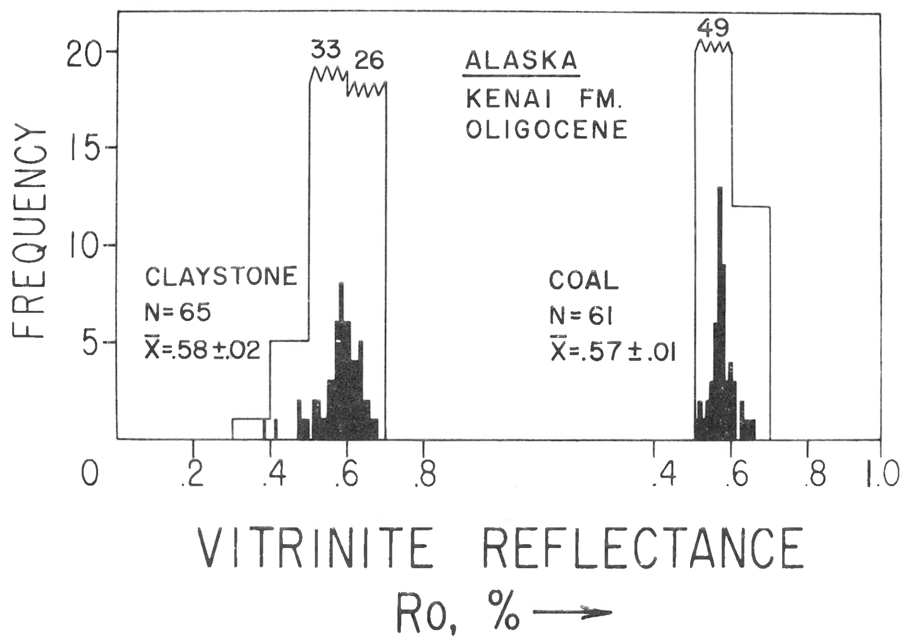

Figure VII–15. Coal-shale pair, Kenai Fm., Alaska (Castaño and Sparks, 1974). The reflectance data on these two histograms are grouped into classes of 0.1 % R_0, and the individual readings are shown by vertical black bars. N refers to the number of readings used in the calculations, and $\bar{x}$ is the arithmetic mean of maximum reflectance. The ± values are the 95 % confidence limits (Dean and Dixon, 1951) expressed in percent R_0.

HF acid treatment is sufficient, and the insoluble residue contains a considerable proportion of vitrinite.

b.) R_0 versus coal rank for non-coal-bearing sequences

There seems to be no reason that the low-grade biogenic and thermal processes that are responsible for the formation of vitrinite in coal would differ in either quality or intensity from those processes in associated clastic sediments. In order to establish an experimental basis for the validity of the reflectance calibration of vitrinite and rank for non-coal-bearing sequences, however, a number of coal-shale pairs were examined. *Figure VII–15* shows the results of the analysis of a coal-shale pair from the Kenai Formation, Cook Inlet, Alaska. It is apparent that the mean values are from the same population, although the range of values is greater in the shale (claystone). Many such pairs have been analyzed and the agreement has generally been good over a wide range of ranks and lithologies. The difference between vitrinite reflectance values of coal-shale pairs tends to increase inversely with the absolute amount of vitrinite in the rock. This suggests that the variance is largely a problem caused by inadequate sample size. Indeed there are practical problems in evaluating reflectance data from sediments where only small sample sizes are available (well cuttings, for example), and we have made an attempt to understand and correct some of them.

A critical element in the evaluation of vitrinite reflectance is a knowledge of the lithology and of the depositional environment. The two most obvious sources of error in our analyses have been weathering or oxidative effects and reworking of second-cycle materials. It is well known that oxidation increases the reflectance (Benedict and Berry, 1966; Benedict *et al.*, 1968). Extreme oxidation is easily recognized, but lesser degrees of oxidation are usually hard to recognize microscopically or in the reflectance histogram. Bioturbation by marine aerobic organisms accompanied by repeated winnowing action, which is prevalent in shallow marine environments, can also be a factor in the oxidation of organic material. Sandstones are found to contain a high proportion of partly oxidized vitrinite, and it is generally desirable to avoid the coarse clastic rocks despite the fact that large carbonaceous fragments are often present.

The problems involved with reworked vitrinite are illustrated in *Figure VII–16*, which depicts two superimposed histograms from cores in a well from the Cook Inlet area, Alaska. The Eocene sample is a carbonaceous claystone from the nonmarine Kenai Formation, and the Upper Cretaceous sample is a bathyal shale in a turbidite sequence. The vitrinite reflectance histogram of the Upper Cretaceous sample is strongly bimodal, which is very common in turbidites. Pollen carbonization studies by R. V. Emmons (personal communication) support the conclusion that the mean reflectance is around 0.65%—not 1.2 to 1.4% as suggested by the second mode. The higher-reflectance vitrinite is considered to be reworked from older rocks or, perhaps, to have been partly oxidized before reaching the depositional site. As a general rule, therefore, the lowest-reflectance vitrinite group in a sample is chosen as representative of the correct LOM or coal-rank equivalent.

Figure VII–16 also presents the concentration of high-boiling-point n-paraffins in addition to the histograms. Based on the vitrinite data, both samples are at LOM 9, or within the initial maturity stage. According to the n-paraffin maturity indices (R_{29} of 1.98 and 1.88) both samples are not petroleum-like and are thus considered to be geochemically immature, as oils obtained from producing fields in the Cook Inlet area have R_{29} ratios of

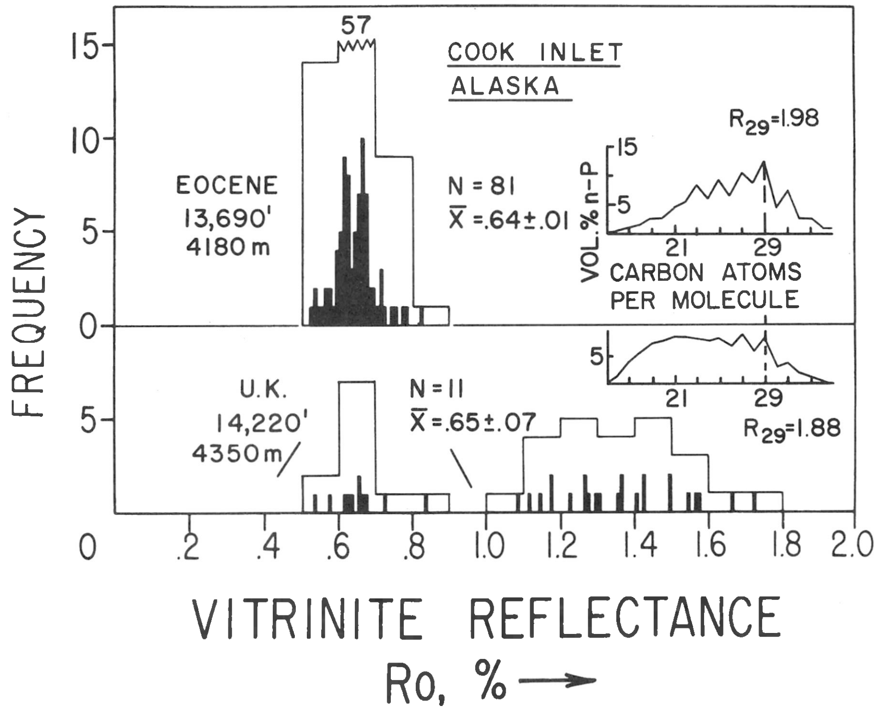

Figure VII–16. Vitrinite reflectance histograms from a well in the Cook Inlet Basin, Alaska (Castaño, 1973). Note bimodal distribution for Upper Cretaceous sample; statistics shown are for the portion enclosed by diagonal lines. Composition of heavy n-paraffins shows that these sediments are immature. Compare with n-paraffin data on *Figure VII–8*.

1.0 to 1.3. These samples serve to further illustrate the regime in which source rock hydrocarbons become mature in young, rapidly subsiding basins. As there is probably close to a thousand meters of uplift at this locality, the estimated maximum paleotemperature for the two samples is around 130°C.

Determination of Thermal History: Vitrinite Reflectance vs. Laumontite Formation

a.) Tejon area, California

1.) Introduction:

The older beds of lower Miocene to Eocene age at North Tejon are strongly faulted and folded, but the middle Miocene and younger beds exhibit a gently northerly dipping homocline (Park, 1961). It is likely that the maximum burial depth for these strata is not much greater than it is at the present time. For this reason present-day well depths were used as maximum depths.

2.) Vitrinite reflectance:

The reflectance-depth plot shown on *Figure VII–17* is a composite profile for four wells studied in the Tejon area. The average line through these data is weighted heavily towards samples of good quality. *Figure VII–18* exhibits an excellent unimodal histogram for a sample at 3,320 meters, which is well within the laumontite-bearing interval in this area.

3.) Laumontite occurrence:

Kaley and Hanson (1955) first reported the presence of laumontite (and its alteration product, leonhardite) in the Tejon area in a well, Standard *CCMO*, at a depth of 3,360 meters. They used microscopic and X-ray diffraction methods for identification of these zeolites.

In the study of Castaño and Sparks (1974) Miocene-Eocene sandstones were examined to establish the sequence of diagenetic mineralization. It was found that laumontite (as well as leonhardite) was rather easily identified in thin section; X-ray diffraction analysis corroborated the microscopic identification. X-ray diffraction patterns of bulk rock samples were inadequate for identification when the concentration was as low as 10–12%; but laumontite peaks are observed where 15–20% laumontite is present. Not all the sandstones are zeolitized, but much of the oil production in this immediate area is from porous,

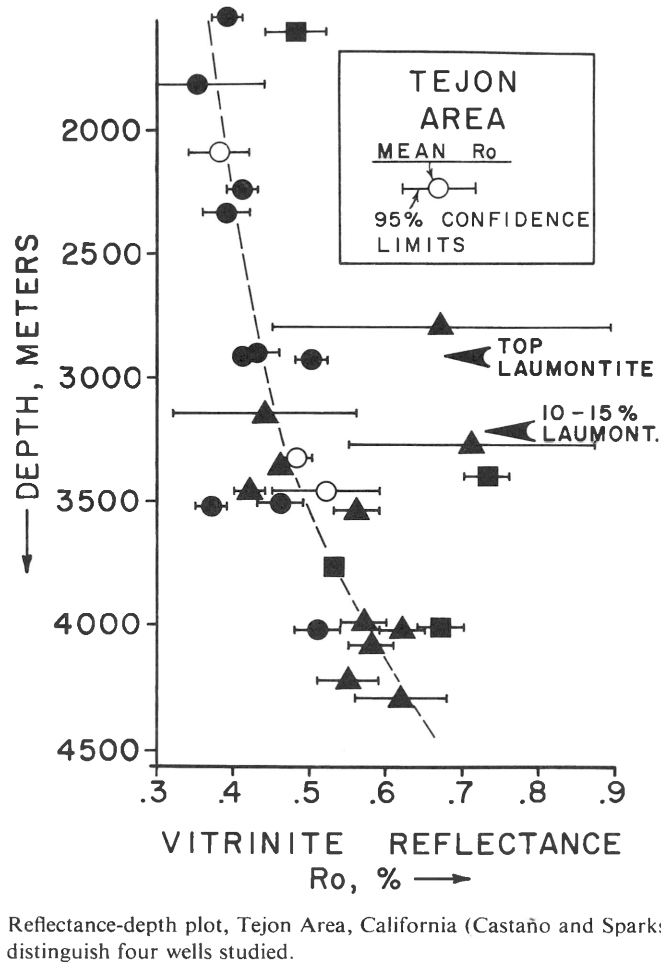

Figure VII-17. Reflectance-depth plot, Tejon Area, California (Castaño and Sparks, 1974). The symbols distinguish four wells studied.

uncemented sandstones within the zone of alteration.

Porous, unaltered, arkosic sandstones typify the beds above the zeolitized section; plagioclase feldspars here have a composition of An_{2-40}. Analcite-bearing submarine basalts of lower Miocene age are interbedded with marine sandstones and shales in the interval 2,300–2,600 meters. The outflow of these basalts has apparently not affected the history of mineral alteration in the subjacent section, and no anomaly in vitrinite reflectance has been observed. Laumontite is first noted at a depth of about 2,900 meters and is found in considerable abundance at depths greater than 3,200 meters. Within the zeolitized zone plagioclase feldspars have the composition An_{2-15}, although sandstones with early carbonate cement have the same composition as the sandstones above the zeolitized zone. Albitization of plagioclase feldspars occur at depths less than a hundred meters shallower than does laumontization.

4.) Subsurface temperatures and geothermal gradient:

Accurate bottomhole-temperature data are extremely useful in relating the changes that take place in the organic and inorganic matter within a sedimentary basin, beginning with early diagenesis and continuing into the domain of low-grade inorganic metamorphism.

It is recognized that the temperature data from mechanical logs are usually inaccurate measures of formation temperatures. Many factors are responsible for the inaccuracy, but the principal one is that temperature equilibrium is not attained during the usual short time span between the discontinuation of mud circulation and the actual logging. Consequently, long-duration tests provide the best bottomhole-temperature information.

Accurate temperature surveys have been used to establish standards by which electrical

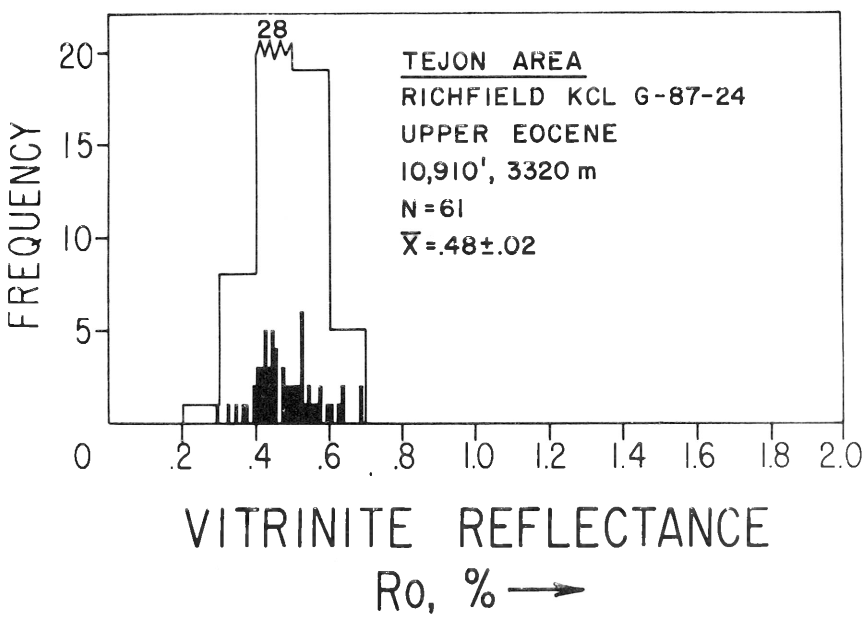

Figure VII-18. Vitrinite reflectance histogram for a sample within the laumontite-bearing interval, Tejon Area, California (Castaño and Sparks, 1974).

log data were corrected. The correction applied to the electrical log data is the difference between the average of the raw temperature data obtained from electrical log runs and that from the temperature survey.

In the Tejon area we used both corrected electrical log temperatures and tests of long duration, ranging up to thirty days. These two sources of data agree rather well (*Fig. VII–19*). A linear-regression analysis yields a geothermal gradient of 2.3 °C/100 meters through the interval studied, while the average gradient extrapolated to a surface temperature of 21 °C is 2.5 °C/100 meters.

The present-day subsurface conditions in the Tejon area can be used to determine the temperature and pressure required for the formation of laumontite, since the petrographic study showed that it is a post-compaction authigenic mineral. The nature of authigenic mineral assemblages is relatively sensitive to pressure and temperature, because zeolites are hydrous mineral phases of low specific gravity (Hay, 1966). As the rocks in the Tejon area are porous and permeable, the subsurface pore-fluid pressure is essentially hydrostatic. The pressure in the interval of 2,900 to 3,200 meters is therefore about 290 to 320 bars, or less than half the load pressure. The temperature in the same interval is 96° to 103 °C.

The average reflectance (R_0 maximum) in the 2,900- to 3,200-meter section is 0.44 to 0.46 %, which, according to our calibration (*Fig. VII–4*), falls at about the boundary between the sub-bituminous B and high volatile C bituminous coal rank (LOM 7–8).

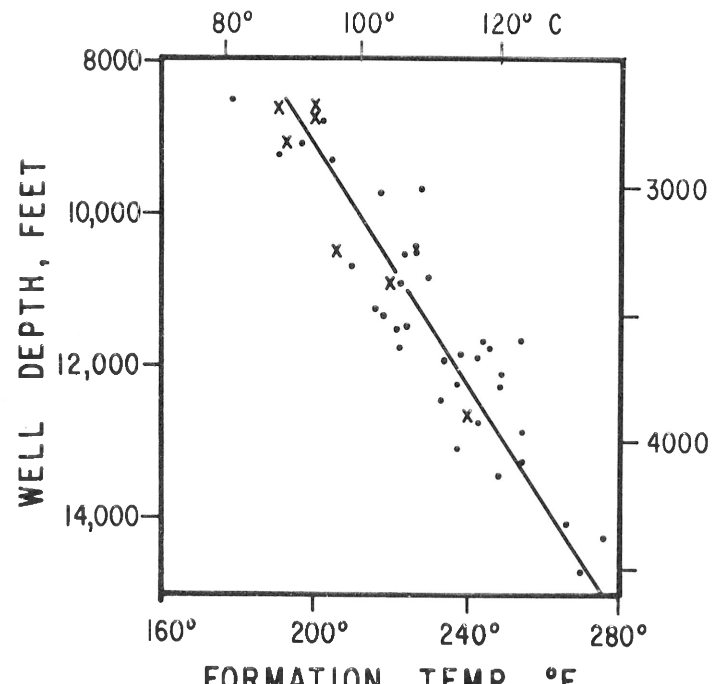

Figure VII–19. Temperature-depth plot for the Tejon Area, with linear-regression, best-fit line (Castaño and Sparks, 1974). Crosses are for long-duration tests; dots are corrected temperatures from electrical logs.

b.) Cache Creek area, California

1.) Introduction:

The Great Valley sequence of late Mesozoic age crops out along the west side of the Great Valley of California. It consists of about 13,700 meters of marine clastic sediments which form an easterly dipping homoclinal succession (Rich *et al.*, 1968; Dickinson *et al.*, 1969). The coeval Franciscan assemblage includes rocks of the zeolite, blueschist, and eclogite facies (Bailey *et al.*, 1964). In the Cache Creek area, Dickinson *et al.* (1969) reported the presence of laumontite as a characteristic alteration product in Lower Cretaceous sandstones of the Great Valley sequence. The estimated maximum burial depth for the top of the exposed section is around 1,500 meters, since beds of Campanian to Maestrichtian age which are present in subsurface to the southeast are presumed to have been deposited in this area as well. In the Cache Creek area the Great Valley sequence was uplifted in earliest Tertiary time and is unconformably overlain by the lower Eocene Capay Shale. Therefore, the dura-

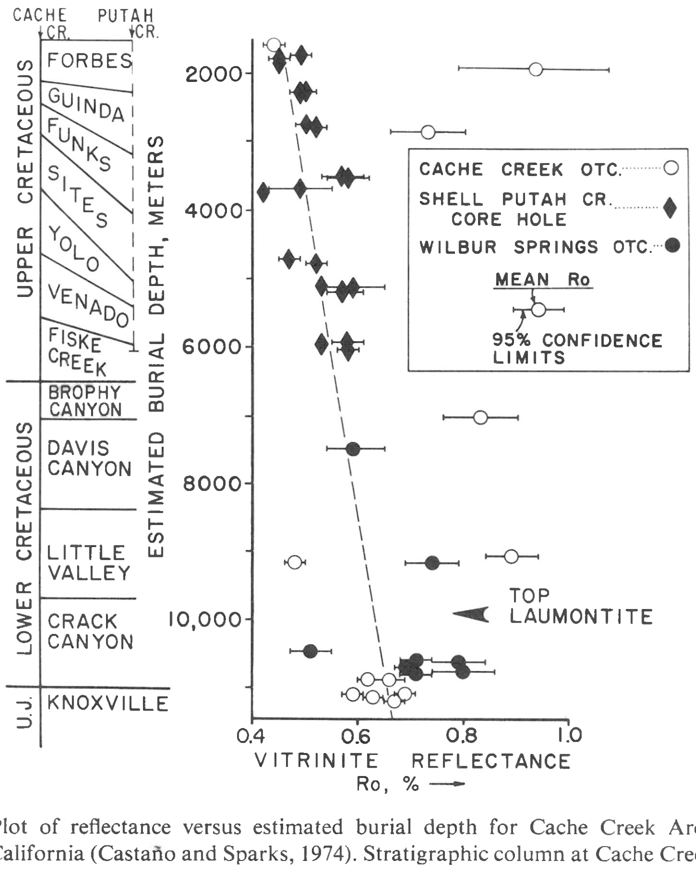

Figure VII–20. Plot of reflectance versus estimated burial depth for Cache Creek Area and vicinity, California (Castaño and Sparks, 1974). Stratigraphic column at Cache Creek adapted from Page (1966); at Cache Creek the Upper Cretaceous is thinner than it is at Putah Creek; the thickness for Cache Creek is presented on the left of the column, Putah Creek on the right.

tion of maximum burial for the Great Valley sequence was probably less than five million years.

2.) Vitrinite reflectance:

Samples for vitrinite-reflectance study were taken from three locations near Cache Creek. Shell's Putah Creek diamond corehole section provided a well-measured, excellent series of unweathered samples through most of the Upper Cretaceous beds. The reflectance data from the coreholes agree well with the data obtained from outcrop (*Fig. VII–20*). Samples with high mean reflectance generally exhibit weathering characteristics, so they were not used in making the interpretation.

In the Crack Canyon Formation, near the base of the Lower Cretaceous section and with a burial of about 11,000 meters, the mean reflectance is only 0.62% (*Fig. VII–21*). The strong unimodal distribution of vitrinite reflectance is typical of the Crack Canyon and "Knoxville" Formations.

3.) Laumontite occurrence:

Based on X-ray analysis of bulk rock samples, Dickinson *et al.* (1969) found that albitized sandstones from the Crack Canyon Formation with an estimated burial depth of 10,000 meters showed clear evidence for the presence of laumontite. They also found samples higher in the section that also yielded peaks suggestive of laumontite, and inferred the occurrence of laumontite in sandstones with burial depths greater than 5,300 meters.

From the study of thin sections from the Great Valley sequence (Castaño and Sparks, 1974), the presence of laumontite was verified in the Crack Canyon Formation, and X-ray

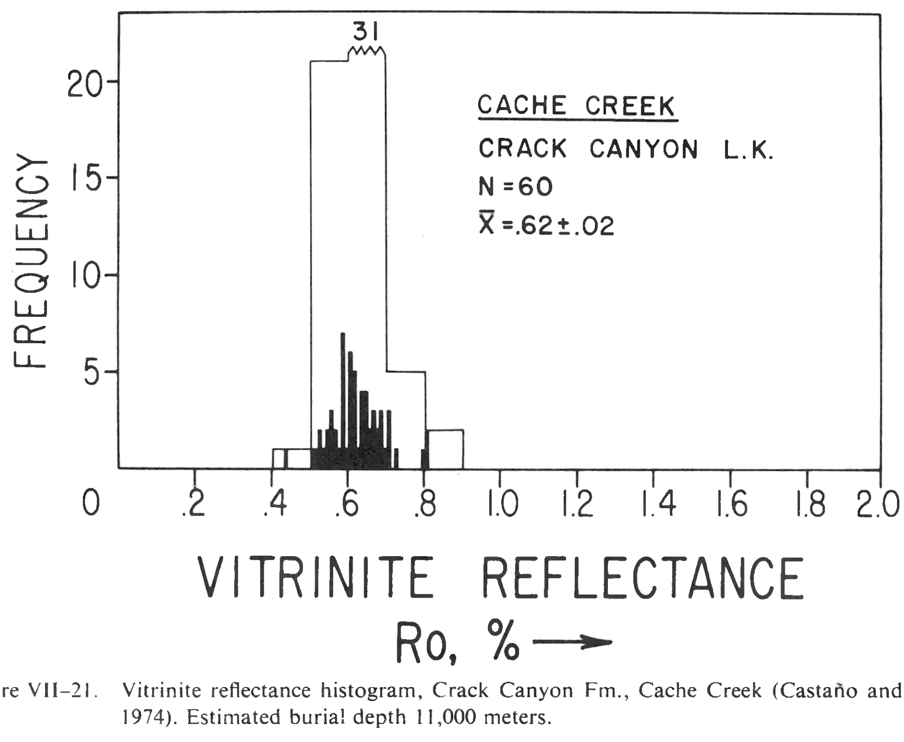

Figure VII–21. Vitrinite reflectance histogram, Crack Canyon Fm., Cache Creek (Castaño and Sparks, 1974). Estimated burial depth 11,000 meters.

diffraction analysis of mineral separates confirmed the mineral identification. However, laumontite was not found in thin section at stratigraphic levels shallower than a burial depth of 10,000 meters. It was pointed out in the discussion of the Tejon area that laumontite peaks do not show up well in X-ray diffraction patterns of bulk rock samples even where laumontite makes up 10–12% of the sandstone. The recognition of laumontite can be made reliably from thin sections, however, in concentrations considerably smaller than 10%, and the X-ray analysis on mineral separates can then be used for positive identification. It is concluded that, by itself, X-ray diffraction analysis of bulk rock samples should not be relied upon for the determination of laumontite.

Analogous to the Tejon area, laumontite is a post-compaction authigenic mineral in the Great Valley sequence, but it amounts to no more than 5–6% of the rock compared with 15–20% in the Eocene at Tejon. Higher permeability and a continuous flow of ions into the system favor a more complete reaction (Hay, 1966); this could account for the higher percentage of laumontite in the more permeable rocks at Tejon.

The fluid pressures prevailing in the Great Valley sequence at maximum burial depth were reconstructed by making two assumptions: (1) that the fluid pressure in the more porous and permeable section would have been essentially hydrostatic, i.e., 0.10 bar/meter, and (2) that the pressures in the impermeable section would have approached load pressure, i.e. 0.23 bar/meter. Porous and permeable sandstones are present in the upper 2,400 meters of the Great Valley sequence at Cache Creek, but through the remainder of the section the highest permeability measured was 0.5 millidarcy. Based on the above assumptions, the pressures at the top of the laumontite-bearing zone were around 1,850 bars at maximum burial.

The average reflectance of vitrinite is 0.63% at the top of laumontite mineralization (*Fig. VII–20*). This is equivalent to a high volatile B bituminous coal rank (LOM 9).

4.) Subsurface temperatures and geothermal gradient:

Although the Great Valley sequence is older than the sediments present in the Tejon area, the effective heating time is comparable for both areas, probably less than five million years. At Cache Creek the reflectance at the shallowest occurrence of laumontite is 0.63%; in the Tejon area the temperature at this reflectance level is 130°C. If we accept the concept of a brief effective heating time at Cache Creek, then the temperature-versus-R_0 data from the Tejon area can be applied directly and may be used as a geological thermometer for the Great Valley sequence of the Cache Creek area.

At Cache Creek the depth of burial at the top of laumontite mineralization is estimated at 10,000 meters. If we use a temperature of 130°C, the calculated paleogeothermal gradient is 1.1°C/100 meters, assuming a surface temperature of 21°C. If we had used a heating time of 75 million years (the approximate age difference between the top of the restored Great Valley sequence and the laumontite-bearing interval), the calculated paleotemperature would be around 77°C, which yields an even lower paleogeothermal gradient of 0.6°C/100 meters.

The Great Valley sequence was deposited as a thick turbidite wedge on volcanic crust (Bailey *et al.*, 1970) adjacent to the oceanic trench. The calculated gradient is consistent with a model of low heat flow in this tectonic setting (Takeuchi and Uyeda, 1965; Dewey and Bird, 1970). The very low calculated paleogeothermal gradient is in marked contrast with the gradient of 2.8–3.6°C/100 meters measured in wells penetrating rocks of the same age in the Sacramento Valley east of the Cache Creek area, which were deposited on crystalline and metamorphic rocks in a normal heat-flow regime.

c.) Factors governing the formation of laumontite

Burial metamorphic assemblages are dependent on the interrelationship between temperature, pressure, and fluid flow. The reaction conditions are also affected by the mineralogical composition, the pore-fluid chemistry, and the partial pressure of CO_2. Although in both areas studied there was an abundance of plagioclase available for alteration, and although the high permeability and continuous flow of ions may explain the higher percentages of laumontite in the Tejon area, no attempt was made to evaluate the factors other than temperature and pressure.

The conditions of temperature and fluid pressure controlling the formation of laumontite in the two study areas were quite different. At the top of the laumontite-bearing interval in the Tejon area the measured temperature is 96°C and the pore-fluid pressure is 290 bars, while in the Cache Creek area the corresponding calculated values are 130°C and 1,850 bars. These data are in agreement with the conclusion of Hay (1966) that in laboratory experiments zeolitic reactions can proceed at much lower temperatures if fluid pressure is roughly one-third load pressure, a situation which prevails in the Tejon area.

Comparison of tops of the laumontite-bearing zones with organic metamorphic parameters shows that laumontite first appears at 0.44–0.46% R_0 in the Tejon area and at 0.62 in the Cache Creek area. These values are equivalent to LOM values of 7 and 9 respectively and to coal ranks of sub-bituminous B to high-volatile C bituminous for the Tejon area and high-volatile B bituminous for the Cache Creek area. These differences support earlier findings that the formation of authigenic minerals is based on a more complex set of factors than is organic metamorphism.

A further comparison shows that Kisch's (1969) boundary of 40% volatile matter (LOM 9) for the formation of laumontite in coal-bearing rocks is extended to lower levels of organic metamorphism (LOM 7) on the basis of the non-coal-bearing sequence in the Tejon area.

CONCLUSIONS

Various techniques for measuring levels of organic metamorphism (LOM) are applicable to the determination of the principal depth zones in which oil, condensate, and dry gas are generated thermally in any given location.

The demonstrated importance of both temperature and time in diagenetic and burial metamorphic mineral facies as well as organic metamorphism, points out a useful relationship between the inorganic and organic processes. Because the formation of authigenic minerals such as laumontite is governed also by a complex interaction of other physical and chemical factors, it appears that measures of organic metamorphism are the better measures of thermal history. We believe that concept of organic metamorphism can play an important role in the study of mineral facies during late diagenesis and very-low-stage metamorphism. We also would like to encourage the use of levels of organic metamorphism to determine the thermal and tectonic history of sedimentary basins.

REFERENCES

Albrecht, P., and G. Ourisson, 1969, Diagénèse des hydrocarbures saturés dans une série sédimentaire épaisse (Douala, Cameroun): *Geochim. et Cosmochim. Acta*, v. 33, p. 138–142 (in French).

Andreev, P. F., A. I. Bogomolov, A. F. Dobryansky, and A. A. Kartsev, 1968, *Transformation of petroleum in nature*: English Transl. by Gaul and Metzner, Transl. ed. by Barghoorn and Silverman, Pergamon Press.

American Society for Testing Materials, 1970, *1970 Book of ASTM Standards, pt. 19, Gaseous Fuels, Coal, and Coke*: Philadelphia, Penn., 502p.

Bailey, E. H., W. P. Irwin, and D. L. Jones, 1964, Franciscan and related rocks, and their significance in the geology of Western California: *California Div. Mines Bull.* 183.

Bailey, E. H., M. C. Blake, Jr., and D. L. Jones, 1970, On-land Mesozoic oceanic crust in California: *U.S. Geol. Survey*, Prof. Paper 700-C, p. C70–C81.

Baker, D. R., and G. E. Claypool, 1970, Effects of incipient metamorphism on organic matter in mudrock: *Am. Assoc. Petroleum Geologists Bull.*, v. 54, no. 3, p. 456–468.

Benedict, L. G., and W. F. Berry, 1966, Further applications of coal petrography: *in Coal Sci.* (*Peter Given, Chm.*), *Advances in Chemistry*, Series No. 55, Am. Chem. Soc., Washington, D. C., p. 577–601.

Benedict, L. G., R. R. Thompson, J. J. Shigo III, and R. P. Aikman, 1968, Pseudovitrinite in Appalachian coking coals: *Fuel*, v. 47, p. 125–142.

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., University Park, Pa., 129p.

Bostick, N. H., 1970, Thermal alteration of clastic organic particles (phytoclasts) as an indicator of contact and burial metamorphism in sedimentary rocks: *Ph. D. thesis*, Stanford Univ., 220p.

Bostick, N. H., 1973, Time as a factor in thermal metamorphism of phytoclasts (coaly particles): *in Congrès International de Stratigraphie et de Géologie du Carbonifère, Septieme, Krefeld, August 1971, Compte Rendu*, v. 2, p. 183–193.

Bray, E. E., and E. D. Evans, 1961, Distribution of n-paraffins as a clue to recognition of source beds: *Geochim. et Cosmochim. Acta*, v. 22, no. 1, p. 2–15.

Brooks, J. D., 1970, The use of coals as indicators of oil and gas: *APEA Journal*, v. 1970, p. 35–40.

Brooks, J. D., and J. W. Smith, 1967, The diagenesis of plant lipids during the formation of coal, petroleum, and natural gas. I. Changes in the n-paraffin hydrocarbons: *Geochim. et Cosmochim. Acta*, v. 31, p. 2389–2397.

Brooks, J. D., and J. W. Smith, 1969, The diagenesis of plant lipids during the formation of coal, petroleum, and natural gas. II. Coalification and the formation of oil and gas in the Gippsland Basin: *Geochim. et Cosmochim. Acta*, v. 33, p. 1183–1194.

Burst, J. F., 1969, Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration: *Am. Assoc. Petroleum Geologists Bull.*, v. 53, p. 73–93.

Castaño, J. R., 1973, Application of coal petrographic methods in relating level of organic metamorphism to generation of petroleum: *Am. Assoc. Petroleum Ge-*

ologists Bull., v. 57, p. 772–773 (Abstract).

Castaño, J. R., and D. M. Sparks, 1974, Interpretation of vitrinite reflectance measurements in sedimentary rocks, and determination of burial history using vitrinite reflectance and authigenic minerals: *Geol. Soc. Am., Special Paper 153*, p. 31–52.

Coombs, D. S., 1961, Some recent work on the lower grades of metamorphism: *Australian Jour. Sci.*, v. 24, p. 203–215.

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: *Inst. Francais Pétrole Rev.*, v. 22, p. 1285–1306 (in French).

Crelling, J. C., and R. R. Dutcher, 1968, A petrologic study of a thermally altered coal from the Pergatoire River valley of Colorado: *Geol. Soc. Am. Bull.*, v. 79, no. 10, p. 1375–1376.

Dean, R. B., and W. J. Dixon, 1951, Simplified statistics for small numbers of observations, *Anal. Chem.*, v. 23, p. 636–638.

Demaison, G. J., 1974, Relationship of coal rank to paleotemperatures in sedimentary rocks: *in Comptes Rendus des Journées Internationales sur la Pétrographie de la Matière Organique Dispersée dans les Sédiments* (in press).

Dewey, J. F., and J. M. Bird, 1970, Mountain belts and the new global tectonics: *Jour. Geophys. Research*, v. 75, p. 2625–2647.

Dickinson, W. R., R. W. Ojakangas, and R. L. Stewart, 1969, Burial metamorphism of the Late Mesozoic Great Valley sequence, Cache Creek, California: *Geol. Soc. Am. Bull.*, v. 80, p. 519–525.

Dobryansky, A. F., 1963, La transformation du pétrole brut dans la nature: *Inst. Francais Pétrole Rev.*, v. 18, no. 1, p. 41–49 (in French).

Dunoyer de Segonzac, G., 1970, The transformation of clay minerals during diagenesis: *Sedimentology*, v. 15, p. 281–346.

Dunton, M. L., and J. M. Hunt, 1962, Distribution of low-molecular-weight hydrocarbons in Recent and ancient sediments: *Am. Assoc. Petroleum Geologists Bull.*, v. 46, no. 12, p. 2246–2258.

Durand, B., and J. Espitalié, 1973, Evolution de la matière organique au cours de l'enfouissement des sédiments: *Acad. Sci. Comptes Rendus*, v. 276, ser. D, p. 2253–2255 (in French).

Erdman, J. G., 1961, Some chemical aspects of petroleum genesis as related to the problem of source bed recognition: *Geochim. et Cosmochim. Acta*, v. 22, no. 1, p. 16–36.

Erdman, J. G., E. M. Marlett, and W. E. Hanson, 1958, The occurrence and distribution of low molecular weight aromatic hydrocarbons in Recent and ancient carbonaceous sediments: *Paper presented at 134th meeting of Am. Chem. Soc.*, Chicago, Sept. 7–12.

Evans, C. R., M. A. Rogers, and N. J. L. Bailey, 1971, Evolution and alteration of petroleum in western Canada: *Chem. Geol.*, v. 8, p. 147–170.

Forsman, J. P., 1963, Geochemistry of kerogen: *in Organic Geochemistry*, ed. I. A. Breger, New York, Pergamon Press, p. 148–182.

Forsman, J. P., and J. M. Hunt, 1958, Insoluble organic matter (kerogen) in sedimentary rocks of marine origin: *in* L. G.Weeks, ed., *Habitat of Oil*, Tulsa, Am. Assoc. Petroleum Geologists, p. 747–778.

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

Hacquebard, P. A., and J. R. Donaldson, 1970, Coal metamorphism and hydrocarbon potential in the Upper Paleozoic of the Atlantic Provinces, Canada: *Canadian Jour. Earth Sci.*, v. 7, p. 1139–1163.

Hanson, W. E., 1959, Some chemical aspects of petroleum genesis: *in* P. H. Abelson, ed., *Researches in Geochemistry*, New York, John Wiley & Sons, p. 104–117.

Hay, R. L., 1966, Zeolites and zeolitic reactions in sedimentary rocks: *Geol. Soc. America, Spec. Paper 84*, 130p.

Heacock, R. L., 1972, Pyrolysis and thin section examination of petroleum source rocks: *Geol. Soc. Amer., Abstracts with Programs*, v. 4, no. 7, p. 532.

Heacock, R. L., and A. Hood, 1970, Process for measuring the live carbon content of organic samples: U. S. Patent 3,508,877, April 28, 1970.

Henderson, W., G. Eglinton, P. Simmonds, and J. G. Lovelock, 1968, Thermal alteration as a contributory process to the genesis of petroleum: *Nature*, v. 219, p. 1012–1016.

Hood, A., C. C. M. Gutjahr, and R. L. Heacock (in press), Organic metamorphism and the generation of petroleum: manuscript accepted for publication in *Am. Assoc. Petroleum Geologists Bull.*

Huck, G., and K. Patteisky, 1964, Inkohlungsreaktionen unter Druck: *Fortsch. Geol. Rheinland Westfalen*, v. 12, p. 551–558 (in German).

International Handbook on Coal Petrography, 1971, Suppl. to 2d ed., Centre National de la Recherche Scientifique, Paris, Rang, Figs. 1–3.

Kaley, M. E., and R. F. Hanson, 1955, Laumontite and leonhardite cement in Miocene sandstone from a well in San Joaquin Valley, California: *Am. Mineralogist*, v. 40, p. 923–925.

Karweil, J., 1956, Die metamorphose der kohlen vom standpunkt der physikalischen chemie: *Deut. Geol. Ges. Zeit.*, v. 107, p. 132–139 (in German).

Kisch, H. J., 1969, Coal rank and burial-metamorphic mineral facies: *in* P. A. Schenk and I. Havenaar, eds., *Advances in Organic Geochemistry 1968*, Oxford, Pergamon Press, p. 407–425.

Kisch, H. J., 1971, Anthracite and meta-anthracite coal ranks associated with 'anchimetamorphic' pyrophyllite and high illite crystallinities: *Abstracts VIII Internat. Sedimentological Congress 1971*, Heidelberg, Germany (BDR), p. 51.

Kisch, H. J., 1974, Coal rank and "very-low-stage" metamorphic mineral facies in associated sedimentary rocks—An introduction: *in Comptes Rendus des Journées Internationales sur la Pétrographie de la Matière Organique Dispersée dans les Sédiments* (in press).

Kubler, B., 1967, Anchimétamorphisme et schistosité: *Bull. Centre Rech. Pau-S.N.P.A.*, v. 1, p. 259–278 (in French).

Kvenvolden, K. A., 1964, Hydrocarbons in modern sediments and the origin of petroleum: *Mines Magazine*, Feb. 1964, p. 24–25.

Landes, K. K., 1966, Eometamorphism can determine oil floor: *Oil and Gas Jour.*, v. 64, no. 18, p. 172–177.

Landes, K. K., 1967, Eometamorphism, and oil and gas in time and space: *Am. Assoc. Petroleum Geologists Bull.*, v. 51, no. 6, p. 828–841.

Long, G., S. Neglia, and L. Favretto, 1968, The metamorphism of the kerogen from Triassic black shales, southeast Sicily: *Geochim. et Cosmochim. Acta*, v. 32, p. 647–656.

Lopatin, N. V., 1971, Temperature and geologic time as factors in coalification:

Akad. nauk, SSSR, ser. geol., Izvestiya, 1971, no. 3, p. 95–106 (in Russian); English transl. by N. H. Bostick, Ill. State Geol. Survey, 1972.

Marchand, A., P. Libert, and A. Combaz, 1968, Physico-chemical criteria of the diagenesis of kerogen: *Compt. Rend., Ser. D.*, v. 266, no. 25, p. 2316–2319 (in French).

Marchand, A., P. Libert, and A. Combaz, 1969, Physico-chemical characterization tests of the diagenesis of several biologically homogeneous organic rocks: *Rev. Inst. Pétrole Ann. Combust. Liquides*, v. 24, no. 1, p. 3–20 (in French).

Martin, R. L., J. C. Winters, and J. A. Williams, 1963, Composition of crude oils by gas chromatography, Geological significance of hydrocarbon distributions: *6th World Petroleum Cong. Proc.*, sec. 5, p. 231–260.

McCartney, J. T., and M. Teichmüller, 1972, Classification of coals according to degree of coalification by reflectance of the vitrinite component: *Fuel*, v. 51, p. 64–68.

McIver, R. D., 1967, Composition of kerogen—clue to its role in the origin of petroleum: *7th World Petroleum Cong. Proc.*, v. 2, p. 25–36.

Neruchev, S. G., E. A. Rogozina, and L. N. Kapchenko, 1973, Main gas-forming phase as one of the stages in catagenetic evolution of sapropel as dispersed organic matter: *Geol. Geofiz*, Oct. 1973, no. 10, p. 14–16 (in Russian).

Page, B. M., 1966, Geology of the Coast Ranges of California: *Calif. Div. Mines and Geology, Bull.* 190, p. 255–276.

Park, W. H., 1961, North Tejon oil field: *Summary of Operations, California Oil Fields*, v. 47, no. 2, p. 13–22.

Perry, E. A., Jr., and J. Hower, 1972, Late-stage dehydration in deeply buried pelitic sediments: *Am. Assoc. Petroleum Geologists Bull.*, v. 56, p. 2013–2021.

Philippi, G. T., 1965, On the depth, time and mechanism of petroleum generation: *Geochim. et Cosmochim. Acta*, v. 29, p. 1021–1049.

Powers, M. C., 1967, Fluid-release mechanisms in compacting marine mudrocks and their importance in oil exploration: *Am. Assoc. Petroleum Geologists Bull.*, v. 51, p. 1240–1254.

Pusey, W. C., 1973a, The ESR method: A new technique of estimating the organic maturity of sedimentary rocks: *Petroleum Times*, Jan. 12, 1973, p. 21–24 and 32.

Pusey, W. C., 1973b, How to evaluate potential gas and oil source rocks: *World Oil*, v. 176, no. 5, p. 71–75.

Pusey, W. C., 1973c, Paleotemperatures in the Gulf Coast using the ESR kerogen method: *Gulf Coast Assoc. Geological Societies, Transactions*, v. 23, p. 195–202.

Retcofsky, H. L., and R. A. Friedel, 1968, Room-temperature proton magnetic relaxation times in a bituminous coal: *Fuel*, v. 47, no. 5, p. 391–395.

Rich, E. I., R. W. Ojakangas, W. R. Dickinson, and W. Swe, 1969, Sandstone petrology of Great Valley sequence, Sacramento Valley, California: *Geol. Soc. America, Spec. Paper 121*, abs.

Seyler, C. A., 1948, The past and future of coal—the contribution of petrology: *S. Wales Inst. Engineers Proc.*, v. 63, p. 213–243.

Shibaoka, M., A. J. R. Bennett, and K. W. Gould, 1973, Diagenesis of organic matter and occurrence of hydrocarbons in some Australian sedimentary basins: *APEA Journal*, v. 1973, p. 73–80.

Sokolov, V. A., 1959, Possibilities of formation and migration of oil in young sedimentary deposits: *in* V. B. Porfirev and I. O. Brod, eds., *Lvow Conf. Transactions, 1957, Moscow, Gostoptekhizdat*, p. 59–62 (in Russian).

Staplin, F. L., 1969, Sedimentary organic matter, organic metamorphism, and oil and gas occurrence: *Canadian Petrol. Geol. Bull.*, v. 17, p. 47–66.

Staplin, F. L., N. J. L. Bailey, S. A. J. Pocock, and C. R. Evans, 1974, Diagenesis and metamorphism of sedimentary organic matter: Submitted for publication in *Am. Assoc. Petroleum Geologists Bull.*

Stevens, N. P., E. E. Bray, and E. D. Evans, 1956, Hydrocarbons in sediments of Gulf of Mexico: *Am. Assoc. Petroleum Geologists Bull.*, v. 40, no. 5, p. 975–983.

Suggate, R. P., 1959, New Zealand coals, their geological setting and its influence on their properties: *New Zealand Dept. Sci. Industr. Res.*, *Bull.* 134, 113p.

Takeuchi, H., and S. Uyeda, 1965, A possibility of present-day metamorphism: *Tectonophysics*, v. 2, p. 59.

Teichmüller, M., 1971, Anwendung kohlenpetrographischer methoden bei der erdöl- and erdgasprospektion: *Erdöl und Kohle*, v. 24, p. 69–76 (in German).

Teichmüller, M., and R. Teichmüller, 1966, Geological causes of coalification: *in* P. Given, ed., *Coal Science*, *Advances in Chemistry*, series no. 55, Washington, D. C., Am. Chem. Soc., p. 133–155.

Teichmüller, M., and R. Teichmüller, 1968, Geological aspects of coal metamorphism: *in* Murchison & Westoll, eds., *Coal and Coal-Bearing Strata*, Edinburgh, Oliver & Boyd, p. 233–267.

Tissot, B., 1969, Premières données sur les mécanismes et la cinétique de la formation du pétrole dans les sédiments. Simulation d'un schéma réactionnel sur ordinateur: *Inst. Francais Pétrole Rev.*, v. 24, no. 4, p. 470–501 (in French).

Tissot, B., Y. Califet-Debyser, G. Deroo, and J. L. Oudin, 1971, Origin and evolution of hydrocarbons in Early Toarcian shales: *Am. Assoc. Petroleum Geologists Bull.*, v. 55, no. 12, p. 2177–2193.

Tissot, B., B. Durand, J. Espitalié, and A. Combaz, 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: *Am. Assoc. Petroleum Geologists Bull.*, v. 58, no. 3, p. 499–506.

Van Krevelen, D. W., 1950, Graphical-statistical method for the study of structure and reaction processes of coal: *Fuel*, v. 29, p. 269–284.

Van Krevelen, D. W., and J. Schuyer, 1957, *Coal Science*: Elsevier, New York, chapters 1, 4, and 10.

Vassoyevich, N. B., Yu. I. Korchagina, N. V. Lopatin, and V. V. Chernyshev, 1970, Principal phase of oil formation: *Moskov. Univ. Vestnik*, no. 6, p. 3–27 (in Russian); English translation: *Internat. Geology Rev.*, v. 12, no. 11, p. 1276–1296.

Winkler, H. G. F., 1970, Abolition of metamorphic facies, introduction of four divisions of metamorphic stage, and of a classification based on isograds in common rocks: *Neues Jahrb. Mineral.*, *Monatsh.*, no. 5, p. 189–248.

Winters, J. C., and J. A. Williams, 1969, Microbiological alteration of crude oil in the reservoir: *Preprints*, *Am. Chem. Soc.*, *Div. Petrol. Chem.*, v. 14, p. E22–E31.

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Tokyo University of Fisheries, Tokyo, Japan

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AEROMAGNETIC SURVEY OF THE PALAWAN-SULU
OFFSHORE AREA OF THE PHILIPPINES

By
W. Bosum[1], J. C. Fernandez[2], E. G. Kind[1] and C. F. Teodoro[2]

——————————(footnote)
[1] Bundesanstalt für Bodenforschung, 3 Hannover-Buchholz, Federal Republic of Germany
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Geological Survey of Japan, 1964, Geological Map of Japan: Scale 1: 2,000,000, one sheet.

Menard, H. W., 1964, *Marine geology of Pacific:* McGraw-Hill, New York, U.S.A., 271 pp.

Murauchi, S., and H. Hotta, 1968, Studies of the continental slope off the Sanriku Coast by seismic profiler survey (in Japanese): *Natl. Sci. Museum. Mem.*, no. 1, p. 37–40.

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Annexed 4 Maps (Maps I–1 to I–4)

to

SEISMIC SURVEYS OFF THE EAST COAST OF KOREA

By

H. U. Schlüter, Bundesanstalt für Bodenforschung and

W. C. Chun, Geological and Mineral Institute of Korea

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Annexed Map (Figure V–1)

to

TERTIARY BASINS IN INDONESIA

By

Geology Department, PERTAMINA