Petroleum Geology of Southeast Asia

edited by
A. J. Fraser, S. J. Matthews and R. W. Murphy

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Contents

Petroleum geology of SE Asia: an introduction

This volume reflects the current broad interest in exploration and production in the energy-hungry SE Asia region. Analysts currently predict that energy production in SE Asia will increase by 85% over the next 15 years and, by the end of this period, consumption may be double that of Europe. Although fairly modest in a global context, production is still sufficient to underpin economic growth rates of up to 8–12% in regions such as Indonesia, the Philippines, Vietnam, Malaysia and Brunei. In contrast, those economies that do not currently benefit from substantial oil and gas production are more stagnant, e.g. Laos, Cambodia and Burma.

SE Asia, including Indonesia, Thailand, Malaysia, Brunei and the Philippines, contains ten oil and gas provinces that individually contain more than three billion barrels of oil equivalent. All of these provinces are Tertiary basins with Tertiary-aged petroleum systems. This represents a considerable resource that has been actively exploited in the past and continues to expand with further exploration. Two main reservoir systems contribute to the majority of petroleum reserves in the region. These are deltaic clastics, e.g. Baram, Rajang and Mahakam deltas, and carbonates, e.g. Luconia, Terumbu and Nam Con Son platforms. They were charged by two key sources types. Lacustrine source rocks which are associated with 'oily' basins and paralic source beds which are typical of gas-prone basins. Key trap types are inversion anticlines and three-way-dip and fault-controlled traps in low net/gross clastic reservoirs, often with variable fluid types in stacked reservoirs with over 1000 ft plus pay zones. Carbonate traps are characterized by broad regional drape features that are seldom full to spill.

The volume covers all aspects of the petroleum geology of SE Asia from economic background, through plate tectonic models, petroleum charging and reservoir systems to detailed field and reservoir studies. In the first paper **Sladen** provides the economic context for all the other papers. He summarises current energy trends in SE Asia and emphasizes the global importance of the regions coal output. Current SE Asia GDP growth is quite phenomenal and fuel oil, gas and coal will be required to underpin this growth. **Sladen** notes a steady growth in oil and gas production particularly in China, Malaysia, Vietnam and Papua New Guinea. In terms of total oil production, SE Asia is a minor world player, but gas may become increasingly important for both domestic and export markets particularly in the emerging gas production areas of Vietnam, PNG and the Philippines. The next three papers complement this economic overview with regional reviews of plate tectonics, petroleum charging and lacustrine systems. **Hall** reconstructs plate movements in SE Asia over the last 50 Ma based on new palaeomagnetic data. He discusses rotational models for Borneo and the resulting implications for the evolution of the South China Sea regions and the progressive motion of the Australian continent. **Todd *et al.*** develop the idea that there are two dominant petroleum source-rock types in SE Asia: paralic and lacustrine. Their presence in any particular basin is reflected by the distribution of oil and gas in the basin. Lacustrine source rocks are associated with oil-prone basins such as Malay, Bohai and Central Sumatra whereas paralic source rocks are typical of gas-rich basins such as Sabah, Luconia, Nam Con Son and West Natuna. **Sladen**, in his second paper, considers the lacustrine source rocks in the context of SE Asian Mesozoic and Cenozoic lacustrine basins and reviews the development of reservoirs in the basins and the charge issues which link exploration for specific sources and reservoirs in these basins.

The 20 papers that lie at the heart of the volume focus on specific areas of SE Asia and the issues and problems of their petroleum geology. The Bongkot gas field in the Gulf of Thailand is the subject of the first of these case studies. **Leo** describes the reservoir characteristics of the deltaic/fluvial sandstones of Oligocene to mid-Miocene age encountered in the field. He concludes that seismic facies analysis was an essential exploration tool in this area, highlighting the Bongkot accumulation as a complex of largely independent structural and stratigraphic closures.

Vietnam is addressed in the next three papers. First **Matthews *et al.*** review the Nam Con Son Basin, offshore South Vietnam, highlighting reservoir issues. **Worden** addresses the controls on porosity reduction with depth in the area of the southern Vietnam continental shelf. He concludes that porosity was mainly controlled by lithic content and in particular compaction of ductile grains and is able to demonstrate a strong relationship between permeability and percentage of ductile grains. The paper by **Mayall *et al.*** complements this contribution focusing on the large carbonate plays of the Nam Con Son Basin.

Indonesia is the focus of the next four papers. **Wight** addresses the petroleum geology and production history of the Sumatra-Java area

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from which the one billionth barrel of oil has recently been produced and highlights southeast Sumatra. **Schiefelbein & Cameron** argue the case for grouping the oils from the area into a number of families, while **Cole & Crittenden** discuss the development of Tertiary syn-rift lacustrine source rocks. **Beach *et al.*** present an empirical study of the controls on effective fault seal in SE Asia based on the analysis of a database comprising some 190 fields from the region. The study suggests, amongst other conclusions, that fault strike was an apparent control, particularly in some Sumatran basins which have experienced some strike-slip movement.

The next five papers present case studies from around the SE Asia archipelago. **Prosser & Carter** describe an onshore Brunei analogue for Miocene subsurface reservoirs in Brunei. Detailed mini-permeameter data is correlated with different facies types and input to a reservoir water floor simulator. This highlights channel and upper shoreface sands as intervals of high permeability and sites of preferential imbibition of water. **Mat-zin & Swarbrick** describe the petroleum geology of the Sarawak Basin, Malaysia. He suggests the main structural control on hydrocarbon accumulations was the presence of a series of wrench controlled 'flower structures'. Geochemical analysis indicates that the oils were largely land-plant derived, in common with many other oils in the region. **Bosence & Wilson** present a depositional model for the many carbonate platform reservoirs in SE Asia based on fieldwork in Sulawesi. **Boult** discusses the exploration history and petroleum potential of the East Papuan Basin. The main producing areas at Hides and Iagifu were delineated by field mapping over 30 years ago. There are now 13 major discoveries from a total of 26 drilled structures. **Blanche & Blanche** summarize the petroleum potential of the Spratly Archipelago, an area of some 150 isolated reefs, banks and atolls in the South China Sea, which is currently the subject of border disputes involving six countries. A diversity of play types is envisaged being an extension of known plays from offshore southern Vietnam and northern Borneo. Charge is highlighted as the critical technical risk, long distance migration being required. **Blanche & Blanche** estimate a reserves potential of 1.5 billion barrels of oil equivalent and suggest that future exploration of this region could only be progressed with the creation of joint development areas.

The final seven papers deal with structural aspects of SE Asian petroleum geology. **Longley** discusses an alternative view of the tectono-stratigraphic evolution SE Asia. **Roques *et al.*** describe the structural development of the offshore Da Nang area, Vietnam and the links to onshore fault trends identified in Palaeozoic basement. **McCarthy** describes the effects of oblique oceanic subduction at the western Sundaland margin. He discusses the various estimates for the amount of the offset along the Sumatran fault system. These range from a minimum of 20–30 km suggested by offsets on Quaternary river systems to a maximum of 460 km from the extent of opening in the Andaman Sea. **Howells** describes the origins and petroleum potential of the Ombilin Basin, onshore Sumatra. **Chambers & Daley** and **Moss *et al.***, in two complementary papers, discuss the structural development and hydrocarbon habitat of the onshore Kutei Basin in East Kalimantan. The basin covers an area of 70 000 km^2, containing 14–15 km of Tertiary sediments. Both authors note an important Pliocene–Recent uplift event associated with trap formation (Samarinda Anticlinorium). Finally **Milsom** reports on the implications of gravity anomalies on the Sabah margin of the SE South China Sea and suggests a model for the location of the Baram Delta related to a variation in onshore and offshore structural trends.

The volume arises from a two-day conference organized by the Petroleum Group of the Geological Society on 26 and 27 September 1995.

As with any conference there are always a number of people working behind the scenes without whose assistance the event would never take place. Firstly we would like to thank the following companies whose financial assistance helped make the conference possible: The BP and Statoil Alliance, Mitsubishi Oil Group, Mobil North Sea Limited, Petroconsultants (UK) Ltd.

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Finally we would like to thank our session chairmen; Dick Murphy (Consultant), Dick Pegrum (Statoil) and Chris Sladen (BP Exploration), the referees of the papers contained in these proceedings and lastly the authors and presenters who put a terrific effort into both the presentation of their papers and completion of the manuscripts. Thanks are also due to Bruce Blanche for his input to the Introductory chapter of this volume.

A. J. Fraser
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Energy trends in SE Asia

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Abstract: SE Asia is undergoing rapid economic growth, achieving annual increases in gross domestic product of 6–15% in a number of countries. In many instances, the growth has been underpinned by rapid establishment and development of indigenous petroleum resources. Accompanying this growth, is a steady and significant increase in energy consumption. To meet the increasing energy requirement, oil, gas and coal production are steadily increasing. Oil consumption considerably exceeds regional production; the supply gap is widening and the shortfall is principally made up by oil imports from Middle East countries. Replacement of produced oil reserves is increasingly difficult in SE Asia. In the future, gas is expected to become a much more significant energy source. In addition to large gas reserves already found, but currently undeveloped, there are a wide variety of exploration opportunities for further gas. Technological breakthroughs expected in the next 5–30 years will also increase the attractiveness of gas as the preferred energy source in SE Asia during the next 50 years. These include advances in the use of gas which is heavily contaminated with CO_2, improvements which enable more commercial developments of deepwater gas, and a continued improvement in coal-bed methane technology.

The object of this short review is first to examine recent trends in energy production and consumption in SE Asia[1]. This includes the major energy sources, principally oil, gas and coal, and also hydroelectric, nuclear and solar energy[2]. After reviewing recent trends, there is an attempt to identify future trends in these energy sources together with issues that will need to be faced by the energy industry as it moves towards the twenty-first century.

SE Asia is characterized by a large population (>40% of the world) in countries that are undergoing rapid economic change. Rapidly expanding economies in countries such as China, Thailand, Vietnam and Philippines demonstrate yearly growth rates of 6–15% gross domestic product (Fig. 1). Population growth in many countries reaches 2% per year, further creating a strong energy demand. Not surprisingly, in 1994, regional energy consumption increased by over 5%[3].

In most instances, expanding economies have been underpinned by rapid development of an indigenous petroleum industry, which has been a key pillar to continued growth. There appears to be little basis to predict a long-term decline in energy demand. Although some countries may experience a period of economic consolidation and flattening in energy demand as their economies mature (for example, South Korea, Taiwan, and later on Malaysia and Thailand), this can be expected to be offset by increases in energy

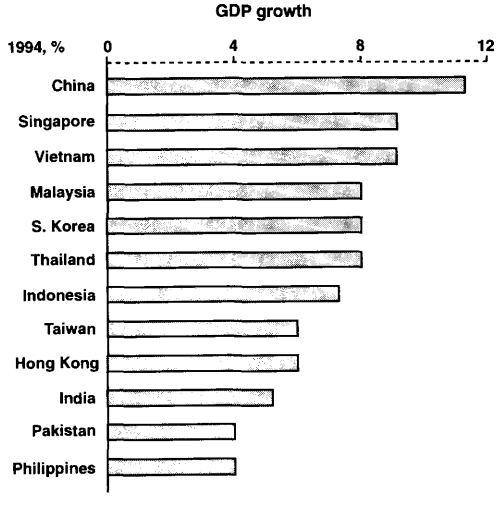

Fig 1. Growth in SE Asia viewed as increases in gross domestic product (GDP) in different countries during 1994 (based on data from Deutsche Bank).

[1] For the purpose of this review, SE Asia is considered to embrace all the countries eastward from Pakistan and India to the Pacific Ocean, from Japan, China and Korea in the north, to Australia and New Zealand in the south. Although beyond many people's definition of SE Asia, it embraces an area with key energy trade links, energy financing relationships and energy construction that consequently denotes a region of more distinctive energy characteristics.

[2] A number of other energy sources exist including wind, waves, wood, oil shale and batteries. Whilst these are sometimes important very locally, they have not been included in this short review.

[3] Energy statistics throughout this paper are based on those published by BP (1995).

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demand elsewhere (for example economic growth in China, India, Vietnam and perhaps Myanmar).

Trends in oil

Oil production and consumption

SE Asia contributes just over 10% of annual world oil production, and during the last five years the region has shown a small, but steady growth in production of 1–2% per year (Table 1). Oil production in SE Asia is currently dominated by China (*c.* 42%), with other major producing countries being Indonesia (*c.* 22%), followed by Malaysia, India and Australia (each *c.* 9%).

All of the major producing countries are struggling to deliver significant increases in oil production and in most cases production has been flat during the last five years (Table 1). The challenge has become one of maintaining current production levels and, in the case of India, there are now indications of a downward trend in oil production. A number of new producers have helped maintain the overall growth in production. Although not significant in world terms, both Vietnam and Papua New Guinea have made relevant contributions to local markets.

Oil consumption in SE Asia has grown steadily at around 6% in recent years. Annual consumption of crude oil in SE Asia in 1994 was *c.* 5.8 billion barrels and second only to coal as the major energy source (Fig. 2). Annual oil production was considerably less than consumption at only *c.* 2.5 billion barrels. The supply gap is steadily widening and is currently *c.* 10 million barrels per day. Imports of oil from outside of SE Asia have doubled over the last 10 years. SE Asia has now overtaken the USA in terms of oil imports. Soon it will overtake Europe to become the worlds largest oil importing region. Growth in demand for transport fuels is particularly strong. The shortfall between consumed and produced oil has consistently been balanced by oil imported from the Middle East.

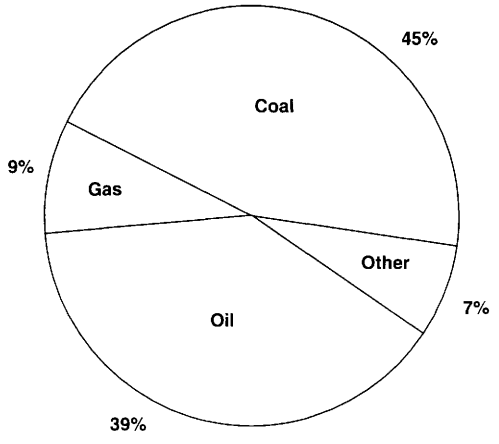

Fig. 2. Primary energy consumption in SE Asia during 1994 (source BP 1995).

Oil reserves and future possibilities

Many currently producing oil-prone basins in SE Asia are struggling to replace produced oil reserves. They are now fairly mature in the extent of exploration that has been carried out. Very few large oilfields have been found in recent years and few giant fields are probably remaining to be found. The significant growth in oil reserves that occurred during the last 40 years is unlikely to be continued at the same rate.

Table 1. *Annual oil production in SE Asia (source BP 1995)*

Country	Annual oil production (million tonnes)					% 1994 world production
	1990	1991	1992	1993	1994	
Australia	28.4	26.9	26.5	24.9	26.9	0.8%
Brunei	7.4	7.9	9.0	8.3	8.5	0.3%
China	138.3	141.0	142.0	144.0	144.9	4.5%
India	34.8	33.0	30.3	29.1	33.6	1.1%
Indonesia	71.9	78.3	74.1	74.3	74.2	2.3%
Malaysia	29.6	30.8	31.3	30.6	30.9	1.0%
Papua New Guinea	—	—	2.5	5.9	5.7	0.2%
Vietnam	2.7	4.0	5.5	6.3	6.9	0.2%
Other SE Asia	8.8	9.3	9.9	9.7	9.3	0.3%
Total	321.9	331.0	331.0	333.0	340.7	10.6%

The current reserves to production ratio (which assumes that no new reserves are found) indicates only 18 years of remaining supply. This is, of course, overly alarmist because some new reserves will undoubtedly be found and recovery from existing accumulations will most likely improve. Nevertheless, it is difficult to envisage any large, sustainable increases in oil production. Meanwhile, future consumption is estimated to increase at between 2% and 4% per year for the next 15 years.

The total reserves base for oil is relatively small compared to the Middle East which currently contains more than 12 times the proven oil reserves of those in SE Asia (Table 2). It is likely that SE Asia will be dependant on the Middle East for crude oil imports for the foreseeable future. Other sources of supply may become more important in the future, for example Alaska, or possibly East Siberia and Sakhalin Island. These sources would introduce more diversity of supply and lower dependence on the Middle East.

Few frontier areas that are thought to be oil-prone remain to be explored in SE Asia. Success in frontier areas will be key to creating any significant growth in oil reserves and production. For the moment, there is some uncertainty in the scale of their contribution to future supply. Possibilities include basins in NW China, Vietnam, E Indonesia and NW Australia, and also perhaps parts of the East China Sea, and Mongolia. The opportunities are often remote, geologically complex, or in deepwater. It seems reasonable to expect very few new oilfields of over 500 million barrels and only a handful of 1000 million barrels or more. Most oilfields are expected be in the 1–100 million barrels range, strongly skewed towards the smaller fields of less than 50 million barrels.

Not only are newly discovered oilfields expected to be mostly small, but they are also expected to be geologically more complex. A combination of complex structural and stratigraphic trap configurations, together with complex reservoir characteristics will make it more difficult to realise their value. To cope effectively with a combination of these kinds of reservoirs and small fields, SE Asia will need to be at the forefront as users of the latest technology if it is to maintain or improve its oil production. Technological improvements will be needed in subsurface imaging techniques for what are expected to often be tectonically complex, highly faulted structures and thin, heterogeneous clastic reservoirs. Reservoir modelling and production technology will need to advance to deliver solutions to producing from these reservoirs.

SE Asia is unusual in having most oil production from non-marine sandstones, principally deposited as lacustrine and deltaic facies, and most oil generated from non-marine lacustrine and deltaic source-rocks. Problems inherent in these hydrocarbon systems are the presence of waxy crude oil in complex reservoirs, characterized by frequently low oil flowrates in complex traps. This creates complicated production issues and often difficult petroleum economics. In contrast, the giant fields of the Middle East are relatively simple traps which contain reservoirs capable of very high oil flowrates. However, there are some advantages of crude oils produced in SE Asia. First, is naturally the close proximity to a very large market, secondly the greater security of an indigenous source of supply, and thirdly the low sulphur content of SE Asia crudes. Overall, these factors enable the oil producers of SE Asia to realise a small price premium against Middle East crudes.

Trends in gas

Gas production and consumption

Steady and significant growth in gas production (*c.* 5–7% per year) has been occurring in SE Asia over the last five years, albeit starting from a fairly low base (Table 3). At present, SE Asia

Table 2. *Proven oil, gas and coal reserves in different regions of the world in 1994 (source BP 1995)*

	North America	South America	Middle East	Europe	Africa	Former Soviet Union	SE Asia
Proven oil reserves (Thousand million barrels)	88	78	660	17	62	59	45
Proven gas reserves (Trillion cubic metres)	9	5	45	5	10	57	10
Proven coal reserves (Thousand million tonnes)	250	10	—	95	61	315	312

Table 3. *Annual gas production in SE Asia (source BP 1995)*

Country	Annual gas production (million tonnes oil equivalent)					% 1994 world production
	1990	1991	1992	1993	1994	
Australia	18.6	19.5	21.1	22.0	25.3	1.4%
Brunei	7.6	7.8	8.1	8.2	8.4	0.4%
China	12.8	13.4	13.6	14.6	14.9	0.8%
India	11.1	12.6	14.3	14.6	15.6	0.8%
Indonesia	40.8	46.4	48.9	50.6	55.8	3.0%
Japan	1.8	1.9	1.9	2.0	2.0	0.1%
Malaysia	16.0	18.3	20.5	22.4	23.4	1.3%
Pakistan	9.9	10.3	10.9	12.1	12.5	0.7%
Other SE Asia	16.6	17.8	19.1	20.7	21.8	1.2%
Total	135.2	148.0	158.4	167.2	179.7	9.7%

annually contributes almost 10% of world gas production. Within the region, gas production is currently dominated by Indonesia *c.* 31%, with Malaysia and Australia *c.* 13% each. China and India are also important gas producers with almost 10% each. All of the major gas producing countries have delivered a steady increase in production over the last five years. In 1994, Indonesia raised production by 10%, Malaysia by 4% and Australia by 15%. In addition there is increasing gas production in many other countries, notably Bangladesh, Pakistan, Thailand and New Zealand. Few countries currently have decreasing gas production; only Afghanistan, where there are production difficulties due to civil unrest, and Taiwan, which has a limited reserves base, have had notable decreases in gas production.

Compared to other regions, SE Asia represents the fastest-growing gas consumer in the world, with consumption having increased seven-fold over the last twenty years. With most gas being consumed within the region, gas consumption and production have remained roughly in balance. Japan continues to be the major gas consumer within the region, importing large volumes of liquefied petroleum gas (LPG) and liquefied natural gas (LNG). Demand grew strongly in 1994 in South Korea (33%), Taiwan (30%) and Indonesia (13%). In contrast to oil, production and consumption of most gas is very much dictated by the need for a guaranteed nearby market to which the gas can be easily transported. Growth in gas use is thus closely tied to growth in local economies, not necessarily the economy of an entire country.

In the strongly developing economies which are now a characteristic of many countries in SE Asia, gas is an ideal alternative energy source to oil for coping with the increasing energy demand. Thailand, Vietnam and Indonesia are each good examples of countries utilizing their gas resources to underpin growing economies. This has included schemes for using gas to generate power and fertilizer, and the use of LPG and LNG.

LPG and LNG have the advantage of being suitable for bulk storage and can be transported for long distances. LNG in particular, has risen rapidly as a key energy source in the more developed countries of SE Asia, particularly in the last 20 years. In 1994, LNG trade within the region grew by 11%. LNG schemes in SE Asia have utilized gas production from Australia, Indonesia and Malaysia and transported the gas to large markets in Japan, South Korea and Taiwan.

Gas reserves and future possibilities

The gas reserves base in SE Asia is currently rather small when compared to other parts of the world such as the Former Soviet Union and Middle East (Table 2). However, considerable new gas reserves are being found in SE Asia and extensive infrastructure is being built, both onshore and offshore. The current reserves to production ratio indicates 50 years of remaining supply, and many new exploration opportunities exist.

Proximity to markets will continue to be a key issue in gas remaining a competitive energy source due to the costs of long distance transport. In the past, many gas discoveries were too small and distant from a market to fund the initial capital intensive infrastructure. Many nearby markets were simply not sufficiently developed to justify gas developments. However, the situation has changed significantly in the last 15 years. As markets have grown and the infrastructure has become more developed, so many smaller gasfields and groupings of

gasfields have been developed. Groups of small fields and satellite discoveries can now be aggregated to form viable developments.

Possibilities also exist for long-distance gas pipeline networks linking a number of countries throughout the region and covering many thousands of kilometres. These networks offer a host of new opportunities and development possibilities for gas. As more infrastructure is built, this can be expected to reduce transportation costs, make many more small gasfields commercially attractive, spur more exploration, and consequently more gas can be expected to be found and developed.

Gas is currently only a very limited part (*c.* 9%) of total energy consumption in SE Asia (Fig. 2). However, growth in production and consumption is strong and expected to continue to rise even more strongly as economies develop in the next Century. As a result, gas will become an increasingly significant part of the total energy budget in SE Asia in coming years.

In the future, we should expect gas to be put to a wider number of applications. The principal use is expected to be for power generation, but in particular circumstances gas may be important as a fertiliser feedstock, for methanol production, chemicals manufacturing, or for other industrial uses. Installation of domestic gas distribution networks has numerous logistical problems reaching individual households in many countries in SE Asia. In addition, the large areas of warm climate do not require gas for central heating. Piping of gas to individual households is therefore considered unlikely. A tendency for domestic consumption of electricity as opposed to gas is therefore anticipated. However, LPG is expected to become increasingly attractive, particularly for domestic cooking and light industries where it is gradually replacing wood, oil and coal.

New markets for LNG can also be expected to develop, particularly China and Thailand. There are many potential new suppliers of gas for LNG such as the Philippines, Vietnam and Papua New Guinea. Malaysia currently has vast reserves of undeveloped gas and these too could be developed for additional LNG. The LNG produced in SE Asia is usually very competitive because the principal alternative source of LNG supply is the Middle East which has much higher transportation costs to the markets of Japan, South Korea and Taiwan. LNG is also considered attractive to many economies in the region as it provides a security and diversity of energy supply, and at a very competitive price to oil.

A host of exploration opportunities exist for adding significant new gas reserves. In addition to adding further reserves in proven gas provinces, there are numerous frontier areas, or areas with as yet very limited exploration. Opportunities include the Andaman Sea, Bangladesh, East China Sea, Cambodia, Laos, Tibet, northwest China, eastern Indonesia, the Gulf of Tonkin between China and Vietnam, and various parts of the South China Sea and East Vietnam Sea.

A number of opportunities for finding new gas reserves also exist by drilling deeper in search of gas in the presently producing oil basins. For example, many of the onshore basins that are producing oil in north and east China, in Indonesia, India and Malaysia have gas potential in deeper sequences but these sequences have often not yet been penetrated by the drill bit. Although the non-marine oil-prone source-rocks responsible for generating oil in these basins tend not to yield much gas during maturation, there are opportunities for oil becoming cracked to gas in the deeply buried sequences, together with additional opportunities for gas generation from deeply buried coals that may be present. Improvements in the drilling and formation evaluation of deep, often high-pressure and high-temperature wells will assist exploration for these kinds of deep gas.

Improvements and breakthroughs in gas processing technology can also be expected to add new gas reserves. The ability to utilize hydrocarbon gas with up to 85% CO_2 pollutants, whilst suitably disposing of unwanted CO_2, would allow vast gas reserves to be developed in SE Asia. For example, giant gas fields of this type have been found but remain undeveloped in offshore areas of Myanmar, Indonesia, the Gulf of Thailand and central Vietnam. The technology breakthrough that would allow development of these gas reserves can be expected in 5–25 years. This would then spur further exploration for CO_2 polluted hydrocarbon gas.

Gas produced from coal-bed methane projects is also expected to offer many opportunities in the future. SE Asia with its vast coal resources (see section below) has numerous possibilities for this kind of gas project. Combined with advances in coal-bed methane technology and an improved understanding of the subsurface behaviour of this kind of gas, a large number of coal-bed methane projects can be anticipated. At the moment, however, there are few projects in SE Asia in contrast to more widespread coal-bed methane producers such as the USA. Notably, China has recently begun a number of coal-bed methane projects and more are expected in the near future.

Improvements in deepwater gas production technology are also expected to create new reserves potential for gas. There are a number of deepwater areas in SE Asia that would benefit. These include parts of the South China Sea, East Vietnam Sea and northern Indian Ocean. Much further into the future, improved understanding of gas hydrate deposits that are developed in many deep oceans, combined with a viable technology, may allow us to access this vast potential gas resource. However, such developments are probably many decades away given the abundance of more conventional gas resources.

Trends in coal

Coal production and consumption

Coal represents the principal energy source in SE Asia and the region currently provides about 42% of world coal production (Fig. 2 and Table 4). Coal is frequently the cornerstone of much heavy industry development, and also has widespread domestic use. A number of countries have extensive coal deposits which, together with oil and gas, have helped both satisfy growing energy demand and support the growing economies. Whilst production has overall grown *c.* 3% each year for the last five years, production growth each year is quite variable with a low of *c.* 0.5% and a high of *c.* 5% (Table 4). Production growth is usually tied closely to the annual economic performance of each country.

Most coal production is by simple opencast, drift and adit mining. In SE Asia, deep shaft mining has seldom been used because of abundant resources either at, or very close to the surface. China dominates coal production in SE Asia with *c.* 65%, followed by Australia and India (each *c.* 13%), and then Indonesia (*c.* 2%). All of these countries have been increasing coal production, most notably Indonesia which tripled coal production between 1990 and 1994 (Table 4). Declining coal production is most significant in Japan and South Korea, where the economies are shifting towards using oil and LNG for energy.

Coals formed widely in SE Asia in basins with Jurassic, early Cretaceous and early Tertiary sedimentary sequences. These coals occur both in the entirely non-marine alluvial and lacustrine basins, and also the basins which had large deltas entering the oceans. There is a complete spectrum of coal rank with lower grade brown coals and lignite not surprisingly more typical of the early Tertiary coals, whereas bituminous or anthracitic coals are more typical of the Cretaceous and Jurassic coals, or rare remnants of older Triassic, Permian and Carboniferous coals.

Coal reserves and future possibilities

SE Asia undoubtedly has enormous proven reserves of coal which are roughly equal in size to those of the Former Soviet Union (Table 2). Together with the Former Soviet Union, coal reserves in SE Asia dominate the world's proven reserves. Vast coal resources occur in China, India, Indonesia, Australia and Mongolia. Many other countries have significant coal resources most notably Vietnam, Thailand, Japan, New Zealand, Pakistan and South Korea. The current reserves to production ratio indicates 170 years of remaining supply in SE Asia. Numerous additional deep coal reserves possibilities exist but are either currently unexplored for, or frequently unappraised, due to the enormous reserves of shallow, easily extractable, coal.

Table 4. *Annual coal production in SE Asia (source BP 1995)*

Country	Annual coal production (million tonnes oil equivalent)					% 1994 world production
	1990	1991	1992	1993	1994	
Australia	106.6	110.5	117.0	117.7	118.3	5.5%
China	530.1	520.3	543.7	558.4	592.0	27.4%
India	103.3	110.9	117.3	121.5	122.9	5.7%
Indonesia	6.5	8.7	14.2	17.6	18.8	0.9%
Japan	5.5	5.3	5.1	4.8	4.6	0.2%
New Zealand	1.6	1.8	1.8	2.0	2.2	0.1%
Pakistan	1.3	1.5	1.4	1.5	1.5	0.1%
South Korea	9.1	8.0	6.4	5.0	3.9	0.2%
Other SE Asia	42.0	42.6	42.7	42.8	43.8	2.0%
Total	806.0	809.8	849.6	871.3	908.0	42.1%

A continuing heavy reliance on coal can be expected in the future. The vast reserves offer a number of possible future exploitation opportunities. In addition to advances in coal extraction technology, we may expect technology improvements in the efficiency of burning and using coal. Improvements in coal-conversion technology may also introduce future opportunities if problems develop in regional supply of oil, and oil prices rise significantly.

Trends in other energy sources

To ensure diversity and security of supply, coupled with cost competitiveness, a variety of other energy sources are expected to continue to play a role in most countries in SE Asia. In many cases, they dilute the need for energy imports, particularly oil. However, oil is likely to remain in strong demand for producing transport fuels unless there are radical changes in the mode of public and private travel.

Hydroelectric energy

A number of significant hydroelectric projects have been completed in recent years, and others are planned. The region now contains *c.* 20% of current world hydroelectric capacity. China, Japan, India, Vietnam, New Zealand and Taiwan have each developed significant contributions of power from hydroelectric energy. Construction of further giant projects is now underway in Vietnam, China and Malaysia. There are however problems in SE Asia, particularly due to the distinct 'wet' and 'dry' seasons that occur in many countries. These cause considerable fluctuations in power production capability.

The creation of large dams for hydroelectric power has raised various issues of environmental impact. There is increasing concern and awareness in SE Asia that many hydroelectric projects cause significant modifications to the landscape, altering river systems, agricultural patterns, rural lifestyles and cultures. Most schemes also require extremely large capital investments that result in complex funding issues and a large financial burden. Even so, there is yet to be clear evidence of a slow down in new hydroelectric energy projects. Environmental concerns coupled with a natural limit on the number of opportunities available are expected to cause a decline in projects in future years.

Nuclear energy

Nuclear energy projects are continuing to grow in SE Asia, with various projects recently completed or underway, particularly in China. Many other countries are now considering nuclear energy projects to supplement and diversify energy supply and reduce oil imports, for example Vietnam. Nuclear energy is viewed by many countries as part of their long-term energy solution, both contributing to and diversifying energy supply, thereby reducing reliance on oil and gas. Japan, for example, plans further increases in nuclear energy production during the next 15 years, with more than 40% of energy produced at nuclear plants by 2010. However, continuing environmental concern over nuclear energy is expected to limit increases in the proportion of energy contributed from nuclear sources.

Geothermal energy

Geothermal energy projects are locally significant in SE Asia, and currently concentrated in areas of high geothermal gradients such as Tibet and west Yunnan in China, Java and Sumatra in Indonesia, Taiwan and New Zealand. At the moment, geothermal energy projects are viable only onshore and are fairly small-scale compared to the major energy sources. Offshore geothermal projects are unlikely to become commercial without a fundamental change in the technology and costs. However, there are many possibilities to introduce more projects into other onshore areas of high temperature such as parts of the Philippines and Indonesia. In addition, deep reservoirs that are found to contain very hot water during deep oil and gas exploration may offer possibilities. Opportunities of this type may evolve in areas such as onshore Indonesia and eastern China.

Solar energy

Solar energy is ideal in areas of SE Asia that have no energy distribution network, particularly the more remote parts of China, Mongolia, Vietnam, Australia and India. Production of solar power units is increasing and the application of solar energy to a wide variety of medical, communications, and lighting uses is expected to continue to expand. At the moment, however, overall use is small compared to oil, gas, coal, nuclear and hydroelectric energy.

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Cenozoic plate tectonic reconstructions of SE Asia

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Abstract: A new plate tectonic model for the Tertiary is proposed, based on the integration of new palaeomagnetic data from east Indonesia recording Philippine Sea plate motion, recent revisions of the history of the South China Sea, and previously available geological and palaeomagnetic data from SE Asia. Early Neogene counter-clockwise rotation of Borneo is interpreted to have closed a proto-South China Sea suggesting a strike-slip boundary in NW Borneo before the Neogene. This rotation suggests that the West Philippine Sea, Celebes Sea and Makassar Strait formed a single basin which opened in the late Paleogene, and widened eastwards. At *c.* 25 Ma a major collision, that of Australia with a Philippine Sea plate arc, trapped Indian Ocean lithosphere which later became the Molucca Sea plate. The collision caused clockwise rotation of the Philippine Sea plate, initiated the Sorong Fault system, and then eliminated the Molucca Sea by subduction on its east and west sides. The effects of collision propagated westwards through the region resulting in the initiation of new plate boundaries marked by regional unconformities. The arrival of the Sulawesi ophiolite, which collided with west Sulawesi in the late Oligocene, was the earliest event in collision between Sulawesi and the Bird's Head microcontinent. Continental crust was thrust beneath Sulawesi in the early Miocene, and the Tukang Besi and Sula platforms were sliced in turn from the microcontinent, transferred to the west-moving Philippine Sea/Molucca Sea plate for a few million years, and finally accreted to Sulawesi. Reconstructing the Molucca Sea and Bird's Head microcontinent suggests that most of the Banda Sea has a late Neogene extensional origin. Collision between the Philippine arc and the Eurasian continental margin in Taiwan at *c.* 5 Ma is the key to present regional tectonics.

Plate tectonic reconstructions of SE Asia may help in understanding the development of sedimentary basins, and the distribution of petroleum resources. Reconstructions of the region should also assist in identifying important controls on its tectonic development (e.g. the role of indentor tectonics), critical events (e.g. collisions or extensional events), and the timing and consequences of plate movements and reorganizations (e.g. their expression as unconformities and their regional correlation). Local, particularly two-dimensional, reconstructions often move problems outside the area of immediate interest, and neglect or fail to recognize both inadequacies and important features of models. Reconstructing a large region requires consideration of the implications of local reconstructions, and may indicate new solutions which can reconcile different data or show that commonly accepted views of regional development cannot be sustained.

During the Cenozoic the SE Asia region (Katili 1975; Hamilton 1979) was bounded to the north and west by a Eurasian plate, and to the south by the Indian–Australian plate. The motions of these plates are known, and their positions provide limits to the zone within which the SE Asian collage of microplates and subplate fragments can be moved in reconstructions. However, the past position of the eastern boundary to the region has been much less certain. This boundary is, and has been, the western edge of the Philippine Sea plate but the motion of this plate has been difficult to link to the global plate circuit because it is surrounded by subduction zones.

New palaeomagnetic data from east Indonesia (Ali & Hall 1995; Hall *et al.* 1995*a*, *b*) permit reconstructions of the Philippine Sea plate and its motion since the early Tertiary. The east Indonesian islands of the North Moluccas include a relatively complete upper Mesozoic and Tertiary sequence of rocks which allow palaeomagnetic sampling over a wide stratigraphic range. The palaeomagnetic data from older sequences can be interpreted with confidence because there are results from younger rocks. The rocks are distributed over a large area so it is also possible to distinguish the effects of rotations caused by local deformation at the plate edge from those recording movement of the entire plate. These new palaeomagnetic data provide a clear indication of rotation of the whole Philippine Sea plate. They can also be

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used to determine poles of rotation for the entire plate, which can account for the new and earlier palaeomagnetic data, and other evidence of motion of the plate, for example, results of magnetic anomaly skewness studies. The calculated poles of rotation can thus be used to reconstruct the position and shape of the plate during the Cenozoic (Hall *et al.* 1995*c*). These reconstructions are linked to recent interpretations of the South China Sea area (Briais *et al.* 1993) to provide boundaries for the regional model of this paper.

During the development of the model an attempt was made to satisfy both geological and palaeomagnetic data. For reconstruction purposes, geological data are essential, but often can be interpreted in different ways, and it is usually impossible to determine amounts of movement between different areas from geological arguments. On the other hand, much of the evidence for movement, and certainly for rotation about vertical axes, can only be acquired from palaeomagnetism and therefore *interpretation* of both geological *and* palaeomagnetic data is essential. Van der Voo (1993) discusses the use and problems of palaeomagnetic results, and provides a summary of data from SE Asia. Distinction between local and regional rotations is often far from clear, particularly because good palaeomagnetic data are sparsely scattered in time and space. In several areas, principally Sundaland–Borneo and the Philippines it is necessary to choose between alternative interpretations of palaeomagnetic data. In such cases decisions were based on regional geological arguments, as discussed by Hall (1996), and account for differences between the models of Rangin *et al.* (1990), Daly *et al.* (1991), and Lee & Lawver (1994). Critical decisions, for example accepting the large counter-clockwise rotation of Borneo in this model, can be tested if reconstructions can be made that are consistent with geological data for the whole region. Thus, the reconstructions here should be seen as a way of distinguishing locally and regionally important data sets, identifying targets for future work, as well as providing a possible model of SE Asia with a new interpretation of its Cenozoic development.

An account of the reconstructions, with a more detailed account of the sources of information, is given by Hall (1996). An animation of the reconstructions, which can be run on either a Windows-based PC or a Mac with adequate hard disc space, is available free from the World Wide Web site at http://glsun2.gl.rhbnc.ac.uk/seasia/welcome.html.

Methods

Philippine Sea Plate motion

Cooperative field investigations by the University of London and the Indonesian Geological Research and Development Centre carried out between 1984 and 1992 (e.g. Hall & Nichols 1990) provided the stratigraphic basis for a systematic palaeomagnetic programme in the north Molucca islands between Halmahera and Waigeo, and the Sula platform. The palaeomagnetic work was the basis for determination of the Philippine Sea Plate motion history (Hall *et al.* 1995*c*), which in turn provided the basis for tectonic reconstructions of SE Asia.

ATLAS model

The reconstructions were made using the ATLAS computer program (Cambridge Paleomap Services 1993). In the ATLAS model the motions of the major plates are defined relative to Africa and its movement is defined relative to magnetic north. There has been little Cenozoic motion of Eurasia and it remains in a similar position in all the reconstructions, although there are small movements of Eurasia due to the plate circuit used in the ATLAS model, particularly for the last 5 Ma. Therefore there are minor differences compared to reconstructions which keep Eurasia fixed in its present position (Lee & Lawver 1994; Rangin *et al.* 1990).

Fragments and tests

Reconstructions of SE Asia (Fig. 1) for the region between 20° S–30° N, and 90° E–160° E, are presented at 5 Ma intervals for 50–5 Ma (Figs 2 to 6). Approximately 60 fragments were used, and they retain their current size in order that they remain recognizable. However, in earlier reconstructions it is likely that fragments had different sizes and shapes or may not have existed, for example in areas of volcanism and extension in the Philippines, Sunda, and Banda arcs. In some cases, this has been incorporated by omitting the fragment before a certain time.

Most minor fragments can be linked to a major plate (Australia, Eurasia, Philippine Sea) and were moved as if attached, or partially coupled to, a plate with known motion. The model attempts to use the simplest possible motion histories. More complex movements were obtained by transferring fragments from one major plate to another. During the reconstruction process possible solutions were tested by asking (1) are palaeomagnetic data satisfied (2) are geological data satisfied, and (3) is there overlap of fragments during movements? Below, the main features of the reconstructions made for different time slices are summarised, with interpretations of the region's development.

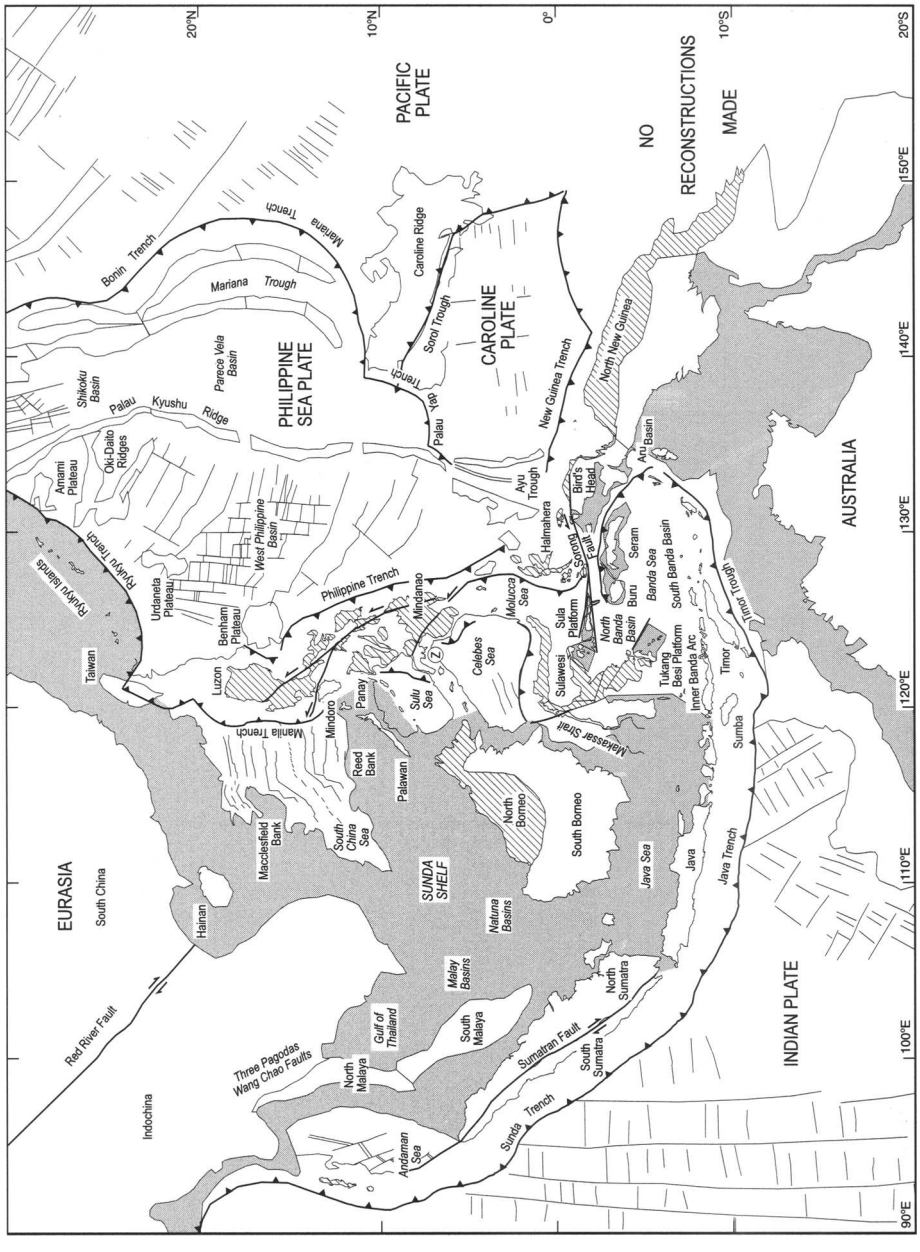

Fig. 1. Simplified present-day tectonic configuration of SE Asia. Shallow marine parts of Eurasian, Sunda and Australian continental shelves are shaded in grey. Hatched areas represent mainly ophiolitic, arc and other accreted material added to Eurasian and Australian margins during the Cenozoic. Principal marine magnetic anomalies are shown schematically for the Indian Ocean, Pacific Ocean, South China Sea, Philippine Sea and Caroline Sea. Circled Z identifies Zamboanga peninsula of Mindanao. Double lines represent active spreading centres. Complexities in the Bismarck–Solomon Sea regions are not shown.