Petroleum systems in Southeast Asian Tertiary basins

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Abstract: Productive Tertiary basins in Southeast Asia have essentially similar geodynamic developments, and share many hydrocarbon habitats and active petroleum systems. In order to facilitate understanding of the essential elements that contribute to the success of petroleum systems I have classified them into a number of groups or 'associations' according to their sedimentary facies. This facilitates use of them as valuable analogues. Five such *facies associations*, containing characteristic and distinct petroleum parameters have been recognised: (i) lacustrine (ii) paralic (iii) open marine shelf (iv) deeper marine and (v) pre-Tertiary. They belong to particular cycles or stages in basin development that provide the context within which the depositional environments and palaeogeography evolve.

Lacustrine facies typify the early stages of synrift development in basins closer or more proximal to the Sundaland province in northern and western SE Asia. Open marine facies, on the other hand, typify the early postrift period and basins in palaeogeographically more distal areas, such as eastern Indonesia and The Philippines. Paralic and bathyal facies characterise the later stages of the synrift and postrift cycles and are widespread throughout the proximal and intermediate parts of the area. Pre-Tertiary source facies, which provide charge in parts of eastern Indonesia and Thailand, are mainly terrestrial in nature.

These differences have important implications for petroleum occurrence, which can be summarised accordingly:

- More proximal basins are dominated by lacustrine to paralic facies in the synrift cycle and have a mainly non-marine sedimentary fill. Petroleum systems with oil charge are dominant.
- More distal basins are dominated by rapid postrift subsidence. In the open marine facies carbonate reservoirs are well-developed, while petroleum systems are mainly gas-prone.
- Around Borneo thick late postrift passive margin delta sequences with oil- and gas-prone coaly source rocks and clastic reservoirs are developed in delta-top environments. Transported terrigenous organic material is commonly found in related deep marine environments and contributes to a marine source facies. Both give rise to prolific petroleum systems.
- Many basins in the Sunda Shelf area lie in an intermediate situation, where a non-marine synrift is followed by a marine postrift cycle. Such basins benefit from lacustrine and paralic source rock and reservoir sequences in both the syn- and the postrift, and are often characterised by multiple petroleum systems.

Evaluation of petroleum potential in Southeast Asian Tertiary basins requires a special approach: in most parts of the World, such as the Middle East and Northwest Europe, source rocks are of marine origin, are relatively consistent in type and quality and are located in well-defined formations of regional extent. In SE Asia the terrestrial and lacustrine source rocks are more difficult to locate, are variable in quality and are often distributed in thin beds throughout thick sequences. These differences mean that predictive extrapolations of charge quality and maturity, and therefore of basin prospectivity, are much more difficult in Southeast Asia: This probably explains why discoveries continue to be made after almost 130 years of exploration!

**Keywords:** Southeast Asia, Tertiary basins, petroleum systems, basin cycles, lithofacies associations

INTRODUCTION

The countries of Southeast Asia host a large number of Tertiary basins, many of which have proved to contain active petroleum systems and prolific reserves of oil and gas (Figure 1). Although oil has been produced continuously for nearly 150 years and many traditional on- and off-shore petroleum provinces are very mature for exploration, significant potential remains, as is repeatedly demonstrated by discoveries in both traditional as well as less well-explored 'frontier' areas.

The basins share a number of important characteristics: They were formed and evolved under a common climatic and geodynamic regime during much the same Eocene / Oligocene to Quaternary time interval (Pubellier & Morley, 2014) and contain a limited range of siliciclastic and carbonate sediment types, largely reflecting a variety of paralic to marine environments. Most were formed as a result of extensive early Tertiary arc roll-back and back-arc extension that produced transtensional rift cycles (and also led to the creation of a number of small ocean basins) and then evolved through a period of mid-Tertiary thermal sag before being subjected to late Tertiary subduction-related transpression and uplift (Doust & Sumner, 2007).

In very broad terms the basins can be grouped according to the nature of their underlying pre-Tertiary 'basement' and their proximity to Sundaland, the continental core Southeast Asia. In Thailand, Malaysia, Vietnam and the western parts of Indonesia this comprises intruded Palaeozoic to Mesozoic fold belts, and in this proximal area the basins evolve through Oligocene to Quaternary continental to marine rift to post-rift cycles, in places affected by late Tertiary inversion events. Basins with similar, but slightly
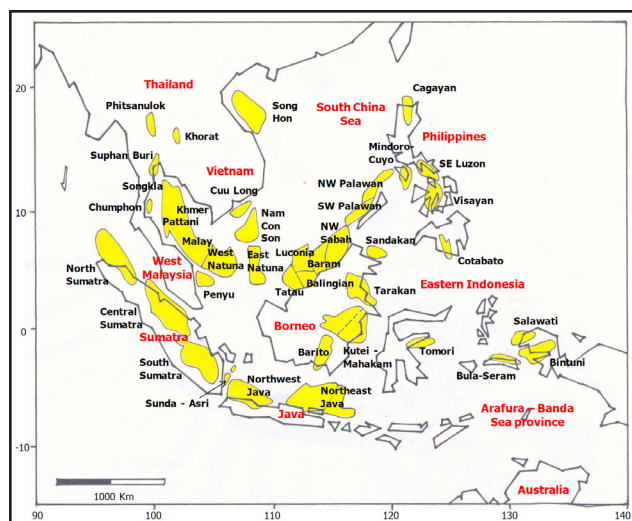
Figure 1: Location of basins with significant petroleum systems referred to in this article.

longer (Eocene to Quaternary) and more marine histories are located more distally in parts of eastern Indonesia, where they overlie accretionary terranes of primarily Cretaceous age. In contrast, basins associated with development of small ocean basins like the South China and Sulu seas are dominated by passive margin post-rift basin cycles associated with major delta developments. Finally, basins in the easternmost parts of Indonesia and in the arc terranes of The Philippines contain largely marine sediments, the former being superimposed on fragments of tectonically-emplaced Australian Mesozoic sequences, the latter forming part of an evolving oceanic arc terrane.

Oil and gas have been found in all of these basin groups thanks to an almost ubiquitous charge system based on widespread terrestrial and lacustrine type source rocks. Working petroleum systems are common, with individual basins often containing more than one source rock sequence. There are, however, very large differences in the volumes of exploitable petroleum that they contain. Partly, this is a consequence of their palaeogeographically-controlled sedimentary facies development and partly it is driven by the ongoing tectonic evolution.

THE PETROLEUM SYSTEM AND ITS APPLICATION IN SOUTHEAST ASIA

The petroleum system is a relatively recent concept which formalises the relationship between oil and gas accumulations and their source and occurrence within the sequence. It was defined by Magoon & Dow (1994), who noted that it '… includes all the essential elements and processes needed for oil and gas accumulations to exist…placed in time and space'. Petroleum systems 'combine the names of the major source rock and the major reservoir rock' and, depending on the level of confidence in the match between source and petroleum occurrence are defined as 'known' (!) if proven through a geochemical match, 'hypothetical' (.) if indicated by the geology but not proven by such a match and 'speculative' (?) if the source is speculative or unknown.

Since 1994 many petroleum systems have been described and the concept has proven to be a very valuable one: It helps to define how, when and where migration has taken place and therefore the stratigraphic and geographical boundaries within which petroleum can occur, and it provides an important learning-set of successful systems that can be used for analogue purposes.

In the context of Southeast Asian Tertiary basins, a number of issues related to the essential elements and associated processes need to be considered when identifying and describing petroleum systems.

- In the basin-fill sequences, paralic to marine facies are predominant and source rocks, reservoirs and seals are commonly interbedded with each other to form multiple thin intervals in often much thicker successions. This makes identification of individual source rocks, reservoir or seal horizons extremely difficult, except locally.
- Many of the processes, such as petroleum generation, migration and accumulation are not time-limited to particular 'critical moments', but are dynamic and on-going, and are actually rather ill-understood. Timing of source rock maturation has proved particularly hard to tie down.
- Workers in these basins have been repeatedly confronted with the difficulty of ascribing formation names to sequences that comprise multiple interbedded lithofacies, particularly those that are strongly time-transgressive in nature. This has especially been the case in the offshore, and has resulted in a regional stratigraphy that is defined by a mixture of formation names, 'cycles'* and 'stages'* amongst others (Petronas, 2007). (*note that I use these terms more generally to denote phases in basin evolution).
- The terrestrial and lacustrine source rock facies provide a limited range of geochemical signatures so it is difficult to relate specific 'pods' of active source rocks to accumulations in specific reservoir sequences. Moreover, there appears to be a considerable amount of mixing of charge from different sources, resulting in intermediate signatures such as those in the Malay Basin (Hutchison & Tan, 2009) and Palawan (Scholten et al., 2006).
- Southeast Asia has a large number of Tertiary basins, and many of them contain more than one petroleum system. This multiplicity, coupled with the fact that the individual basins, although separate from each other, contain petroleum systems that commonly resemble each other very closely, justifies the collective approach used by Doust & Sumner (2007) – grouping the petroleum systems into types.

In summary, the interbedded petroleum parameters and the rapid lithofacies variations mean that if maximum use is to be made of the analogue value of the concept, systematic petroleum system (PS) description requires particular treatment in Southeast Asia. I group petroleum systems according to the type of depositional environment cluster or *facies association* from which the main charge originates.

This enables comparable PSs to be grouped into facies-based petroleum system types or PSTs. Moreover, because in general basin cycles and stages tend to be characterised by particular facies associations with related source, reservoir and seal combinations, I link PSs from different basins according to their situation within basin history. The local tectonic situation then influences the typical trap types or *play types* that are representative of such PSTs.

I emphasise that this review examines the subject at a high-level, and does not describe any of the petroleum systems in detail. It aims to provide a framework for the classification of petroleum systems in Southeast Asia, and is complemented with a discussion of the important contributory parameters and processes as well as of some of the important issues that impact on their evaluation.

In many of the basins, a number of oil families have been recognised (eg. Simon *et al.*, 1997; Hutchison & Tan, 2009; Peters *et al.*, 1999). Although a geochemical match between source and petroleum in the reservoir is ideal for petroleum system recognition, it is important to recognise that different oil families may be derived from one such system: Often the differences may be due to mixing from different sources, to multiple phases of generation, or to biodegradation at shallow depths.

THE TECTONOSTRATIGRAPHIC PHASES IN BASIN DEVELOPMENT

All of the basins, whatever their origin or nature, have an evolutionary history that often involves Early Tertiary rifting followed by mid to late Tertiary thermal subsidence, with or without inversion (Pubellier & Morley, 2014). This evolution is expressed in a number of cycles and stages, each with its characteristic suite of sedimentary facies associations (Figure 2). I limit the discussion to basin types that contain a working petroleum system with significant oil and/or gas accumulations.
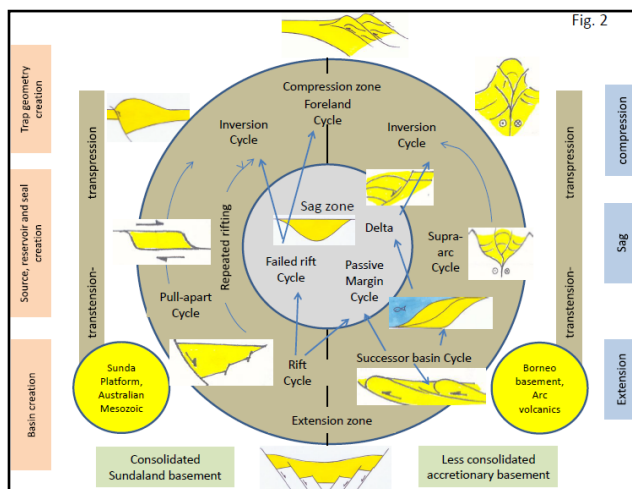
Figure 2: Schematic 'evolution wheel' of Southeast Asian Tertiary basins. Most pass from extensional to sag and/or compressional regimes, commonly associated with strong transtension or transpression. Qualitative differences exist in basins that evolved on Sundaland basement (left) and on less stable accretionary basement (right).

The synrift cycle

This includes the sediments deposited during periods of active extensional or transtensional faulting, and normally corresponds to the interval following basin creation in the Eocene and Oligocene. In many cases the cycle originates from pull-apart within wrench fault zones. Geometrically, in the early stages basins usually have half-graben geometry, but many amalgamate later to form wider, more symmetrical rift zones. Two main stages, Early and Late (Figure 3a) may be distinguished (Doust & Sumner, 2007).

a. *Early synrift*: During this stage faulting is at its most active, and a significant topography is created. The patterns of lithofacies development are surprisingly consistent whether the depositional environment is continental or marine (Figure 3b): Sediment supply to the basin is usually limited in this stage and, where the fault-driven subsidence rate is high, the result is a characteristic suite of lithofacies that commonly includes deep lacustrine or marine shales.

b. *Late synrift*: This corresponds to a period of waning fault activity when sediment supply keeps pace with or exceeds subsidence and, except in more distal basins which become flooded by the sea at this time, the basin topography gradually becomes filled with a shallowing sequence of paralic deposits (Figure 3a).

The postrift cycle

Following the cessation of faulting, basins commonly pass into a cycle of thermal subsidence or sag. In Southeast Asia this is often accompanied by an extensive transgression during which open marine shales and carbonates accumulated, many of the latter in the form of reefs. The postrift cycle often overlies a number of isolated synrift grabens and its extent usually forms the area of the basins as they are currently defined. I recognise two stages…

a. *Early postrift*: Following the cessation of extensional rift faulting large parts of Southeast Asia were affected by regional subsidence, probably linked to the early stages of South China Sea development or subduction roll-back along the Java-Sumatra trench (Pubellier & Morley, 2014). In most places this resulted in a transgression over the exposed rift shoulders and the deposition of an open marine sequence of shales and, on relatively high blocks, carbonates. In most basins this stage encompassed the Early Miocene, but in more distal, eastern areas it began already in the Oligocene.

b. *Late postrift*: During the Middle Miocene and later periods, collisional events and increased rates of subduction started to have an important influence on Southeast Asia. Compressional forces resulted in inversions accompanied by local erosion in many areas, while extensive uplift took place along the Indonesian Arc and in Borneo especially. The adjacent basins were subjected to an increasing influx of sediments that built thick, upward shallowing regressive deltas. In more distal basins, remote from large land masses, marine conditions and carbonate growth continued.

We can recognise two geodynamic situations:
- *Intra-continental sags*, overlying 'failed rifts'. In these sags the sequence typically begins with open marine

to basinal shales surrounding carbonate reefs that developed on residual high blocks. In more distal basins these facies characterise the entire Postrift Cycle while in those closer to the Sundaland there is an upward passage into regressive paralic sequences.

- *Marginal sags* characterise the flanks of oceanic back-arc basins like the South China and Sulu seas as well as areas of thinned crust (South China Sea, Makassar Strait). Here the early post-rift marine shales pass upwards into very thick multiple sequences of paralic to deeper marine clastic facies with gravity-driven growth fault and toe-thrust belts.

Inversion and compression cycles

Collisional events and continued subduction along the Java-Sumatra Trench resulted in extensive uplift and erosion of land areas in the later postrift period (eg. Hall, 2015). As well as providing source areas for thick deltaic and marine deposits, these events resulted in repeated phases of basin inversion and structural development, including folding and thrusting. Sediments deposited during these periods may form syn-tectonic foreland-type cycles locally interbedded in the postrift cycle.

Other basin cycles

In the eastern part of Southeast Asia and in The Philippines basin evolution was dominated by back-arc extension and translational collision events.

Figure 3: Synrift basin models. (a) Early and late stages of rift development. (b) The Lacustrine facies association in the Early synrift stage: Lithofacies development is surprisingly consistent in both non-marine marine situations. Many reservoir sands are interbedded in clays and shale and can form stratigraphic/structural traps.

a. *Supra-arc cycles.* Basins in the archipelagic part of The Philippines were created by multiple pull-apart and inversion events related to wrenching along the Philippines fault, and involving co-existing marine and paralic environments lying above an arc-related basement suite of intrusions, volcanic rocks and deeper marine sediments (CCOP EPF). They appear to form largely single-cycle basins, but may involve up to three stages:

i. Supra-arc 1: Oligo-Miocene, characterised by minor faulting and subsidence, with non-marine and shallow marine sediments.

ii. Supra-arc 2: Middle to Late Miocene, characterised by accelerated subsidence and faulting with volcanism and some inversion; mainly deeper marine sediments and carbonates.

iii. Supra-arc 3: Plio-Pleistocene, volcanism, wrenching and local inversion.

b. *Post collision cycles.* In parts of Borneo, evolution of the present basins followed the formation of compressional fold belts (represented for example by the Rajang and Crocker groups of Sarawak and Sabah). The early stages of these basins represent 'successor-basin' cycles with apparently limited petroleum prospectivity. With continued subsidence and sedimentation, however, such cycles pass upward into prolific postrift-type sag cycles.

Further to the southeast, around the Banda and Arafura seas, the pre-Tertiary basement consists of fragments of Australian continental crust that have been transported westwards along sinistral wrench faults and incorporated into the Asian plate. Many of the Tertiary basins in this area are difficult to classify, but it is one of the only areas in Southeast Asia where the pre-Tertiary has contributed to active petroleum systems.

LITHOFACIES ASSOCIATIONS AND THEIR ASSOCIATED PETROLEUM SYSTEM TYPES (PSTS)

In this tropical, climatically stable province the basins throughout the Tertiary are characterised by a particular suite of non-marine to deeper marine lithofacies that are strongly correlated with depositional environment (Figures 3 and 4). These lithofacies are commonly interbedded so intimately that recognition of individual source, reservoir and seal rocks is barely possible; rather they occur in groups or *facies associations* which, from the point of view of petroleum occurrence have particular characteristics. In this context I consider facies associations to comprise *groups of lithologies deposited in related depositional environments, containing source rocks, reservoirs and seals of distinct origin and development.* The distinctions are sufficient, I believe, to justify their contribution to the definition of separate PSTs. Emphasis is laid on the sequence providing the active petroleum charge (Magoon & Dow, 1994). I distinguish the following:

The lacustrine association

This is typically developed best in early synrift cycles, where shallow and deep lake fluvio-lacustrine to lacustrine
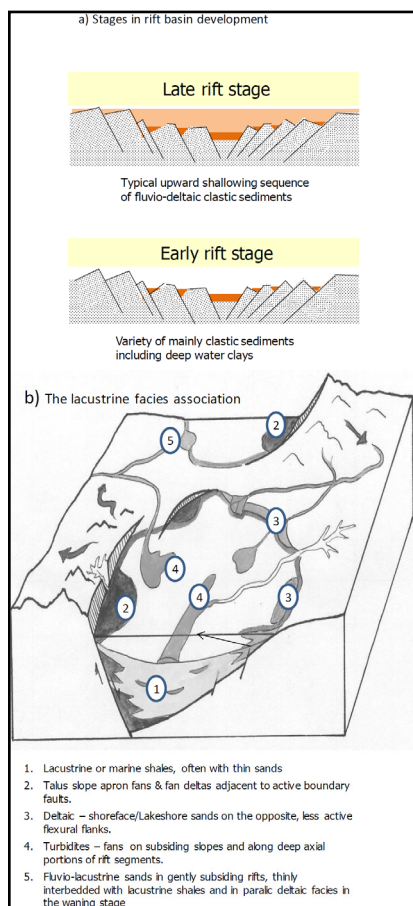
source rocks of excellent quality are commonly developed (Figure 3b). They contain Type I –II / Organofacies C (*sensu* Pepper & Corvi, 1995) algal organic matter (including Botryococcus and Pediastrum), have TOC's of 1% up to 10%, are very oil prone with HI's of over 400 and in many cases form sequences tens of metres thick. In some of the larger basins this facies association also contains fluvio-deltaic Type III/Organofacies D, E and F organic matter. This variety is illustrated in the synrift grabens of the Central Sumatra Basin, where the predominant organofacies varies according to the local depositional environment (Rodriguez & Philip, 2015). Reservoirs in this facies are commonly thin, immature and poorly-sorted lake-shore,

deltaic or turbiditic sands. Porosities are reasonably good, but decline rapidly with depth. The sand content is very variable and is partly dependent on active faulting: Radovich (1997) describes sand-rich upward-fining aggradational para-sequences in fluvio-lacustrine environments in the Pattani Basin offshore Thailand. As they are interbedded with sealing lacustrine shales such sands provide moderate quality, multiple reservoir/seal pairs. In the hanging walls of half-graben rift faults coarser talus-fans are developed. The latter may form attractive reservoirs where a side-seal against the footwall blocks exists (eg. Janti Fan, Sunda Basin, Bushnell & Temansja, 1986). Organofacies C oils generated from this association are low in sulphur, are waxy and have API gravities of more than 20 degrees with Pr/Ph ratios of less than 3.

Petroleum systems in the lacustrine facies association (Figure 5) belong to the Early Synrift lacustrine PST of Doust & Sumner (2007) and are dominated by oil charge. A typical example is the Lan Krabu – Pratu Tao (!) PS, located in the Phitsanulok Basin in onshore Thailand (Bal *et al*., 1992), where the main play is represented by the Sirikit (Flint *et al*., 1988) and Pru Krathiam fields.

Basins with lacustrine association petroleum systems in the Early Synrift stage are widespread in Indonesia (see Doust & Noble, 2008), on- and offshore Thailand, Vietnam and West Malaysia. They host many of the most prolific oil-producing PSs in SE Asia, such as those in the Central Sumatra and Malay basins. In the tables below, the petroleum system is named, where possible using local nomenclature (source formation – main reservoir formation), the basin names are shown in parenthesis and comments are given on the main reservoir facies and main trap types.
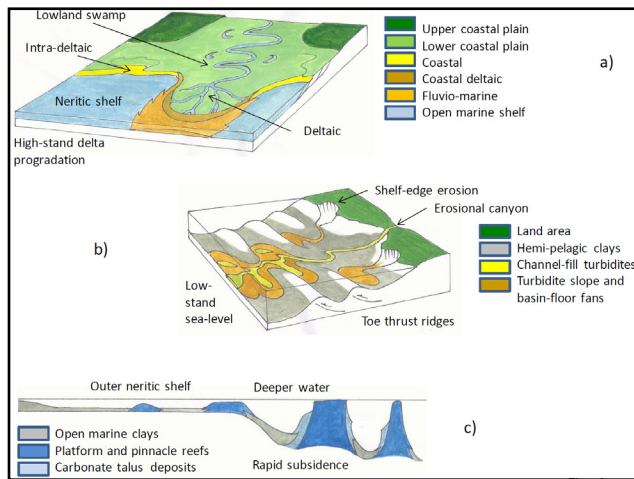
Figure 4: Schematic models showing depositional environments in (a) the Paralic coastal plain to coastal (b) the Open Marine Shelf and (c) the Open Marine Shelf facies associations.
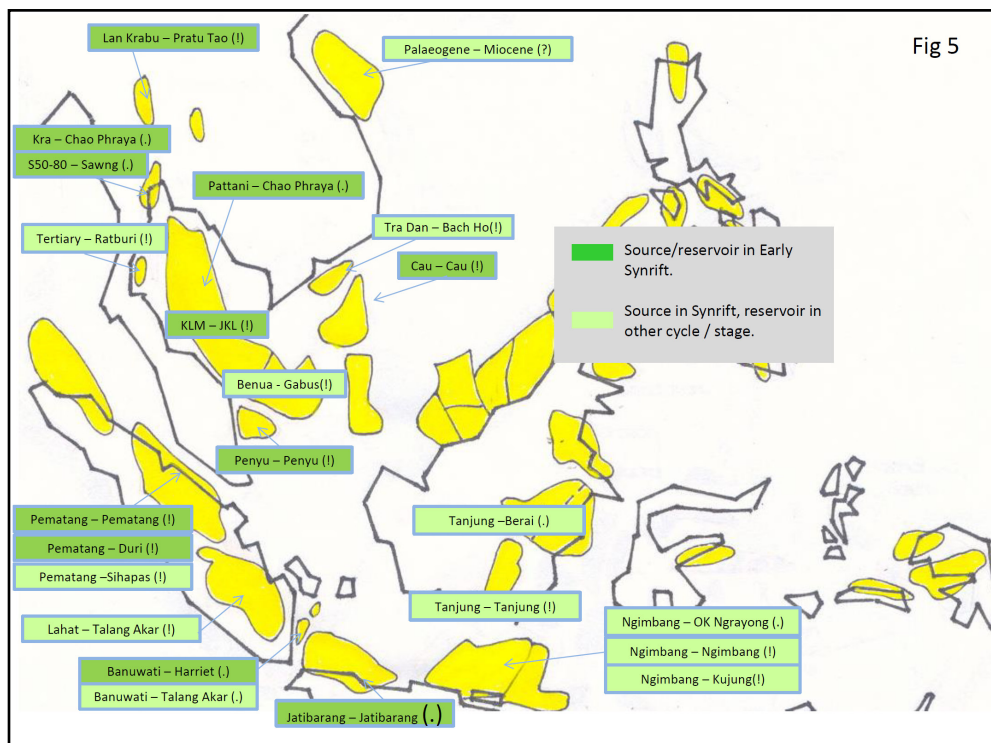
Figure 5: Petroleum systems belonging to the Lacustrine facies association.

Table 1a: Lacustrine association petroleum systems; source rock and main reservoir in the same synrift stage (Figure 5).

•   Jatibarang – Jatibarang (.) PS (NW Java) –fluvio-lacustrine reservoir tuffs in basement drape structure (Adnan *et al.*, 1991).
•   Pematang – Pematang (!) PS (Central Sumatra) – fluvial and alluvial fan reservoirs in inversion anticlines and combination traps.
•   Pematang – Duri (!) PS (Central Sumatra) – fluvio-marine and carbonate platform reservoirs in inversion anticlines and drape structures.
•   Banuwati – Harriet (.) PS (Sunda –Asri) – reservoir in drape above basement.
•   KLM - JKL (!) PS (Malay) – fluvial and coastal reservoirs related to basement drape, buried hill and inverted rift structures.
•   Penyu – Penyu (!) PS (Penyu) – fluvio-lacustrine reservoirs in basement drape, stratigraphic pinch-out and inverted rift traps types.
•   Pattani – Chao Phraya (.) PS (Pattani Trough and Khmer) – lacustrine turbidite, alluvial fan, fluvial and fluvio-marine reservoirs in basement drapes and tilted fault blocks in the Synrift (Pattani) and Postrift (Khmer) cycles.
•   Lan Krabu – Pratu Tao (!) PS (Phitsanulok) – fluvio-lacustrine and alluvial fan reservoirs in basement drape, buried hills and tilted fault blocks.
•   Kra – Chao Phraya (.) PS (Songkla) - fluvio-lacustrine and alluvial fan reservoirs in basement drape, buried hills and tilted fault blocks.
•   S50-80 – Sawng (!) PS (Suphan Buri) – alluvial fan and fluvio-lacustrine reservoirs in tilted fault blocks, hanging-wall roll-overs and stratigraphic traps. This description applies also to the PSs in the Fang and Petchabun basins in onshore Thailand (Bidston & Daniels, 1992), not discussed here.
•   Cau – Cau (!) PS (Nam Con Son) – coastal and fluvio-marine sands and fractured basement in tilted fault blocks (Simon *et al.*, 1997), sealed by Oligocene shale.

Table 1b: Lacustrine association petroleum systems; source rock in the synrift and main reservoir in the pre-rift (basement) or younger cycles or stages (Figure 5).

•   Benua – Gabus (!) PS (Natuna Sea) – fluvio-marine to marine reservoirs in inversion anticlines in the Late Synrift.
•   Pematang – Sihapas (!) PS (Central Sumatra) – fluvial, fluvio-marine and marine reservoirs in inversion anticlines and stratigraphic traps in the Late Synrift.
•   Lahat – Talang Akar (!) PS (South Sumatra) – fluvio-marine and carbonate platform reservoirs in inversion anticlines and straigraphic-structural traps in the Late Synrift to Early Postrift.
•   Banuwati – Talang Akar (!)PS (Sunda-Asri) – fluvio-marine and carbonate platform reservoirs in inversion anticlines, basement-fringing reefs and stratigraphic-structural traps in the Late Synrift to Early Postrift.
•   Ngimbang – OK Ngrayong (.) PS (NE Java) – carbonate platforms/reef and turbidite reservoirs in the Early Postrift.
•   Ngimbang – Ngimbang (!) PS (NE Java) – fluvio-marine to marine sands in inversion structures and stratigraphic traps in the Early to Late Synrift.
•   Ngimbang – Kujung (!) PS (NE Java) – carbonate reef reservoirs in the Late Synrift.
•   Tanjung – Tanjung (!) PS (Barito) – deltaic and fluvio-marine reservoirs in the Late Synrift to Early Postrift.
•   Tanjung – Berai (.) PS (Kutei) – carbonate platform and deltaic reservoirs in inverted anticlines in the Early Postrift.
•   Tertiary – Ratburi (!) PS (Chumphon) – karstified Permian carbonate reservoirs of the pre-rift basement relief (Heward *et al.*, 2000).
•   Tra Dan – Bach Ho (!) PS (Cuu Long) – fractured and eroded basement igneous oil reservoir in inverted buried hill structure encased in lacustrine shale, exemplified by the Bach Ho play (Du Hung & Van Le, 2004; Xuan Cuong *et al.*, 2005).
•   Palaeogene – Miocene (?) PS (Song Hon) – carbonate build-ups and marine clastics in tilted fault blocks and inversions in the Late Synrift and Early Postrift.

The paralic (coastal plain to coastal) facies association

This is the most common petroleum-prospective facies association in Southeast Asia, and is characteristic of the late synrift and the late postrift in many proximal basins (Figure 4a). The term *paralic* refers to the cluster of lower coastal plain to coastal and deltaic environments that are represented by interbedded fluvial and deltaic sequences with channel and mouth bar reservoir sands and coal and coaly-shale source facies. Organic matter accumulated peat swamp, lake and mangrove environments and the resulting source rocks may have TOCs of up to 80%, comprising terrigenous organic material dominated by Type III/Organofacies F (vitrinite), but with minor Type II/Organofacies D and E, cutinite and resinite. Hydrogen indices are usually significantly less than 400 and Pr/Ph ratios exceed 3. Such source rocks are very widespread, but may vary considerably in thickness and quality. Critical to the development of a rich charge system is an extensive area of tropical lowland swamp environments developed during high-stand periods. One may assume that

when the delta top areas were at their greatest extent such areas become 'factories' of terrigenous organic material. In fluvio-marine environments a more marine signature can be often be detected (Summons *et al.*, 1994).

Reservoirs are represented in a variety of paralic environments, and include fluvial channel, coastal-deltaic and shoreface sands. A distinction can be made between deltaic and intra-deltaic situations (Figure 4a): The former tend to be fluvial or tidal dominated, the latter are generally more wave dominated. The percentage of sand varies enormously and the corresponding reservoir properties also: Porosities may be up to 30%, but they decline rapidly with depth due to quartz overgrowth and pressure solution, although in many arkosic sands feldspar dissolution has led to a modest recovery of porosity at depth. We can also recognise significant differences between paralic systems developed on the Sunda Shelf and those developed around Borneo. In the latter, the passive margin delta sequences are associated with the *deeper marine facies association* (see below) and are characterised by growth faults that have a fundamental impact on the sand distribution and trapping geometry. The sealing capacity of paralic facies inter-beds depends on several factors, such as the ratio of sand to shale, which diminishes upwards in upward-coarsening deltaic

packages, and on their continuity – they can be expected to be better in marine flooding-surface shales than in flood-plain clays. As a result in many cases the optimum balance between interbedded reservoirs and seals for trapping lies in the nearshore fluvio-marine environment.

The paralic coastal plain to coastal facies association characterises portions of the Late Synrift transgressive deltaic and Late Postrift regressive deltaic sequences and corresponds in part to the Synrift and Postrift coal/coaly shale PSTs of Doust & Sumner (2007). Petroleum systems of this type are dominant in Indonesia (Doust & Noble, 2008) and Malaysia, but are also found in parts of the Philippines, Vietnam and Thailand (Figure 6). They host many of the most prolific oil-producing PSs in SE Asia, such as those in South Sumatra and Borneo. In the list below, the basins with Late Synrift and Late Postrift examples are tabulated separately. Basin names are shown in parenthesis and, unless otherwise noted the main reservoir lies in the same stage as the source.

## Open marine shelf – slope facies association

The sediments in this group were deposited in open marine shelf (neritic) environments and comprise shales and limestones with occasional thin sandstones (Figure 4c). Open

Table 2a: Paralic association petroleum systems, late synrift to early postrift or early post-collision (in Sarawak and Sabah) (Figure 6).

• Talang Akar – Main/Massive (!) PS (NW Java) – Late Synrift to Early Postrift deltaic sands (west of the basin) and carbonate platforms (east), partly inverted.
• Talang Akar – Palembang (.) PS (South Sumatra) – lacustrine-paralic source (Late Synrift) and Late Postrift fluvio-marine to marine reservoirs, inversion anticlines and stratigraphic-structural traps.
• Talang Akar – Talang Akar (!) PS (South Sumatra) – lacustrine-paralic source and reservoirs in inversion anticlines and stratigraphic traps.
• E-I Group (!) PS (Malay) – fluvio-deltaic coaly shale source, fluvial, coastal and shallow marine reservoir sands in Late Miocene basin-centre inversion anticlines.
• Half Graben (.) PS (Tatau) – carbonate reefs and Cycle I – III fluvio-marine clastics in Oligo-Miocene inverted graben structures, coaly shale source.
• Lambir – Lambir (.) PS (Tatau/Balingian) – Oligo-Miocene fluvio-marine clastics in wrenched Mio-Pliocene folds, coaly shale source.
• Sabah Inboard (.) PS (NW Sabah) – Early Miocene fluvio-marine clastics in steeply inverted Mio-Pliocene anticlines.
• Pattani B-C (!) PS (Pattani) – Late Synrift source, Late Postrift fluvial, deltaic and coastal reservoirs.
• Dua – Nam Con Son (!) PS (Nam Con Son) – carbonate reservoirs such as in the Dai Hung play lie at the base of a marginal sag cycle (Simon *et al.*, 1997; Lee *et al.*, 2001).

Table 2b: Paralic association petroleum systems, late postrift (includes some Mio-Pliocene biogenic PSs, Figure 6).

• Biogenic – Parigi (.) PS (NW Java) – carbonate platform reservoir, stratigraphic traps, thrusted trends.
• Balikpapan – Balikpapan (!) PS (Kutei-Mahakam) – steep inversion folds involving growth-faulted fluvial, deltaic and coastal sands (Darman & Handoyo, 2013).
• Tabul – Tarakan (.) PS (Tarakan) – deltaic to fluvio-marine sands, growth faulted and mildly inverted.
• Tertiary – Miocene Biogenic (?) PS (NE Java) – Fluvio-marine and carbonate reservoir in stratigraphic traps.
• Tertiary – Pliocene Biogenic (?) PS (NE Java) – as above, mainly marine reservoirs.
• Baram Delta (!) PS (Sarawak and Brunei) – Growth-faulted and inverted structures, shallow marine Miocene reservoirs (Schreurs, 1997; Darman & Handoyo, 2013).
• Stage IV Outboard (.) PS (NW Sabah) – Mio-Pliocene fluvio-marine and turbidite sands in growth fault and inversion anticlines.
• Dent – Tungku-Dent (.) PS (Sandakan) – as above, some bathyal source facies (see Jong, 2015).
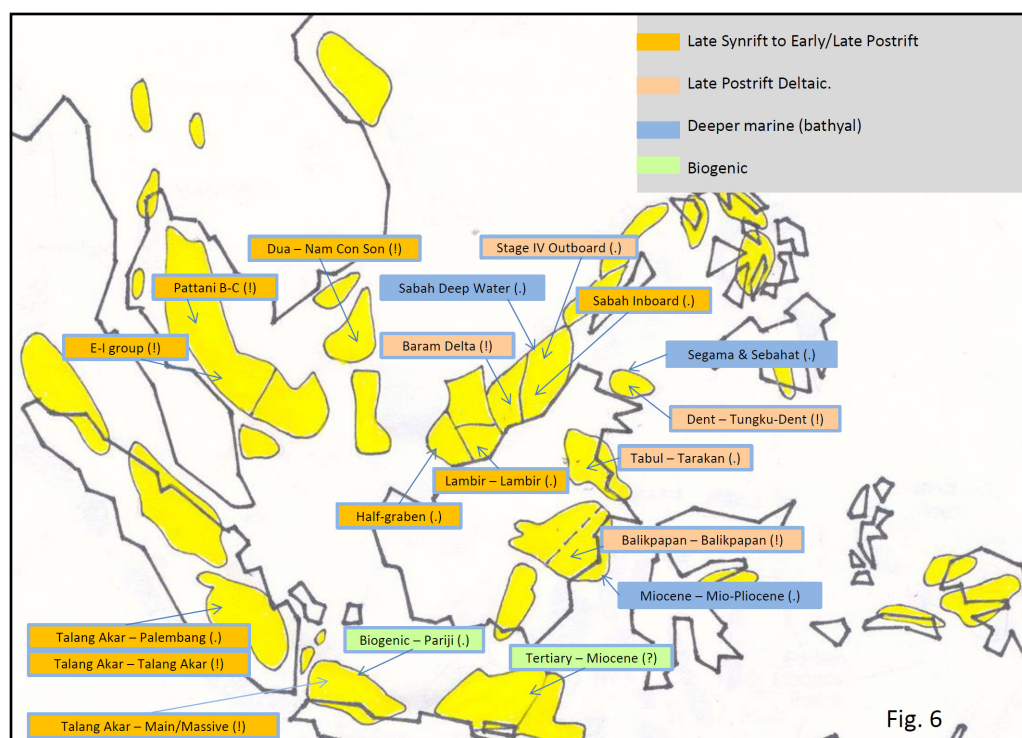
Figure 6: Petroleum systems belonging to the Paralic and associated Deeper Marine facies associations.

marine shales are very widespread in many basin cycles, but are most characteristic of the Ealy Postrift, when a regional period of sag resulted in extensive marine transgressions in Southeast Asia. Palaeogeographically more distal situations, such as those in eastern Indonesia, were already flooded during the late synrift cycle and remained open marine into the postrift. The open marine shales are rather homogeneous and contain on average about 1 – 1.5% TOC, consisting largely of fragmented terrestrial organic material, Type III/II Organofacies D and B, transported by suspension into the offshore. Although the source material is marginal in quality, Jordan & Abdullah (1992) show evidence that the Early Postrift reef carbonate reservoir of the Arun play in North Sumatra has been charged from the surrounding open and deeper marine Bampo and Baong shales. They indicated that adjacent to the reef, TOC values are lower (<0.4%) than normal for the area (1.4 – 1.9%), suggesting depletion due to expulsion of hydrocarbons. Because the organic material is dispersed, such source rocks probably require high maturities for expulsion and they commonly provide a mainly gas charge. Oils are similar to those derived from paralic source rocks but as they contain a marine Organofacies B contribution, they tend to be less waxy.

Although thin neritic sands are present in several areas, the main reservoirs of this association comprise shallow marine carbonate bodies, which accumulated in areas of limited clastic sediment supply, mainly on shallow basement or residual rift-related horsts or tilted fault blocks. Many originated as carbonate platforms and evolved into pinnacle reefs as subsidence progressed (Figure 4c). Many publications describe the complex reservoir character, geometry and internal facies distribution of both platform

and pinnacle reefs (eg. Grotsch & Mercadier, 1999; Kosa et al., 2015). In the carbonate build-ups of Central Luconia, for instance, diagenesis of back-reef facies results in porosities of up to 40% (Epting, 1980). In deeper marine basinal environments clastic and calci-turbidites may be present.

The Open marine shelf facies association is largely equivalent to the Early Postrift marine petroleum system of Doust & Sumner (2007), and although it contains petroleum systems belonging mainly to the Early Postrift, in more distal basins representatives may be present throughout the Postrift and even in the Late Synrift (for example in the North Sumatra Basin). Basins with petroleum systems belonging to this association are found mainly in eastern Indonesia (see Doust & Noble, 2008) and in Borneo, where they form mainly gas-bearing provinces (Figure 7).

A separate family of basins with open marine facies associations is present in the archipelagic volcanic arc portion of the Philippines. I cluster the petroleum systems in these basins as Supra-Arc Cycle PSs on the basis on their common arc-related origin and their open marine to bathyal character (Figure 7). The Visayan Basin has a non-marine early rift fill with Type III/II source rocks (TOCs on average 1-4 %; Brooks et al., 1992), but in most basins deeper water and bathyal facies with carbonates and poor quality clastic reservoirs dominate the sequence.

In the list below (Table 3), the basin is shown in parenthesis and, unless otherwise noted the main reservoir lies in the Early Postrift.

Deeper marine facies association

The deeper offshore slope and basin-floor of Late Postrift passive margins contains slope channel and fan reservoirs,

Table 3a: Open Marine Association petroleum systems, mainly Early Postrift (Figure 7).

• Tertiary – Terimbu (.) PS (eastern Natuna Sea) – probably paralic to marine charge to carbonate buildups, pervasive CO2 contamination
• Bampo/Baong – Peutu (!) PS (N Sumatra) - contains the gas/condensate Arun carbonate reef play.
• Baong – Ketaupang (.) PS (N Sumatra) – reservoirs in Early to Late Postrift reservoir clastics in inversion folds
• Gumai – Gumai (!) PS (S Sumatra) – thin turbidite reservoirs. This PS relies on the locally high TOCs (<8%) found in flooding surfaces in the Gumai shale (Ginger & Fielding, 2005).
• Klinjau – Klinjau (.) PS (Kutei Mahakam) – paralic-marine source and carbonate / deltaic reservoirs.
• Tertairy – Kais (.) PS (Bintuni) – Carbonate reefs, marine shale seal.
• Klasafet – Kais (!) PS (Salawati) – Open marine to bathyal source feeding shallow pinnacle reefs.
• Tomori – Tomori/Minahaki (!) PS (Tomori, Sulawesi) – Open marine to bathyal source feeding shallow platform fractured carbonates in overthrust structures (Tiaka play, Husanusi *et al.*, 2012).
• Luconia (.) PS (Central Luconia) – Extensive Oligocene - Late Miocene carbonate platform and pinnacle limestone province covering a large area; gas-bearing buildups sealed by deep marine shales. Charge unidentified.
• Pre-Nido – Nido (.) PS (NW Palawan) reef petroleum system (Grotsch & Mercardier, 1999). The charge is assumed to be derived from an adjacent 'Pre-Nido' synrift lacustrine – paralic sequence (Branson *et al.*, 1997).
• Palaeogene (?) PS (SW Palawan) – Open marine to bathyal synrift source and turbidite reservoirs in a thrust belt and foreland.

Table 3b: Open Marine – Bathyal Association petroleum systems in Philippines Supra-Arc cycle basins, stages 1, 2, and 3 (Oligo-Miocene to Quaternary) (Figure 7).

• Ibulao – Labuagan (.) PS (Cagayan) – bathyal source in stage 2, coastal to turbidite clastics and carbonate reef reservoirs in stage 2.
• Nakal – Putut (.) PS (Cotabato) – source in stage 1, coastal sand reservoirs, inversion structures in stage 2.
• Batangan – Ananawin (.) PS (Mindoro – Cuyo) – paralic to marine source rock in stage 1, reservoirs mainly carbonate reef/platforms in stage 2.
• Vigo – Vigo (.) PS (SE Luzon) – deeper marine source with turbidite reservoirs, fault block, drape and reef traps.
• Taog – Cebu (.) PS (Visayan) – marine to bathyal source and reservoirs in stage 1.
• Toledo – Barili (.) PS (Visayan) – Paralic to marine source in stage 2, carbonate reefs/platforms in stage 2 (CCOP; Brooks *et al.*, 1992; Durkee, 2001).

Table 4: Deeper Marine Association petroleum systems, associated with Late Postrift deltas (Figure 6).

• Miocene – Mio-Pliocene (.) PS (Mahakam). Guritno *et al.* (2003) describe toe-thrust anticlines with slope and base-of-slope turbidites belonging to the Merah Besar play and indicate the importance faulting in trapping. Ruzuar *et al.* (2005) report that turbidite sands often accumulated on the slope in low-stand deltas.
• Sabah deep water PS (.) (Ingram *et al.*, 2004; Madon *et al.*, 2015). This PS is very sand-rich: The Kumunsu play comprises stacked mid to late Miocene turbidite fan sands involved in fault-propagation folds. Evidence for repeated trap failure and filling can be seen, resulting in complex relations between oil and gas occurrence.
• Segama (.) PS (Sulu-Sandakan) – Post-collision to postrift coastal reservoirs.
• Sebahat (.) PS (Sulu-Sandakan) – Variety of reservoirs in carbonates and open- to deep marine sands.

many of which are thick and have excellent porosity and permeability. They were eroded from the shelf and shelf-edge during low-stand periods and were deposited as turbidites from density currents in bathyal environments (Figure 4b). They alternate with Mass Transport Deposits (MTDs) and hemi-pelagic clays, which provide excellent seals. Often the sands are stacked in ponded depressions between topographic swells situated above toe-thrusts on the slope.

Source material comprises terrestrial plant fragments including leaves eroded from the coastal plain and shallow shelf during low-stands and transported into deeper water together with the turbidite sands (Peters *et al.*, 2000; Guritno *et al.*, 2003; Saller *et al.*, 2006). In areas adjacent to where organic production is abundant, such as those offshore from major deltas, this material can form deeper marine source rocks. Compared to the originally deposited paralic 'parent', the organic material is more oxidised and has lower hydrogen content, however, and is relatively more gas-prone. Although such source rocks probably do not have regional extent and their distribution is difficult to predict, they tend to be closely associated with turbidite reservoir sand facies (Saller *et al.*, 2006), providing potentially short migration paths. In situations where marine organic material is present in the surrounding sequence, such as in North Sumatra (see section 3 above) and Palawan (Scholten *et al.*, 2006), this may lead to charge from mixed sources.

The Deeper marine facies association corresponds to the deeper water zones belonging to the Late Postrift
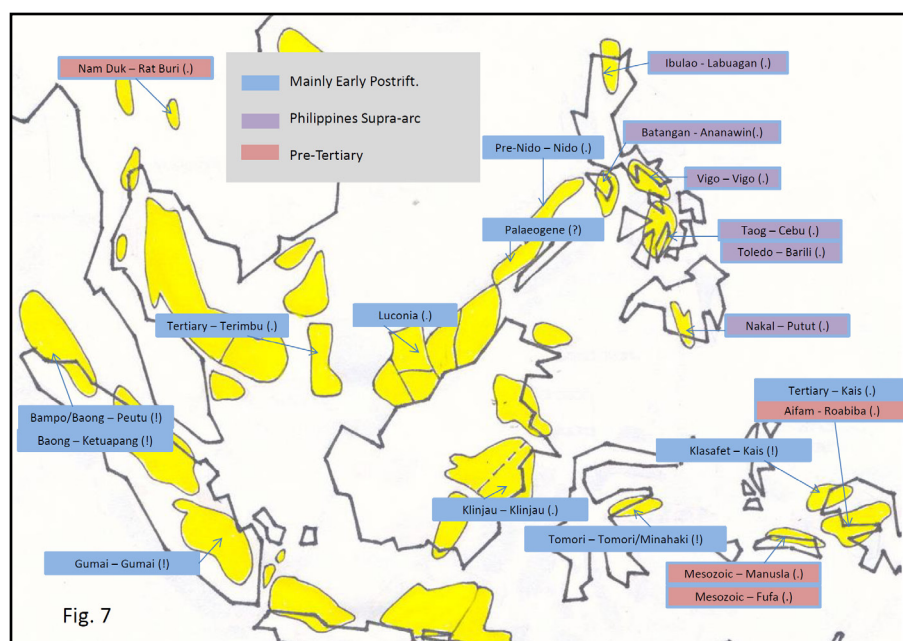
Figure 7: Petroleum systems belonging to the Open Marine Shelf / slope and pre-Tertiary facies associations.

Table 5: Pre-Tertiary petroleum systems (Figure 7).

• Nam Duk – Rat Buri (.) PS (Khorat Plateau Thailand). On the western edge of the basin two gas fields belonging to a unique wholly Palaeozoic system petroleum system are located (Kozar *et al.*, 1992). The gas is produced from thrusted Permian carbonates and the source is thought to lie in Permo-Carboniferous lacustrine (probably synrift) deposits.
• Mesozoic – Manusela (.) PS (Arafura – Banda Sea province). A petroleum system of Mesozoic age, where charge probably arises from paralic coaly Permo-Triassic rocks similar to those of the Sahul Group in NW Australia (Bradshaw *et al.*, 1997; Peters *et al.*, 1999; Doust & Noble, 2008): In the Bula/Seram basin, the Oseil play (Charlton, 2008) resides in Jurassic reservoir sands of coastal origin involved in a thrust structure.
• Mesozoic – Fufa (.) PS (Bula – Seram) – the reservoir here is of Plio-Pleistocene age.
• Aifam – Roabiba (.) PS. (Bintuni) – In the Bintuni Basin charge is from Type III paralic Permian source rocks and reservoirs lie in fluvio-marine Jurassic sandstones.

regressive deltaic petroleum system of Doust & Sumner (2007) and are Miocene to Pliocene in age, but in more distal basins it may be found in the Late Synrift also (Figure 6).

Pre-Tertiary associations

Pre-Tertiary charge contributing to PSs in Southeast Asia is found in two areas: in the Khorat Plateau in Thailand and in eastern Indonesia (Peters *et al.*, 1999), where the source generally belongs to lacustrine or paralic facies associations, as reported by Bradshaw *et al.*, 1997, who include them in the 'Gondwanan Super System' of Australia. They are summarised briefly in Table 5.

CHARACTERISTIC TRAP ASSOCIATIONS AND SEALS

A great variety of trapping geometries is present in the basins thanks to the complex Tertiary geodynamic and tectonostratigraphic evolution. Many of the traps are associated to some extent with transtensional or transpressional stresses in this tectonically active area. While the source and reservoir facies associations define the petroleum systems as discussed above, the trapping style

defines the families of petroleum accumulations within it, which we can call *plays*.

While many authors classify plays according to other criteria, such as reservoir formation (eg. Ginger & Fielding, 2005) or facies (Doust & Sumner, 2007) according to individual convenience, for this article I consider the trap type to define plays and *play types* (Doust, 2010). Where the trapping styles are characteristic for particular cycles and stages in basin evolution, they will be discussed in that context. Play descriptions are beyond the scope of this article, but where possible, example plays are referred to. Structural, topographic and structural/stratigraphic or combination traps are present (diagenetic trapping is yet to be demonstrated).

Structural traps

a. Faulted anticlines. These are very common in the Late Synrift and Late Postrift stages of back-arc basins in western Indonesia, such as in South Sumatra (IPA, 1990), where trapping is often complicated by reverse faulting, normal cross faults and sand pinch-outs. The Talang Akar field (South Sumatra) represents a typical and successful play type. The degree of faulting is very variable and has

an influence on the relative trapping of oil and gas.

b. Inversion anticlines. Transpressional re-activation of existing faults occurs almost everywhere in SE Asia and inversion anticlines, typified by 'Sunda Folds' form one of the most common trap types in nearly all of the basins and basin cycles. Traps associated with inverted rift cycles related to reverse movement along half-graben boundary faults are described, for instance, in the Malay and Natuna basins (Petronas, 1999; Burton & Wood, 2010). Such inversions are linked to anticlines that form the main traps in many of the shallower deltaic sequences in both the Late Synrift and Late Postrift (eg. Hutchison & Tan, 2009).

c. Footwall and hanging wall fault traps. Fault-dip traps that rely on fault-sealing either through sand:clay juxtaposition or as a result of clay-smear in the fault, are common in many basins especially in late postrift deltas, where they are commonly associated with steeply-dipping faults. Examples of footwall closure plays include the Gannet and Magpie fields in the Baram Delta (Sandal, 1996). The Maharajah Lela field, also in the Baram Delta (Kabbej & Menard, 2013), is a good example of a deep hanging wall play.

d. Growth-fault and inverted rollover anticlines. These are characteristic of the Late Postrift marginal deltas of Borneo, where many fields occur in hanging wall anticlinal closures. They vary considerably in development depending on the nature of the detachment in the underlying shale sequence and subsequent tectonism: Most of the larger growth faulted fields like Seria, SW Ampa and Champion (Sandal, 1996) have been inverted to some extent by time-transgressive waves of inversion (eg. Schreurs, 1997; Tingay *et al*., 2005). As a result the trapping geometries may be highly faulted and complex. This has a strong influence on the distribution and retention of oil and gas (for a discussion see Longley, 2005).

e. Thrust anticlines. Thrusted anticlines with steep reverse faults occur in collision zones and adjacent inverted zones. In the foreland portions of the Sumatra and Java back-arc basins strings of fields are located along thrust zones, many of them basement-rooted (Doust & Noble, 2008). Thin-skinned thrust traps are probably rarer, but Husanusi *et al*. (2012) for example, describe low-angle detachment thrusts affecting carbonates in the Tomori Basin of Sulawesi. The most important traps in this category lie on the lower continental slopes of growth-faulted marginal deltas, where they form toe thrust anticline trends. In Sabah, the most distal of these are interpreted to be compressional and related to subduction while the more proximal ones have been linked to gravity slumping (Legrand *et al*., 2015). These traps, where combined with turbidite fan reservoirs contribute to some of the most prolific recent discoveries in SE Asia (Ingram *et al*., 2004).

Topographic traps

a. Carbonate Reefs. Platform and pinnacle carbonate reefs and build-ups form characteristic traps in many of the more marine cycles and basins of SE Asia, especially in the Early Postrift stage. Trapping occurs where porous carbonate bodies, usually developed on or against structurally high blocks, form isolated bodies surrounded by clays and shales. In the prolific Central Luconia province of Sarawak transgressive shales provide excellent top and side seals, while silty foresets belonging to prograding phases may intersect the reef top or flank and result in up-dip leakage along 'thief zones' (Doust, 1981).

b. Basement horsts and buried Hills. Such structures comprise topographic features within rift zones and often arise from differential faulting during basin creation. Their prospectivity depends on (a) the presence of porosity and (b) their situation surrounded by rich lacustrine source rocks of the Early Synrift. A variety of pre-Tertiary rocks may be involved, ranging from karstified tower-carbonates (Nang Nuan play, Chumphon Basin; Heward *et al*., 2000) to fractured Cretaceous granodiorite (Bach Ho play, Cuu Long Basin; Trinh Xuan Cuong *et al*., 2005).

c. Drape closures involving Tertiary sediments are often associated with basement topography, and may provide additional reserves to the basement accumulation, as in the Cuu Long Basin (Nguyen Du Hung & Hung Van Lee, 2004). In some basins, ongoing tectonic uplift results in drape above growing structures: Eubank & Makki (1981) describe examples from the Central Sumatra Basin.

Stratigraphic and combination traps

a. Deltaic sequences. Such traps require an efficient charge system, favourable stratigraphic relationships in gently-dipping strata with few faults, and top and side seal integrity (Atkinson *et al*., 2006). While these conditions are present in many basins, large, purely stratigraphic traps are probably rare, partly because their tapping geometry is difficult to define. Lateral facies changes and depositional pinch-outs affect many fields, but they mainly define stratigraphically trapped elements within primarily structural traps, see for instance the IPA field atlases (IPA, 1990; 1991), where examples such as the Badak field in the Kutei Basin occur. Atkinson *et al*. (2006) note the important contribution of stratigraphic trapping in the Widuri Field in the Asri Basin. Several authors have suggested that erosional (ie. sub-unconformity) traps may have good potential (eg. Petronas, 1999), but only few such situations have been identified, eg. The Nuri field, Brunei, (Sandal, 1996).

b. Turbiditic sequences. In bathyal environments channel and fan sands may accumulate as turbidites in 'mini basins' on the slope, where they become ponded in synclinal areas between toe-thrust ridges. So far

most discoveries appear have been made, however, where such channels and fans cross the ridges to form combined structural/stratigraphic traps.

THE PETROLEUM SYSTEMS IN THEIR COUNTRY CONTEXT

Although many successful petroleum systems have been recognised in Southeast Asia, several others have yet to be defined. In this paper an attempt has been made to prepare a list that is as comprehensive as possible based on published information and my own interpretation. Petroleum systems are not 'cast in stone' and, as new information becomes available, their identification is made easier. In this article a tentative list is presented in section 5 above, with information that in some cases is based on limited input. The widespread nature of charge, however rich or minor it may be, and the often arbitrary definition of basin boundaries in SE Asia, means that some subjectivity in the definition of petroleum systems is inevitable. In this article, therefore, some assumptions have had to be made here and there: It is expected and hoped that the conclusions will be revised and up-dated in the future as exploration continues. In principle, only those petroleum systems that are associated with commercial or potentially commercial accumulations are included here. Doust & Noble (2008) summarised the petroleum systems of Indonesia and this paper extends the list to the remaining countries in the area, Malaysia, Vietnam, Thailand and the Philippines.

In many cases, both charge and reservoir/seal combinations reside in the same basin cycle or stage. The widespread absence of regional seals, except in the Early Postrift, however, means that reservoirs in shallower cycles may be charged from older cycles.

I have tried to make the list complete as of 2016, but exploration continues and some recent results will certainly have escaped my attention. I feel confident that with time other successful petroleum systems will be identified and confirmed. Many basins and cycles without proven petroleum systems contain excellent developments of all the essential parameters, but do not qualify because the processes of source rock maturation, migration and accumulation either do not work or have not yet been demonstrated to work well enough to result in commercial accumulations. In view of the often presently-active charge, source rock maturation is a critical issue – and one that is hard to tie down in Southeast Asia, where heat flows are very variable and source intervals are difficult to define.

Indonesia

For a full discussion the reader is referred to Doust & Noble, 2008 and Bradshaw *et al*., 1997, both of which review the petroleum systems of Indonesia in more detail. Here only a summary with tables is presented. Indonesia has by far the largest number of petroleum-productive basins in Southeast Asia and contains the greatest variety of PSTs. The basins are located in three main areas (i) on the Sundaland platform in the west (ii) on the east side of the island of Borneo and (iii) in the eastern part of the archipelago. The characteristics of these three areas highlight many of the main aspects of petroleum system development in Southeast Asia.

Palaeogeographically the Sunda Shelf basins lie in proximity to pre-Tertiary continental areas, and many of the basins have a dominantly non-marine (particularly lacustrine) synrift history, reflected in prolific oil production. The favourable geological environment, moreover, results in the development of source, reservoir and seal rocks in most or all of the basin stages, and many have multiple petroleum systems stacked one above the other: this leads to a significant amount of mixing and complex facies development. The extremely high thermal gradients in parts of Sumatra contribute to maturation at very shallow depths in some of the shallower rifts. Seals are poorly developed or are intra-formational in the lacustrine and delta sequences and the only regional seal lies at the base of the postrift. As a result most of the production comes from late synrift reservoirs and include, in one case, volcaniclastics (Adnan *et al*., 1991). Early postrift carbonate PSTs are less common in this proximal area, but are found in the North and South Sumatra basins, which were subject to early subsidence and marine influence.

The basins on Kalimantan typically contain thick Marginal Sag deltas of Late Tertiary age similar to those in Malaysian NW Borneo. Sediments are derived from the uplifted Borneo hinterland and are associated with large active river systems. They are typically growth-faulted and, as a consequence of continuing uplift, the proximal parts of the deltas have been folded into tight anticlines. The Mahakam Delta in particular contains one of the most prolific petroleum systems in Southeast Asia, with representatives in both the delta top and deeper water environments (Guritno *et al*., 2003). An illuminating comparison between the Mahakam and Baram deltas is given in Darman & Handoyo (2013). A fascinating aspect of the Borneo deltas is their apparent geological similarity, but very different prospectivity; some, like the Mahakam and Baram being extremely rich while others, like the Tarakan and Sandakan, tending to disappoint: Explanations for the differences may possibly be sought in the nature and history of their respective hinterlands, both of which have a strong influence on the volume and quality of the source and reservoir facies and the structural development (Satayana *et al*., 1999).

In eastern Sulawesi and Irian Jaya petroleum systems characterised by open marine facies are more dominant, with most reservoirs being located in carbonates. Petroleum charge is, however, dominantly terrestrial Type III Organofacies F augmented with marine Type II Organofacies A and/or B (see Peters *et al*., 1999). The province is less rich in oil and gas than the western part of the country, but is less well-known and exploration is certain to reveal new insights. Both thermogenic and biogenic gas (>98% methane) has been discovered, the latter in fore-arc and foreland basins (Satayana *et al*., 2007). Characteristic for the area is the presence of prospective Mesozoic rocks of

Australian continental affinity that underlie the Tertiary basins (Bradshaw *et al*., 1997). In the Bintuni and Bula basins these contribute to some of the only pre-Tertiary petroleum systems in Southeast Asia.

Malaysia/Brunei

In Malaysia the petroleum systems have before now only been described for the Peninsula part of the country (eg. Hutchison & Tan, 2009). These contain oil-prone lacustrine synrift rift and paralic gas-prone coaly shale postrift type systems typical of basins on the Sunda Shelf. They are of Oligocene to Early Miocene and Middle to Late Miocene age, respectively. Oil families have been recognised corresponding to both of these charge systems, some representing a mixture of the two. In the main part of the Malay Basin, where there has been considerable postrift subsidence, gas charge to Late Miocene inversion anticlinal structures comes from the Postrift E-I Group PST. Oil charge from the synrift PS is limited to areas where postrift subsidence is minor and the lacustrine source is not over mature (Petronas, 1999).

Petroleum system definition in East Malaysia and Brunei is far more complex. The offshore of Northwest Borneo forms an extensive area of thick young Tertiary sediments, somewhat arbitrarily subdivided into provinces rather than basins, each with its semi-distinct geological character and petroleum potential. Seafloor spreading events and the related closure of the Palaeo-South China Sea in the early to mid-Tertiary, followed by uplift and rotation of Borneo during the Late Tertiary (Pubellier & Morley, 2014), has led to a complex basin evolution dominated by transtensional and transpressional movements. Some of the basins originated as post-collision cycles and developed into progradational deltaic belts. In the Baram Delta and Northwest Sabah, these form highly prolific late postrift marginal sags with growth faults, dominated by coal/coaly shale charge and paralic reservoir/seal sequences. Repeated inversion events created and modified traps (Tingay *et al*., 2005). Recently, attention has shifted to deeper water, where the bathyal portions of the deltas are being explored. As well as proving to form rich petroleum provinces, these toe-thrust areas are revealing new insights into slope and base of slope petroleum systems.

In the distal offshore the open marine carbonate system of the Central Luconia (.) PS with its gas-bearing reefs, developed at several periods above repeatedly rifted and thinned subsiding crustal blocks, later to be buried below delta sequences prograding from the southeast.

Due to the episodic nature of events related to the evolution of the South China Sea, involving repeated episodes of rifting, the basins containing the most successful petroleum systems are mainly younger than in West Malaysia, of mid Miocene to Quaternary age.

I have made use of the accepted province divisions as a basis for classification and have attempted to recognise petroleum systems of distinct character within them. It should be emphasised that these are preliminary interpretations which, with more data can almost certainly be refined or altered. In most cases I have used the currently most commonly used nomenclature (Petronas, 2007), which means that the petroleum system names have mixed origins.

Philippines

Due to the limited exploration large uncertainties exist in defining the petroleum systems and their development in the Philippines, and in this paper many assumptions have been made. Extensive use of the CCOP web-site and Philippines Dept. of Energy 1996 publication has been made. Two contrasting basin types characterise the archipelago.

In the east Late Tertiary basins formed by transtensional faulting above an island-arc complex: These are grouped here as Supra-Arc basins, formed by wrench movements along the Philippines fault and its splays (a process akin to the 'arc-parallel extension' seen in other parts of the World). The modest exploration success in them, in spite of the widespread presence of marine carbonate reservoirs and shale seals suggests that charge may be constrained to some extent, perhaps in part due to limited source potential in many of the open marine facies. In this respect the archipelago contrasts with the large hinterland swamp lowland organic material factories adjacent to the prolific deltas of Borneo and elsewhere. Many clastic reservoirs are argillaceous with volcanic components and are of poor quality (Maclaurin *et al*., 2006).

In the east and south, basin development is related to the formation of small ocean basins (South China Sea, Sulu Sea) and the petroleum potential in their synrift-postrift cycles more closely resembles that of the Malay basins. Mixed charge into early postrift carbonate buildups has provided the greatest success, but potentially interesting deltaic and foreland/fold-belt cycles are present also.

Thailand (& Cambodia)

Petroleum systems in Thai basins overwhelmingly belong to the Early Synrift oil-prone lacustrine family (Bidston & Daniels, 1992; Ridd *et al*., 2011; CCOP EPF; Pradidtan & Dook, 1992). Many of the basins are small and isolated, with triangular pull-apart geometries bounded by wrench faults. Type I lacustrine source rocks of Organofacies C are widely developed, interbedded with reservoir sands of limited thickness and quality and draped over buried hills of pre-Tertiary rock (Permian limestone in the Chumphon Basin). Gas is found in the postrift cycle in the eastern and southern Gulf of Thailand (Pattani Trough); elsewhere the Postrift is very thin or absent.

The Palaeozoic Nam Duk – Rat Buri (.) thrusted PS is developed on the western edge of the Mesozoic Khorat Plateau basin.

Vietnam

The few Vietnamese basins that contain active petroleum systems are concentrated in the southern offshore on the Sunda Shelf (CCOP EPF). They have characteristic Lacustrine Synrift and Paralic PSTs, the latter formed on

a non-growth-faulted passive margin. Traps and reservoirs are varied: In the Cuu Long Basin they are represented by fractured and weathered basement granodiorite in re-activated buried hills (Cuong *et al.*, 2005), while in the Con Son Basin the main field's reservoir consists of a reef situated in the Early Postrift (Simon *et al.*, 1997).

Gas is widespread, but in many areas, high carbon dioxide levels are encountered (as in western Indonesia and the western part of offshore Sarawak) and represent a significant risk. The origin of the CO_2 is controversial, but may be related to de-gassing of carbonates and/or catagenesis of deeply-buried coals along crustal faults bordering the South China Sea (Cooper *et al.*, 1997).

CONCLUSIONS

In Southeast Asia, where there are a large number of productive Tertiary basins with essentially similar geodynamic development and hydrocarbon habitats, and where many active petroleum systems can be identified, it is advantageous to group them as much as possible. Doing so facilitates understanding of the essential elements that contribute to their success, and makes it possible to appreciate the variety of their development and use them as valuable analogues. The petroleum systems, here grouped into petroleum system types (PSTs), are hosted in a limited number of 'lithofacies associations'. These associations comprise groups of sedimentary facies that contain characteristic and distinct petroleum parameters. Five such associations have been recognised: (i) lacustrine (ii) paralic (iii) open marine shelf (iv) deeper marine and (v) pre-Tertiary, and they are characteristic of particular cycles or stages in basin development. The characteristic rift to postrift basin development forms the context within which the depositional environment and palaeogeography evolve.

Lacustrine facies typify the early stages of synrift development in basins closer or more proximal to the Sunda Shelf in northern and western SE Asia. Open marine facies, on the other hand, typify the early postrift period and basins in palaeogeographically more distal areas, such as eastern Indonesia and the Philippines. Paralic and bathyal facies characterise the later stages of the synrift and postrift cycles and are widespread throughout the proximal and intermediate parts of the area. Pre-Tertiary source facies, which provide charge in parts of eastern Indonesia and Thailand, are mainly paralic in nature.

Thus we can summarise the character and implications for petroleum occurrence according to the situation of the basin with respect to the pre-Tertiary Sundaland crustal block:

- More proximal basins: These are dominated by lacustrine to paralic facies in the synrift cycle and have a mainly non-marine sedimentary fill. Charge is from lacustrine and coaly shale source rocks and is strongly oil-prone. Postrift subsidence is often limited so source rock maturation may be affected. The basins are sensitive to inversion.
- More distal basins: These basins are dominated by rapid postrift subsidence. In the open marine facies carbonate reservoirs are well-developed, while most source rocks and petroleum systems are mainly gas-prone.
- Around Borneo, rapid subsidence and proximity to uplifted area led to the development of thick Late Postrift passive margins with delta sequences. Oil- and gas-prone coaly/coaly shale source rocks and clastic reservoirs in both delta-top and deep water environments give rise to often prolific petroleum systems with both oil and gas.
- Intermediate basins: In many basins on the Sunda Shelf, where subsidence rates are lower a non-marine synrift is followed by a marine postrift cycle. Such basins benefit from lacustrine and paralic source rocks and reservoir sequences in both the syn- and the postrift.

Because of the particular character of the charge system, the evaluation of petroleum potential in Southeast Asian Tertiary basins carries special challenges to those used to the subsurface of most other parts of the World. In the Middle East and Northwest Europe, for instance, the source rocks are located in well-defined formations or horizons of regional extent and are relatively consistent in type and quality. They are of marine origin and are also best developed during transgressive periods. In SE Asia, on the other hand, the terrestrial and lacustrine source rocks are patchy, difficult to locate, variable in quality and are commonly distributed in thin beds through often thick sequences…and, many appear to be developed in delta-top and deep water environments deposited during high- and low- stands rather than in transgressive periods. These differences mean that predictive extrapolations of charge quality and maturity, and therefore of prospectivity, are much more difficult in Southeast Asia.

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