

Petroleum systems in New Zealand basins – an analogue approach

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Abstract

Most of New Zealand's Cretaceous to Tertiary sedimentary basins evolved through an essentially similar geological history. This started with phases of rifting in a continental margin environment, was followed by an extended phase of postrift passive margin subsidence, and continued up to the present day in a transpressional regime that resulted in extensive uplift and erosion. The sedimentary sequences in the basins are also essentially similar, and have the potential to contain working petroleum systems, although so far only in the Taranaki Basin have they been demonstrated to result in commercial accumulations. In this paper, an attempt is made to define the petroleum systems that can be identified in the basins as well as those whose presence is implied by what is known about the tectonostratigraphic evolution. The synrift to early postrift phases of basin history contain (or potentially contain) characteristic petroleum system types, based on terrestrial to marginal and deeper marine deltaic source and reservoir rocks. These petroleum system types can be used in the prediction of petroleum prospectivity in less well-known basins, as can similar petroleum system types identified in analogous productive synrift – postrift basins in SE Asia and SE Australia, whose characteristics are summarized here.

Introduction

Some of New Zealand's sedimentary basins contain working petroleum systems, while in others they have yet to be identified. Many of the basins are of a frontier nature and, based on what is known of their sedimentary fill and tectonic history, are potentially prospective for oil and gas. At an early stage of exploration, the evaluation of such basins is greatly facilitated by considering what types of petroleum systems and plays they might contain, based on comparisons and analogies with those developed in similar basins elsewhere. Currently, acreage in several frontier basins is under offer for exploration by the New Zealand Government, and a means to select the most potentially promising areas has considerable value.

Analogue methods can, however, be very disappointing or misleading if used without a realistic appreciation of their limitations. Direct comparisons of the prospectivity of basins based on geological similarity have often proved both difficult and unrewarding. Relatively minor, but crucial differences between similar basins tend to undermine the value of such comparisons. An important first step, therefore, is to break the problem down to a scale at which meaningful comparisons can be made and build an overall picture from there.

In this paper I present a structured means by which analogues can, I believe, be meaningfully applied to the evaluation of the potential prospectivity in New Zealand's basins. The methodology is summarized in Doust (2003). In essence, it involves the recognition of families of petroleum systems and the plays that occur within them, and relating these to fundamental tectonostratigraphic phases in sedimentary basin evolution. It rests on the common observation that many basins or, more particularly, cycles in basin history, share characteristics with respect to petroleum-related parameters.

Tectonostratigraphic stages in basin evolution

In the early eighties, Kingston et al. published a global system for basin classification (Kingston et al. 1983). They recognised that most basins pass in their evolution through several relatively standard phases or cycles, and on this basis they defined a number of basin and basin-cycle types. For instance, a simple half-graben rift basin may comprise only one cycle, and can be identified as a single-cycle basin type. It may, however, develop through a more complex history with synrift and postrift cycles. In this case a number of successive basin cycle types can be distinguished.

Kingston et al. characterized and defined each cycle type by its plate position and the nature of its basin-forming tectonics (either divergent or convergent). The cycles could then be subdivided according to the nature of the depositional sequence they contain and by the style of tectonics that modify them. With slight modification, their classification can still be applied globally – though it is usually convenient to make use of or refer to terms more commonly used in the industry. In this paper I shall call them tectonostratigraphic stages or cycles.

By following Kingston et al.'s basin cycle concept, sedimentary basins can be broken down into standard component parts, and comparisons that would not be possible between basins considered as a whole can be made. We can review the parameters important to petroleum system development in standard cycle types, thereby considerably expanding the scope for analogue comparison and avoiding some of the issues that make comparisons between complete basins difficult. Naturally, it is necessary to incorporate as much geologic information as possible in basin cycle definition, so that we have a good grip on parameter development and range of variation. Following Kingston et al., we need to take account of and incorporate:

- The **geodynamic framework** – this controls the basin origin and its evolution on a large-scale, thus providing the background for the sedimentary and tectonic response.
- The **sedimentary response** – through the evolution of processes related to the depositional environment, this controls the sedimentary sequence, or succession of rock types represented in the basin.
- The **tectonic history** – the nature and intensity of this defines the structural style of the basin-fill, and therefore the potential trap development.

Note that a large amount of this information can be derived or extrapolated from reconnaissance seismic and a few calibration wells, coupled with more regional geological considerations.

New Zealand basins generally follow a synrift – postrift evolution, in Kingston et al.'s terminology, passing through interior fracture – marginal sag – convergent plate margin cycles. The main geodynamic drivers were reviewed in King (2000) and the stages or cycles in tectonostratigraphic evolution were summarised by Baillie and Uruski (2004):

- | | | |
|------------------------|---------|---|
| • Early Mesozoic | prerift | back-arc continental margin sedimentation followed by a major erosional phase |
| • Late Mesozoic-Eocene | synrift | transgressive margin; paralic sedimentation in plate-edge rifts |
| • Oligocene | | postrift passive margin subsidence |
| • Miocene-Quaternary | | regressive convergent margin |

This evolution resembles that of several synrift-postrift basins elsewhere in the world, especially some of those in SE Asia, and we can make use of elements of these to help in preliminary evaluation of basin potential. However, other basins (such as some of those in SE Australia) contain analogous cycles that we can also make use of, thereby increasing the scope of the information we can use for prediction.

Relation of basin cycles to petroleum systems

Basin cycles are by definition important and distinct phases in basin history, often bounded by regional unconformities triggered by tectonic events. Each cycle may contain one or more fully developed sedimentary sequences, in which source rocks, reservoirs and seals may be represented, as noted by Posamentier and Allen (1999), who also noted where they tend to occur. Very generally, we might recognize the following potential within the proximal and distal parts of a sedimentary sequence:

<i>Potential for:</i>		<i>source</i>	<i>reservoir</i>	<i>seal</i>
Lowstand (LST)	proximal facies	none	widespread	very risky
	distal facies	risky	widespread	excellent
Transgressive (TST)	proximal facies	good	restricted	good
	distal facies	excellent	very risky	condensed
Highstand (HST)	proximal facies	terrestrial	excellent	risky
	distal facies	risky/good	risky	interbedded

The Petroleum system concept (Magoon and Dow 1994) relates all petroleum accumulations in an area to their parent charge (“pod of active source rock”) and main reservoir/seal levels. It thus describes a natural system that encompasses the origin and destination of petroleum resources in the subsurface. To achieve this, it relies on a clear geochemical match between the source rock and the petroleum accumulations it charges.

Where source, reservoir, seal and structural elements are all developed within one sedimentary sequence or basin cycle and are stacked in the proper order, we can directly relate petroleum systems to individual tectonostratigraphic cycles or stages in basin development. Such conditions are quite common, for instance where a marine transgressive source rock is overlain by highstand deltaic reservoirs sealed intra-formationally or covered by shales belonging to the lowstand of the overlying sequence. Where this is the case, we can make predictions relating to petroleum system development based on our knowledge of basin cycle evolution. This is not always the case, since partial or complete seal failure may allow charge to reach a younger or older basin cycles and charge reservoirs there (often resulting in mixed charge), but even in such situations, we can learn a lot through comparison of petroleum systems from analogous basin cycles.

New Zealand basin cycles and petroleum systems

A summary of the geological development of New Zealand’s basins and the geodynamic drivers of basin evolution is shown in Fig 1. Early geodynamic drivers include complex rift-spreading events and plate reorganizations that led to prolonged periods of plate margin extension and subsidence. The later basin history has been dominated by subduction and dextral transpression which, since the Miocene, have resulted in widespread compression and inversion. Although precise dating of the cycle periods is often ill-defined (and sometimes conflicting) in the literature, in general a mid-Cretaceous to Tertiary synrift-postrift evolution can be recognized in all of the basins.

It is usually possible to recognize a distinct *early synrift* period, during which faulting was very active and sedimentation took place in broad, but relatively isolated grabens and half-grabens marginal to the New Zealand micro-continent. In some of the basins this period was apparently relatively short-lived and/or was interrupted by periods of partial inversion leading to repeated rifting events (eg in the Northland and West Southland basins).

In the subsequent or *late synrift* period, fault activity gradually waned and the early synrift topography was covered and filled-in by deltaic sediments rich in coals. In some areas deltaic environments covered large areas and persisted into the early Tertiary, for example in parts of the Taranaki and West Coast basins.

By the *early postrift* period, faulting had ceased and was followed by a period of quiescence and subsidence, generally encompassing much of the early Tertiary (but continuing up to the present day in some more distal areas). During this transgressive period a variably thick sequence of continental

margin mudstones accumulated. Open marine carbonates, probably corresponding to a period of maximum transgression, are widespread in the Oligocene.

In the *convergent margin* period (initiated in the early Miocene), dextral transpression coupled with subduction east of North Island led to the uplift and erosion of basinal areas adjacent to the Alpine fault. As a result, thick regressive deltaic sediments accumulated in the proximal parts of several of the basins. In the Taranaki foreland basin these include important turbidite developments. *Late postrift* subsidence characterized parts of many basins unaffected by the transpressive movements.

The petroleum systems of New Zealand have not been formally documented, but using information from Crown Minerals (2000a,b, 2004) and recent publications, preliminary identifications can be made (Fig 2). Events charts for each of the basins can be found in Crown Minerals (2000a). Correlation of petroleum accumulations with their specific charge formation, a pre-requisite for petroleum system definition, is made difficult by poor geochemical discrimination between the predominantly coaly source rocks and the petroleum accumulations. The complex nature of the interbedded lithofacies also complicates the identification of discrete source, reservoir and seal formations. However, by placing sequences in their basin cycle context we can identify the main probable active source formations and the main and subsidiary reservoir levels probably charged from them. It is probable that considerable mixing of charge has taken place from similar source rocks distributed at several levels in the sequence.

1. Taranaki Basin (Figs 3, 4):

- Source and potential source formations:
 - Pakawau Group (late Cretaceous): Early synrift cycle – terrestrial coals and coaly shales (includes Rakopi Formation)
 - Kapuni Group coals (Paleocene-Eocene): Late synrift cycle – terrestrial and estuarine coals and coaly shales
 - Paleocene source, probably marine organic mudstones (early postrift Waipawa Fm type), not yet identified in the basin, but apparent from oil in Kora towards the northern part of the basin.
- Productive reservoir formations:
 - Kapuni Group (Paleocene-Eocene): Late synrift cycle – coastal plain, coastal and deltaic sands with good porosity (ϕ) and permeability (k), stacked, with intraformational seals, becoming more marine upwards – the main reservoirs in the basin
 - Tikorangi limestone & Moki sandstone (Oligocene – Miocene): Early postrift outer shelf to deeper marine fractured carbonates and turbidite sands, good ϕ , poor k .
 - Mount Messenger & Pliocene sands (Late Miocene- Pliocene): Late postrift deeper marine turbidites and volcanoclastics with good ϕ and limited k .
- Petroleum / source rock matching:
 - Oils are waxy, derived from terrestrial source rocks with marine influence. Maui oil is typed to the Pakawau Group (Rakopi Formation) and McKee oil is typed to an Eocene Kapuni Group source.
 - Kora & Tangaroa oils are matched with Paleocene marine-type source rock

From the above, the following Petroleum systems (PSs) can be proposed:

1. **Pakawau – Kapuni (!) PS:** Charge of oil and gas from early synrift cycle into late synrift cycle, with subsidiary charge to early and late postrift reservoirs (eg Tikorangi Limestone). So far, no lacustrine facies have been identified in the early synrift.
2. **Kapuni - Kapuni (!) PS:** Charge of oil and gas from late synrift cycle to late synrift cycle, with subsidiary charge to early and late postrift reservoirs (eg Tikorangi Limestone and Mount Messenger Formation).
3. A third possible PS, involving charge from a Waipawa-type, possibly early postrift cycle Paleocene source rock, to various postrift cycle reservoirs, could be present in the northern part of the basin. As yet, however, this cannot be defined.

Note that charge from the Pakawau and Kapuni group coals cannot be geochemically distinguished, while the lack of a thick regional seal between them suggests that charge from them could be mixed: Thus alternatively, we could combine petroleum systems 1 and 2 to define the **Pakawau/Kapuni-Kapuni (!) PS**. Note that most of the migration appears to be late Tertiary, but that secondary migration towards the south may have taken place, as is suggested by the oil saturation in several shallow late postrift reservoirs in this area.

2. East Coast Basin

- Potential source formations:
 - Whangai Formation (Late Cretaceous): Early postrift cycle, gas-prone source rock with TOC mainly <1%, deposited in outer shelf – upper bathyal environment
 - Waipawa Shale (Late Paleocene): Early postrift marine dark shales with Type II/III terrestrial plant material (TOC <6%), gas and oil prone source rock, deposited in outer shelf – upper bathyal environments (Killops et al. 1996)
- Potential reservoir formations:
 - Deep water sands (Late Cretaceous and Oligo-Miocene): Late synrift, postrift and convergent margin cycle bathyal sands. Most Cretaceous sands have poor reservoir characteristics, but some early Tertiary sands have good porosities
 - Coastal and shallow water sands and carbonates (Miocene-Pliocene) in convergent margin cycle sequences. Many of these are locally developed and are of variable reservoir character.
- Petroleum occurrences: numerous oil and gas seepages and small accumulations derived from mixed Cretaceous and Late Paleocene sources. Oils appear to arise from marine source rock with minor terrestrial input (Field et al. 1997).

The complex structure of the basin may have resulted in juxtaposition of younger source rocks with older sequences, allowing for stratigraphically-downward migration. From the above, it can be anticipated that the following Petroleum systems (PSs) may be present:

1. **Whangai – Cretaceous/Tertiary (?) PS**. Largely gas charge from early postrift cycle to synrift, postrift and convergent margin cycle reservoirs
2. **Waipawa – Cretaceous/Tertiary (?) PS**. Oil charge from early postrift cycle to synrift, postrift and convergent margin cycle reservoirs

A working petroleum system with commercial accumulations has, however, yet to be confirmed in this and the following basins.

3. West Coast Basin (Fig 5)

- Potential source formations:
 - Paparoa Coal Measures (late Cretaceous-Paleocene): Early synrift cycle – mainly gas, but also oil-prone terrestrial coal / coaly shale with Type II/III organic matter, TOC < 2.3%. Some lacustrine facies present.
 - Brunner Coal Measures (Paleocene - Late Eocene): Late synrift cycle – deltaic coals / coaly shales with TOC <4.8%, HI <300.
 - Kaiata Mudstone (Late Eocene-Oligocene): Early postrift cycle – marine organic oil shales, Type II, TOC<1%, deposited in troughs
- Potential reservoir formations:
 - Paparoa-Brunner formations (late Cretaceous-Eocene): Early - Late synrift cycle arkosic sands and conglomerates
 - Cobden limestone (Oligocene): Early postrift deeper marine fractured carbonates.
- Petroleum occurrences: Numerous thermogenic gas and oil seepages related to coaly source rocks

From the above, at least one working Petroleum system (PS) can be envisaged. A second one, based on the Kaiata Mudstone, could potentially be developed if sufficient burial has taken place.

1. **Paparoa/Brunner – Brunner (?) PS:** Early to late synrift cycle oil and gas charge to synrift and postrift cycles, depending on the extent of inversion

4. Canterbury Basin

- Source and potential source formations:
 - Late Cretaceous coaly facies: Early-Late synrift cycle – marine-influenced terrestrial coals / coaly shales, TOC <12%, HI <340.
 - Paleocene marine black shales: Early postrift, good source rock with HI < 300, oil and gas prone
- Reservoir formations:
 - Clipper Sandstone (late Cretaceous): Early synrift cycle – fluvial - coastal plain sands and conglomerates with good porosity and limited permeability
 - Tertiary fluvial, estuarine and marine sands and limestones with locally high porosities
- Petroleum accumulations:
 - Galleon & Clipper gas/condensate is typed to Cretaceous source
 - Gas shows in Late Cretaceous - Paleocene

From the above, only one Petroleum system (PS) can be proposed:

1. **Late Cretaceous (!) PS.** Early-late synrift cycle mainly gas charge to early and late synrift reservoirs

5. Great South Basin

- Potential source formations:
 - Hoiho Group (late Cretaceous): Early synrift cycle – terrestrial coals / coaly shales with TOC>2%, HI >200
 - Taratu Formation (late Cretaceous): Early postrift cycle – terrestrial coals / coaly shales (in north of basin only)
 - Tartan Black Shale (Paleocene): Early postrift cycle – marine organic mudstones with <8% TOC, HI<230.
- Potential reservoir formations:
 - Hoiho Group (late Cretaceous): Early synrift cycle – coastal plain sands, porosities <25%
 - Kawau Sandstone (late Cretaceous): Late synrift cycle – shallow marine sands
- Petroleum accumulations: gas / condensate accumulation in Kawau. Oil shows in Late Cretaceous, with shows in Paleocene-Eocene sands.

From the above, only one Petroleum system (PS) can be proposed:

1. **Hoiho – Hoiho/Kawau (.) PS,** situated entirely within the synrift cycle. Younger potential source rocks appear to be immature.

Petroleum system types

The petroleum systems identified above share many characteristics and, following the procedure discussed by Doust and Lijmbach (1997) can conveniently be grouped into two or three **Petroleum System types**, or **PSTs**, characteristic of the main synrift and early postrift basin cycles (Fig 2): Nearly all are characterized by similar coal/coaly shale source and deltaic to marine reservoir types:

1. The **Early synrift deltaic PST**, with charge from marine-influenced coal and coaly shale source rocks into interbedded lower coastal plain to paralic reservoir/seal pairs. This PST has probably provided an oil and gas charge, through primary and secondary migration, into synrift and postrift reservoirs.
2. The **Late synrift deltaic PST**, with charge from marine-influenced coal and coaly shale source rocks into interbedded paralic to shallow marine reservoir/seal pairs. This PST is very similar to 1, differing only in its slightly more marine character. It has probably provided an oil and gas charge, through primary and secondary migration, into late synrift and postrift reservoirs.
3. The **Early postrift marine PST**, with charge from outer shelf/upper bathyal Waipawa Shale type source rock into mainly Tertiary reservoirs. Although this source is apparently widespread in New Zealand basins, it is largely immature (Killops et al. 1996) and this PST appears to have restricted potential (derived oils being recognized mainly where volcanics have resulted in locally high subsurface temperatures).

The first two PSTs appear to have very similar charge characteristics. It is useful to separate them, however, since in analogous basins (see below) early and late synrift PSTs have proven to have different characteristics. The composition of the early synrift is currently only partly known and is anticipated that, as more data become available, its possibly more varied nature will become evident – for instance, it may prove to contain important lacustrine developments, with Type I/II source rocks.

As noted above, a large amount of mixing of charge has probably taken place, due to the imperfect nature of seals in the interbedded lithologies. This may have been compounded in places by re-migration following late postrift inversion.

The tectonics and basin stratigraphy of frontier New Zealand basins have many of the elements needed for the development all three PSTs. Where conditions are favourable therefore; for instance, where appropriate burial and structural development have occurred, it is possible that they are developed (see Table 1). Thus, using reconnaissance subsurface data, the potential analogue value of the PSTs can be assessed. PST analogs can also be recognised, however, in other synrift-postrift basins, such as those in SE Australia and SE Asia.

Table 1. Potential for petroleum system development in frontier New Zealand basins (data largely from Crown Minerals 2000a,b, 2004).

Northland Basin

	Early synrift	Late synrift	Early postrift	Late postrift
Source presence & type	Coals in Jurassic & Early Cretaceous Tanihwa Fm	Possibly coaly sequence	Marine organic mudstones / oil shales	
Reservoir/seal presence & type		Terrestrial – nearshore sands and shales	Eocene turbidites and shales	Miocene volcanoclastics and turbidites / shales
Trap styles	Rotated fault blocks, unconformity traps	Drapes over rift blocks, Miocene anticlines	Anticlines formed in Miocene	
Hydrocarbons		Gas shows		

Wanganui Basin

	Early synrift	Late synrift	Early postrift	Late postrift
Source presence & type			Coaly facies (north), mature?	Paralic facies?
Reservoir/seal presence & type			Local inner shelf sands and limestones	Miocene volcanoclastics and turbidites / shales
Trap styles	Rotated fault blocks, unconformity traps	Drapes over rift blocks, Miocene anticlines	Anticlines formed in Miocene	
Hydrocarbons			Gas shows	

West Southland

	Early synrift	Late synrift	Early postrift	Late postrift
Source presence & type	Backswamp / Lacustrine black shales	Coal measures and oil shales	Carbonaceous mudstones	
Reservoir/seal presence & type		Coastal plain, fluvial and shallow marine sands	Oligocene marginal marine sands	Miocene submarine fans
Trap styles		Drape folds	Reverse fault anticlines, reef mounds?	Reverse fault anticlines
Hydrocarbons			Gas shows	

Petroleum systems in analogous basins

The Tertiary basins of SE Asia form, like the New Zealand basins, a family of synrift – postrift basins, characterized by early Tertiary rifting, subsidence and transgression followed by late Tertiary transgression, uplift and regression. The time interval involved is slightly younger in SE Asia, but the overall histories are comparable. Doust and Lijmbach (1997) and Doust (2003) described *petroleum system types* from these basins. They recognized four, corresponding to the four main cycles of tectonostratigraphic development. Their main characteristics are:

1. **Early synrift lacustrine petroleum system**, with Type I/II largely oil charge to early and late synrift cycle reservoirs
2. **Late synrift transgressive deltaic petroleum system**, with Type II/III oil and gas charge to synrift and early postrift reservoirs
3. **Early postrift marine petroleum system**, with a Type II/III primarily gas charge to early postrift cycle reservoirs, often carbonates associated with the period of maximum transgression
4. **Late postrift regressive deltaic petroleum system**, with Type II/III oil and gas charge to late postrift cycle reservoirs.

Doust and Noble (2006 in press) classified the petroleum systems in Indonesian basins into these PSTs and provided details of their characteristics. They recognized that the distribution and development of the PSTs depends on a number of factors, including source rock facies and maturity, variability in the development of reservoir-seal facies and the style of structural trap formation. However, five basic families of basins could be identified: Proximal, Intermediate, Distal, Borneo and Eastern Indonesian, dependant on their geodynamic situation and evolution. In each, one or more of the PSTs is present or dominates: For instance, in the Proximal basin family, the Early Synrift PST is dominant, while in

the Distal family the Late synrift and Early postrift PSTs dominate. This reflects closely the relative representation of the tectonostratigraphic basin cycles in these basins.

SE Asian analogue PSTs can be applied to New Zealand basins if we can recognize similarities between them and the tectonostratigraphic basin cycles that contain them. The typical plays and oil/gas fields they contain can then be used to predict what kind of prospects may be developed and what their volumetric and productive potential might be.

In comparison with Indonesia (and SE Asia in general) the phase of lacustrine deposition in the early synrift appears to be minor or absent from New Zealand basins, to be replaced with deltaic facies (although there is some evidence for lacustrine shales in basins in the west of South Island). Also, there is no charge from the late postrift and the character of the early postrift PST differs. This is a reflection of greater marine influence throughout basin history consequent on the plate marginal situation of the rifts in New Zealand. In this respect, the latter can be compared to some of the intermediate to more distal basins in Indonesia, such as the distal parts of the South Sumatra Basin and the North Sumatra. However, two synrift PSTs, with characteristics similar to the Late synrift transgressive PST of SE Asia, are well developed in several basins in New Zealand, as described above.

Perhaps the most important aspect of this type of analysis, however, is the recognition that similar basin and cycle types contain particular suites of lithofacies corresponding to particular depositional environments, whose distribution dictates the development and quality of source rock, reservoirs and seals. With some exceptions, probably largely due to climate differences, the lithofacies types found in Indonesian basins resemble those in New Zealand. This means that the petroleum parameters of the various lithofacies types can be compared and also used for analogue purposes through their proxy - depositional environment. Thus we can, I believe, use the depositional environment evolution to guide our predictions of which petroleum systems may be present.

A second set of synrift – postrift basins with many similarities to those in New Zealand, including essentially common and synchronous basin-forming geodynamic drivers and plate margin situation, are developed on the continental margins of SE Australia. Of these, the most important for analogue purposes are the Gippsland and Otway basins. Petroleum systems are present in the synrift only: As in New Zealand, the postrift contains no source potential and is rarely mature.

In the Gippsland Basin, a deltaic-type synrift petroleum system has been recognized, arising from the extensive Latrobe coal sequence of late synrift (Bishop 2000) – The **Latrobe (!) PS** (Fig 6). Early rift phases of similar character (Strzelecki and Golden Beach groups) may also contribute. Both charge the Latrobe reservoirs of the late synrift with oil and gas and are sealed by shales of the transgressive early postrift. Both of these PSs are directly comparable to the synrift PSTs of New Zealand and have been employed in analogue studies; see for example Baillie and Uruski (2004), who compared Deepwater Taranaki with Gippsland.

The excellent prospectivity of the Gippsland basin, however, owes much to a phase of late Eocene compression and inversion, which created channelised topographic unconformity traps at the top of the Latrobe reservoir. Subsequent tectonic development has been minor, so the system is an extremely efficient one. In many New Zealand basins, the main traps were not developed until the convergent margin phase of transpression (absent from SE Australia).

Conditions similar to Gippsland characterize the Otway Basin (Fig 7), although the prospectivity appears so far to be substantially less clear. This can probably be attributed partly to the significantly greater burial of the most of the synrift, pushing it into the gas window and degrading reservoir potential, and partly to the lack of an early phase of trap formation. Petroleum system elements similar to those in Gippsland are present, however.

Edwards et al. (1999) placed the petroleum systems of basins in SE Australian basins in the context of an Austral Petroleum Supersystem, and recognized a time-stratigraphic geochemical grouping of petroleum occurrences into three main families or subsystems which we can compare with the PSTs defined above:

1. A3: Late Cretaceous – Eocene subsystem, with fluvio-deltaic land-plant source rocks (including the oleanane biomarker). This is largely comparable to the Late synrift PST of New Zealand
2. A2: Aptian – Albian subsystem, with peat swamp and marginal marine land-plant and marine algal source rocks. This is likely to correlate with the Early synrift PST of New Zealand, although marine source facies have not yet been identified in New Zealand basins at this level.
3. A1. Late Jurassic – Early Cretaceous subsystem with a variety of lacustrine, fluvio-lacustrine and marginal marine source facies. This subsystem is not yet known to form the basis for a petroleum system in New Zealand, but Jurassic coals have been located in the Northland Basin, and they may characterize some of the poorly controlled early phases of the synrift.

Play analysis

Petroleum systems are defined by their charge and main reservoir destination, and their extent by the distribution of accumulations derived from the active source. Each petroleum system contains families of accumulations, usually called plays, which typically occur in the same reservoir formation and/or have a similar trapping configuration. I believe that analogous petroleum systems will tend to contain similar suites of plays, dependant, of course, on factors like the local structural development and its timing versus that of source rock maturity. Where this can be confirmed, it provides a means to predict which plays could be present – an important consideration at a frontier stage of exploration.

Doust (2003) proposed a hierarchic definition of plays, in which distinction is made between *play level*, typically the formation or lithostratigraphic unit of the reservoir, and the *play* itself, which is a subdivision of the latter, defined by trap type. The play level, being dependant on the basin stratigraphy, is easier to relate to the petroleum system than the trap type, which depends largely on the structural development. The play level, therefore, can provide analogues: the trap type reflects more the local tectonic development. A convenient means to compare petroleum system types and play levels from different basins is to plot the depositional environment evolution of a basin against

the basin stages or cycles (Doust 2003). Examples of such “trajectory plots” for the Taranaki and Westland basins are shown, together with those of potential analogue basins in Australia and SE Asia (Fig 8). Along each trajectory, the known commercially significant play levels are indicated. It is suggested that where trajectories coincide, productive play levels identified in better known basins could be predicted to occur in less well-known basins. The prediction of which actual plays could be present depends then on comparison of the tectonic history.

Examples of play levels, expressed as lithofacies types rather than formations (which are basin-specific) have been given in Doust and Sumner (2006 in press) for basins in SE Asia. They include

- Associated with the early synrift; alluvial fans, lacustrine deltaic/turbidite sands, volcanoclastics and fractured prerift basement
- In the late synrift: fluvial and deltaic sands. These are difficult to differentiate further, as most accumulations in these sequences are multi-level, including a variety of delta-related reservoir types.
- In the early postrift: marine carbonates (reefal build-ups and carbonate platforms)
- In the late postrift: deltaic, coastal plain, shallow marine and turbidite sands.

Clearly some of these are relevant to New Zealand basins, while others, for instance those related to lacustrine environments are probably less so. Examples of plays in the Taranaki Basin are listed and described in Crown Minerals (2004). They include thrust features, inversion structures, extensional structures, volcanic edifices, half-graben fills, submarine fans and diagenetic traps. Using this classification and the analogue basins reviewed above, we can make use of reconnaissance data and make preliminary predictions of what types of plays could be present in New Zealand basins.

Reservoir facies: these are closely related to depositional environments. All New Zealand basins have reservoir potential, the development depending on the palaeogeographic proximity to land areas or the basin margin:

- In the synrift sequences, reservoir facies are widespread and are typically non-marine to shallow marine alluvial to fluvial and deltaic. If and where deep lake facies are located, lacustrine turbidites could be present. Seals are mainly interbedded and are best developed in the more distal facies. All basins except for the East Coast Basin have well-developed synrift facies.
- In the postrift, the sequence is typically of marine origin and reservoirs are less common. They are represented by open marine carbonates and, in some later stages, by deep marine turbidites. Shallow marine facies are present only in the most proximal parts of basins, while seals are widespread. Distal basins such as the East Coast and Great South basins have extensive postrift facies. Volcaniclastic and volcanic diagenesis may contribute to reservoir facies (Crown Minerals, 2004).
- In the convergent margin phase, uplift and erosion resulted in the accumulation of regressive facies, and a great variety of shallow to deep marine clastic and carbonate reservoir facies are present, including non-marine, deltaic and submarine fan sands and coastal/shelf carbonates. Their distribution depends on the local tectonic history and whether they lie proximally or distally in the basin. Many are locally developed only, allowing scope for stratigraphic trapping. The Taranaki Basin has extensive deep water reservoirs belonging to this phase, and the more proximal parts of most other basins such as Canterbury and Great South can be expected to contain both shallow and deeper marine reservoirs.

Trap types: These can be conveniently related to tectonic style:

- Tensional traps: These can occur in both syn- and postrift cycles, and involve pre-, syn- or postrift sequences. Main trap types associated with early synrift cycles include tilted footwall fault blocks, horst and trap-door structures, sometimes truncated below angular unconformities. The potential for all of these exists in all New Zealand basins, while hanging-wall roll-over structures may still be found in areas of thicker synrift development, such as in the Taranaki Basin. Late Tertiary post inversion tension has led to tilting and block faulting affecting the postrift in the Taranaki Basin, and such traps could be present in basins close to the Alpine fault.
- Traps formed through subsidence: Traps in this domain include those due to facies change along dipping flanks as well as drape over structural relief. Such traps are likely to occur in basins less affected by the convergent margin cycle, such as the Canterbury, Great South and Northland basins, probably largely affecting the postrift.
- Uplift/Inversion traps: Anticlines associated with inversion of synrift basin boundary and basement-block faults are common in New Zealand basins affected by the convergent margin basin cycle. They affect both syn- and postrift sequences and form the main traps in the Taranaki Basin. They can be expected to be present the West Coast, East Coast, Wanganui and West Southland basins.
- Compressive traps: Compressional thrust anticlines, formed in the convergent margin phase, represent an important play (Tarata thrust play) in the Taranaki Basin, where they affect pre-, syn- and postrift reservoirs. Such fold belts have been identified also in the Northland, East Coast (largely offshore) and Great South (near-shore) basins, and they could potentially be present in the West Southland and West Coast basins.

If we combine the potential for reservoir facies and trap type distribution for different basins and parts of basins with the likelihood of charge from the petroleum system type predicted to be present, we can make preliminary estimates of the plays likely to be present. These estimates can be used to judge the possible value of the basin and also help to identify potential target plays.

Conclusions

A methodology for the application of analogues in frontier type exploration is presented. It involves identification of the main cycles of basin formation and of the characteristics of the sequences involved with respect to petroleum prospectivity. Productive basins have petroleum systems associated with some or all of the basin stages, and it is possible to group these into characteristic petroleum system types (PSTs) that can be used in analogue prediction.

Based on information contained mainly in local literature (Crown Minerals 2000a,b, 2004) it is possible to recognize or propose the existence of a number of petroleum systems in New Zealand basins. These can in turn be grouped into PSTs and compared with those in other, similar basins such as those in SE Asia and SE Australia. Some elements of the petroleum systems and plays in the latter areas can be used as appropriate as analogues, others probably not, but both can be used in prospectivity prediction in the less-well known and frontier basins of the country.

In order to do this, a general knowledge of the geodynamic setting, probable basin sedimentary sequence and tectonic development is needed. The reconnaissance seismic and wildcat well data that exist provide a good basis for such evaluation. It is hoped that the evaluation of New Zealand's less-well basins can benefit from such analyses, and it should be emphasised that at a frontier stages of exploration, as much attention should be paid to the identification of the petroleum systems and play types likely to be present as is given to the direct evidence provided by seismic and well results.

Acknowledgements

I am grateful to Crown Minerals for permission to make use of several illustrations in their publications. I am also very grateful to Peter King of the Institute of Geological and Nuclear Sciences who generously reviewed the text with great care and insight. He corrected many errors of fact and brought several important facts and issues to my attention. I consider this paper to be a "first-pass" only, and to be subject to revision and re-interpretation. Nevertheless, I hope that it will contribute to the stimulation of new insights into the petroleum potential of New Zealand basins.

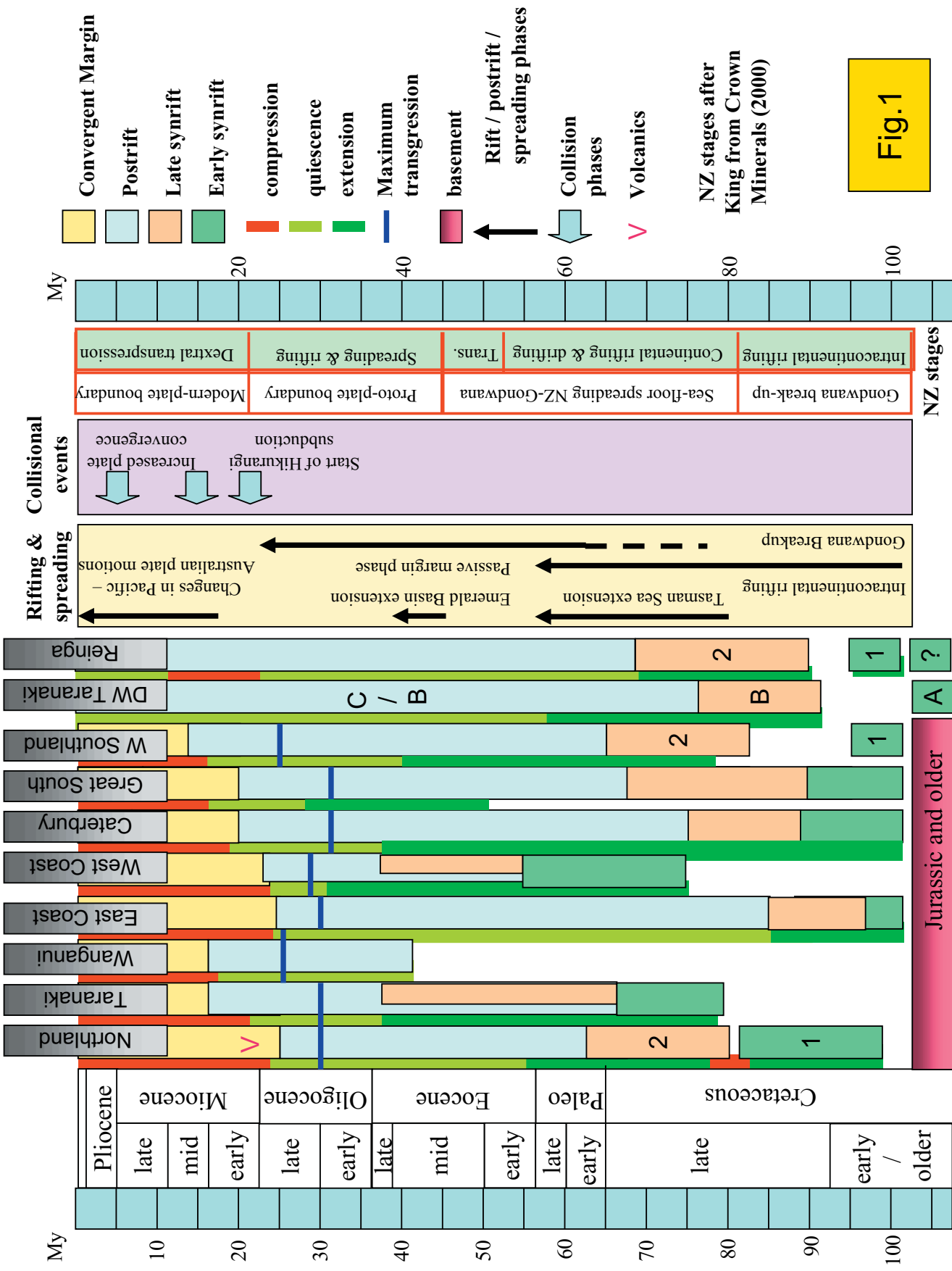
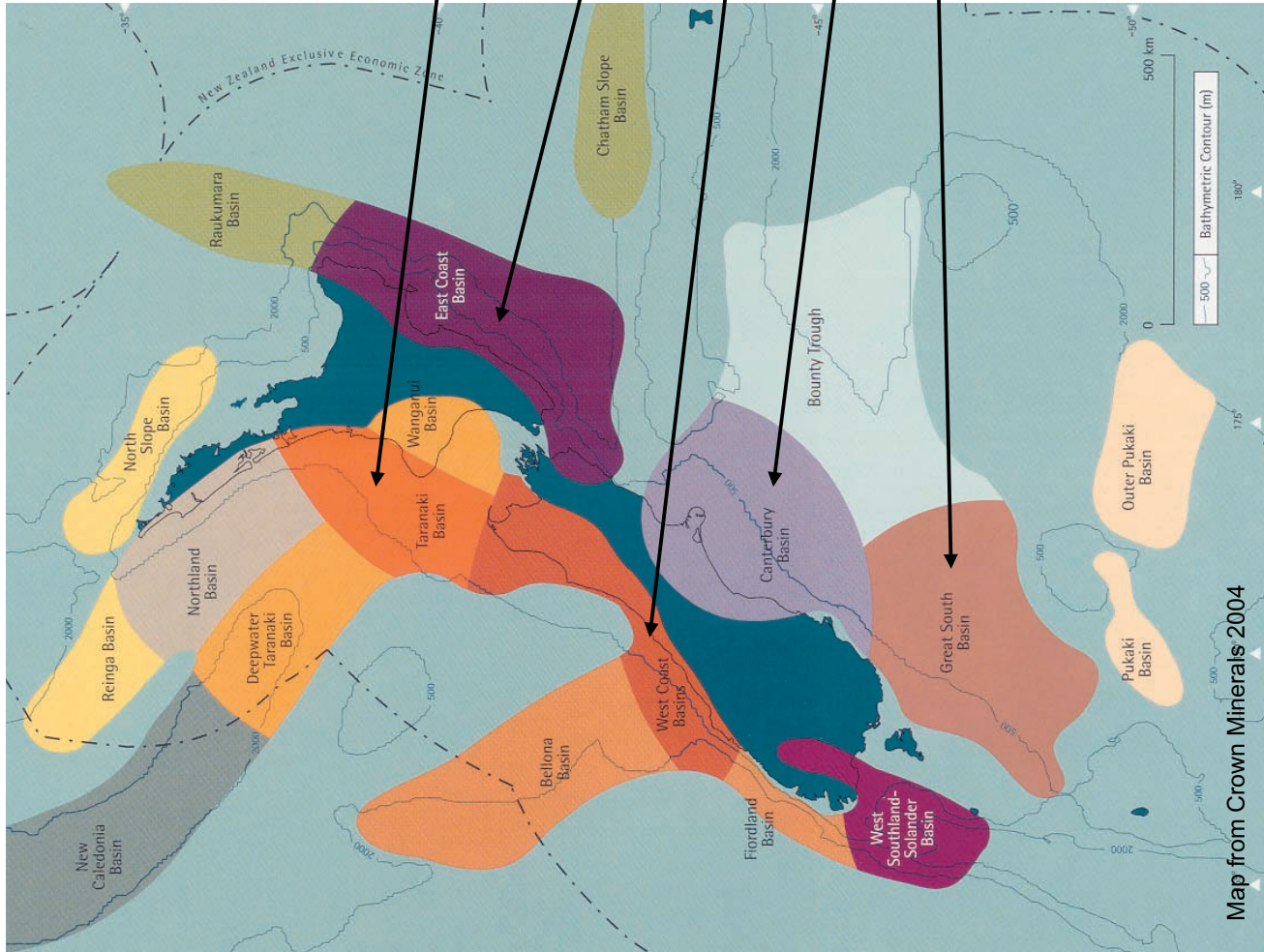


Fig.1

1. New Zealand basins: Tentative basin stages and tectonostratigraphic cycles correlated with tectonics and geodynamic events. The cycle boundary times are approximate only since proximal and distal parts of the basins appear in some cases to enter different stages at different times (eg. Taranaki, West Coast). Multiple phases of synrift development are indicated by numbers, and for deepwater Taranaki, the megasequences of Baillie and Uruski (2004) are identified.

Fig.2



Petroleum system (PSS) identified and proposed

- Taranaki Basin**
- Pakawau – Mangahewa/Kapuni (!)
 - Kapuni - Mangahewa/Kapuni (!)
 - OR Pakawau/Kapuni–Mangahewa/Kapuni (!)
 - plus...potential PS based on Paleocene

- East Coast Basin**
- Whangai – Cretaceous/Tertiary (?)
 - Waipawa – Cretaceous/Tertiary (?)

- West Coast Basin**
- Paparoa/Brunner – Brunner (?)

- Canterbury Basin**
- Late Cretaceous (!)

- Great South Basin**
- Hoiho – Hoiho/Kawau (.)

Petroleum system types (PSTs)

- Early synrift deltaic PST
- Late synrift deltaic PST
- Early postrift marine PST

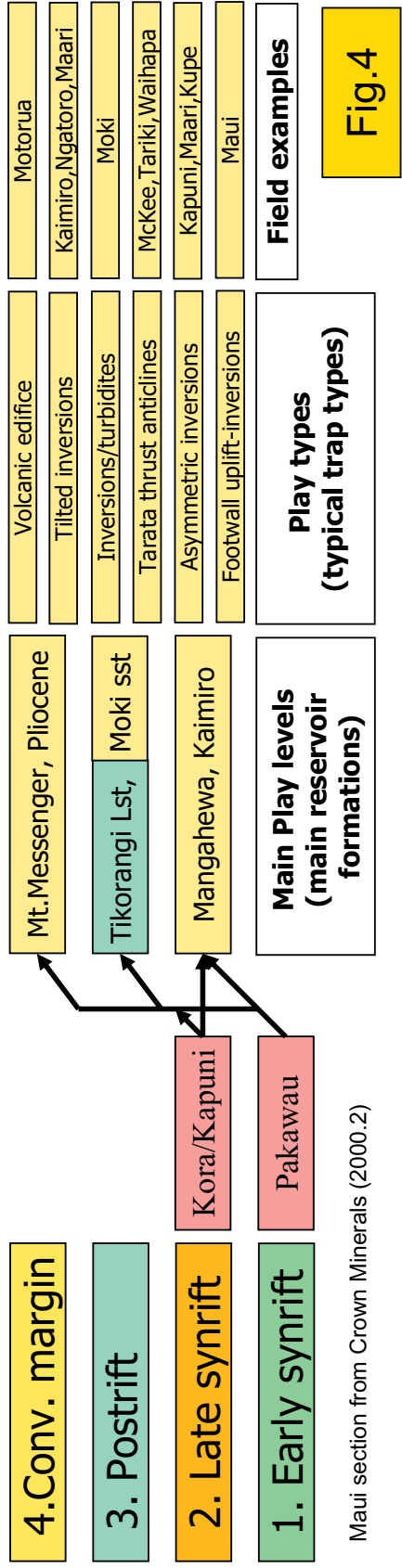
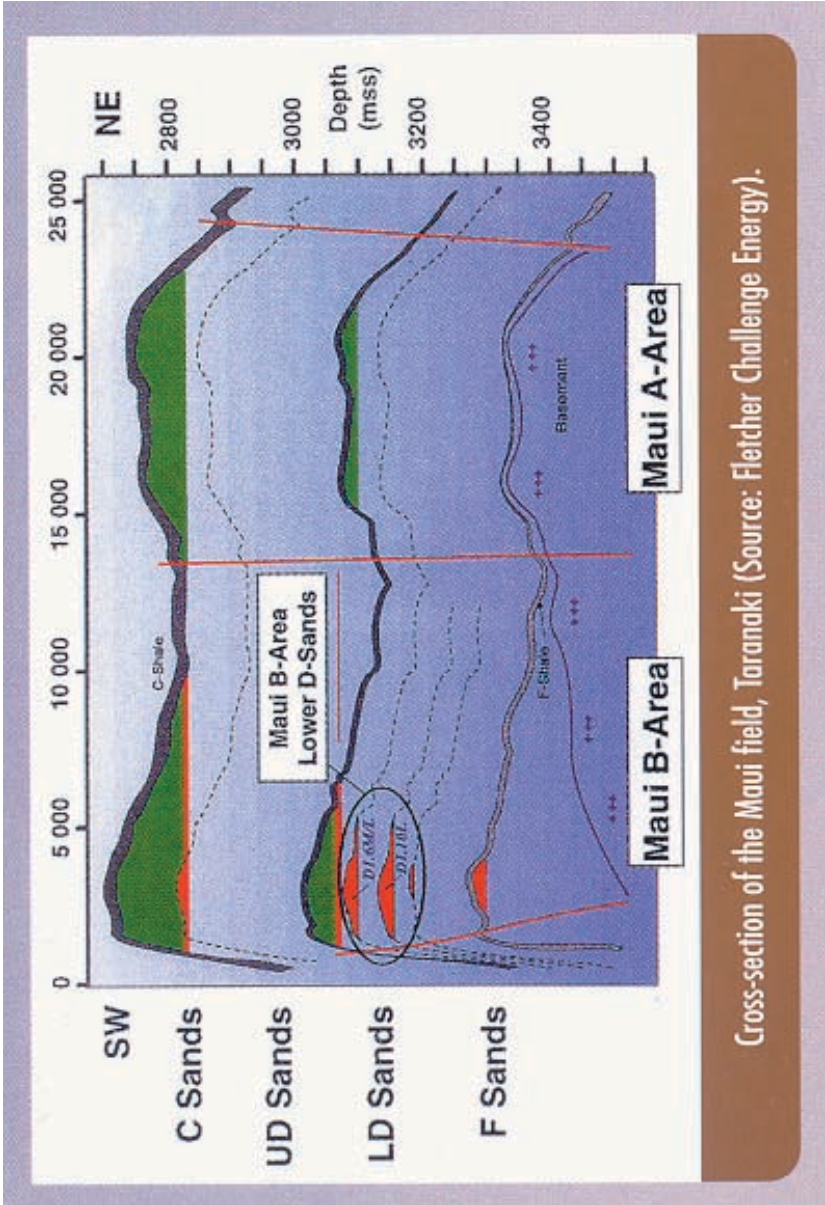
2. Sedimentary basins of New Zealand, with Petroleum Systems and Petroleum System types (PSTs) identified or proposed in this paper. Known – (!), hypothetical – (.) or speculative – (?). PSTs are identified by coloured balls.

Possible petroleum systems

- Pakawau-Kapuni (!)
- Kapuni-Kapuni (!)
- ...plus a possible PS based on Paleocene charge

Alternative (main) petroleum system

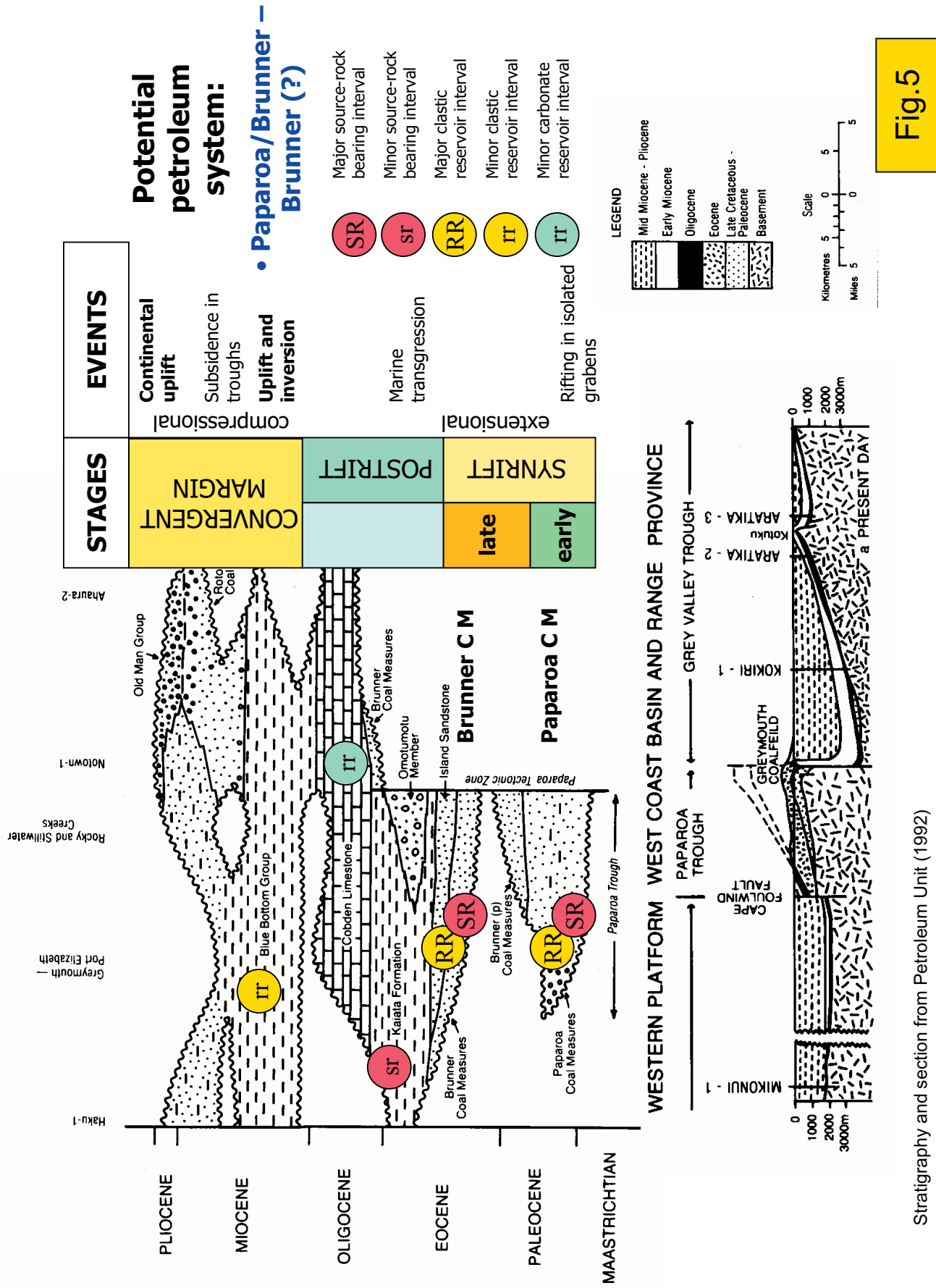
- Pakawau/Kapuni-Kapuni (!)



Maui section from Crown Minerals (2000.2)

Fig. 4

4. Taranaki Basin: Petroleum system analysis. Note that the Maui profile (Crown Minerals, 2000.2) shows multiple reservoir-seal levels and evidence for an early synrift half-graben below the F sands. If such half grabens should prove to be more widespread in New Zealand basins, there could be scope for lacustrine facies (with rich oil charge) in the early synrift.



5. Westland Basin: stratigraphy, basin stages and potential petroleum systems. Stratigraphy and section from Petroleum Unit (1992).

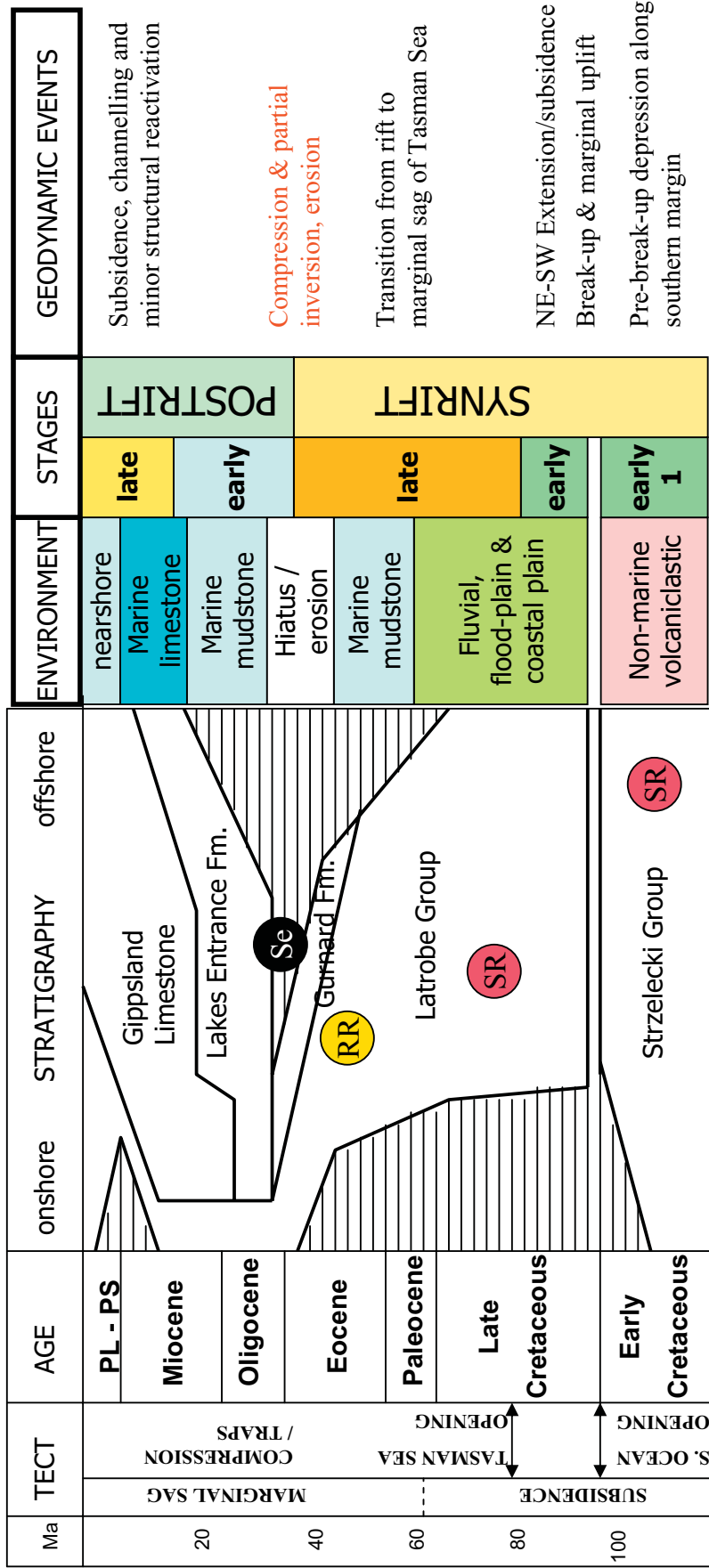


Fig.6

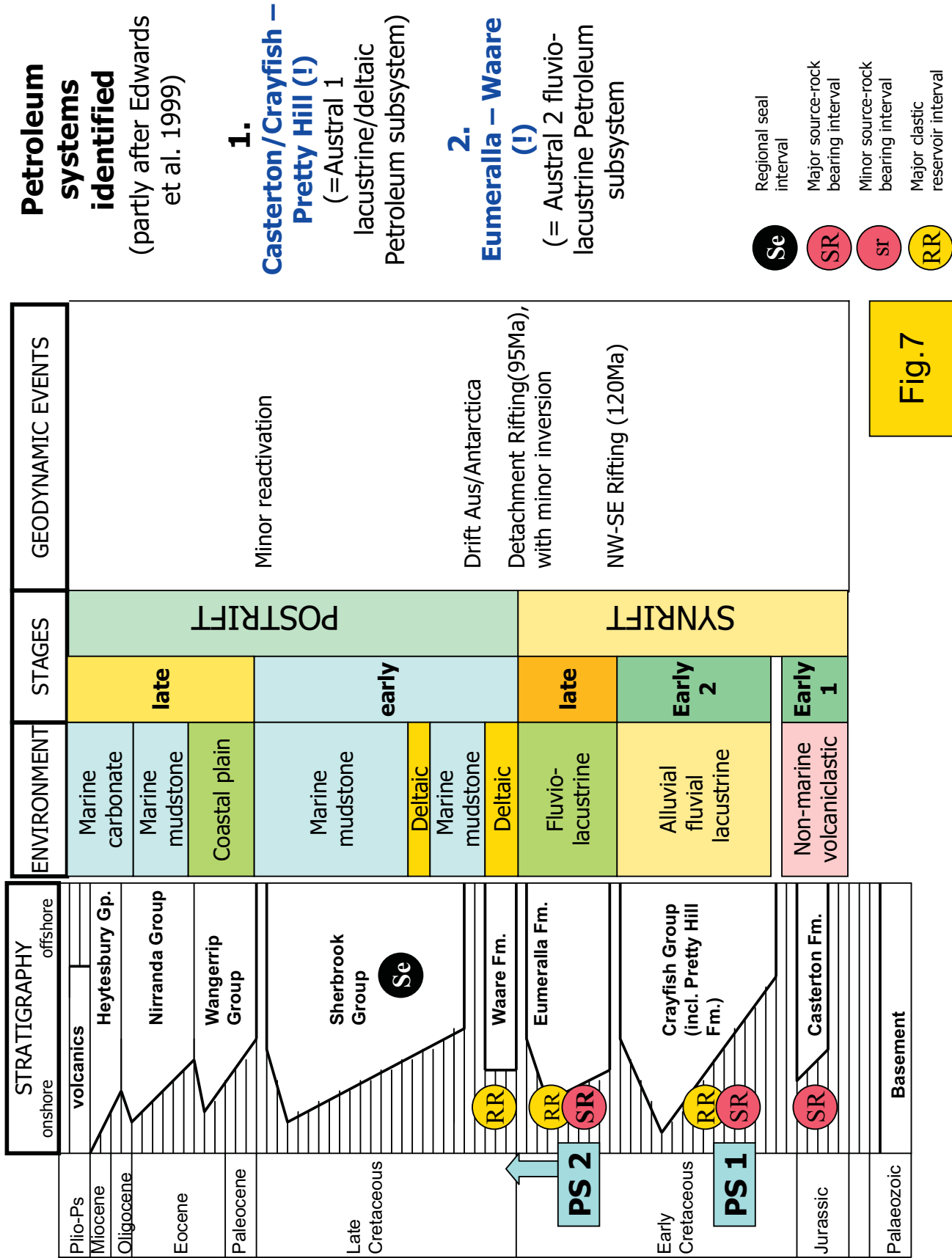


Main petroleum system: Latrobe (!),

probably equal to the A2-A3 subsystems of SE Australia and to Early-Late synrift PSTs of New Zealand.

Stratigraphy simplified from Rahmanian et al. 1990

6. Gippsland Basin, Australia: Basin stages and potential petroleum systems. Simplified stratigraphy after Rahmanian et al. 1990.



Petroleum systems identified

(partly after Edwards et al. 1999)

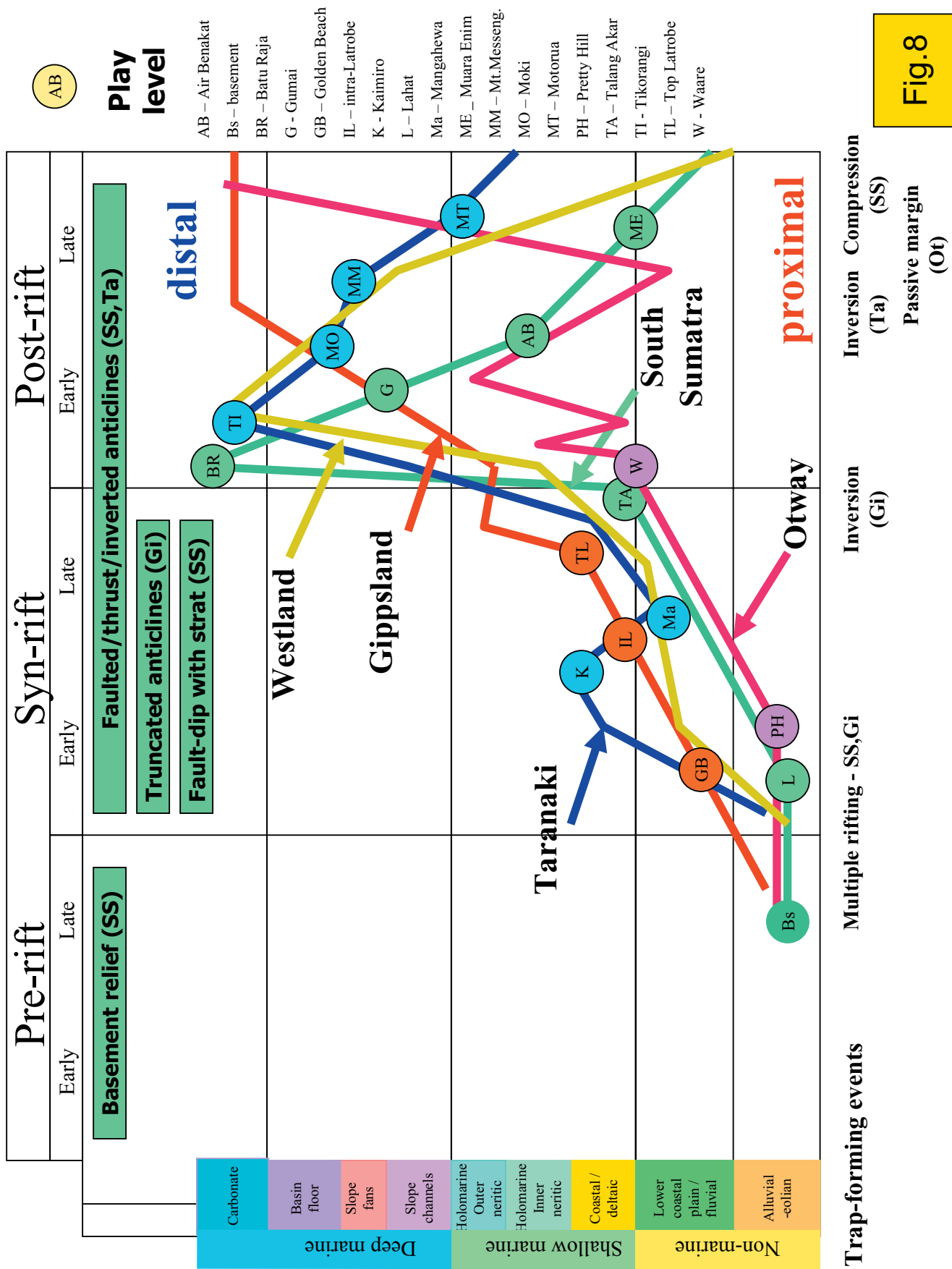
1. Casterton/Crayfish – Pretty Hill (!)
 (=Austral 1 lacustrine/deltaic Petroleum subsystem)

2. Eumeralla – Waare (!)
 (= Austral 2 fluvio-lacustrine Petroleum subsystem)

- Regional seal interval
- Major source-rock bearing interval
- Minor source-rock bearing interval
- Major clastic reservoir interval

Fig.7

7. Otway Basin, Australia: Basin stages and potential petroleum systems. Simplified stratigraphy after Krassay et al. 2004.



8. Trajectory plots for the Taranaki and Westland basins, New Zealand, compared with the Gippsland and Otway basins, SE Australia and the South Sumatra Basin, Indonesia. Known commercial play levels for each basin are indicated on the basin trajectories and identified on the right. Gi = Gippsland, SS = South Sumatra, Ta = Taranaki, Ot = Otway. With the exception of South Sumatra, all source intervals lie in the synrift.

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