

New Zealand's changing configuration in the last 100 million years: plate tectonics, basin development, and depositional setting

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Abstract

New Zealand's sedimentary basins with proven or perceived prospectivity for hydrocarbons have formed over the last 100 m.y. Today, these basins sit astride or adjacent to the Pacific-Australian plate boundary, and represent the southernmost petroleum provinces on the western Pacific rim. This paper documents the changing shape of New Zealand's landmass and offshore areas in response to tectonic influences through time, and discusses the implications for petroleum systems development.

The Cretaceous to Recent sedimentary succession in New Zealand corresponds to a 100 m.y. 1st-order transgressive-regressive 'megasequence', that evolved within a tectonic continuum from intra-continental rift to convergent margin orogenic belt. Seven tectonically controlled second-order depositional cycles, of 5 to 25 m.y. duration, are correlatable between regions as major, unconformity-bound transgressive or regressive packages.

In the Late Cretaceous a lineament of rift sub-basins existed in the west, linked to a Tasman Ridge transform zone. Syn-rift deposits include coarse-grained potential reservoir units and, more importantly, thick coal-rich source rock intervals. Rapid deposition and high heat flow associated with rifting led to early hydrocarbon generation locally. To the east of the active rift zone the sea began to transgress low-lying coastal plain areas from c. 80 Ma.

By the end of the Paleocene a passive margin had developed around the sub-continent, including broad marine embayments at the landward ends of the Bounty Trough and New Caledonia Basin. Rising base level allowed the accumulation, on broad coastal plains, of thick coal measure sequences that are proven source rocks. Marine rocks with source potential, most notably the Waipawa Formation black shale, were also deposited. Re-worked transgressive shoreline sandstones, derived from a weathered hinterland, constitute the pre-eminent reservoir fairway in several basins. With ongoing regional subsidence, fine-grained seal rock facies were deposited in distal regions, and gradually transgressed across the shoreline sandstone tracts.

By Late Oligocene times land areas were minimal. Oblique extension associated with Emerald Basin rift propagation created a complex series of sub-basins as far north as eastern Taranaki. Highly variable basin-fill lithofacies include deep-water turbidites that are proven reservoirs.

Southward propagation of the Hikurangi subduction zone and inception of a through-going plate boundary in the earliest Miocene heralded the onset of convergent tectonics, uplift and expansion of land areas, and increased terrigenous sedimentation within most basins. As dextral convergence gradually increased, the proto-New Zealand landmass was 'squeezed' into an elongate belt parallel to the plate boundary. With southward migration of the Australian-Pacific rotation pole, and rotation of the Hikurangi margin, the focus of compression and arc volcanism shifted southwards, and extension began in the north. Large structural anticlines formed as a result of basin inversion, particularly within central-western fold-thrust belt areas. Thin-skinned structures formed within both fore-arc and back-arc settings in the proto-North Island. The onset of source rock maturity was enhanced by locally rapid and thick sedimentation, and by higher heat flows associated with extension or volcanism. Reservoir units of Neogene age mainly comprise regressive deep-water to shelf sandstones of variable quality, derived from a variety of older sedimentary rocks and uplifted basement terranes.

The stratigraphic record in New Zealand

New Zealand's sedimentary basins with petroleum prospectivity have formed in Cretaceous to Cenozoic times. Rocks of early Cretaceous age and older are generally considered to be economic basement, although some source and reservoir potential may exist in some basement terranes. The unconformity that separates basement and cover rocks formed through long-lived erosion and peneplanation upon the cessation of early Cretaceous convergent tectonics along the Gondwana margin (Rangitata Orogeny). Oldest strata above basement are mid-Cretaceous, and occur locally in the East Coast, Great South, West Coast, northern Taranaki, and offshore Northland basins.

The composite Cretaceous-Cenozoic succession in New Zealand basins constitutes a broadly transgressive-regressive 'megasequence', that records the gradual submergence and re-emergence of the New Zealand sub-continent over a 100 m.y. period (see King et al. 1999). This megasequence corresponds to a depositional cycle of first-order duration (e.g., Vail et al. 1991; Mitchum & van Wagoner 1991). It has a tectonic origin, ultimately reflecting thermodynamic processes in the asthenosphere, and essentially records generic basin development and fill from initial continental rifting to convergent margin orogenesis (see discussion in King et al. 1999).

The entire succession is simplistically illustrated in Figure 1, together with a schematic relative base level curve that was constructed by assessing areas of emergence and submergence of the New Zealand sub-continent through time (from maps in Figure 2), relative to present-day land areas and shoreline position. The curve approximates changes in available accommodation space, at least for marine deposition, and helps to portray broad depositional patterns and inherent cyclicity that have resulted from the interplay of tectonic, eustatic, and oceanographic processes.

Second-order cycles and paleogeography

Many unconformities punctuate the first-order succession. Several of the more significant of these can be correlated between regions, and form the basis for subdividing the New Zealand-wide succession into subordinate depositional cycles. Unconformity-bound cycles of second order duration (3-50 m.y.) are illustrated in Figure 1.

Except for a broadly regressive trend in the late Neogene, and a transgressive trend in the mid-Cretaceous, the schematic base level curve derived for the Cretaceous-Cenozoic record in New Zealand does not seem to match long-term (first-order) changes in global sea level (Figure 1; after Haq et al. 1987). Some unconformities bounding second-order cycles show an apparent match with base-level shifts on the global curve. However, rather than having a eustatic origin, the New Zealand second-order cycles are considered to reflect local tectonic phases related to syn-rift, passive margin, and active margin evolution (King et al. 1999).

In proximal areas, the unconformity at the base of each cycle represents a period of base-level fall and relative lowstand, and the overlying preserved interval represents the ensuing transgression and relative highstand. The proportion of these depositional tracts varies between cycles; older cycles are broadly transgressive and younger cycles are broadly regressive.

From a petroleum exploration perspective, second-order cycles are important for identifying regional depositional trends and for correlating key facies belts between regions. However, specific source, reservoir, or seal rock intervals generally correspond to stratigraphic units (formations or members) of third-order (0.5-3 m.y.) or fourth order (0.08-0.5 m.y.) cyclicity.

The relationships between tectonic setting and sedimentary style within second-order depositional cycles are discussed below (after King et al. 1999), and illustrated with a series of paleogeographic maps for selected time slices (Figure 2). The tectonic reconstruction template for these maps is explained in King (manuscript submitted). The paleogeographic interpretations are based primarily on the following review volumes: Nathan et al. (1986), Field & Browne et al. (1989), Wood et al. (1989), Turnbull & Uruski et al. (1993), Isaac et al. (1994), King and Thrasher (1996), Field & Uruski et al. (1997), Cook et al. (1999). The maps also draw upon paleogeographic interpretations in Herzer et al. (1997), Matthews et al. (1998), and King et al. (1999).

Cycle 1: mid-Cretaceous

The oldest sediments overlying the basal megasequence boundary include mid-Cretaceous non-marine and marine transgressive deposits (e.g. in East Coast and Marlborough), and terrestrial deposits (e.g. in northern Otago, Great South Basin, Chatham Islands, and West Coast). In western New Zealand, there is a major gap in the sedimentary record from the Ngaterian (Cenomanian) to the end of the Piripauan (lower Campanian). An intra-Piripauan unconformity is regionally extensive in eastern New Zealand. All of the mid-Cretaceous succession above basement and below the end-Piripauan unconformity corresponds to one second-order cycle (Cycle 1, Figure 1).

Early sedimentation was generally within normal fault-controlled grabens associated with Gondwana break-up prior to opening of the Tasman Sea (e.g. Laird 1981, 1993, 1994). The initiation of this extension was around 103 Ma (see review in King et al. 1999).

The early basin-fill successions of Cycle 1 generally comprise coarse-grained clastic rocks, deposited in alluvial fan, meandering river, and braided river environments. Mid-Cretaceous rocks in northeast Taranaki Basin and in the Chatham Islands appear to have been deposited in a marginal marine (estuarine-deltaic) environment, probably with some fault control. Early Cretaceous rocks of the East Coast are largely marine.

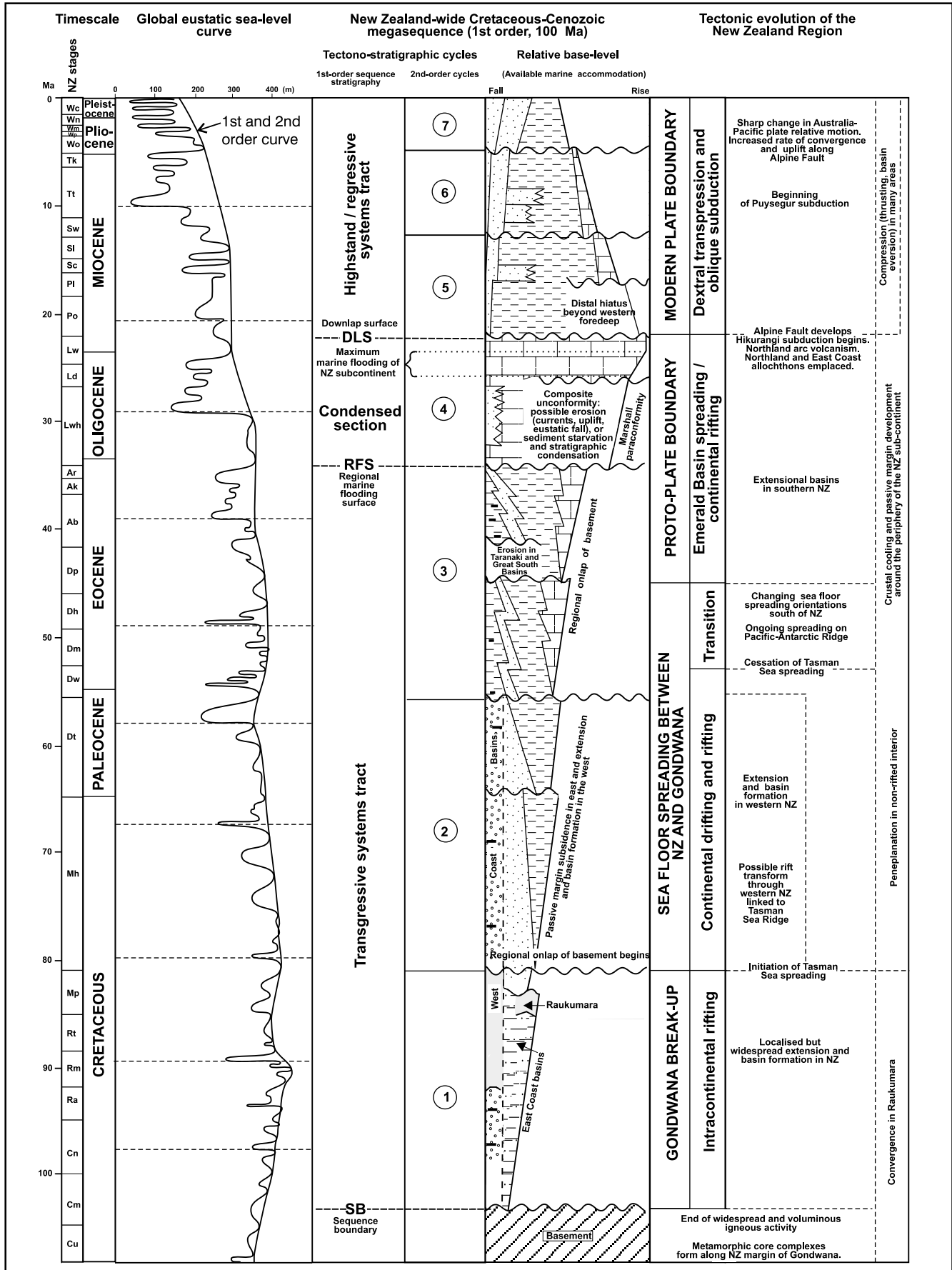


Figure 1: Summary of the Cretaceous-Cenozoic stratigraphic succession in New Zealand, and some factors broadly controlling deposition (simplified after King et al. 1999). Timescale after Crampton et al. (1995) and Morgans et al. (1996); global sea level curve after Haq et al. (1987). A “curve” of changing relative base level for deposition is depicted as the right-hand edge of the graphic lithology column. This curve approximates the trends of regional marine transgression and regression with respect to the proto-New Zealand landmass, as illustrated in Figure 2.

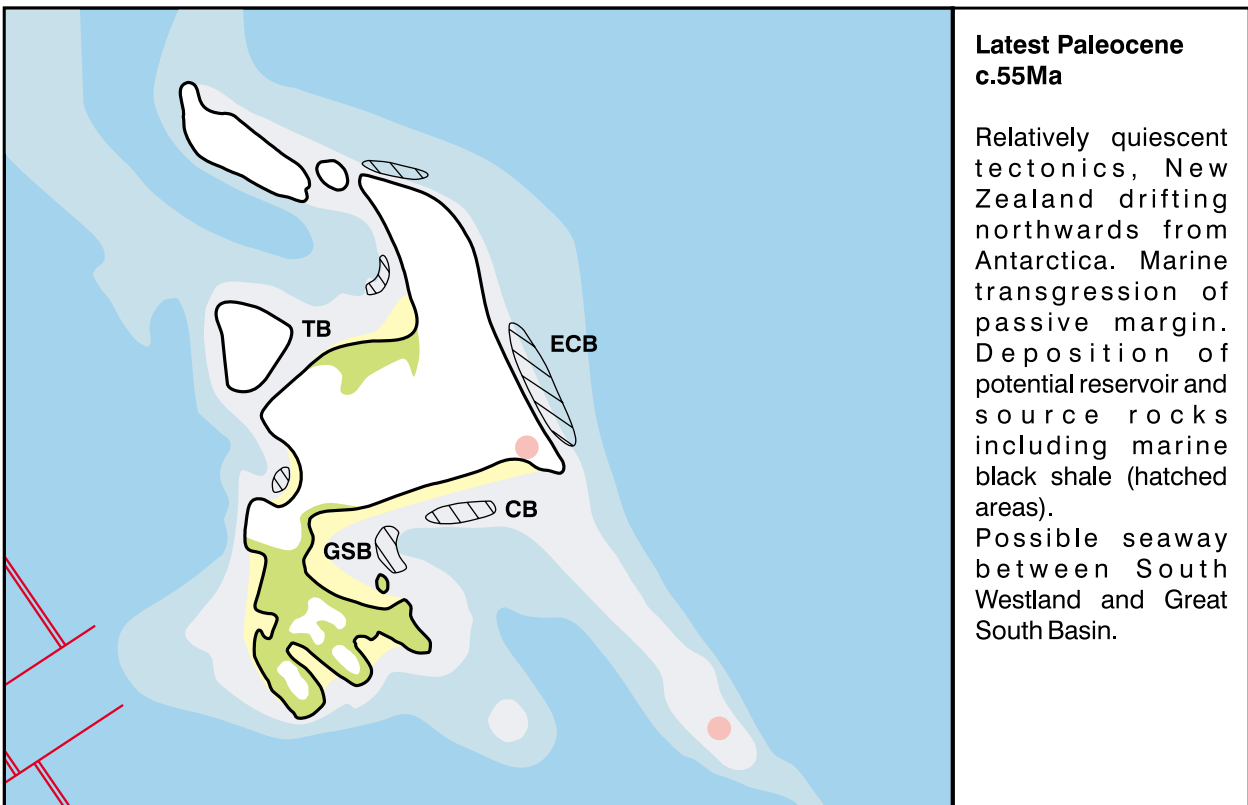
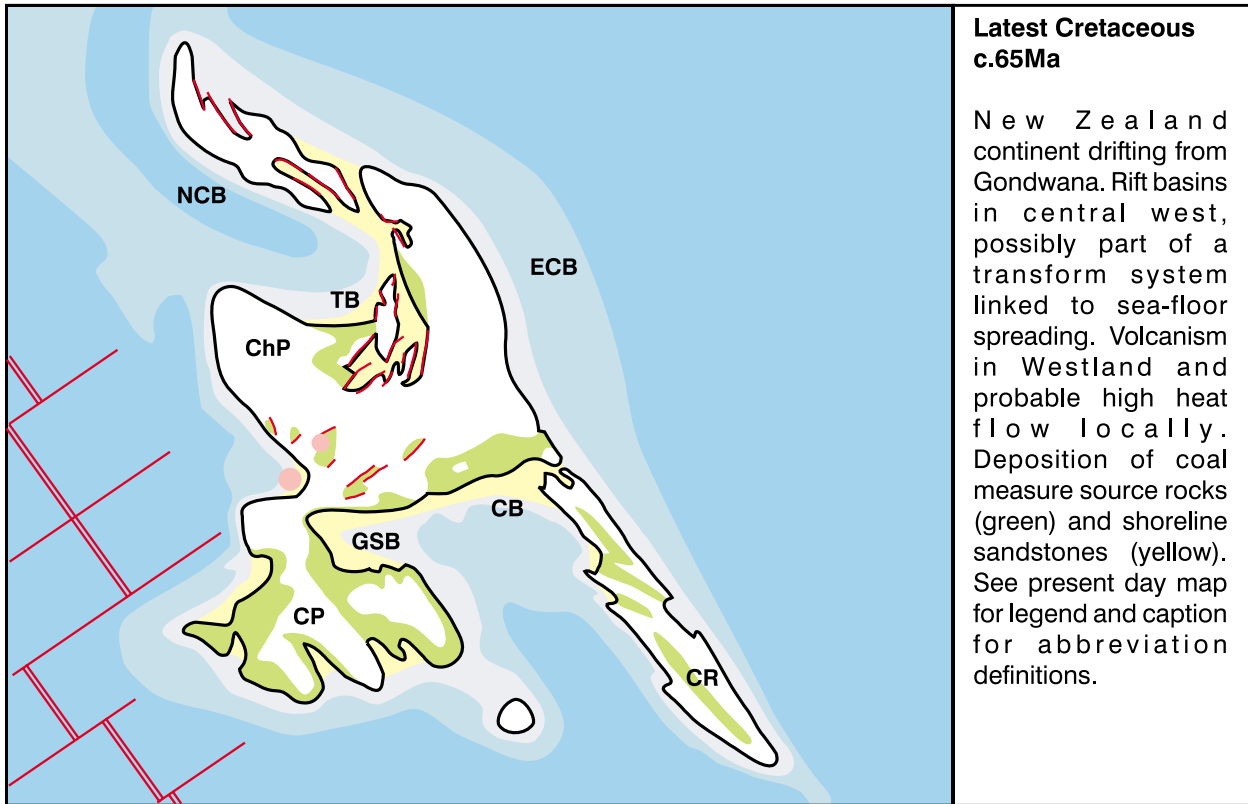
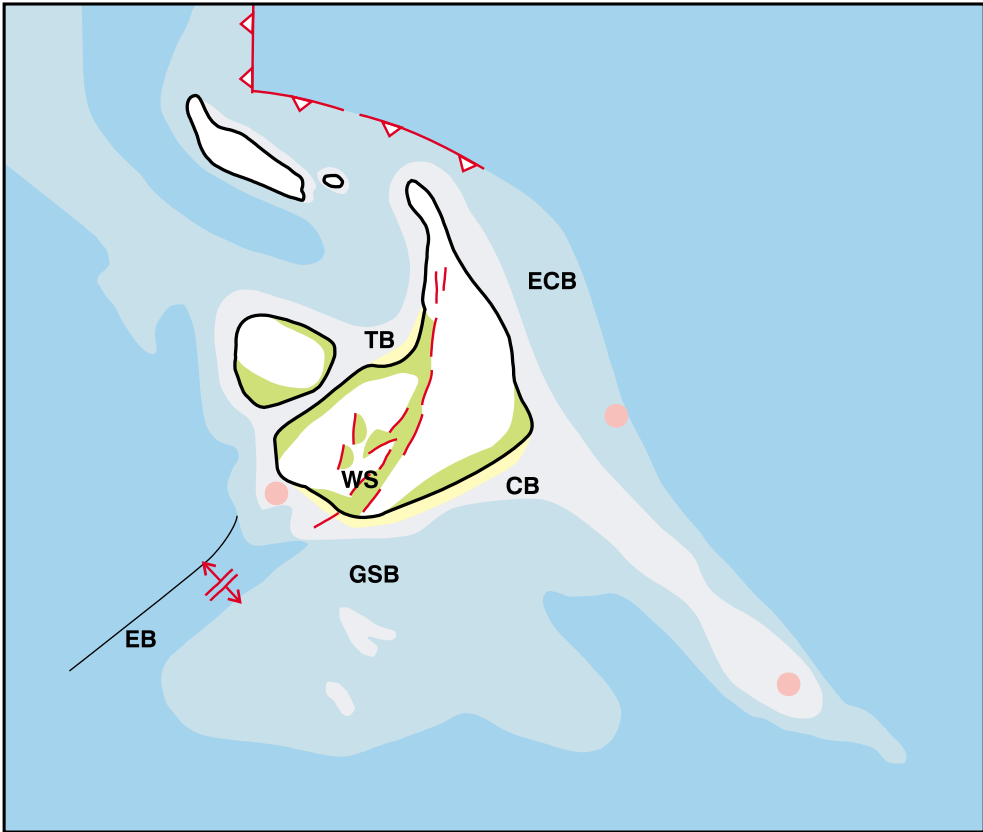
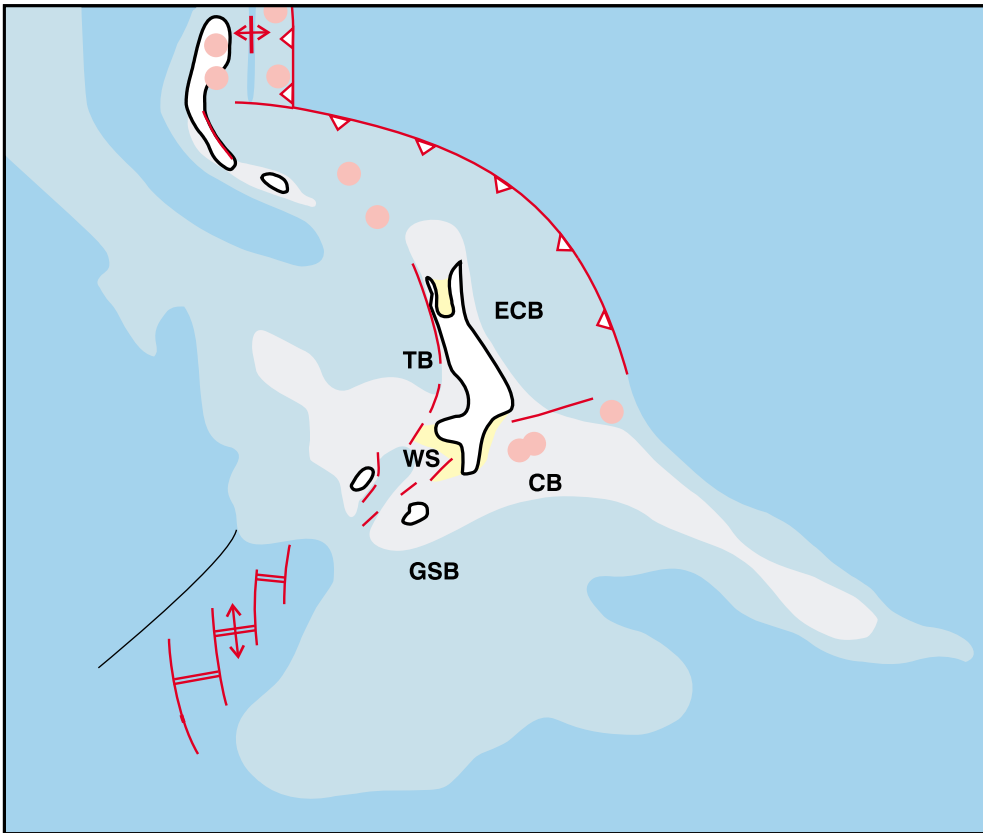


Figure 2: Paleogeographic re-constructions of New Zealand for the latest Cretaceous and Cenozoic. The tectonic template for the maps is described in King (submitted manuscript). Bold line depicts paleo-coastline. Colour coding: white = terrestrial non-deposition; green = terrestrial deposition; yellow = marginal marine sand-dominated facies; pale blue-grey = shelf; mid-blue = slope or submarine rise; dark blue = deep ocean. Basins depicted include: Taranaki (TB), East Coast (ECB), Canterbury (CB), Great South (GSB), and Western Southland (WS). ChP = Challenger Plateau, CP = Campbell Plateau, CR = Chatham Rise; NCB = New Caledonia Basin; NB = Norfolk Basin; PT = Puysegur Trench; EB = Emerald Basin. Faults, subduction zones, and seafloor spreading centres shown in red. Pink circles = active volcanism.



**Middle Eocene
c.40Ma**

Incipient subduction north of New Zealand. Emerald Basin opening south of New Zealand. Rift propagating through western Southland to Taranaki. Likely high flow in south. Challenger Plateau breached by marine seaway. Deposition of potential source and reservoir rocks.



**Late Oligocene
c.25Ma**

Maximum marine inundation of New Zealand subcontinent. Minimal clastic supply. Widespread deposition of carbonates (seal rocks, or potential fractured reservoirs)

Figure 2 continued.

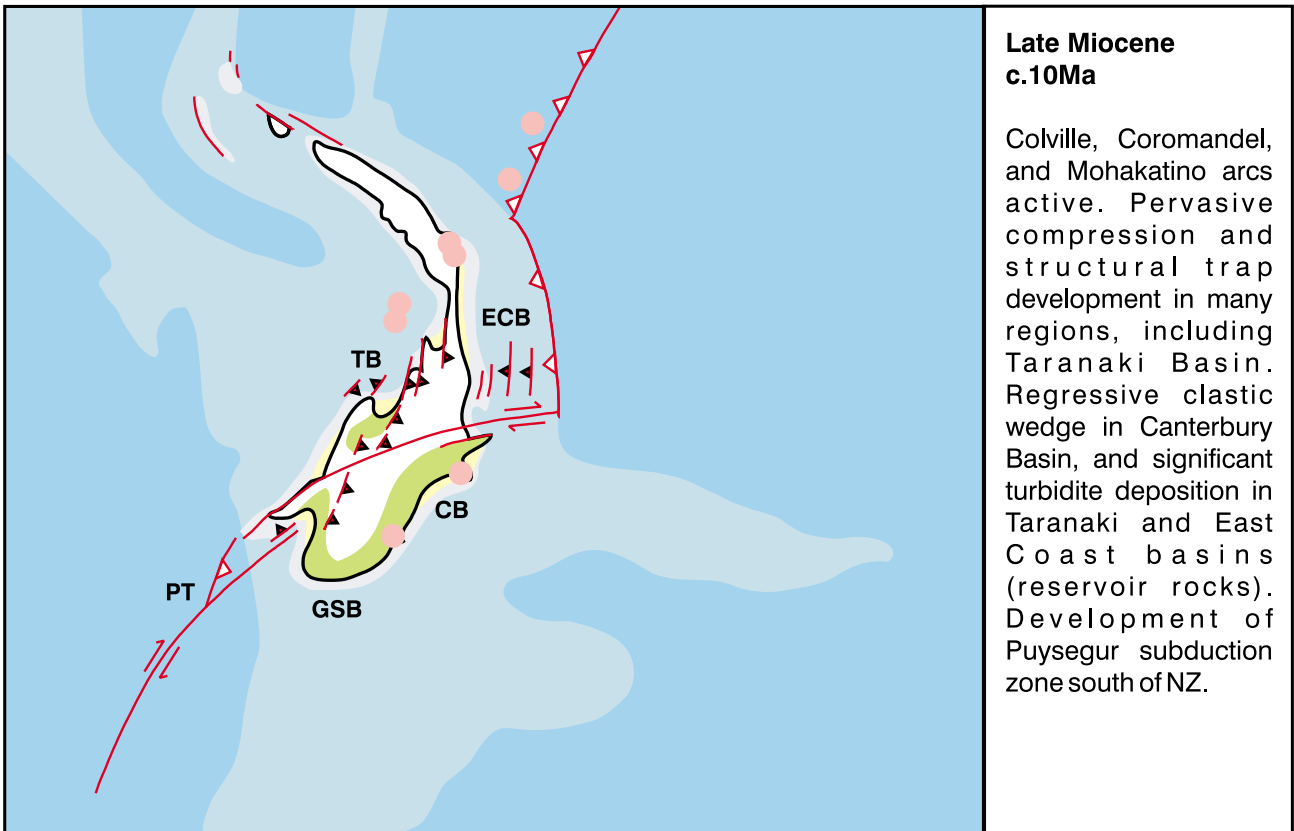
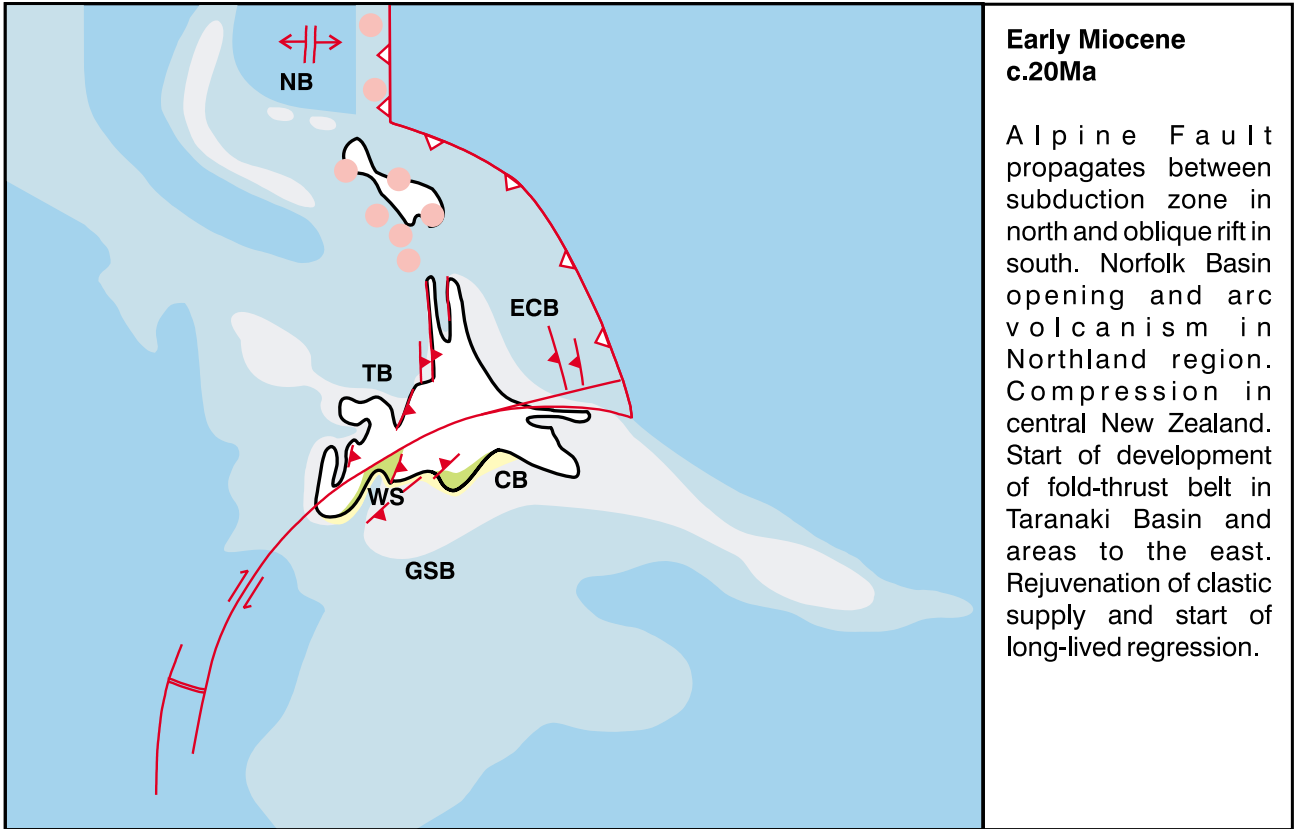
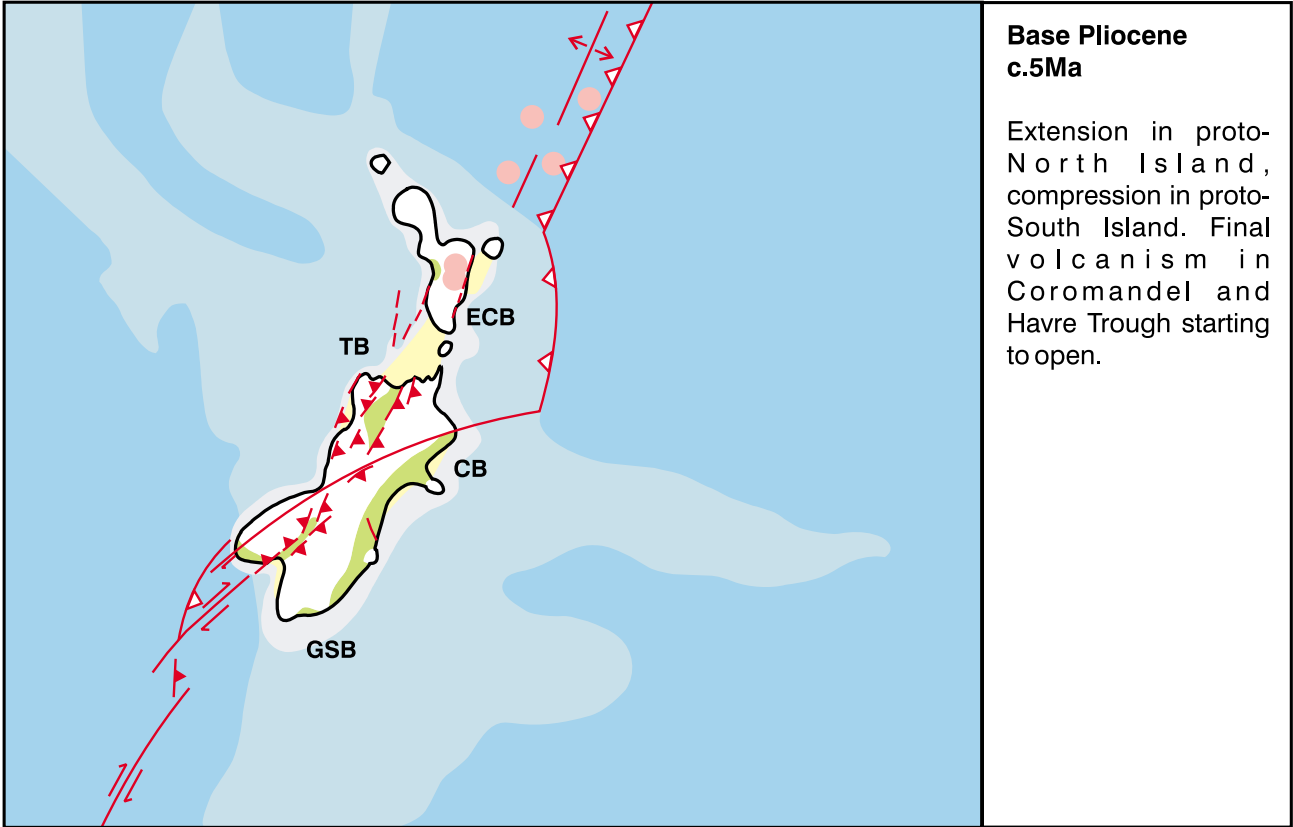
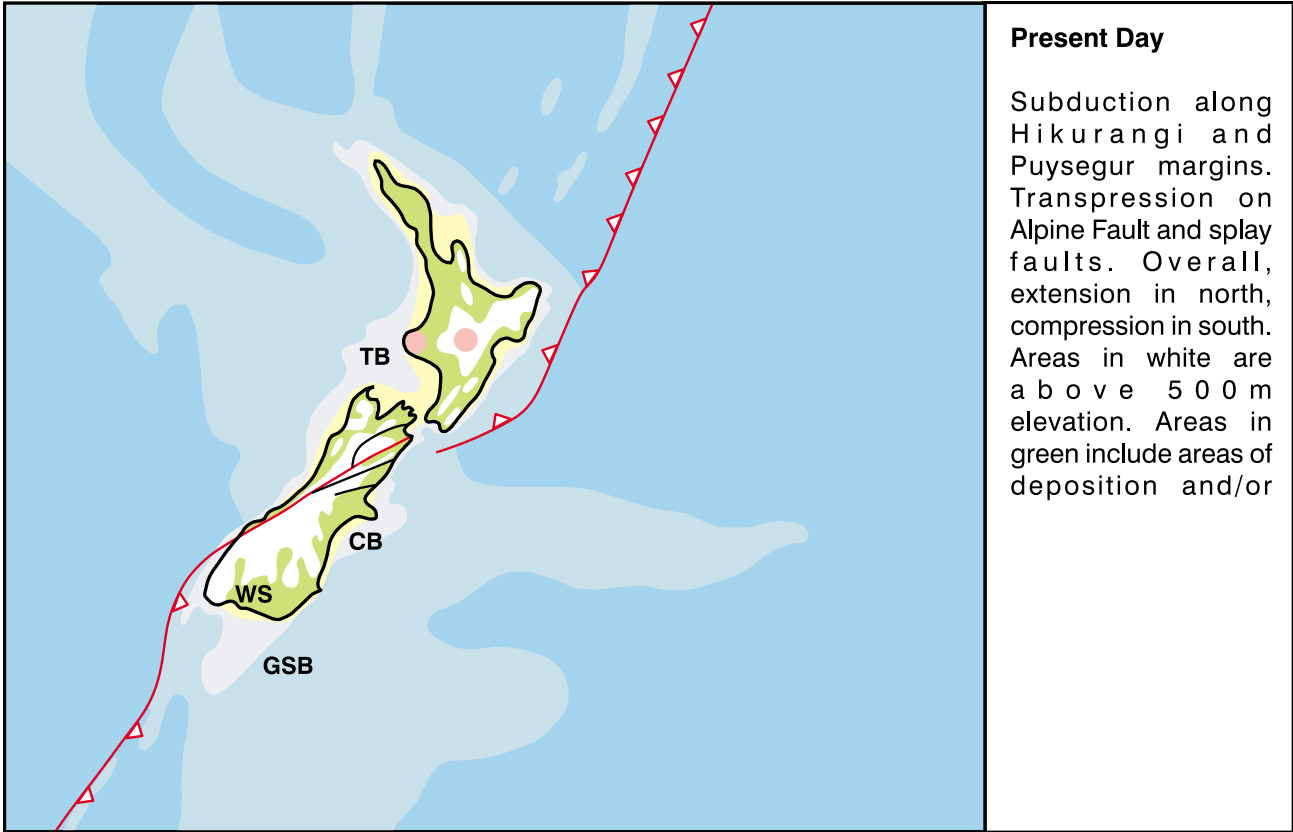


Figure 2 continued.



**Base Pliocene
c.5Ma**

Extension in proto-North Island, compression in proto-South Island. Final volcanism in Coromandel and Havre Trough starting to open.



Present Day

Subduction along Hikurangi and Puysegur margins. Transpression on Alpine Fault and splay faults. Overall, extension in north, compression in south. Areas in white are above 500 m elevation. Areas in green include areas of deposition and/or

Figure 2 continued.

Cycle 2: Late Cretaceous to Paleocene

Cycle 2 was deposited during the Haumurian (upper Campanian-Maastrichtian; Late Cretaceous) to Paleocene, contemporaneous with Tasman Sea spreading. By the Late Cretaceous extensional basins were confined to western New Zealand (Figure 2, 65 Ma). These basins probably formed part of a rift transform zone linked to the Tasman spreading centre (e.g. Laird 1981, Thrasher 1990, Laird 1994).

Although there were significant areas of exposed basement and an active rift topography in the west, marine transgression of coastal plains had also started. In fact in many areas this cycle equates with regional marine transgression across basement, related to passive margin subsidence around the drifting New Zealand sub-continent. The first major marine transgression occurred in eastern New Zealand at about 80 Ma, and in western New Zealand significant marine flooding only began in the latest Cretaceous (e.g. c. 67-65 Ma in Taranaki Basin).

Cycle 2 rocks in the western basins mainly comprise terrestrial to shallow-marine facies. Areas between the rifted western sub-basins were eroded and peneplaned. In eastern basins, coeval sediments were deposited primarily in coastal plain and transgressive shallow marine to bathyal sedimentary environments. On the East Coast, sediments of this age are typically marine sandstones, flysch and shales.

By early-mid Paleocene times, only a few rift transform sub-basins remained in Westland and southern Taranaki. Elsewhere passive margin deposition prevailed. The top of Cycle 2 corresponds to the end of Tasman Sea-related extension in western New Zealand (Figure 2, 55 Ma). At the end of rifting, localised uplift and erosion became less marked, and a widespread regional unconformity developed in the west due either to protracted subaerial peneplanation, very broad doming and erosion, and/or the amalgamation of successive episodes of marine planation. In some places the post-rift unconformity was long lived, with sedimentation not beginning again until near the end of the Eocene.

By the end of the Paleocene a post-rift passive margin had developed around the sub-continent (Figure 2, 55 Ma). The entire region was tectonically quiescent, and had started to founder. Broad marine embayments with wide shelf areas are notable in the Canterbury and Taranaki basins, at the landward ends of the Bounty Trough and New Caledonia Basin respectively. About this time there was also a change in marine environments around the paleo-margin of New Zealand, particularly in the east, resulting in deposition of the Waipawa Formation black shale and its lateral equivalents (e.g. Killips et al. 1996). This formation is significant for its source rock potential.

Cycle 3: Eocene

Upon cessation of Tasman spreading at about 52 Ma (Gaina et al. 1998), the New Zealand sub-continent continued to drift away from Antarctica during the Early to early-Middle Eocene, and was remote from any plate boundary (Stock & Molnar 1982 & 1987, Kamp 1986a & 1986b, Sutherland

1995). During this period of comparative tectonic quiescence, basin development was characterised by regional post-rift rift crustal cooling and passive continental margin subsidence (e.g. Ballance 1993).

Cycle 3 equates with this passive margin phase in most areas. The stratigraphic architecture of Cycle 3 is exemplified by the progressive onlap of marginal-marine and shelf facies across coastal plain regions. Some areas, such as southern Taranaki, northern West Coast, Wanganui/Waikato, and interior Northland, persisted as areas of emergent basement. Other areas, such as parts of Western Southland and West Coast, reverted to non-deposition once Cretaceous-Paleocene rift subsidence had ceased. Elsewhere, steady marine transgression continued across former rift depocentres and intervening basement areas. In south Westland, and distal parts of the Great South Basin, marine clastic sedimentation was supplanted by carbonate-dominated sedimentation, whereas in Marlborough carbonate deposition was already prevalent.

An intra-cycle (intra-Porangan) unconformity is identified in Taranaki Basin, Great South Basin, and onshore Otago, and corresponds to a basinward facies shift (lowering of base level). Conversely, a rise in base level is apparent in other parts of the West Coast, and Western Southland, where sedimentation resumed across former peneplain areas.

The changes in sedimentation style relate to the onset of seafloor spreading and oblique extension within the Emerald Basin south of New Zealand, which impinged upon southern and western parts of New Zealand (Figure 2, 40 Ma).

This new extensional tectonic regime (Moonlight Tectonic Zone or Moonlight Aulocogen; Norris et al. 1978) marked the initial stage in the development of an Australian-Pacific plate boundary in the New Zealand region (e.g. Carter & Norris 1976, Kamp 1986a, Sutherland 1995, Lamarche et al. 1997, Wood et al. 1996). Away from the propagating continental rift zone in southwestern New Zealand, a subdued topography, broad coastal plain areas, and a gently subsiding passive continental margin continued to exist. In the far north, a subduction zone is inferred to have been propagating southwards from the New Caledonia region.

Cycle 4: Oligocene to earliest Miocene

Cycle 4 spans the Oligocene to earliest Miocene, and corresponds to the period of maximum submergence of the proto-New Zealand landmass (Figure 2, 25 Ma). Cycle 4 consists primarily of carbonate rocks, deposited on extensive shallow marine platforms, and in deep water. The cycle contains numerous unconformities, the origins of which remain enigmatic (see Carter 1985, Carter and Landis 1982, Fulthorpe et al. 1996). Some of the unconformities may be erosional, created either by deep-sea currents that formed as the circum-Antarctic current evolved, local uplift (and in places karstification), or sea-level fall. Others may have entailed non-deposition and sediment starvation, which could have resulted from dwindling clastic supply as land areas were flooded by the sea, or in the case of distal Taranaki

Basin, by the capture of sediment in an adjacent, rapidly subsiding proximal foredeep trough (King and Thrasher 1996).

The base of Cycle 4 corresponds to the regional flooding surface (RFS) of the first-order megacycle (Figure 1). Well-developed greensands are often present at this stratigraphic level, indicating a considerable reduction or starvation of clastic supply caused by the relatively sudden regional marine transgression. This surface generally coincides with the Eocene-Oligocene boundary. However, in eastern areas such as Great South Basin, northern Canterbury Basin and Marlborough, the transition from clastic-dominated to carbonate-dominated sedimentation began much earlier, in keeping with the generally earlier onset of marine transgression in those areas. In Marlborough a very thick carbonate interval is present. In most other areas however, the carbonate-dominated interval is generally very thin compared with clastic successions above and below, even though it spans at least 10 m.y. duration.

Regional crustal foundering and marine inundation in the Oligocene is commonly considered to represent the culmination of passive margin development. However, by Oligocene times parts of the New Zealand sub-continent were no longer tectonically quiescent, and slow regional subsidence was being overprinted by local tectonism associated with initial development of the Australia-Pacific plate boundary. This tectonic activity probably accounts for some of the diverse unconformities present within this second-order cycle. In Western Southland and probably the West Coast region, local basin subsidence was controlled by an increasingly oblique extensional regime (Moonlight Aulocogen). At the same time, Pacific Plate subduction had become established to the northeast of New Zealand (Ballance 1976, Isaac et al. 1994, Herzer 1995). Rapid Oligocene subsidence in Taranaki Basin could reflect development of the Moonlight Tectonic Zone to the south, or incipient subduction of the Pacific Plate to the east (see King, submitted manuscript).

Cycle 5: Early Miocene

In the earliest Miocene the Alpine Fault evolved as a link between west-dipping Hikurangi subduction in the northeast, and Emerald Basin spreading and oblique extension in the southwest (Figure 2, 20 Ma). The Alpine Fault became the primary focus of dextral dislocation between the Pacific and Australian plates in the New Zealand region. Relative motion across this plate boundary increased in rate and became increasingly convergent throughout the Neogene (Walcott 1978, 1987).

Cycle 5 is the oldest of three second-order cycles recognised within the Neogene regressive portion of the Cretaceous-Cenozoic succession. Its base is marked by the first influx of primarily terrigenous sediments upon the carbonate-dominated sediments of Cycle 4. This lithologic boundary corresponds to the downlap surface (DLS) of the first-order megacycle (Figure 1). It marks the onset of uplift and erosion of clastic source areas coincident with the inception of the convergent plate boundary through New Zealand. Although

this lithologic change is fairly abrupt, its age is generally only poorly defined, as within the Waitakian to Otaian.

In most areas the basal portion of Cycle 5 is fine-grained, although sandstones were deposited around the fringes of rising land areas in Western Southland and Canterbury. In addition, alternating sandstone and siltstone or flysch-like sequences were deposited in the Murchison Basin, western Moutere Depression, and Wairarapa. The first minor pulses of deep-water sandstone deposition began in eastern Taranaki and the East Coast (Hawke's Bay and Wairarapa).

Cycle 6: Middle-Late Miocene

The base of Cycle 6 is marked by an unconformity at approximately the Lillburnian-Waiuan boundary, which marks a major transition in tectono-sedimentary patterns, particularly in western New Zealand. This transition probably relates to a change in plate boundary configuration, which in turn is indicated by a significant change in volcanic style and orientation in the North Island (Kear 1994, Herzer 1995), and by the initiation of subduction along the Puysegur Trench (Figure 2, 10 Ma). Some of the depositional outcomes of this event include: a change to terrestrial sedimentation in the Te Anau Basin, local inversion and erosion on the West Coast; non-deposition in Marlborough; final reverse faulting on the Taranaki Basin northeastern margin, followed immediately by submarine andesitic volcanism and associated sedimentation. There is no significant event recorded at the Lillburnian-Waiuan boundary on the East Coast, although a major intra-Waiuan event is present (Field & Uruski et al. 1997).

Cycle 6 comprises generally coarser-grained deposits than Cycle 5, but is otherwise comparable. Most basins remained primarily marine, and turbidite deposition became significant in Taranaki and the East Coast. The most distal deposition was in the Great South Basin, although this was tempered by a phase of gentle deformation in the basin's northwest corner. Some areas, such as Marlborough, accumulated thick bathyal successions.

Cycle 7: Plio-Pleistocene

Cycle 7 spans the Pliocene to Recent; its base is marked by a significant unconformity. The cycle contains a considerable volume of coarse clastic sediments, and is overall strongly regressive. These characteristic depositional signatures reflect an increased tempo of convergent margin uplift, erosion, and outpouring of clastic sediments into most New Zealand basins during the Plio-Pleistocene. Rotation of the Hikurangi margin resulted in a southwards shift in the focus of compression in western basins, and the initiation of extensional basins further north, as well as southward migration and re-orientation of active arc volcanism. Gradually, increasing dextral convergence 'squeezed' the proto-New Zealand landmass into an elongate belt parallel to the plate boundary, with a concomitant increase in rates of uplift, erosion, and supply of clastics to neighbouring basins (Figure 2, 5 Ma).

Cycle 7 is commonly severely disrupted or in places completely absent as a result of intra-basinal uplift, erosion,

and/or non-deposition. In areas such as Taranaki and present-day offshore Canterbury there was substantial outbuilding of the continental slope margin and dramatic expansion of shelf areas. This progradation was significantly enhanced during periods of glacio-eustatic falls. In some areas, particularly adjacent to the rising Southern Alps (e.g. Moutere Depression, Canterbury), thick, coarse-grained fluvial sediments were deposited extensively.

Relationships between tectono-stratigraphic history and evolution of petroleum systems

Hydrocarbon generation and accumulation within sedimentary basins relies on the timely occurrence of several geological and thermal history conditions. The critical parameters in any petroleum system include: adequate source, reservoir, and seal rocks, trap development, burial and heating of source kitchens, and migration of hydrocarbons into traps. The relationships between paleogeographic evolution of the New Zealand sub-continent and the broad evolution of petroleum systems is summarised below, and in Figures 1 and 3. The discussion deals only with broad tectonic events and depositional facies trends within the second-order tectono-stratigraphic development of New Zealand's Cretaceous-Cenozoic sedimentary basins (Figure 1). It also only deals with a hypothetical petroleum system nationwide, that is a composite derived from individual basins, and which shows the cumulative potential age span of each generic petroleum system element (Figure 3).

Oil and gas finds

Oil and gas have been discovered in reservoirs of widely varying age in New Zealand (Figure 3). However, commercial production has so far only been established in Taranaki Basin, from reservoirs of Paleocene age or younger. Outside of Taranaki, hydrocarbons have been recorded in older (i.e. Cretaceous) reservoir units, as sub-commercial discoveries (offshore Great South Basin and Canterbury), shows during drilling, or as surface seeps. Other productive intervals of note include Late Eocene lacustrine oil shales in western Southland, and Miocene turbidites in East Coast.

Reservoir Rocks

Most known petroleum reserves are reservoirised in Paleogene shoreline and coastal plain sandstones (Cycles 2-3), in Taranaki Basin. These sands were deposited in a late rift or post-rift passive margin setting. All younger reservoir rocks were deposited contemporaneously with the development of the convergent plate boundary through New Zealand. They reflect an increased tectonic tempo and general outpouring of coarse clastics from rising land areas. In Taranaki, they include a variety of lithofacies: Oligocene foredeep turbidites, earliest Miocene foredeep limestones that have been fractured by overthrusting, Miocene slope and basin-floor fan sandstones, Miocene volcanoclastics associated with submarine volcanoes, and Pliocene shelf sandstones.

A similarly broad range of facies variants with reservoir rock potential is present within the Cretaceous-Cenozoic succession elsewhere in New Zealand. Some compelling reservoir fairway targets include: Cretaceous-Paleogene, passive margin, coastal plain and shoreline sand tracts in Great South Basin, Canterbury, and possibly offshore Northland; Eocene syn-rift, coarse-grained, terrestrial and shallow marine units in western Southland and West Coast; and Miocene active margin, sand-rich, bathyal turbidites and shelf deposits in East Coast and western Southland.

Seal rocks

Fine-grained clastic rocks (mainly marine) were commonly deposited during passive margin transgression (Cycles 2 and 3), and convergent margin regression (Cycles 5-7). In the earlier cycles, coarse-clastic supply to basins was progressively reduced as base level rose and fine-grained clastic sediments were extensively deposited, particularly in shelf and deeper marine environments. These rocks are, or have the potential to be, effective regional seals for trapping hydrocarbons. The onlapping stratal relationships also provide considerable scope for stratigraphic trapping plays. In Taranaki Basin, shelf mudstones act as cap rocks and as intra-reservoir seals to several marginal marine-terrestrial sandstone reservoirs.

Mudstones deposited during the Neogene (Cycles 5-7) represent the eroded and often re-cycled products of older rocks uplifted due to plate boundary-related tectonism. These fine-grained rocks are particularly voluminous in many areas. In these younger cycles however, fine-grained rocks may not be sufficiently compacted to act as suitable seals.

Between the long-lived periods of clastic mudstone deposition, fine-grained carbonate-rich rocks (micritic limestones and calcareous mudstones) were widely deposited, largely coincident with the phase of maximum marine transgression (Cycle 4). The sealing potential of these limestones is illustrated in Taranaki Basin, where upper parts of the Eocene succession are over-pressured beneath regional Oligocene carbonates.

Source rocks

The oldest potential source rocks are late-Early Cretaceous coarse-grained clastic rocks of variable carbonaceous content. These units are largely non-marine, and were deposited in fault-angle depressions and sub-basins that formed during Gondwana break-up, mainly in the Canterbury and Great South Basin regions. Oil shows have been recorded in strata of this age in the Great South Basin. Early Cretaceous rocks of the East Coast are largely marine, but sometimes contain re-worked carbonaceous detritus.

The most significant source rock intervals occur mainly within Cretaceous to Eocene syn-rift and passive margin terrestrial and marginal marine coal measure sequences of Cycles 2 and 3. These source rock lithologies are present in all Cretaceous-Eocene basins in New Zealand except perhaps

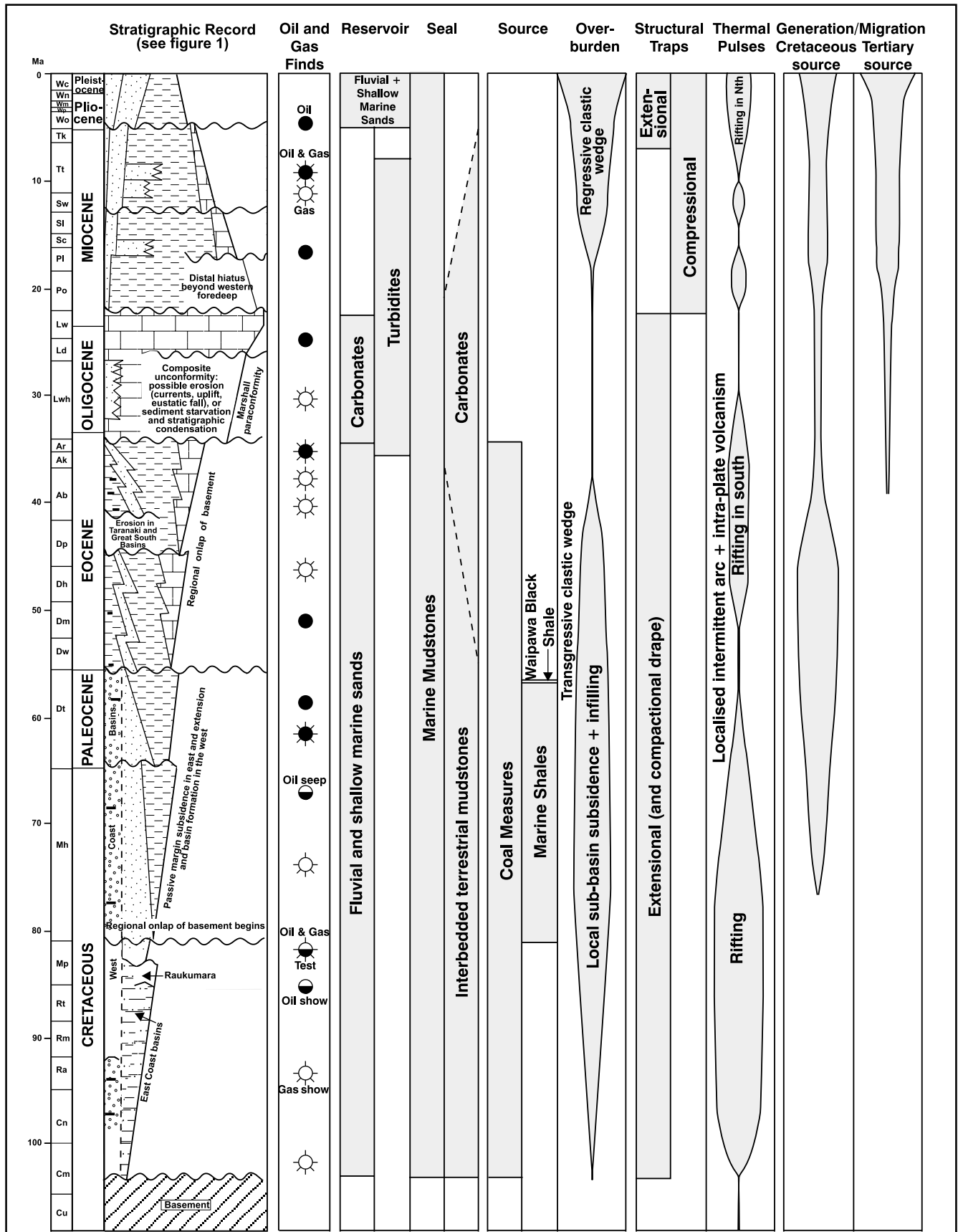


Figure 3: Summary petroleum systems diagram for New Zealand Cretaceous-Tertiary sedimentary basins. Oil and gas finds in Paleocene and younger reservoirs relate mainly to Taranaki Basin. The time spans of the constituent petroleum system elements are cumulative, and reflect a range of scenarios within individual basins. Because of this complexity, a critical moment for hydrocarbon charge is not depicted.

the East Coast, where sediments of this age are typically deeper-water flysch and shales, and in general are not considered to be important source rocks (Field & Uruski et al. 1997). The most promising regions of primarily terrestrial source rock distribution are illustrated in Figure 2.

Younger strata with high organic contents may have source potential, but have generally not been sufficiently buried to generate hydrocarbons, or have since been uplifted above the oil generation window.

A distinctive marine black shale interval (Waipawa Formation) has significant source potential in the East Coast and Great South basins, and elsewhere (Figure 2, 55 Ma; after Killops et al. 1996). It typically comprises dark, non-calcareous, micaceous siltstone deposited within dysaerobic outer shelf to upper slope depositional environments (Killops et al. 1996, 1997, 2000, Field & Uruski et al. 1997). The paleo-environmental significance of the black shale is enigmatic, but its deposition may be related to changing oceanic circulation patterns during the latest Paleocene (Killops et al. 1996).

All Taranaki oils exhibit geochemical evidence of a contribution from marine source rocks (Killops et al. 1994). These source rocks were presumably shales deposited periodically across coastal plain areas during regional post-rift transgression.

Structural traps

All of the commercial discoveries made in the Taranaki Basin involve structural traps that formed during the Neogene, in various phases of deformation related to convergent plate boundary development. The main trap styles include inverted anticlines (e.g. Kapuni, Kupe fields), and thin-skinned thrusts (e.g. McKee Field). The giant Maui Field structure formed through a combination of reverse faulting and doming, followed by normal faulting along one flank, which exaggerated the elevation of the structure relative to adjacent potential kitchen areas. Fields such as Kaimiro also have a hybrid trapping mechanism, involving compression followed by extension. Volcanic edifices formed the structure of the Kora discovery offshore, and probably form part of the trapping mechanism in the onshore Moturoa Field.

In the Great South and Canterbury basins, early rift structures are prominent, as are compactional drape features above fault block highs. Similar traps are evident in western Southland, and are related to both Cretaceous and mid-late Eocene extensional phases in that region. The majority of potential trapping structures in the East Coast and West Coast basins were formed by convergent tectonics in the Neogene. Neogene compressional structures are also evident in northwestern Great South Basin, northern Canterbury Basin, and in western Southland.

Because of the complex structural evolution of most New Zealand basins, depositional facies distributions also tend to be highly complex. As such, a myriad of potential

stratigraphic plays is conceivable. Just two examples include: pinch-out of transgressive shoreline sandstones onto basement (and capped by transgressive or highstand mudstones), and pinch-out of deep-water turbidites onto seabed anticlines.

Overburden, thermal regime, and maturation

There are several New Zealand basins in which potential source rock areas are overlain by thick sedimentary sections, such that active generative kitchen areas are likely to have developed. In general, the thick, rapidly deposited regressive successions of Cycles 5-7 are the most important overburden units for maturation of source rocks. Thick successions accumulated in areas where tectonic subsidence of sub-basins associated with plate boundary evolution was matched by a substantial influx of eroded clastic detritus, or where a regressive clastic wedge developed across a gently subsiding passive margin.

There are several periods and tectonic episodes in which heat flow at the base of the sedimentary succession may have been increased, thereby accelerating source rock maturation. The first of these episodes involves crustal thinning and extension associated with Gondwana break-up. Similar processes probably occurred as the Emerald Basin opened south of New Zealand in the late Paleogene, although any increase in basal heat flow may have been restricted to basins in the southwest. Crustal extension in northern New Zealand in the last 5-10 m.y. has also led to locally increased heat flows (e.g. Armstrong et al. 1996). Volcanism was associated with all of these extensional episodes. In addition, a series of volcanic arcs have erupted in the north throughout the Neogene. Intra-plate volcanism has occurred sporadically throughout the Cenozoic. The volcanism may only have had a localised effect on basin heat flows (e.g. Stagpoole and Funnell in press).

The Cretaceous to Paleogene-aged source rocks have generally only achieved sufficient maturity for oil generation and expulsion following accelerated burial in the Neogene. However, in some areas with high rates of Cretaceous syn-rift basin subsidence and sediment infilling, as well as high heat flow, burial of source rocks may have been sufficient for oil generation to have started by the end of the Cretaceous (e.g. in Taranaki, East Coast), or perhaps earlier (Great South Basin; see Funnell and Allis 1996, King et al. 1998, their figure 5). Eocene source rocks have primarily reached maturity in the Neogene.

Concluding remarks

Depositional trends in most New Zealand basins are broadly similar. In the broadest sense the overall sedimentary succession is transgressive from late Cretaceous to Oligocene times, and regressive during the Neogene. Subordinate transgressive and regressive cycles are also recognisable. The similarity of facies architecture between basins suggests that certain regional factors were controlling depositional style across large areas of the New Zealand sub-continent at any one time. In general, sedimentation patterns reflect the crustal

response to significant plate tectonic events in the southwest Pacific region. Because of the relatively poor correspondence between global sea level oscillations and marine onlap/offlap trends in New Zealand, eustatic controls on depositional architecture are considered to be subordinate to tectonic influences.

There is a correlation between tectono-stratigraphic evolution and petroleum systems evolution in New Zealand basins. The pre-eminent petroleum source rocks are coals and carbonaceous mudstones, deposited in the late Cretaceous and Paleogene. Thick coal measure intervals accumulated, both within rapidly subsiding rift sub-basins, and on low-lying coastal plains. Peat swamp development was enhanced by progressively rising base level as the post-rift continental margin subsided. At the same time, because extensive land areas still persisted, a considerable volume of coarse clastic detritus was also available for deposition. Most of the coarse clastics that were transported into the sea were deposited close to the shoreline, due to the "bulldozing" effect of ongoing marine transgression. These shoreline sand tracts are laterally extensive and form attractive reservoir play fairways in many basins. Turbidite facies are a comparatively minor component of the Late Cretaceous-Paleogene succession, except in the Marlborough and East Coast areas. Conversely, they form a significant part of Neogene regressive depositional systems, and in some areas are the most highly prospective reservoir intervals within those successions.

There has been considerable tectonic deformation in New Zealand since the late Eocene, due to development of the Australia-Pacific plate boundary through the region. Structural styles are varied, and patterns of late Cenozoic faulting, uplift, and subsidence within individual basins are complex. A legacy of this is that patterns of sedimentation, erosion, and re-working are similarly complex. In addition, heat flow within basins has varied according to the degree of lithospheric thickening or stretching, and volcanism, and in response to denudation and burial. These factors have affected the timing and amount of source rock maturation. The net result is that a large number of trapping and hydrocarbon charge scenarios are conceivable within New Zealand's basins. The widely varying size and reservoir age of known petroleum accumulations are entirely consistent with the known geologic complexity of these basins. Because of this complexity, future discoveries can be expected in a variety of play types, with varying reserve sizes. The discovery of one or more very large fields remains a distinct possibility.

Acknowledgements

This review paper draws upon the accumulated contributions of several researchers at GNS over recent years, including: G. Browne, B. Field, R. Funnell, R. Herzer, S. Killips, T. Naish, V. Stagpoole, R. Sutherland, R. Sykes, R. Wood, H. Zhu. G. Cutress and S. Shaw are thanked for drafting the figures. D. Darby, R. Sutherland, and S. Duggan reviewed the manuscript. This paper was funded by the Foundation for Research, Science and Technology, contract C05806.

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