Basin and petroleum systems analysis of the West Coast region, South Island, New Zealand

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Abstract

The West Coast region of New Zealand's South Island is situated at the eastern edge of the Australian plate where it is being overthrust and dextrally offset against the Pacific plate along the Alpine Fault. This region includes a number of Cretaceous-Cenozoic basins that have high prospectivity for petroleum.

Onshore basement terranes narrow southwards as a result of increasing shortening approaching the Alpine Fault. The Median Batholith separates (and includes) equivalents of the mid-Paleozoic Lachlan and New England fold belts to the southwest, from a succession of accreted Permian-Early Cretaceous oceanic arc and sedimentary marginal terranes to the northeast. A belt of formerly-thick crust emplaced at130–105 Ma, forms the inboard belt of the Median Batholith.

Middle Cretaceous intraplate extension began immediately after the climax of convergent margin arc-related crustal thickening (105 Ma), as a precursor to the Tasman Sea opening which ensued at about 83 Ma. Coarse terrestrial (including lacustrine) facies (Pororari Group) are mapped in outcrop and in seismic data, in NW–SE oriented depocentres up to 15 km wide. Latest Cretaceous to Paleocene extensional systems (Paparoa Trough, Pakawau Graben) are oriented normal to the Pororari trend. This transtensional system, which contains the most important source rocks for oil and gas in Taranaki Basin, was active concurrent with Tasman Sea opening, and probably relates to the propagation of an associated oceanic transform feature.

Late Eocene - Oligocene extensional depocentres are widespread on land, within the rejuvenated Paparoa Trough and in new basins such as the Murchison Basin. Late Eocene terrestrial systems containing coal measures are succeeded by bathyal, variably calcareous Oligocene strata. Long-lived paleo-highs are capped by platform carbonates. This complex mid-Cenozoic basin system reflects a zone of diffuse deformation connecting a new sea-floor spreading centre to the south of New Zealand (Emerald Basin) with a new or rejuvenated subduction boundary to the north.

Near the end of the Oligocene, a significant change in relative plate motion resulted in dextral offset that was manifest at least in part as compression within the West Coast region. Much of the shortening was accommodated by overthrusting and compressional inversion of high-angle normal faults in what is now the eastern margin of the basin system. The Miocene basin elements, (eg Murchison, Grey Valley) were in essence flexural foredeep basins during this compressional episode, and burial associated with their deposition induced an oil and gas charge from Cretaceous and Eocene source rocks. An originally very large oil reservoir is indicated by seepages associated with the Kotuku Anticline in the Grey Valley, which together with the Blackwater structure in the Murchison Basin has had oil tested from Miocene submarine fan sands.

Late Miocene to present day deformation of the region has been dominated by the Alpine Fault, which exhibits both right-lateral and transpressive reverse offsets. The accommodation of a major bend in the system has resulted in some complex structure within the northern part of the West Coast Basin system, including a zone of distributed deformation extending to just beyond the coast.

The complex and temporally variable nature of West Coast Basin evolution has given rise to a wide range of stratigraphic habitats, allowing for a wide range of possible petroleum systems.

Keywords: West Coast New Zealand basins, basement influence on sedimentation, Cretaceous extension, Neogene transpressional regime, petroleum systems, petroleum prospectivity.

Introduction

The West Coast Basin region of the South Island of New Zealand occupies the eastern edge of the Australian plate. The region is bounded to the east by the NE-trending Alpine Fault and the N-trending Waimea-Flaxmore Fault System, and is essentially continuous into the southern part of the Taranaki Basin. Extensive Cretaceous and Cenozoic sedimentary deposits in the region record many of the same tectonic-driven features of Taranaki Basin, and the petroleum potential of a number of sub-regions is suggested from surface oil and gas seeps, and from promising, but not yet commercially successful, exploration results.

The West Coast basins (see Nathan et al. 1986 for a synthesis) display – in time and space – a wide range of depositional settings related to the rapid development and destruction of sedimentary troughs and submerged platforms, as the crust of the region responded to a succession of vertical and horizontal displacements during the evolution of the plate boundary.

In this paper we revisit the evolution of these depositional systems in the light of recent concepts regarding the Cretaceous and Cenozoic evolution of the New Zealand region, and consider how the interplay between syntectonic sedimentation and superposed deformation affect the development of hypothetical petroleum systems within the West Coast region.

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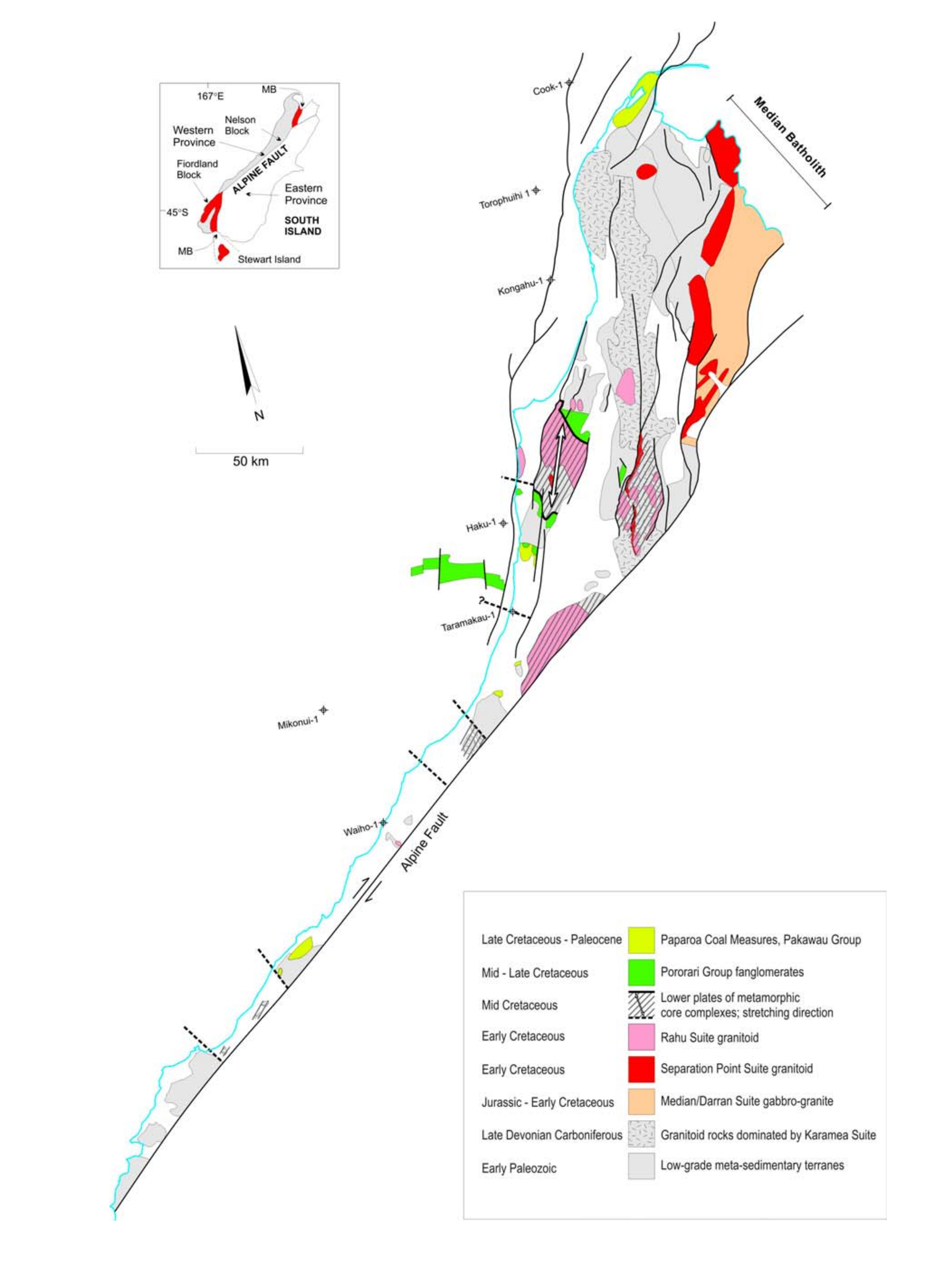

Figure 1. Basement geology of the West Coast region, and exposure of Cretaceous sedimentary units.

Origins and significance of basement suites

The geological framework within which New Zealand's Late Cretaceous-Cenozoic sedimentary basins formed was established along the convergent margin of the Gondwana super-continent in the Paleozoic and Mesozoic up until about 100 Ma (e.g. Tulloch, in press, Mortimer et al, 1999, Tulloch & Kimbrough, 2003).

The Gondwana margin terrane sequence occurs on both sides of the modern plate boundary. Figure 1 depicts the distribution of basement suites as well as Cretaceous sedimentary units in the West Coast region. In the northeastern part of the region, the easternmost basement element (Median Batholith) is juxtaposed across the Waimea-Flaxmore Fault System against Permian and Triassic island arc (Brook Street) and forearc basin terranes (Maitai/Murihiku), with accretionary prism suites east of the Dun Mountain Ophiolite Belt.

Further west, basement rocks are predominantly plutonic igneous bodies intruded into Early Paleozoic metasedimentary terranes - the Buller Terrane in the west and Takaka Terrane to the east, juxtaposed along the Anatoki Thrust. These terranes correlate to the Bendigo-Ballarat terranes within the Lachlan Fold Belt of eastern Australia (Cooper & Tulloch 1992). Approximately 50% of the plutonic rocks are Paleozoic in age, and most of the rest are Jurassic–Early Cretacous plutonic and minor volcanic rocks. The latter are the most relevant here because the continental margin arc system in which they formed played a major role in setting the crustal architecture upon which intra-plate extension and basin formation was subsequently imposed.

The Jurassic-Early Cretaceous magmatic arc system is dominated by the Median Batholith, which is largely made up of two margin-parallel plutonic belts (Tulloch & Kimbrough, 2003): outboard (now eastward), the Median/Darran Suite; and inboard, the Separation Point Suite.

The Median/Darran Suite is represented in the northern West Coast region by the Rotoroa Complex, gabbro-diorite-granitic rocks emplaced in relatively thin continental margin crust between 175 and 130 Ma (Late Jurassic and earliest Cretaceous). The Separation Point Suite was emplaced between 130 and 105 Ma and includes the granulite facies Western Fiordland Orthogneiss, which is locally represented in the West Coast by Glenroy Granulite.

West of the Separation Point batholithic belt, the early Paleozoic Buller Terrane was intruded by isolated plutons of both Separation Point Suite and more or less contemporaneous Rahu Suite.

All of these basement belts have counterparts within the Pacific plate part of New Zealand, offset from the West Coast region along the Alpine Fault. The Southland and especially Stewart Island elements are much less affected by Cenozoic deformation allowing their petrogenesis to be more easily elucidated (Allibone and Tulloch 2004, 2008).

Significant crustal thickening likely attended the formation of the voluminous Separation Point Suite. A generally accepted model for the formation of such high Sr/Y ("HiSY") granitic-monzodioritic magmas requires partial melting of basaltic crust at pressures equivalent to a minimum of 45 km (Drumond & Defant 1990, Atherton & Petford 1993), and thermobarometry of the exposed arc base in Fiordland indicates depths significantly in excess of 45 km. Assuming that the dense residual crustal root had not been removed by delamination, buoyancy considerations indicate that the over-thick crust of the inboard, HiSY pluton belt would have been balanced by an Andean-style mountain range along the Cretaceous continental margin – the Cordillera Zealandia (Tulloch et al. 2006).

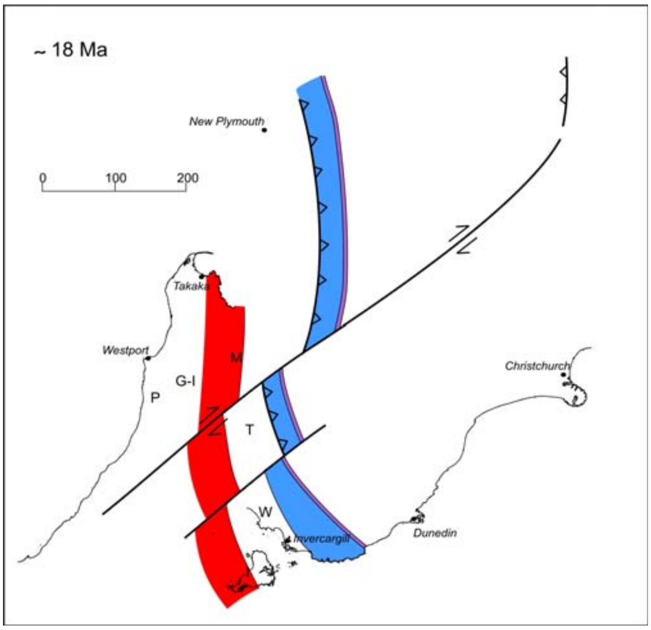

Figure 2. Major structures and depocentres during the early-mid Miocene. M = Murchison Basin (then much wider than now), G-I = Grey-Inangahua depocentre, P = Paparoa inversion. Major basement units shaded as in Figure 1.

Because the youngest HiSY pluton at 105 Ma (Tulloch & Kimbrough 2003) precedes initial extension and basin sedimentation by only c. 3 Ma, this mountain range, at least 800 km long based on the known distribution of Separation Point suite granites onshore and offshore, would likely also have stood as a major supplier of quartzo-feldspathic sediment to subsequent Cretaceous rift basins.

The inferred belt of initially thick crust associated with the Separation Point Belt, and still evident from the bathymetric expression of the Challenger and Campbell plateaus, has influenced the development of basins in response to later tectonic drivers, as discussed below.

Late Cretaceous rift systems: precursor and contemporaneous with separation from Australia and Antarctica

Widespread intra-plate extension within Zealandia between about 100 and 80 Ma (Crampton et al. 2004) is indicated by abundant field, seismic and petrological evidence. In the West Coast region, this includes thick coarse-grained graben fill of the Pororari Group (including Otumotu Formation in South Westland) (Nathan et al, 1986), associated with a series of metamorphic core complex features (Tulloch & Kimbrough 1989, Tulloch 1995). Carbonaceous facies are associated with most occurrences of the Pororari Group and represent an important potential petroleum source rock.

A further indicator of extension is suggested by the core of Greenland Group basement from total depth in the Taramakau-1 well. This unit has extensive fractures which are coated with hematite, a common feature in Greenland Group rocks immediately above detachment faults in the Paparoa Core Complex in outcrop some 45 km to the north. The Taramakau-1 structure could be an uplifted extension to a basal detachment associated with the Takutai Graben mapped by Bishop (1992) offshore to the NW and striking within a few kilometres of the well location.

In the West Coast Basin region, the extension direction (NNE-SSW relative to present-day geography) for rift systems older than about 84 Ma appears to parallel the trend of the basement suites and hence the strike of the Gondwana margin. However, based on restoration to the 90 Ma configuration, Beggs et al (2008, see their Fig. 2), suggest (based on restoration to the 90 Ma configuration) that this rift system trended oblique to the margin and more or less parallel to the subsequent separation margin represented by the SE margin of the Campbell Plateau. This phase of rifting was clearly a precursor to sea floor spreading from about 84 Ma which ensued firstly in the Tasman Sea to the southwest, and shortly afterwards to the southeast of the Campbell Plateau, (Cande et al. 1989, Royer and Rollet, 1997, Kula et al. 2007).

The relatively widespread exposures of core complexes within the basement of the West Coast (Tulloch 1995) may be related to late Cenozoic uplift associated with the Alpine Fault to the southeast (Seward 1989). The extent of these features suggests a significant degree of stretching of Zealandia in the interval between the culmination of plate convergence at about 105 Ma and the inception of sea floor spreading at about 84 Ma. Whereas much of the on-land expression is the fabric within footwall basement rocks, the offshore region can be expected to preserve a greater proportion of graben-fill, as observed by Bishop (1992) offshore from Greymouth and further afield on the Challenger Plateau by Wood (1991).

Later, a separate extensional system operated in western New Zealand concurrently with sea floor spreading in the Tasman Sea (about 70–55 Ma). This phase of extension is represented in the West Coast region by the Paparoa Coal Measures in the Greymouth area and by the Pakawau Group in northwest Nelson, extending into and across the Taranaki Basin to the north. The grabens containing these units (Fig. 1) trend NNE, more or less orthogonal to the earlier system, and probably along a projection of a major transform system between Tasman and Southern Ocean spreading centres.

Some of the extensional fabric observed within basement outcrops on the West Coast may be associated with this later Cretaceous extension, instead of, or in addition, to the earlier phase. A transtensional regime with sinistral movement of about 34 km has also been suggested to account for inferred provenance and paleogeographic relationships (Nathan et al. 1986, Bishop et al. 1992, Bassett et al. 2006), and dated at 73–64 Ma by associated alkalic magmatism (Sewell et al. 1988, Tulloch & Kimbrough 1989, Phillips et al. 2005).

To date, there is no evidence for the existence of rifting of this episode offshore of the West Coast, except for the edge of the Paparoa depositional system. Paparoa Coal Measures include obvious potential source rocks where they do exist, and have been identified as the source for oil seeps associated with the Kotuku Anticline inland from Greymouth (Killops, 1996).

Much of the West Coast region is lacking in Cretaceous section altogether, including for example the Murchison Basin, where the case for a petroleum system relies on Eocene source rocks.

Paleocene-Early Eocene unconformity

Scattered outcrops of a Late Cretaceous to Eocene sequence, much of which is flows of the Arnott Basalt in South Westland (Nathan et al, 1986) indicates a transgressive continental margin sequence there that is similar to coeval sections of eastern New Zealand.

From the Greymouth area and northwards into the southern Taranaki Basin, there is a pronounced unconformity between Late Cretaceous and locally Paleocene coal measures below, and mid to Late Eocene terrestrial to marine strata above. This long-wavelength regional unconformity is also recognised in the Western Southland basins (Turnbull et al, 1993). It seems likely that the broad regional uplift indicated by the distribution of this unconformity is related to the propagation, from the south, of the extensional system that became the Emerald Rift during the mid Eocene. A system of extensional basins developed subsequent to the unconformity.

Late Eocene and Oligocene basin system

The continental margin sequence represented in scattered outcrops along the South Westland coast includes foraminiferal and muddy limestone of the Abbey Formation, capped by late Eocene Otitia Basalt and associated volcaniclastics (Nathan et al. 1986).

This area is separated by a belt approximately 100 km wide that is lacking in Eocene section, from a system of extensional Eocene depocentres, such as the re-activated Paparoa Trough and the Inangahua and Murchison basins. In these areas, the basal sediments are the Brunner Coal Measures, which are up to a few hundred metres thick. This formation is also found in Golden Bay and the Nelson city area, and is continuous into the Kapuni Group of Taranaki Basin. Nathan et al. (1986) show that both coal measures and capping marine beds are older in the south (Hokitika area) and younger in the Murchison area, which therefore appear to have occupied a saddle between the West Coast and the Taranaki Eocene extensional systems.

Much of the Eocene succession in the Paparoa and other graben is composed of the Kaiata Formation, a marginal marine mudstone-dominated unit with intercalated coarse clastics (eg Omotumotu Member in the Greymouth area, Nuggety Member in Murchison) associated with bounding extensional faults.

The supply of clastic sediment in the region was largely exhausted by about the end of the Eocene. During the Oligocene, essentially the entire region was drowned and accumulated carbonate-dominated sediment. In general, those areas which were under extension in the late Eocene developed thick (100–1000 m) sections of muddy, bathyal facies during the Oligocene, while thinner shelf sequences rest on or near basement in the extensive areas that were not drowned until the Oligocene. Again, there is a counterpart facies series in Taranaki Basin (eg Hood et al. 2003a, b).

While the Oligocene carbonates are generally viewed as a reliable regional seal, some of the shelf facies, including the Cobden Limestone in the Grey Valley basin, may serve as reservoirs and conduits for migration.

Neogene overprint of the transpressional plate boundary

In the Late Oligocene, between 30 and 25 Ma, there was a major re-orientation in relative plate motion vector for the Australian plate relative to the Pacific Plate (eg Sutherland, 1999), which is reflected in the depositional systems of West Coast and other New Zealand sedimentary basins, as well as in the structural style as discussed below.

Previously under E-W extension governed by a nearby pole of rotation, by the early Miocene the principal compressional stress

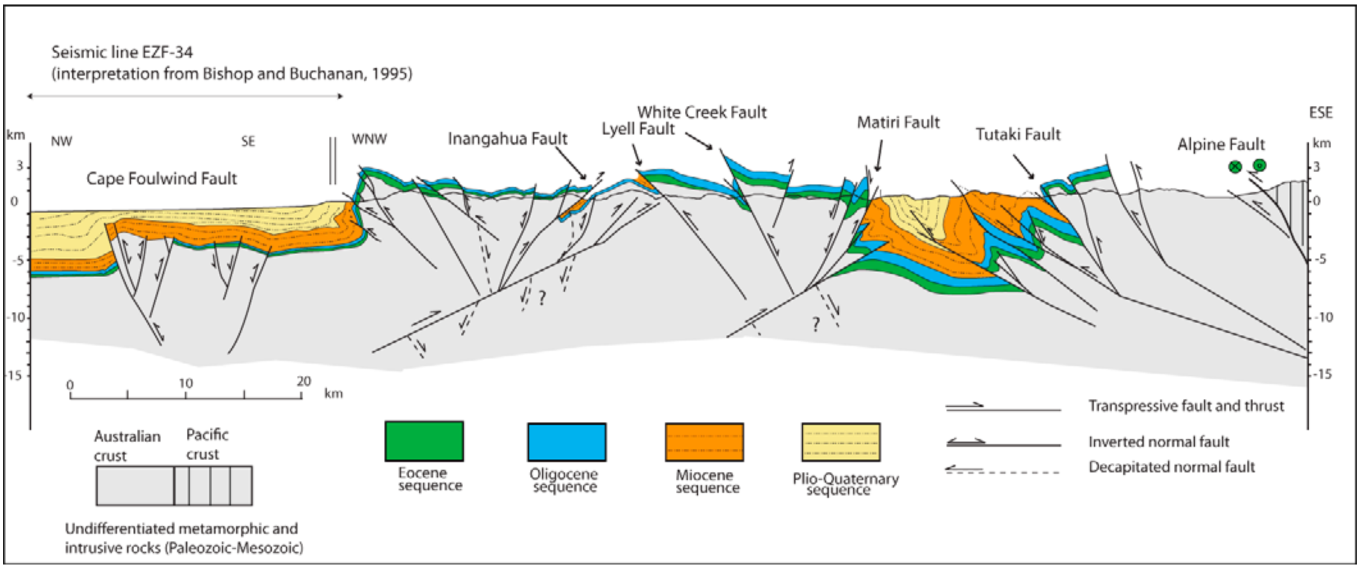

Figure 3. Structural profile across the West Coast region illustrating the style of deformation arising from successive stages of deformation, including late-stage compression related to the Alpine Fault. Based on Ghisetti and Sibson (2006).

across the West Coast Basin System was oriented southwest-northeast. The Flaxmore-Taranaki fault system accommodated considerable shortening towards the northeast, by overthrusting of the stratified basement suites such that the area immediately to the southwest, including the Murchison Basin, acted as a foredeep and filled with coarse clastics derived from the growing ranges.

Figure 2 depicts the West Coast basin system during the early Miocene based on the 18 Ma reconstruction of King (2000). The Alpine Fault functioned as a more or less pure strike-slip element of the plate boundary, and juxtaposed growing ranges within the Pacific plate margin with the foredeep Murchison Basin system in the Australian plate margin (Longford Formation).

In the Greymouth segment of the West Coast basin system, the SW-NE-directed compression is manifest as a more classical inversion of the Eocene graben to form the Paparoa-Brunner Anticline, west of a rapidly-subsiding trough (Grey-Inangahua Depression) that filled with progradational clastics which include potential reservoir sands analogous to the Moki sands in the Taranaki Basin. Burial associated with this trough accounts for maturation of Late Cretaceous coals, the source for abundant seeps and shows in the area.

The offshore West Coast basins remained relatively starved of clastic sediment until the late Miocene. The Alpine Fault became transpressional from about 6.4 Ma, creating a flexural effect in the adjacent edge of the Australian plate (the footwall). Strongly progradational coarse clastic depositional systems arising from the growth of the Southern Alps in the hanging wall of this major structure are the dominant Neogene element of the offshore and South Westland basin systems.

Geometry of finite deformation resulting from superposed tectonic events

The inherited architecture of the basement and the sequence of tectonic events described previously have left a strong imprint on:

1. the location of first order discontinuities;
2. finite deformation displayed by the cover sequences; and,
3. the vertical and horizontal mobility of adjacent crustal blocks that host the source-seal hydrocarbon system.

The present structural grain of the South Island West Coast is dominated by N–S to NNE–SSW trends, with closely spaced sets of high-angle reverse faults and asymmetric folds (Ghisetti & Sibson, 2006: see their figures 4 and 10). These structures define a mixed style of thick and thin-skinned deformation, with up-thrusting of the basement, and propagation of low angle thrust faults in the shallow cover sequence associated with folding and detachments on low competence horizons. The deformation style is strongly influenced by lithological heterogeneity between the rigid basement and the cover strata, and contrasting mechanical properties in the sedimentary sequence.

As is evident from offshore seismic data in the southern and eastern regions of the Taranaki Basin (Bishop, 1992b, King & Thrasher 1996, Hill et al. 2004), the high-angle faults that have controlled the location of the Miocene-Pliocene siliciclastic depocentres are in many cases inherited normal faults reactivated in compression during multiple episodes of inversion (Bishop & Buchanan 1995, Muir et al. 2000, Ghisetti & Sibson 2006). Relics of the original rift basins are recognised as “everted” structural highs bounded by oppositely dipping, inverted normal faults.

The Kongahu, Cape Foulwind, Wakamarama, Pikikiruna, Matiri and Grey Valley faults (Bishop & Buchanan 1995, Ghisetti & Sibson 2006) provide the best examples of long-lived faults persistently reactivated through different tectonic regimes. These faults define sharp tectonic boundaries between sedimentary depocentres of different ages, with basement rocks in the hanging wall, sometimes covered by remnants of the former extensional basins, and siliciclastic, syn-compressional, early-Middle Miocene to Pliocene basins in the footwall.

Inverted faults typically dip > 50^{o}, and may have relatively minor amounts of vertical separation relative to their dimensions. In some cases, seismic lines show a change in vertical separation from normal in the basement to reverse in the cover sequence along the same fault plane, suggesting that the reverse slip is less than the original normal offset.

The accommodation of shortening on pre-existing normal faults requires that: (1) inherited structures maintain favourable orientation relative to the changed stress field, and (2) the differential stress needed for fault reactivation is less than that needed for the creation of new cross-cutting structures (Sibson

1995). Though many of the inherited normal faults have met these conditions to some extent, the reactivation of steep faults has been unable to accommodate the total amount of shortening accumulated since the late Oligocene, resulting in the propagation of new cross-cutting thrust faults (dipping 30–45°) that decapitate the older faults (Buchanan 1991).

This structural setting (Fig. 3) is especially well recognised in the Murchison Basin that lies adjacent to the Alpine Fault margin. In this area, systems of low-angle thrusts nucleated into the basement and propagated as low angle detachments in the sedimentary cover, controlling localised syntectonic subsidence and siliciclastic sedimentation. Proximal to the basin margin, rigid basement buttresses bounded by decapitated portions of the original normal faults override the sedimentary sequence, and induce drape folding in low competence horizons.

Thus, the location of fault-propagation folds and fault-controlled structural traps is dominantly controlled by a suite of long-lived discontinuities in the basement, but the subsequent progressive build-up of deformation during the evolution of the Australia-Pacific plate boundary has resulted in a complex geometrical setting with large detachments at the basement-cover interface and the eventual disruption of potential hydrocarbon traps.

Conclusions

A consideration of the petroleum prospectivity of the West Coast Basin system needs to take careful account of the unique juxtaposition of basin elements, which reflect the complex tectonic evolution of the region. Depositional systems and major structures exhibit the influence of basement architecture as well as the successive tectonic regimes that have been imposed.

Once the complexity is understood and properly factored in, a range of potentially commercial petroleum systems can be postulated. Both Cretaceous and Eocene strata contain proven source rocks, and potential reservoir units occur at many levels. Oligocene carbonates and Eocene and younger mudstone units should form effective seals. Two quite distinct episodes of shortening account for maturation and trap formation in different parts of the basin system: early to mid-Miocene in the main onshore sub-basins from about Greymouth northwards; and more recent offshore and to the south.

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