Recent progress in understanding the structure and petroleum potential of southern South Island's frontier basins

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Abstract

New seismic reflection data have been collected during the last few years from the northern margin of the Great South Basin, Canterbury Basin, Solander Basin, Puysegur Bank, and Fiordland margin. In addition, a major review and re-analysis of all available data and material from the Great South Basin has recently been completed and a GNS monograph published.

East of Stewart Island, the Great South Basin is a large mid-Cretaceous rift basin containing >8 km of sediment. Water depths vary from 0-2000 m, approximately 35,000 km of seismic data have been collected during the last 30 years, and eight wells have been drilled. Oil and gas shows, combined with a condensate discovery in Kawau-1A, demonstrate that the basin is highly prospective. Subsidence models for the basin indicate that there may have been mantle plume activity during rifting, with implications for heat flow and source rock maturity in the Great South Basin and other mid-Cretaceous rift basins in New Zealand.

West of Stewart Island, the Solander and Balleny basins are the offshore extension of Western Southland, which formed during Cretaceous and late Eocene extensional tectonics, but have been significantly deformed by later strike-slip and convergent tectonics. The region within 50 km of the coast has been explored for oil and gas, and two offshore wells have been drilled, but the region remains under-explored. Crustal and high resolution seismic reflection/refraction data, and very detailed bathymetric data have been acquired during the last 7 years from the Solander Basin and Puysegur Bank-Fiordland margin. The new data allow the structure of the region to be better determined, and dredge samples place new age constraints on Balleny Basin stratigraphy. Refraction and reflection data from the Puysegur Bank and Puysegur trench-slope show that most of the area is underlain by sediments >3 km thick, and may be prospective.

The Canterbury, Great South, and Western Southland basins certainly contain both liquid and gaseous hydrocarbons. However, the basins are under-explored and there is no commercial production in the region. Drilling the basins remains a moderately high risk venture, but has the potential for high return. If hydrocarbon production is developed, it is likely that a large resource inventory will ultimately be established in the region.

Introduction

Southern South Island, New Zealand, is surrounded by large sedimentary basins containing up to 8 km of Cretaceous-Cenozoic sedimentary fill (Figure 1). Despite promising shows and tests from wells, there has been only low-level petroleum exploration in southern South Island since the mid 1980s. However, continuing research interest in the region has resulted in several synthesis monographs being published, and significant new data acquisition during the last decade (Tables 1 & 2, Figure 2).

This paper summarises some recent advances in understanding the structure, stratigraphy, and petroleum geology of the Great South Basin, Solander Basin, and Balleny Basin. It also presents a brief comparison and overview of the petroleum systems of basins surrounding South Island, including the Canterbury Basin and Taranaki Basin.

Great South Basin

East of Stewart Island, the Great South Basin is a large mid-Cretaceous rift basin containing >8 km of sediment (Figure 3).

Basin	Ship	Year	Data acquired
Balleny	L'Atalante	1993	Swath; seismic reflection (2 air guns)
Balleny	Tangaroa	1996	Seismic reflection (1 air gun); dredge samples
Solander	Ewing	1996	Seismic reflection/refraction (20 air guns)
Great South	Ewing	1996	Seismic reflection/refraction (20 air guns)
Canterbury	Ewing	1996	Seismic reflection/refraction (20 air guns)
Canterbury	Ewing	2000	Seismic reflection

Table 1: Relevant recent research cruises.

Basin	Reference	Summary
Canterbury	Field, Browne, et al. 1989	Synthesis monograph
Great South	Cook, Sutherland, Zhu, et al. 1999	Synthesis monograph
Western Southland	Turnbull, Uruski, et al. 1993	Synthesis monograph
Solander	Sutherland & Melhuish 2000	Structure of southern Solander Basin from R.V. Ewing data.
Canterbury, Great South	Killops et al. 1997	Oil-source correlation
Taranaki	King & Thrasher 1996	Synthesis monograph

Table 2: Selected relevant publications.

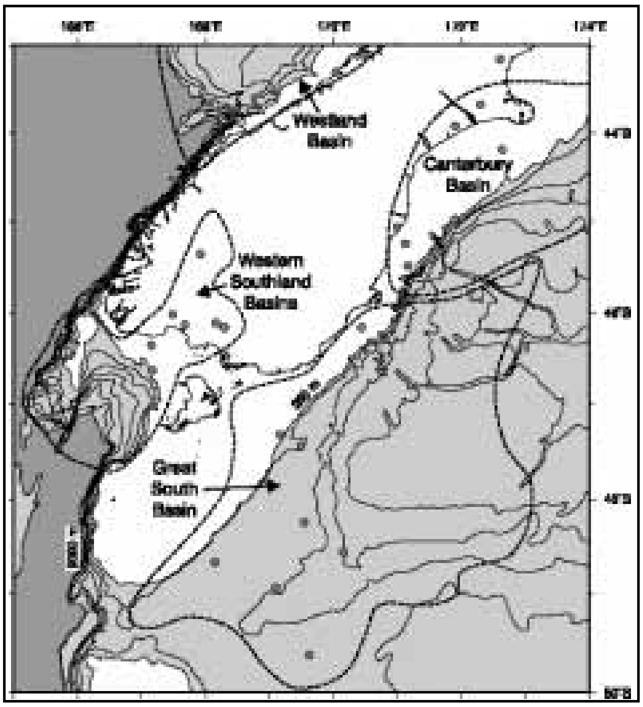

Figure 1: Hydrocarbon basins of southern South Island. Western Southland basins include the Te Anau, Waiau, Solander, and Balleny Basins. Bathymetry (250 m contours) after CANZ 1997. Water depths 250-2000 m shown as light shade, and >2000 m is dark shaded. Petroleum exploration wells, including shallow wells, shown as shaded circles.

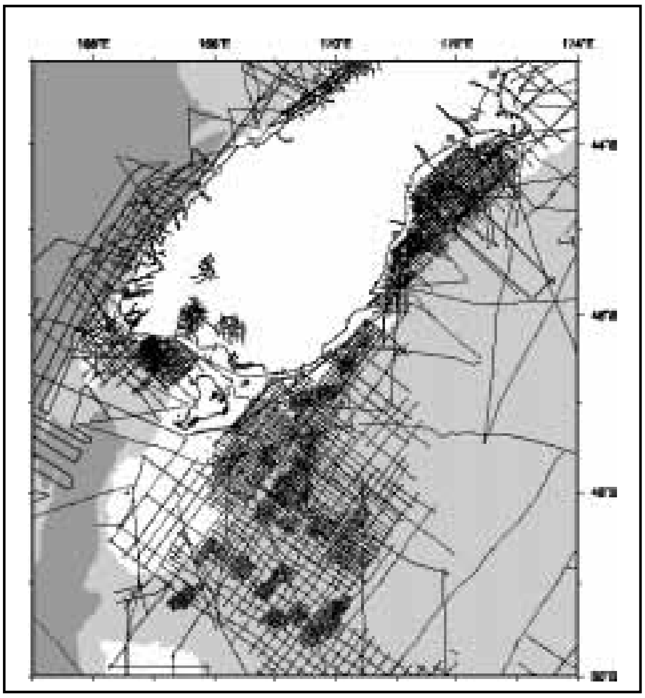

Figure 2: Coverage of seismic lines. Recent academic research data (Table 1) shown bold. Water depths 250-2000 m shown as light shade, and >2000 m is dark shaded. Petroleum exploration wells shown as shaded circles.

Water depths vary between 0-2000 m, approximately 35,000 km of seismic data have been collected during the last 30 years, and 8 wells have been drilled (Figures 1 & 2). There were oil and gas shows in four of the wells, and Kawau-1A tested gas at 6.7-3.8 MM cfd with 7% CO_2 and 24 bpd condensate (47.8 API). The overall reserve at Kawau-1A is calculated at 461 bcf gas.

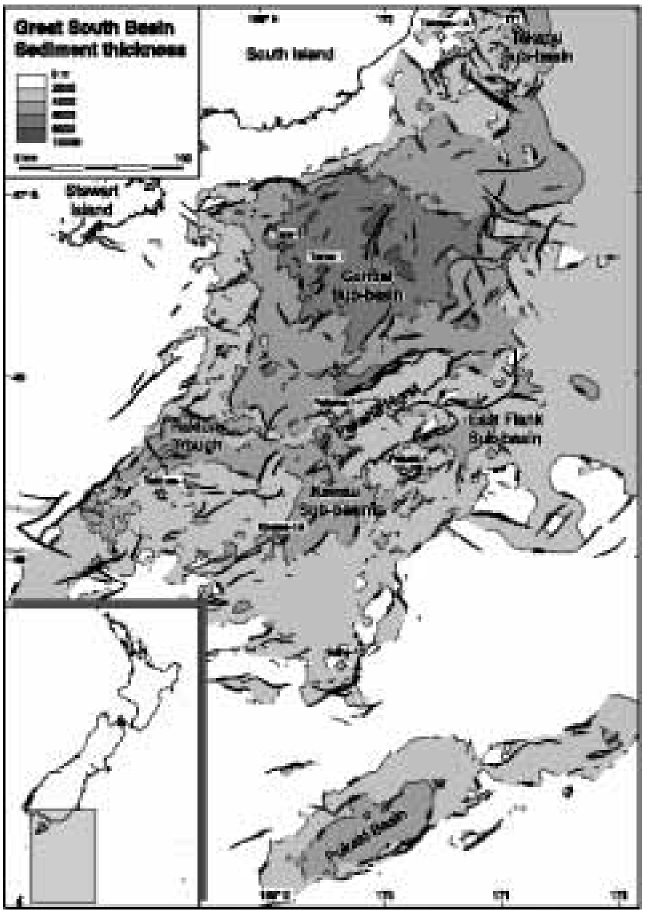

Figure 3: Great South Basin total sediment thickness (simplified after Cook et al. 1999). Exploration wells and sub-basins are labelled.

Previous work includes brief published basin summaries (Carter 1988a & b, Beggs 1993) and unpublished petroleum industry reports (e.g. Anderton et al. 1982). The recently published GNS monograph (Cook et al. 1999) reviews all existing data and presents significant new work on the stratigraphy, structure, and petroleum geology. Some of the new results presented by Cook et al. (1999) are summarised below.

Stratigraphy and basin history

Cook et al. (1999) propose a new stratigraphy based upon re-analysis of well log data and new paleontological analysis (Figure 4). A total of 24 seismic reflectors were mapped during the study, of which eight represent significant lithostratigraphic boundaries and form the basis of a suite of isopach and structure maps.

The Cretaceous syn-rift basin fill is assigned to the Hoiho Group, which is inferred to range in age from about 105 to 83 Ma (Motuan-Piripauan). Local topography, dominated by the elevated northwestern margin of the basin and the Pakaha Horst, was controlled by active normal faults. Slope-fan and slump deposits formed adjacent to active faults, while alluvial processes formed broad plains in basinal areas. The deepest and most extended parts of the basin, particularly the Central sub-basin, accumulated well stratified lacustrine or restricted marine deposits fringed by deltas and heavily vegetated plains and swamps.

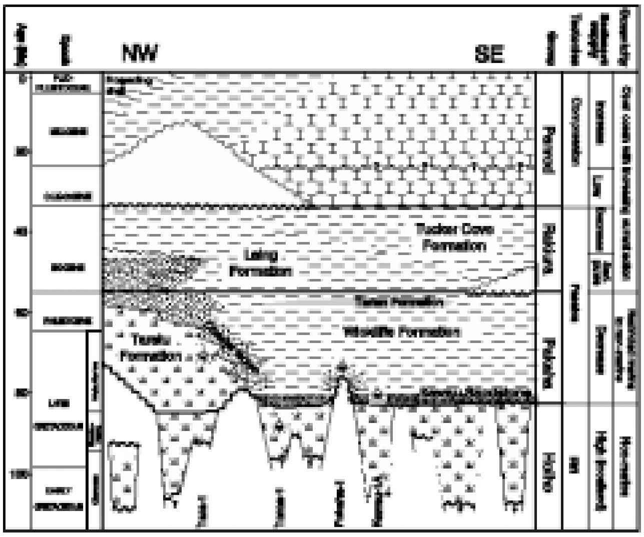

Figure 4: New lithostratigraphy of the Great South Basin, with main hydrocarbon occurrences shown (after Cook et al. 1999).

Regional subsidence and extensive marine flooding of the basin from about 83 Ma (Piripauan) resulted in deposition of the transgressive Kawau Sandstone, which defines the base of the Pakaha Group. Quartzose clastic terrestrial sediments of the Taratu Formation were deposited along the northwest margin, while marine siltstones of the Wickliffe Formation were deposited in deeper parts of the basin. Shallow-marine sandstones and organic-rich lower coastal plain sediments were deposited near the steadily transgressing shoreline.

Minor normal faulting continued during deposition of lower Pakaha Group strata, and widespread drape structures formed as Hoiho Group strata were differentially compacted. Unconformities developed above basement highs, with progressive onlap by overlying strata. Drape structures were the hydrocarbon exploration targets drilled by the Pakaha-1, Pukaki-1, Hoiho-1C, Rakiura-1, and Kawau-1A wells.

Some uplifted blocks remained emergent during latest Cretaceous time, but by late Paleocene time the basin was dominated by deposition of marine siltstones. The upper part of the Pakaha Group contains late Paleocene organic-rich dark shales of the Tartan Formation, which has TOC values up to 8% and is oil-prone.

The Eocene Rakiura Group is marked by an increase in carbonate content of marine sediments, representing a shift to open marine conditions as the basin continued to subside. The lower part of the Rakiura Group is characterised by a thick submarine fan sequence in the Central sub-basin, but a condensed sequence or unconformity in the southeast. A new extensional plate boundary propagated into southern New Zealand during Middle Eocene time, causing significant faulting and changes in sediment source area farther west, but there is little evidence for faulting within the Great South Basin. A change from delta and submarine fan deposition along the northwest margin of the basin, to calcareous silt and chalk deposition, was probably related to sediment capture by the deepening Solander Basin.

The base of the Oligocene to Recent Penrod Group is marked by a significant change to more carbonate-rich sediment in southeastern parts of the basin, and is an unconformity along the northwestern margin. This reflects decreased Oligocene land area and increased ocean current action. The change to transpressional tectonics at the nearby plate boundary in latest Oligocene or Miocene time was associated with regression, increasing clastic sediment supply, and rapid shelf accretion along the northwest margin. Southeastern parts of the basin have been isolated from terrigenous sediment supply by strong ocean currents. Penrod Group sediment is generally less than 500 m thick over most of the Great South Basin, but a combination of shelf processes, current action, and rapidly changing tectonics has produced a complex internal stratigraphy. Deformation during Penrod Group deposition was restricted to the northwest margin of the basin, where minor reverse faulting occurred and gentle anticlines formed. The Takapu-1A, Toroa-1, and Tara-1 wells were drilled on these structures. Intraplate basaltic volcanism has been intermittent since Late Eocene time.

Basin subsidence: implications for maturity in NZ basins

The Great South Basin has a relatively simple tectonic history compared to other sedimentary basins around New Zealand. It was formed during mid-Cretaceous rifting and, apart from slight compression along its northwest margin, has passively subsided since then. Subsidence during rifting is mainly an isostatic response to crustal thinning, whereas subsidence after rifting is associated with diffusion of thermal anomalies in the lithosphere. The magnitude of subsidence during each phase can be predicted by simple models (e.g. McKenzie 1978).

A relatively large region in the centre of the Great South Basin has experienced a post-rift tectonic subsidence of >2200 m, equivalent to about 4 km of sediment deposition and a 700 m increase in water depth. This is much larger that predicted by most thermal-mechanical models, given reasonable extension estimates for the basin. The post-rift subsidence was not accompanied by faulting, leaving only two possible explanations. Either the lithosphere in the region was anomalously hot during rifting, or the region was supported by upwelling asthenosphere during rifting.

Both explanations predict higher than average heat flow in the basin during Cretaceous and early Cenozoic time. Further, it is not known how widespread the processes were. Most other basins in New Zealand have had their post-rift subsidence history modified by later deformation. It is known that upwelling mantle usually produces long wavelength (>600 km) dynamic topography (White et al. 1987). Thus, relatively high heat flow may have persisted over much of New Zealand during the Late Cretaceous and Paleogene, with obvious implications for the regional maturity of source rocks buried during Cretaceous and early Cenozoic time.

Western Southland basins

The Western Southland basins have a complex structure (Fig. 5) formed by multiple phases of Cretaceous-Cenozoic extension, strike-slip, and transpression. Two deep (>2000 m) wells have been drilled onshore, and two offshore. The offshore Parara-1 well had oil stains in late Eocene sandstones, but all four wells were plugged and abandoned. Oil seeps are known onshore and excellent source rocks crop out. The Late Eocene Orepuki oil shale was mined early last century and yielded up to 330 litres of liquid hydrocarbons per tonne of rock.

New data from offshore Western Southland

There has been a major international effort to understand the active plate boundary in South Island during the last decade and this has led to the acquisition of several new data sets. In southwest New Zealand, the plate boundary is a complex zone of faulting along the western edge of the Western Southland basins (Figure 5). Three significant new data sets have been collected since 1993 (Table 1).

Swath and low fold seismic data collected by the *L'Atalante* in 1993 provide a better understanding of the regional tectonic setting (e.g. Collot et al. 1995, Delteil et al. 1996, Lamarche et al. 1997), but most data were collected in water depths >2000 m and are hence of little value to petroleum exploration companies.

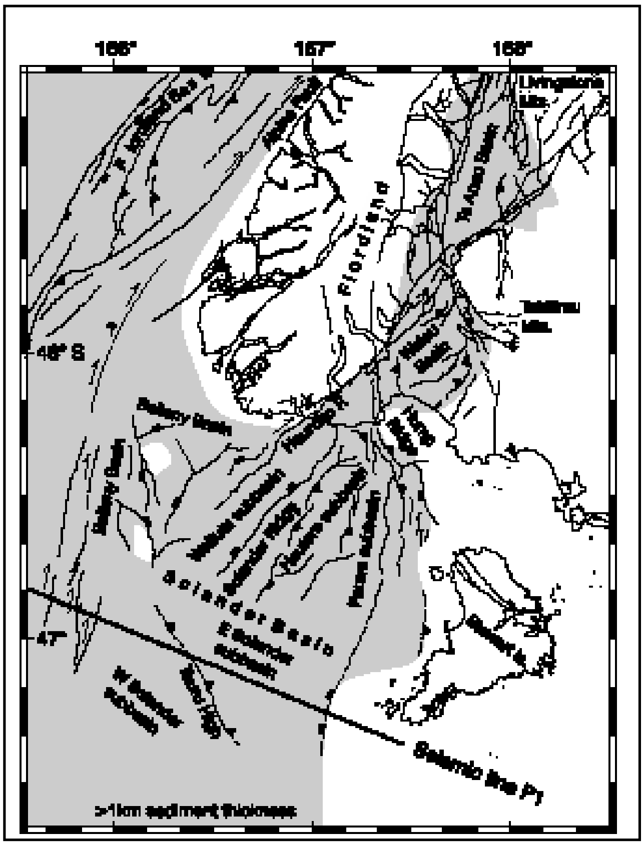

Figure 5: Structure and nomenclature of Western Southland basins (modified after Sutherland & Melhuish 2000). Shaded area shows regions with >1 km sediment thickness.

Likewise, most seismic data collected by the *Tangaroa* in 1996 is low fold and was collected in water deeper than 2000 m. However, three high resolution seismic lines collected across the Balleny Basin during the *Tangaroa* survey were accompanied by a suite of dredge samples, which are the first samples from the basin. Work is in progress on these samples to determine their age and environment of deposition (Barnes et al., work in progress). The objective of the *Tangaroa* survey was to better understand the structure and Quaternary evolution of the Fiordland margin. Consequently, the rock dredging and seismic data acquisition was primarily aimed at overburden rock. However, most of the Balleny Basin stratigraphy is exposed at the seabed and possibilities exist for sampling more strata in this fashion.

Crustal seismic reflection data collected by the *R. V. Maurice Ewing* in 1996 are high fold and image structures to 30 km depth (e.g. Figure 6). Data were collected in the Canterbury, Great South, Solander, Fiordland, and Westland basins (Figure 2). The P1 line, which crosses the southern Solander Basin, Puysegur Bank, and Puysegur Trench (Figure 5), has revealed several previously unknown aspects of the Solander Basin and Puysegur Bank region (Melhuish et al. 1999, Sutherland & Melhuish 2000). The existence of the Tauru High and associated faults was established (Figure 6). The faults can be traced into the upper mantle (Figure 6), and have been a primary control on Solander Basin evolution (Sutherland & Melhuish 2000). Farther west, the Puysegur trench-slope is shown to be mainly sedimentary in character, and sedimentary velocities are confirmed by sonobuoy measurements to >3 km depth (Melhuish et al. 1999). The angle of the slope, its reflection character, seismic velocities, the nature of the subducting plate, and persistence of bottom-simulating-reflectors suggest that the slope is composed of deformed basinal sediments and may contain hydrocarbons. However, the unknown stratigraphy, rough seas, very remote location, and relatively deep water make this a very high risk area for hydrocarbon exploration.

Reconstruction of South Island basins

The development of satellite and swath mapping technologies during the last decade has meant that the Cretaceous-Cenozoic history of global plate motions is now much better known. When combined with syntheses of regional geology, this allows the frontier basins of southern South Island to be placed into their regional context (Figure 7). It also improves our understanding or their potential petroleum systems, and allows comparison with better known basins, such as Taranaki Basin (e.g. King & Thrasher 1996).

Phase 1: Mid Cretaceous rifting (100-80 Ma)

Pervasive rifting of the New Zealand sector of Gondwanaland caused widespread normal faulting and local basin formation

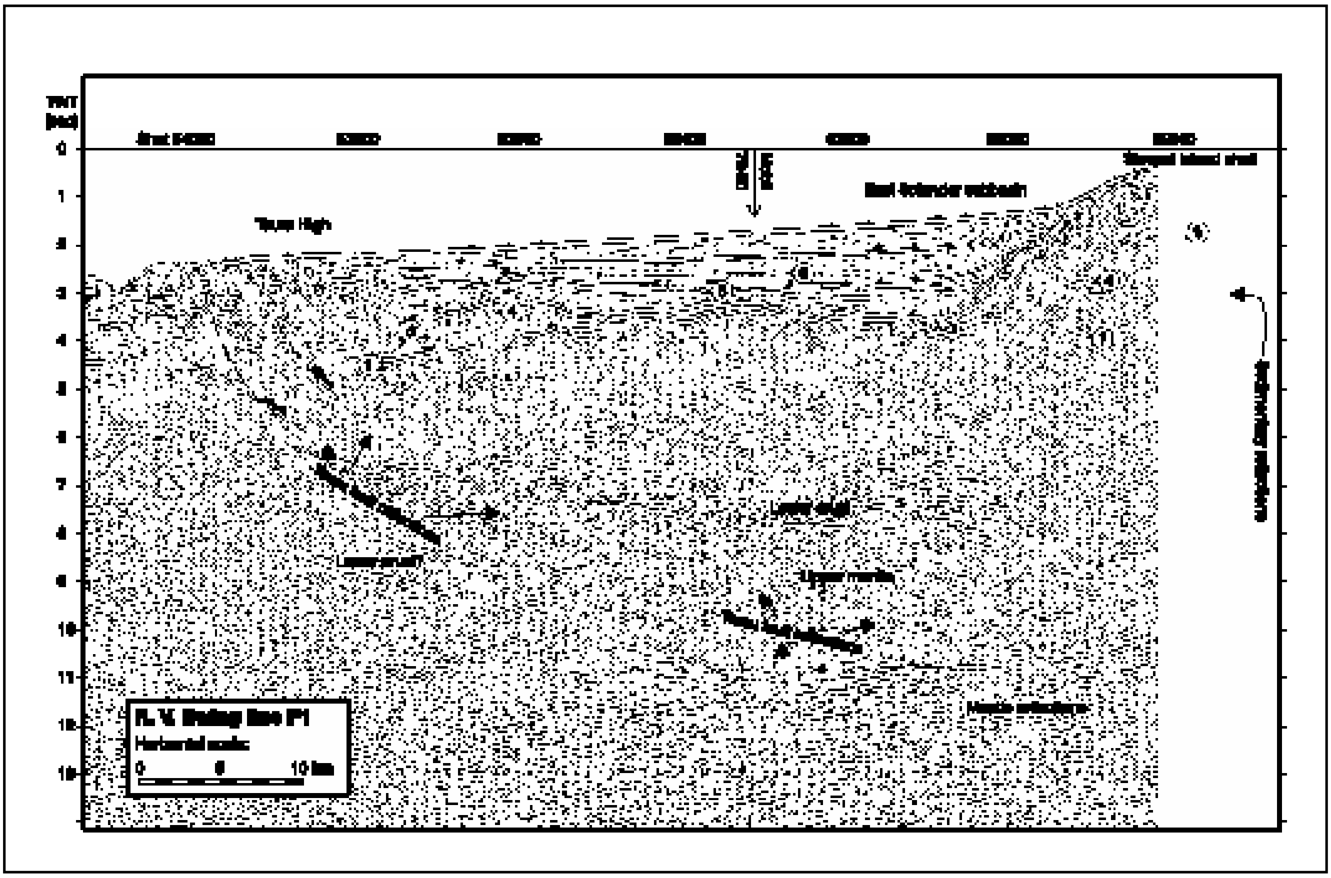

Figure 6: Example of seismic data acquired by R.V. Ewing in 1996. This section is across the East Solander Sub-basin (after Sutherland & Melhuish 2000) and shows sedimentary reflectors (1 = basement, 2 exists only west of the Tauru High, 3 = top Oligocene?, 4 = top Early Miocene?, 5= Middle Miocene, 6 = top Miocene), lower crust, and upper mantle reflections. The Tauru Fault controls basin structure and can be seen cutting the entire crust and part of the upper mantle. For location see Figure 5.

(Figure 7). Rifting culminated in Tasman Sea and Pacific Ocean seafloor spreading. Primary physiographic features such as the Bounty Trough and southern margins of the Challenger and Campbell Plateaux formed at this time. This was the main phase of Great South Basin formation, but sedimentary units associated with this episode are known from most basins around South Island (King et al. 1998).

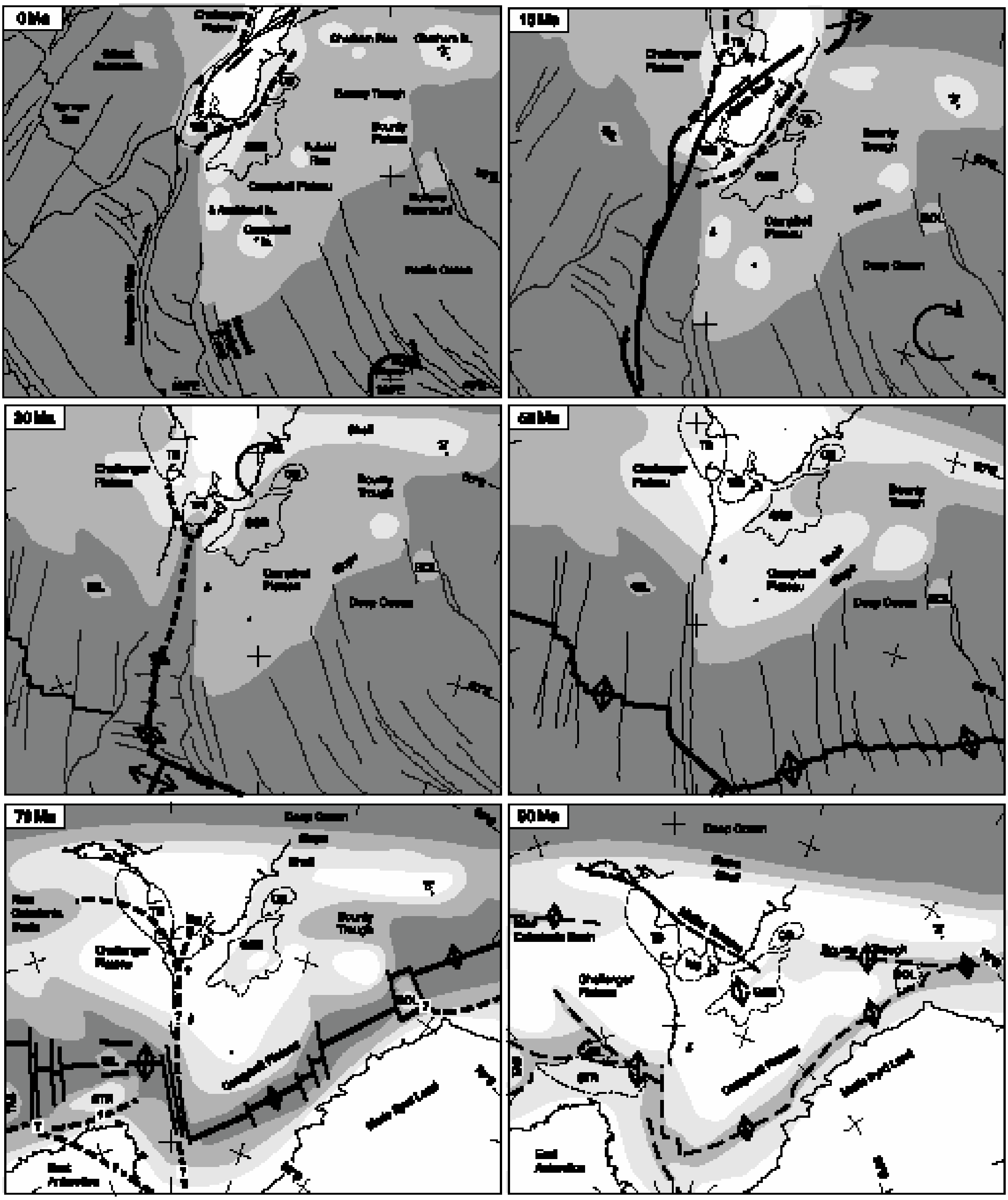

Figure 7: Paleogeographic reconstructions of southern New Zealand, showing locations of Canterbury Basin (CB), Great South Basin (GSB), Western Southland basins (WS), and Taranaki Basin. Darker shades show progressively greater water depths (land, shelf, slope, deep ocean). Arrows show direction of plate motion and black lines show seafloor fabrics. 100-80 Ma, final breakup of Gondwanaland; 80-55 Ma, minor faulting in Taranaki Basin and western South Island; 55-45 Ma, quiescence; 45-0 Ma, evolution of present Australia-Pacific plate boundary from extension to transpression as the relative pole of rotation migrates. Modified after Cook et al. 1999.

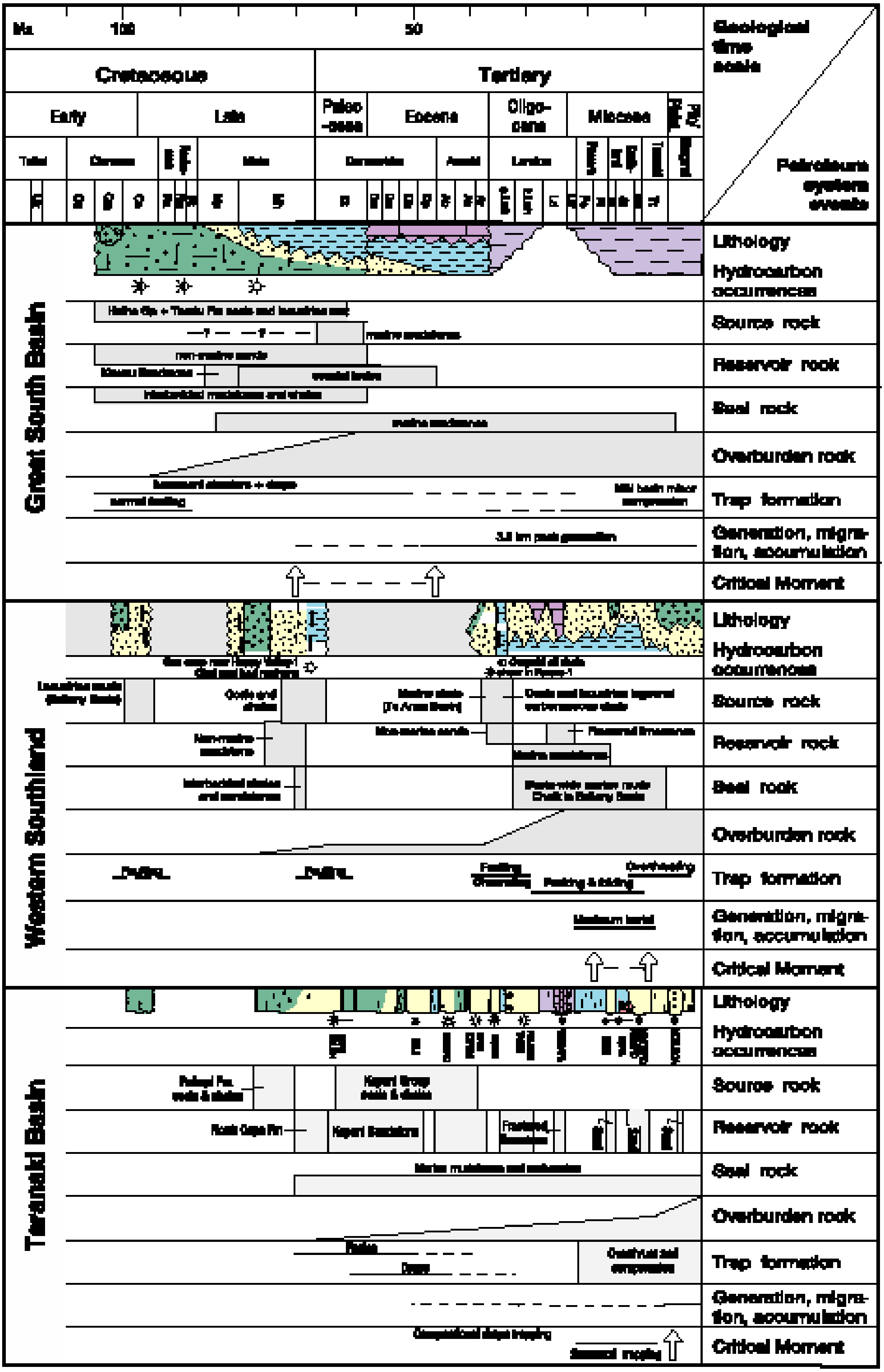

Figure 8: Petroleum systems of the Great South, Western Southland, and Taranaki basins. Modified after King & Thrasher (1996) and Cook et al. (1999).

Phase 2: Late Cretaceous-Paleocene transtension (80-55 Ma)

Seafloor spreading in the Tasman Sea and South Pacific Ocean was well established by the end of chron 33r (79-83 Ma). Continental faulting over most of New Zealand ceased as plate motion became focused on the spreading ridges. However, evidence for continued faulting is known locally in northwestern South Island, Western Southland, and Taranaki Basin.

Although the faulting is relatively localised and probably represents only minor amounts of relative plate motion, its effects were significant from a petroleum exploration perspective. Faulting locally controlled facies and hence source-reservoir rock distribution in Taranaki Basin (Pakawau Group) and Western Southland (Ohai Group).

Phase 3: Late Eocene-Oligocene rifting and transtension (45-25 Ma)

At about 45 Ma, a new plate boundary was initiated through New Zealand. During its early stages of development the pole of relative rotation was very close to South Island, resulting in progressively greater extension south of New Zealand, but only very slight deformation within South Island. Extension during this interval formed the Solander Basin, Solander Trough, and a passive margin along the western edge of the Campbell Plateau. During Oligocene time, the pole of relative plate rotation migrated southeast, causing a change to transtension and strike-slip at progressively increasing tectonic rates in South Island (Figure 7).

Phase 4: Miocene-Quaternary transpression (25-0 Ma)

The changing relative plate motion has resulted in progressively greater tectonic rates and an increased strike-slip and transpressional component with time (Figure 7). This has led to the uplift of the Southern Alps, widespread sedimentation of reservoir and overburden rock, and the formation of compressional structures.

Petroleum systems of South Island basins

Petroleum systems of the Great South, Western Southland, and Taranaki basins are compared in Figure 8. Source rocks are primarily mid Cretaceous-Eocene coal measures with varying marine influence, but Cretaceous-Eocene lacustrine mudstones in Western Southland and Paleocene marine shales with TOC up to 8% in Great South Basin are also proven to be good source rocks. Reservoir rocks are primarily sandstones or fractured limestones. Seal rocks are mudstones and carbonates. In the case of Western Southland, Taranaki Basin, and western Canterbury basin, rapid burial and hence increased maturity has been associated with Miocene-Quaternary convergent tectonics and increased sediment supply. In the Great South Basin and eastern Canterbury Basin, burial is mainly associated with rift-related subsidence.

Western Southland-Taranaki Basin comparison

There are many similarities between the stratigraphic and structural histories of Western Southland and the Taranaki Basin. This is expected because the two regions were adjacent to each other for most of their Cretaceous-Paleogene history (Figure 7). However:

1. The Solander Basin experienced greater Eocene-Oligocene extension and subsidence than elsewhere around South Island, probably resulting in increased heat flow, more rapid lateral facies changes, and greater fault control on facies.

2. Although there has been very significant shortening across the Taranaki Fault, the western Balleny Basin and onshore Western Southland has been more deformed during Miocene-Quaternary time than most of the Taranaki Basin. Structures are therefore more complex over most of Western Southland, local uplift has been greater, and there has been greater potential for loss of hydrocarbons after primary migration.

3. Western Southland is known to contain Late Eocene lacustrine mudstone (Orepuki mudstone) with excellent source rock characteristics.

Great South-Canterbury-Taranaki Basin comparison

The Great South Basin and Canterbury Basin are similar and formed during the same mid-Cretaceous rifting event. Both basins have condensate discoveries (Galleon-1 in Canterbury Basin flowed gas at 10 mcfd with 2300 bpd condensate from a 21 m hydrocarbon column). The basins differ from Taranaki Basin in two important respects. Firstly, their main phase of formation was primarily related to mid-Cretaceous extension of the Campbell Plateau and Bounty Trough, rather than later Cretaceous and Cenozoic tectonics. Secondly, the magnitude of Cretaceous subsidence was greater in the Great South Basin and eastern Canterbury Basin, leading to a greater marine influence over most of their Cretaceous-Cenozoic history.

Coal measures with varying marine influence have been demonstrated to have good potential for mixed gas and oil in all three basins (Killops et al. 1997, Sykes et al. 1998, Cook et al. 1999). In the Great South Basin, Cretaceous-Paleocene marine shales are also proven to be excellent oil-prone source rocks, but are only thought to be mature in deepest areas of the basin, or in regions of elevated heat flow.

Overview of prospectivity

The Great South, Canterbury, and Western Southland basins are all proven to contain the necessary components of a viable petroleum system, and each basin has oil seeps or sub-commercial discoveries. The very under-explored nature of southern South Island has both advantages and disadvantages. The advantages are that there are many undrilled structures and it is relatively easy to obtain an exploration permit. The disadvantages are that the region is remote from infrastructure and markets, and that the distribution of source, reservoir, and seal rocks is known only from sparse well data, seismic facies mapping, and outcrop analogues.

The small number of wells makes risk assessment difficult for the region, but initial data from all the basins are promising. Obvious similarities between Western Southland and the Taranaki Basin, combined with outcrop knowledge of the Orepuki oil shale, make Western Southland prospective. The region has the additional advantage that it may be possible to make discoveries onshore.

Oil and gas shows in 6 of the 12 offshore wells, combined with the discovery of two sub-commercial gas-condensate fields, demonstrate that the Canterbury and Great South basins contain significant volumes of hydrocarbons. A discovery of modest size onshore in the Canterbury Basin may be economic to develop, due to the close proximity of Christchurch, South Island's biggest city. However, the remote offshore nature of the main basin area requires that a sizeable resource inventory be established before it is economic to develop hydrocarbon production. The combined size of the two basins is large (~100,000 km^2) and there are many large untested structures. Therefore, it seems likely that continued exploration, combined with economic fluctuations, will eventually make it feasible to develop the offshore Great South and Canterbury basins.

In conclusion, the basins of southern South Island certainly contain both liquid and gaseous hydrocarbons. However, the basins are remote, under-explored, and there is no commercial hydrocarbon production in the region. Drilling the basins remains a moderately high risk venture, but has the potential for high return. If hydrocarbon production in the region is developed, it is likely that a large resource inventory will ultimately be established.

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