

PETROLEUM POTENTIAL OF THE WEST SOUTHLAND SEDIMENTARY BASINS

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Abstract

Seismic mapping of the West Southland basins as part of the Cretaceous and Cenozoic Project has elucidated the stratigraphic and structural history of the region. At the same time a range of potential hydrocarbon traps have been mapped, many for the first time.

Onshore, the Te Anau and Waiau basins developed initially as tensional rifts and potential traps were formed by rollover against listric faults. In the late Oligocene, uplift and erosion is locally important near the basin axes. This unconformity marks the onset of regional compression which continues to the present day. Neogene compression and syn-tectonic sedimentation produced a variety of possible traps by tightening earlier tensional rollover and by rollover on the back of thrusts and reverse faults.

Offshore, from east to west, the Solander, Waitutu and Balleny basins shared a similar history to that of the onshore basins. North-easterly-trending normal faults controlled sedimentation during the Cretaceous and Palaeogene. The effects of Neogene compression are more intense in the northeast and die away to the south and west such that the Balleny Basin appears to have been relatively undeformed by compression. Several closures were formed during the compressive episode as sedimentary basin fill was driven back up fault ramps to form large anticlines against basement blocks.

With coal measures buried to depths which should ensure maturity and abundant marine mudstones in the Miocene section it is likely that hydrocarbons have been generated and trapped in the region. The number of closures both onshore and offshore suggests that the region is a target-rich environment.

Introduction

The Western Southland region was the focus of an extensive seismic mapping project undertaken by the Division of Geology and Geophysics (GEO) of D.S.I.R. as part of the Western Southland Cretaceous and Cenozoic Basins Project (Turnbull *et al.*, 1991 - in press). Eight horizons (including the sea-bed) were mapped at a scale of 1:250,000. Isopach maps were generated for the intervals between the mapped horizons and a total sediment isopach map was also produced (Uruski and Cahill, 1991). Onshore, seismic data used was shot by New Zealand Petroleum (Dundon, 1985) and Amoco (Dawson Geophysical Co./Golden Geophysical Corp., 1986; Cendrowski and van Niewenhuise, 1987), and geological control was provided primarily by GEO's continuing programme of outcrop mapping, by early hydrocarbon exploration wells (Alton Oil Development Ltd., 1958) and latterly by the results of modern hydrocarbon exploration drilling (Carter and Rainey, 1988a, b). Offshore, control relied, almost entirely, on two hydrocarbon exploration wells, Parara-1 (HIPC0, 1976) and Solander-1 (BP, 1985). More than 3,000 line kilometres of seismic data of various vintages were interpreted for this project. All of these data are now open-file (HIPC0, 1973, 1976; Clarke, 1986).

In the course of this work, the tectono-stratigraphic history of the basins was elucidated, units containing possible

source, reservoir and seal rocks were identified and a wide range of structural closures were mapped (Uruski and Turnbull, 1990; Turnbull *et al.*, 1991 - in press). This article reviews the region's stratigraphy and tectonics, outlines the probable hydrocarbon kitchen areas and discusses the likelihood of structural trapping of hydrocarbon fluids.

Locations and Physiography

The study area includes the Te Anau and Waiau basins onshore and the basins at the head of the Solander Trough offshore (Figure 1). The offshore region is divided into the Solander and Balleny basins by the extension of the Moonlight Fault System. Both offshore basins started as several smaller discrete depocentres which filled, grew and merged with time.

The Te Anau Basin overlies the Fiordland basement in the north and west, is constrained by complex, faulted basement blocks of Triassic to Cretaceous island arc affinities to the east, and by the Takitimu Mountains to the south. The Waiau Basin is also bounded by the Fiordland Block to the west, and by the Takitimu Mountains to the northeast and the Longwoods Range to the east.

The Fiordland complex includes three major blocks. Southwest Fiordland is characterised by Paleozoic metasediments, and Western Fiordland includes a wide range of metasediments and gneisses. Eastern Fiordland is

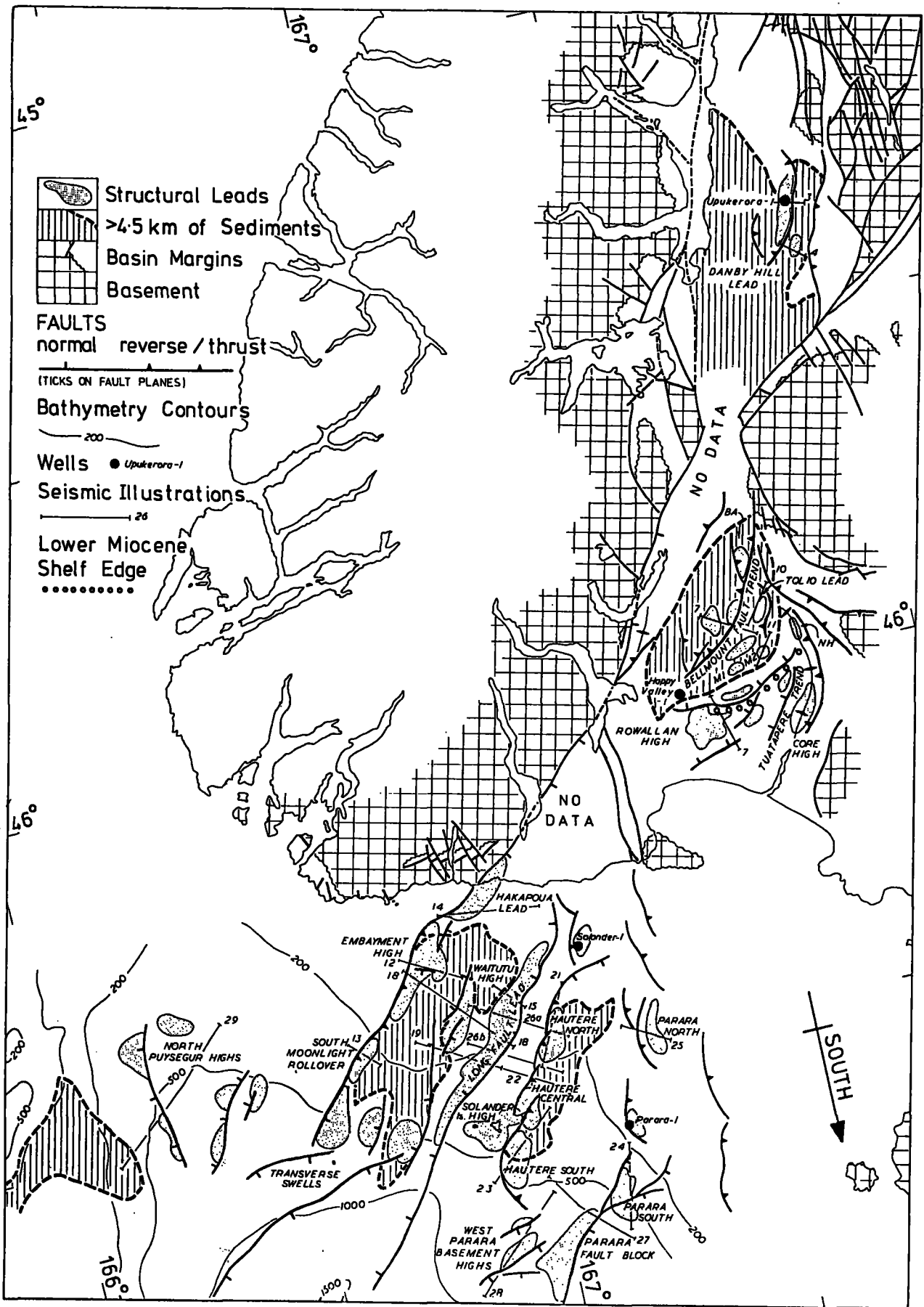


Figure 1: Location map showing sedimentary basins, controlling faults, recent exploration wells, inferred kitchen areas and structural petroleum leads. Leads, structural trends and wells referred to in the text are labelled: WAIU BASIN - NH-Closure in Nose of Tuatapere Anticline, BA-Bellmount Anticline, M1 and M2 are the possible carbonate mounds. Ticks on faults show dip of fault planes, triangles indicate thrusts, straight ticks indicate normal faults. Bathymetric contours at 200, 500, 1000 and 1500 metres.

dominated by granitic intrusives and was an important sediment source area for the onshore basins, particularly in the Eocene and Oligocene. The Takitimu Mountains and the Longwoods Block are components of a Permian island arc, the Brook Street Terrain (Bishop *et al.*, 1985) which extends southwards into Stewart Island. Together, the Fiordland complex and the Brook Street island-arc rocks form basement in the study area.

Hump Ridge separates the Waiau Basin from the onshore portion of the Waitutu Basin. It is an uplifted ridge cored by basement rocks with Fiordland affinities (Bishop *et al.*, 1991). This ridge passes southeastwards into the shallow basement of the Hump-Stewart Shelf.

The Solander Basin is traversed by four fault systems which divide the basin into three sub-basins. The Solander Ridge, bounded by Long Fault to the west and the Solander Fault to the east separates the offshore part of the Waitutu Basin from the rest of the basin. The Parara Fault Trend further subdivides the Solander Basin into the Hautere (the original name for Solander Island) and Parara sub-basins. Finally, the eastern basin margin is formed by the Hump-Stewart Shelf which was carried over the eastern part of the basin by the Hump-Stewart Thrust System.

The Balleny Basin is floored by a complex fragmented basement which divides it into two main sub-basins, the Providence Basin, the offshore extension of the Puysegur Group, and the Puysegur Basin which underlies the bathymetric Puysegur Bank. Puysegur Bank is the northernmost end of the MacQuarie Ridge, the island arc system below which the Australian plate is being subducted below the Pacific plate.

Although water depths increase to the south, depths to basement also increase in the same direction and sediment thicknesses of more than 3 kilometres and (as much as 5 kilometres) are observed at the southern termination of data coverage. The southernmost extent of thick sediment cover will remain unknown until good quality seismic data are shot in deeper water. It is possible that the basins could continue southwards into the Emerald Basin, perhaps a further 500 kilometres.

Tectonics and Stratigraphy

Five tectonic episodes are recognised in the West Southland region; Cretaceous extension, Paleocene to mid-Eocene rebound, Late Eocene to Oligocene extension, Late Oligocene to Pliocene compression and Pliocene extension. Each of these episodes is characterised by sedimentary and structural responses. A generalised stratigraphic column (Figure 2) outlines the times during which Cretaceous and Tertiary sediments are known to have been deposited in the region. The shaded regions represent either non-deposition or times for which no representatives have been observed. New Zealand series and stage names are given. Undulating lines represent unconformities which may be either regional or local in extent.

Cretaceous Extension

Cretaceous sediments were deposited in extensional basins (Figure 3) which developed as the Gondwana margin stretched and thinned prior to, and following, the development of the Tasman Sea. The major structures, particularly the Waitutu Basin, were essentially half-grabens controlled by northeast-trending normal faults, downthrown to the

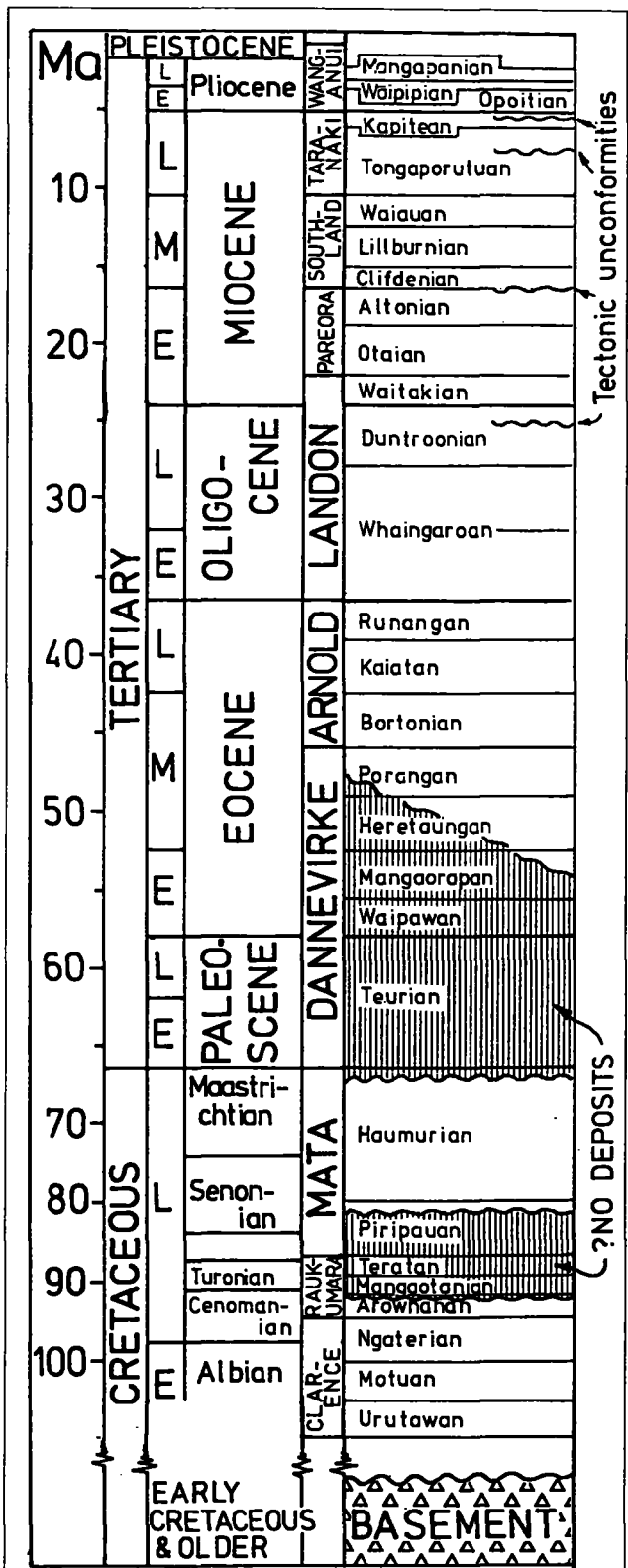


Figure 2: Generalised stratigraphic column for the Western Southland Region.

northwest. Structural development appears similar to that of non-magmatic passive margins such as Galicia (Mauffret and Montadert, 1987).

Two Cretaceous sequences are represented onshore, separated by a period of non-deposition of 10 Ma and by a distance of 90 kilometres. The Puysegur Group (Bishop, 1986; Lindqvist, 1990) of southwest Fiordland (Figure 1) is of Early Cretaceous age and the Ohai Group at the

WAITUTU BASIN

part of line S84-29

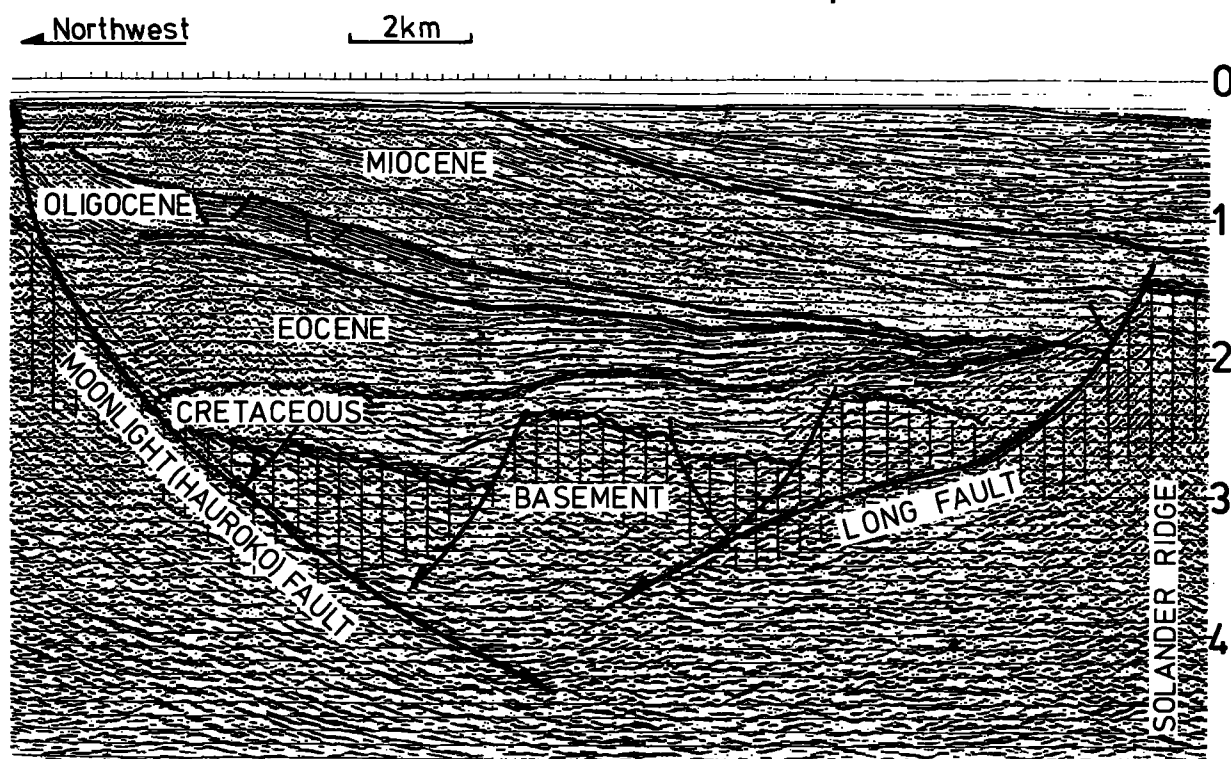


Figure 3: Seismic Line across Waitutu Sub-basin. Note southeasterly diverging fans of Cretaceous sediments controlled by northwesterly throwing faults. Movement commenced on the Moonlight Fault System in the Eocene and simultaneous sedimentation produced the northwesterly diverging wedge. Latest and Post-Miocene reversal on the Moonlight Fault System resulted in truncation of Miocene and later sediments at the sea-bed.

northeastern corner of the Waiau Basin is of Late Cretaceous age (Bowen, 1964; Sykes, 1985). Both Groups consist of terrestrial sediments. The Puysegur Group sediments represent a remnant of a widespread lacustrine rift basin (Lindqvist, 1990) containing abundant black shales in several facies while the Ohai Group includes thick (20 m) sub-bituminous coals which have been mined for many years.

Cretaceous rocks have not been tested by the drill nor observed in outcrop at other locations. However, seismic interpretations suggest that Cretaceous rocks may be widely present within at least five discrete sedimentary basins and particularly in the Waitutu and Waiau basins (Figures 3 and 4).

Paleocene to mid-Eocene Rebound

Paleocene rocks are unknown in the region. It is thought that Western Southland was uplifted during the Paleocene to form a source area that may have fed the Great South Basin (Anderton *et al.*, 1982; Beggs, pers. comm.). Late Cretaceous to Early Tertiary peneplains have been described from the region since the early part of this century (e.g. Suggate *et al.*, eds., 1978). Rebound of the new continental margins, following opening of the Tasman Sea could account for this uplift. Although no Paleocene sediments have been drilled in the offshore regions, where only two wells have been drilled, Paleocene rocks may be present to the west of Solander Ridge or to the south of the explored region.

Late Eocene and Oligocene Extension

The Moonlight Fault System originated in the Late Eocene as a result of renewed tension, probably with a dextral shear component. The main expression of this faulting was the formation of southeastwards-throwing normal faults which effectively broke the backs of the Cretaceous listric fault blocks to form a new half-graben along the Parara Trend and to create full grabens in the Hautere and Waitutu and Providence basins. Depositional style was similar in the Eocene to that of the Cretaceous, with fault-controlled terrestrial sedimentation, this time northwestwards-facing half-grabens (Figure 3). Eocene sediments in the Puysegur Basin appear to be normal marine basin margin sediments on seismic sections, although much of the basin has been uplifted and removed by later tectonism.

The first recorded sediments following the Cretaceous were the Middle and Late Eocene Balleny Group of the Puysegur region, followed 10 million years later by the Nightcaps Group which were widely deposited in the Waiau Basin. In both regions, terrestrial sediments, including coal measures, were succeeded by shallow marine sequences. In the Waiau Basin, marine sandstones were encountered by the Happy Valley-1 well (Carter and Rainey, 1988b). Along the eastern side of the Waiau Basin, the latest Eocene sediments represent a widespread lacustrine sequence.

A marine transgression commenced in the Late Eocene and continued into the Oligocene to culminate at the

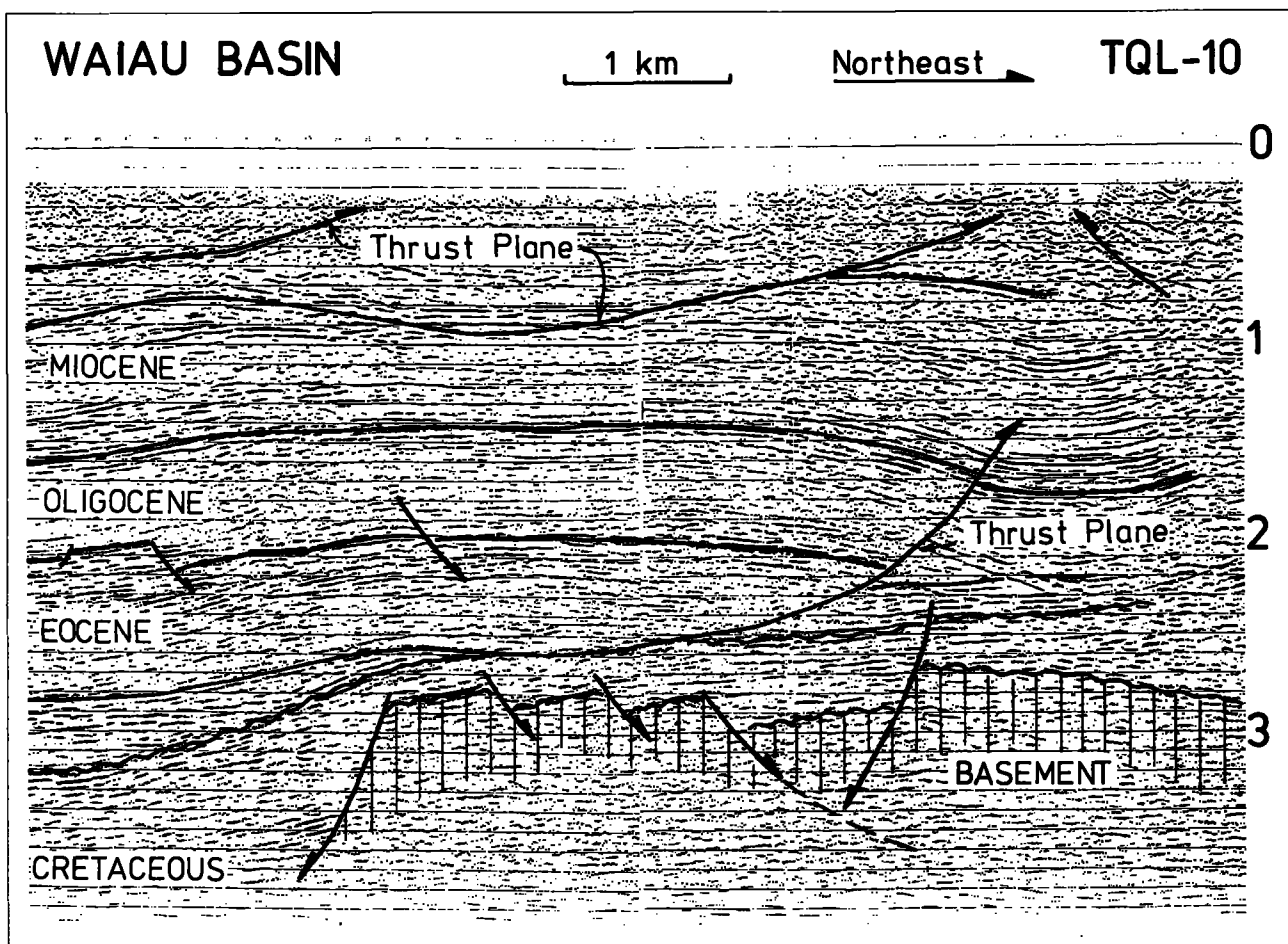


Figure 4: Part of Line TQL 10, Waiiau Basin showing the TQL10 structure. Direction of thrusting is eastwards or towards the reader. Possible source rocks are Cretaceous and Eocene coal measures. The Eocene Sequence is sand-rich and the Oligocene sequence contains distal submarine fans in a marine mudstone background. Both reservoirs and seals should be encountered in these sequences. The lower part of the Miocene sequence is carbonate-rich and may provide good reservoirs and the rest of the Miocene is dominated by mudstone.

maximum extent of flooding in the Late Oligocene. Deposition was apparently much slower during the Oligocene as sediment thicknesses are correspondingly less (Figure 3). This may partly be due to an increased strike-slip component to faulting and consequently a decreasing tensional component. Although the Oligocene was a period of transgression (and thin sequences might be expected, sedimentation easily maintained pace with faulting).

During the Oligocene, submarine fans were deposited across the margin of Fiordland into a deep marine muddy environment. The eastern side of the Waiiau Basin received only thin mudstones except for an easterly derived carbonate-rich submarine fan. In the Late Oligocene, the western clastic fans were succeeded by shallow marine sandstones. In the onshore Balleny Basin, Oligocene marls unconformably overlie the Late Eocene shallow marine sequence. This unconformity is not observed offshore, so it may be a local tectonic feature.

The Solander-1 well stopped in Late Oligocene coal measures sitting on a quartz-diorite basement while most of the Oligocene sequence in the Parara-1 well was deposited in marine conditions. Seismic mapping (Uruski and Cahill, 1991) suggests that the Parara and Hautere sub-basins were connected during the Oligocene and that they were also connected to the Waitutu and Balleny Basins across the

northern end of Solander Ridge. Large areas of land remained emergent throughout the Oligocene, particularly along the Hump-Stewart Shelf, the Parara High, the Solander Ridge and below the present eastern flank of Puysegur Ridge.

Near the end of the Oligocene, an erosional unconformity removed much of the Oligocene sequence from the centre of the Waiiau Basin and cut down into the underlying Eocene in places (Uruski and Turnbull, 1991). The denuded region is approximately along strike from the Solander Ridge. The western flank of the Solander Ridge is also denuded of Oligocene sediments and in some regions of Eocene sediments also. This flank of the Waitutu Basin was the hinge zone for deposition of both Eocene and Oligocene sediments in the Waitutu Basin.

This tectono-stratigraphic episode can be explained by onset of dextral transtensional movement in the Late Eocene and by a gradual southwards migration of the pole of rotation of the Pacific plate relative to the Australian plate (Stock and Molnar, 1982). This caused a gradual decrease in the tensional component while the transverse component increased. In the Late Oligocene, relative motion in the Southland region, if not along the proto-Alpine Fault, went through a neutral, pure strike-slip phase before becoming transpressional. This is witnessed by the decrease in rates of normal faulting observed on seismic data (Figure 3), by the onset of growth

of the Hautere North anticline (Figure 5) and by the eventual formation of the Late Oligocene erosional unconformity.

Late Oligocene to Pliocene Compression

The Late Oligocene unconformity marks the onset of compression in Western Southland. Strike-slip motion, principally along the Moonlight Fault System, became progressively more compressional with time. Major thick-skin thrusts developed along the Moonlight Fault System (Uruski and Turnbull, 1991). The Takitimu Mountains, carrying the Ohai Depression on their leading edge, were thrust over the northern part of the Waiiau Basin and the Hump Ridge-Stewart Shelf region was thrust similarly over the margin of the Solander Basin. In both cases, these thrust wedges loaded the basins in front, effectively forming foreland basins bounded laterally by the strike-slip Moonlight Fault System. Uplift along the Hump Ridge Thrust explains the sequence of unconformities observed in the southern Waiiau Basin.

While these major thrusts were forming along the Moonlight Fault system, compressive stress was transmitted into the basins partly reversing many of the Eocene and Oligocene normal faults. Major structures, such as the Solander and Parara anticlines, were initiated by the earliest compression and grew while compression continued. The Solander Basin widens southwards and a basement ridge, which strikes approximately east-southeast, intervenes (Uruski and Cahill, 1991). Very little compressive stress was

transmitted across this ridge or to the west of the Moonlight Fault System.

The Early Miocene records shallowing in the Waiiau Basin with the development of a broad carbonate shelf along its eastern margin. This shelf fed carbonate-rich turbidites into the central Waiiau Basin. A local erosional unconformity is mapped in the southern Waiiau Basin at the end of the Early Miocene. This unconformity cut a channel, trending almost north-south into the underlying Oligocene sequence. A thick southerly transported fan sequence occupies the northern part of the offshore Waitutu Basin, feeding out into what appears to be a quieter marine environment. Marine sandstones, limestones and mudstones are recorded in the Parara-1 well while thick sandstones and dark grey, calcareous mudstones were sampled by Solander-1. These latter sediments included silty and coaly partings.

The Late Miocene was dominated by sandy facies onshore, and although both fans and channel sands are observed offshore (together with occasional limestones), the Late Miocene offshore was dominated by mudstone deposition. The lateral extent of the basins increased offshore as more basement highs were inundated and covered by sediment. By the end of the Miocene only the northern Puysegur High in the Balleny Basin and the Hump-Stewart Shelf in the eastern Solander Basin remained free of sediments.

In the final phase of compression, the sediments of the northern Waitutu Basin were thrust up the ramp of the

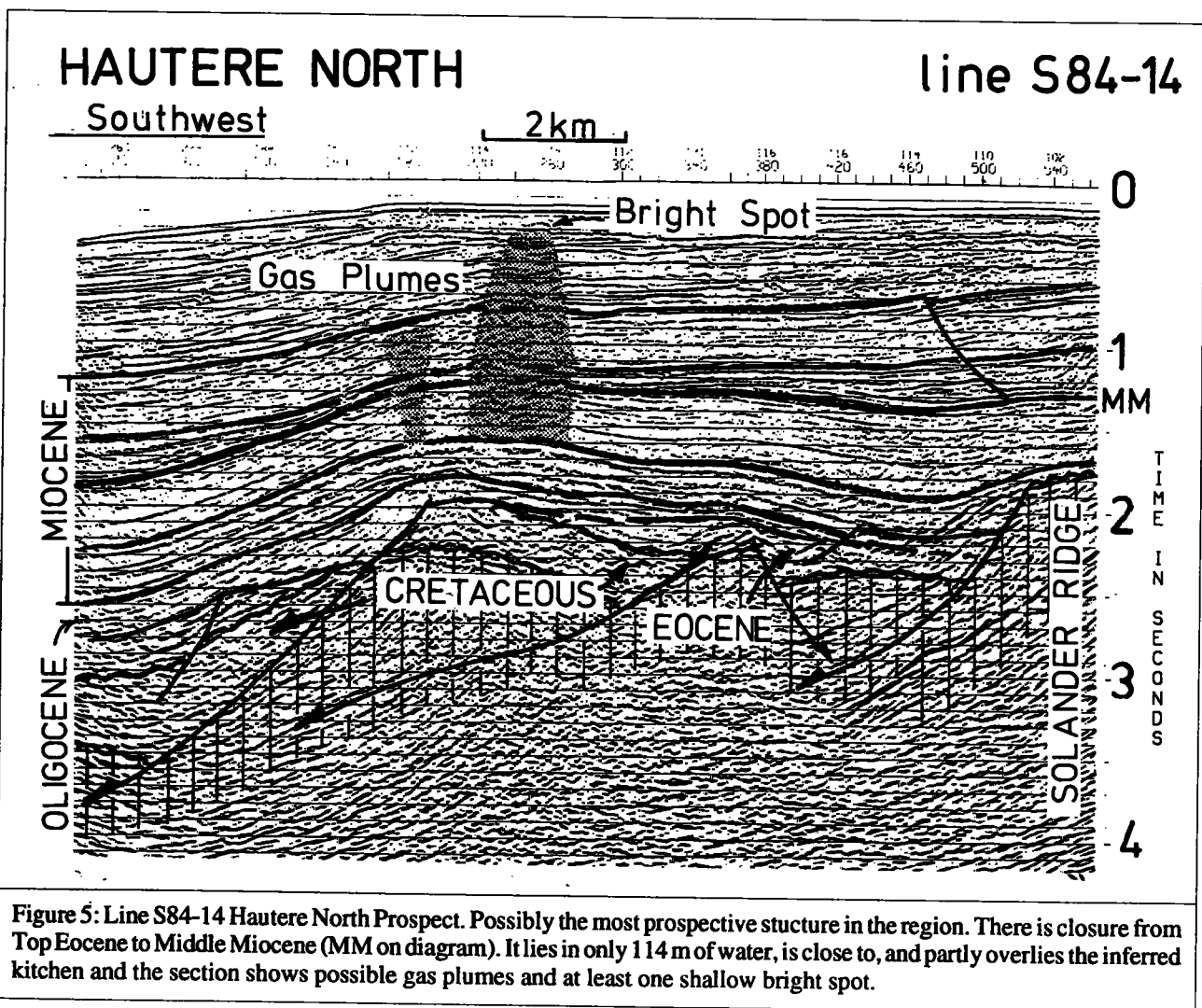


Figure 5: Line S84-14 Hautere North Prospect. Possibly the most prospective structure in the region. There is closure from Top Eocene to Middle Miocene (MM on diagram). It lies in only 114 m of water, is close to, and partly overlies the inferred kitchen and the section shows possible gas plumes and at least one shallow bright spot.

Moonlight Fault System until Eocene rocks were truncated either at the sea-bed or onshore in the Waitutu Basin. Many of the structural closures observed in this study were completed during this phase.

At the same time, the western margin of the Balleny Basin was uplifted to form Puysegur Bank. Consequently, the entire sedimentary column from Late Eocene onwards is now exposed at sea-bed outcrop (Figure 1). This uplift must be related to the developing subduction zone to the west in Puysegur Trench. Puysegur Bank itself is a thick sedimentary wedge; basement is observed at depth and prominent basement highs underlie the eastern flank of Puysegur Bank.

Pliocene-Pleistocene Tension

The final tectonic episode produced a set of normal faults in the overthrust Hump-Stewart Shelf block. Two possible causes could be gravitational collapse following thrusting and regional "back-arc" tension resulting from subduction of the Australian plate below the Pacific plate at the Puysegur Trench.

Onshore, the Pliocene sequence records continued regression with terrestrial sediments encroaching southwards, well into the Waiiau Basin. A restricted marine connection remained open around the northern end of Hump Ridge, although the southern basin was virtually isolated. Volcanic mounds are observed on seismic data, along the offshore extension of the Moonlight Fault System, while the Solander Island volcanics are dated as Pleistocene. During the Pliocene and Pleistocene sediments overlapped the eastern basin margin offshore until (at the present day) several hundred metres of sediments overlie the Hump-Stewart Shelf.

From the Early Miocene onwards, the sequence in the Waiiau Basin appears to be regressive, while, in the present offshore region, marine sediments gradually encroached onto long-lived basement highs.

Hydrocarbons

Elements of Generation and Entrapment

One of the main problems for hydrocarbon exploration in Western Southland has been identification of a good source rock. However, possible source rocks are abundant. In the Cretaceous, coals, such as those at Ohai could be significant while lacustrine carbonaceous mudstones are plentiful onshore in the Balleny Basin and in parts of the Waiiau Basin. Equivalents of the Paleocene Waipawa black shales may be present in the offshore regions, particularly of the Balleny Basin. Black shales have been reported from both Campbell Island (Beggs, 1978) and the Great South Basin (Anderton *et al.*, 1982). In the Eocene sequences, both coals and lacustrine units are again abundant and coals were reported offshore in the Oligocene of the Solander-1 well. The only hydrocarbons produced from the Southland region so far come from an Oligocene oil shale near Orepuiki (Wood, 1969).

Sedimentary thicknesses of more than 4.5 kilometres are thought to be great enough to ensure maturation of the coal measures. Barrett (1988) and Shaheen and Hutson (1989) conclude that much of the coal measure sequences in the Waitutu and Solander basins must be mature. Similarly, the inferred coal measure sequences in the Waiiau Basin must also have reached a high degree of maturity. Barrett (1988) further concluded that peak maturation had been reached within the last 10 million years.

Sandstones are abundant in the column. Much of the Cretaceous and Eocene sequences observed onshore are terrestrial to shallow marine sandstones, often with good porosity. The Solander-1 well drilled a thick Oligocene sandstone sequence and also penetrated several hundred metres of Late Miocene sandstones. Similarly, the Parara-1 well encountered sands of Oligocene, Early and Late Miocene ages as well as thick Eocene sandstones.

Although marine mudstones are not observed until latest Oligocene to Early Miocene times, muddy facies are common throughout the Cretaceous and Eocene. In the onshore Balleny Basin lacustrine turbidite sequences contain much black mudstone which could act as both source and seal. The Cretaceous sequence in the Ohai Depression contains at least 10 % mudstone (Sykes, 1985; 1989) while mudstones are even more common in the overlying Eocene sequence. The Eocene of the onshore part of the Balleny Basin is largely marginal marine to marine and contains thick (approximately 150 m) mudstone with sandy interbeds before passing into a deepening Oligocene sequence of marls and cherts (Lindqvist, 1990). By the Miocene, marine conditions were well-established in most basins and marine mudstones are widespread.

Structural Leads

All the elements necessary for hydrocarbon generation and entrapment are present in the Western Southland Basins. The area's complex deformational history resulted in a large number of structural closures in all basins. Cretaceous and Eocene faulting was tensional on listric normal faults which produced gentle rollovers on the downthrown blocks and drape over upthrown shoulders. Later compression tightened many of these tensional rollovers and created many more. The final section of this article discusses structural closures mapped during the present project. Stratigraphic traps are not discussed although these will be of increasing importance once the presence of hydrocarbons in the Western Southland basins is proven.

Waiiau Basin

There are three main structural trends which may provide petroleum leads in the Waiiau Basin. These are the Tuatapere Anticline on the eastern flank of the basin, the Rowallan Trend in the south central part of the basin and the Bellmount Structural Zone in the north central basin (Figure 6).

The Tuatapere Anticline is cored by a basement horst block which has been overlapped by inferred Cretaceous sediments and overlain by a terrestrial Eocene and marginal marine sequence followed by Oligocene to Pliocene marine sediments. Miocene and Pliocene compression resulted in development of a large rollover anticline on the upfaulted side of the eastwards-dipping Tuatapere Thrust. Following uplift, the anticline was eroded to expose Late Eocene sediments in its core.

The Tuatapere Anticline plunges northwards, curving to northwestwards. Below the eroded core of the anticline there is closure only at top Cretaceous level, but in the nose of the plunge, closure is observed at all levels from top Cretaceous to Late Miocene. The core high is by far the larger structure, with an area of approximately 20 square kilometres, while the closure at the nose of the anticline generally covers less than 5 square kilometres. The core high would have to rely on Late Cretaceous or Eocene mudstones for seal and

migration from within the basin for charge. Reservoir should not be a problem. The closure at the nose of the Tuatapere Anticline however, is closer to the potential source area and buried by a Miocene and Pliocene succession which includes thick mudstone.

The Rowallan High is developed on the shoulder of a normal fault along the northwestern flank of the Tuatapere Anticline. It is closed between the top basement and the top Eocene surfaces and has an area of approximately 40 square kilometres at the top Cretaceous closure. As in the Tuatapere core high, the source for any hydrocarbon charge in this structure, would have to be in the deep part of the basin to the north. However, seals of Oligocene age may be provided by the deep marine mudstones observed elsewhere.

At the surface, the Bellmount Structural Zone is exposed as a major eastwards-verging fault and an anticline system which carry the McIvor Syncline as a piggy-back basin. The Bellmount Fault is the surface expression of a set of southeastwards-verging reverse faults and thrusts which were generated by severe compression of pre-Pliocene sediments against the listric normal Hauroko Fault. As these sediments were pushed up the steepening-upwards fault ramp, constriction increased and caused folding and reverse faulting and thrusts in the sedimentary pile. A series of rollover anticlines developed on the backs of the thrusts and many are preserved in good positions to form structural traps.

The core of the Bellmount Anticline crops out at the surface, is complexly faulted, and may not be a good trap unless there is a particularly good seal. However, there are a total of seven distinct closures in this structural zone with an average area of closure of approximately 10 square kilometres. One of only two possible Oligocene closures observed in the Waiau Basin is located along this trend on seismic line TQL 10 (Figure 4). The TQL 10 structure may be the best lead in the Bellmount Structural Zone as it overlies the possible hydrocarbon kitchen area, it probably contains good marginal marine and marine sands of Late Eocene age and may contain the distal members of Oligocene submarine fans which were shed into a muddy, deep-water environment. The Oligocene sequence was succeeded by the ubiquitous Miocene deep-water marine mudstones.

The final lead in the Waiau Basin is a mounded facies of Middle Miocene age which may represent carbonate mounds. They are located basinwards of the Early Miocene carbonate shelf edge, are lensoidal and downlap onto the top Early Miocene reflector and onto later reflectors or, on some lines, they stack vertically.

Waitutu Sub-Basin

Three structural trends also form closures in the offshore Waitutu Sub-Basin; the Moonlight Fault System, the Long Fault System and a transverse swell running between these faults just south of the latitude of Solander Island.

The Moonlight Fault System continues offshore from the Hauroko Fault. Its history of movement started during the Eocene tensional phase and this fault has been a major control on sedimentation since. Many of the structures along it were formed by the Late Miocene and Pliocene phase of compression when the basin fill was pushed up its listric fault ramp. The northernmost closure, against a large embayment in the Hauroko Fault, is the largest, covering an area of approximately 40 square kilometres. Cretaceous,

Eocene and Oligocene surfaces are closed against the fault plane. Thick terrestrial sequences, probably including coal measures are believed to be locally mature, sandstones should be abundant in the Cretaceous and Eocene sequences and the Oligocene sequence may contain both sands and shales. The overlying Miocene sequence undoubtedly contains abundant marine mudstones.

Other closures are mapped further southwest along the Moonlight Fault System at both top Cretaceous and top Eocene surfaces. The top Eocene closures are four-way structural closures formed by less severe compressional ramping than that observed in the Waiau Basin. Their location suggests that they would have been more distant from land than the embayment high and consequently, the overlying Oligocene sequence may contain more mudstone and is probably an excellent seal. Any hydrocarbon charge into these structures would have to migrate from deeper regions to the north or from the south.

The Long Fault controlled Cretaceous sedimentation in the Waitutu Basin, but occupied the hinge position for deposition during the Eocene and Oligocene. Consequently, the Oligocene sequence is always thin or absent on the eastern side of the basin as the top Oligocene surface represents an unconformity. However, closure against the fault is observed at top Cretaceous, Eocene, Oligocene and Early Miocene surfaces. The top Cretaceous closure covers an area of approximately 90 square kilometres while the top Eocene and Oligocene closures are restricted to discrete structures. The closure at the top of the Early Miocene is stepped to the southwest along the Long Fault. Source, reservoir and seal for this lead is similar to those for the embayment high, although as the Oligocene is very thin or absent, the Early Miocene sequence may provide the seal for Late Eocene reservoirs.

The transverse swell consists of three discrete Cretaceous highs, each associated with faults but not reliant on faults for seal. The Eocene sequence appears to have been draped over the Cretaceous highs but no closure is observed at the top Eocene level. Each high has an areal extent of approximately 25 square kilometres. Their distance from land suggests that they may be sealed by the distal marine mudstones which should be expected further offshore.

Solander Basin

The two main structural trends in this basin are the Solander Ridge and the Parara Trend. Solander Ridge separates the Waitutu sub-basin from the main Solander Basin. It is a flat-topped basement ridge bounded to the northwest by the Long Fault and to the southeast by the Solander Fault Zone. The latter is a complex of northeast-trending fault planes probably originating in the Eocene. Solander Ridge formed a partial tectonic barrier to transmission of compressive stress into the Waitutu Basin with the most severe deformation contained to the east. The most spectacular expression of this, mainly Miocene, deformation is the Solander Anticline which can be traced a distance of fifty kilometres along the Solander Fault.

Four discrete closed highs are mapped along the Solander Anticline. The northern one was the site of the Solander-1 well which penetrated Oligocene terrestrial sediments sitting on basement. This well was dry, but it may not have been hydrostatically connected to the rest of the anticline because a splay of the Solander Fault Zone separates it from the

Northwest

2km

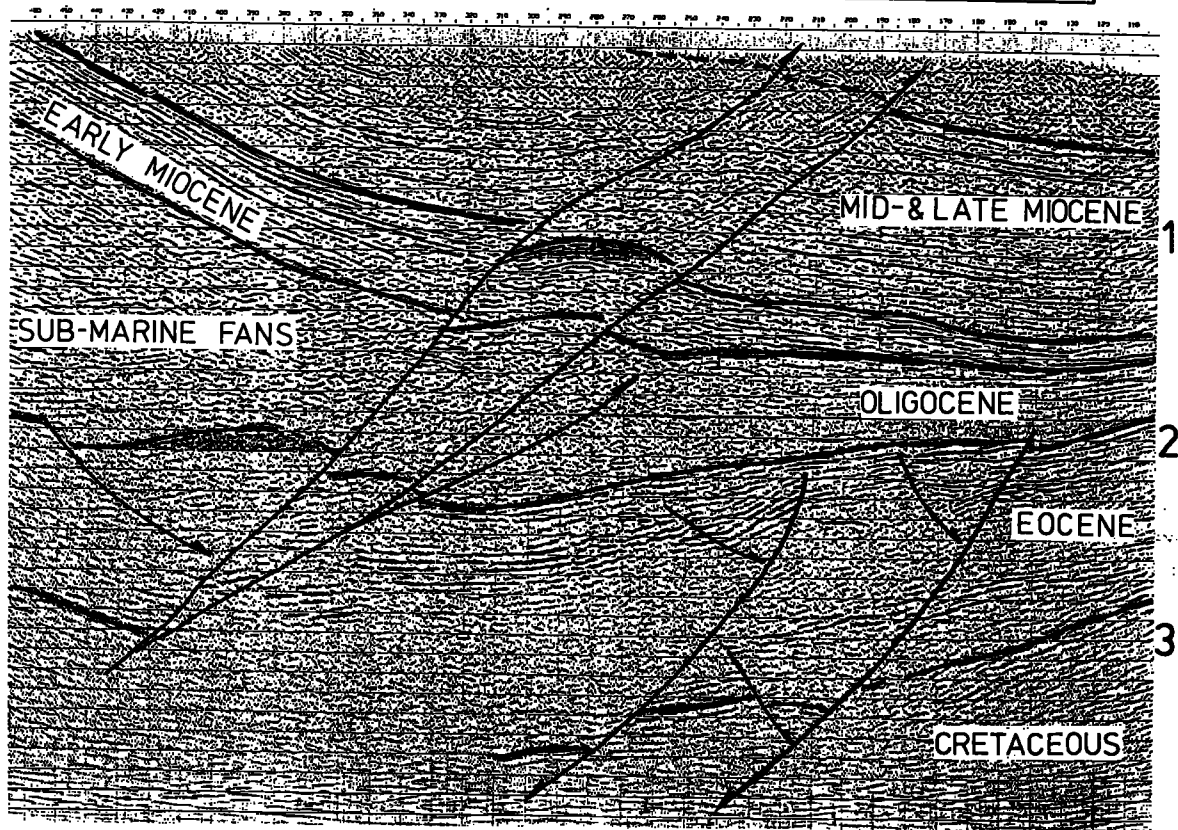


Figure 6: Part of seismic line TQL-15 across the Bellmount Fault Zone. The Bellmount Fault Zone is a complex of reverse faults which include both high angle reverse faults and thrusts. It has the appearance of an inclined compressive flower structure. It is likely that it was the site of Miocene dextral strike-slip motion. Rollovers are formed at various stratigraphic and structural levels within this fault system.

kitchen area. This splay brought Miocene sediments, probably mudstones, into contact with the Oligocene sandstones effectively sealing them from the probable kitchen area to the southwest.

The other three closures are ideally placed to receive a hydrocarbon charge from the inferred kitchen area immediately below. The northern structure of the three, Hautere North, has four-way closure at top Oligocene and top Early Miocene levels and fault closure at top Eocene. The largest closure is at top Early Miocene and it has an area of approximately 20 square kilometres. A seismic section approximately along the axis of the anticline (Figure 5) shows a noisy zone immediately below a shallow bright spot and above the peak of the structure. This may be a hydrocarbon indicator representing a gas plume rising from the reservoir.

Hautere Central is a complex high, developed at the overlap of two fault planes of the Solander Zone. Closure relies on the faults and the area is split by one of them. Closure is observed from top Oligocene to top of the Early Miocene covering an area of approximately 15 square kilometres.

The main expression of the Hautere South structure is at top Early Miocene level, where it only partly relies on fault closure. Its top Oligocene expression conversely relies entirely on fault closure. Hautere South is thought to have

formed as a result of Late Miocene compressional wrench faulting against the restraining curve of Solander Fault. The area under closure in this structure is approximately 40 square kilometres.

Both Solander-1 and Parara-1 sampled Early Miocene sandstones, if the same facies persists through the Hautere sub-basin, all three Hautere structures may contain reservoirs at top Early Miocene level.

A Late Miocene closure is observed below Solander Island. It is not known if it is real or whether a velocity pull-up caused by the Solander volcanics is responsible. The velocity effect of the Solander Island volcanics has not been allowed for in this study, but drape across the flank of Solander Ridge is also a possible cause. If the Hautere structures are charged with hydrocarbons, so could any structure at the crest of Solander Ridge.

Parara Sub-basin

The Parara Trend is a series of en echelon basement faults which were partially reversed by the Miocene compression event. Three main structures are mapped along this trend. Parara-1 was drilled on the flank of the closure and into the Parara Fault Zone. Closure is observed at top Eocene to top Early Miocene levels and covers a maximum area of approximately 7 square kilometres. "Dead oil" was reported

in this small structure, either because the crest of the structure was not penetrated or because oil had passed through. This structure is remote from the possible kitchen area in the Hautere Sub-basin, but it appears to have been charged at some time.

Parara South is a drape structure across a fault block. Four-way closure is observed at the top Early Miocene and the top of the Oligocene. The area enclosed by this structure is approximately 20 square kilometres. Both of these sequences were sand-prone in both Parara-1 and Solander-1. Parara South may be sourced from the inferred kitchen to the northwest or from the downfaulted half-graben it overlies. It is not immediately apparent on seismic data because of the velocity "pull-down" resulting from the sloping sea-bed.

Parara North is developed on the upthrust block of a partially reversed normal basement fault. Four-way closure is observed at top Early Miocene level and covers an area of approximately 20 square kilometres. A horizontal flat spot is visible on some lines and this may be a direct hydrocarbon indicator. This closure is updip of the Parara-1 structure, so any hydrocarbons which may have passed through Parara-1 could have migrated into the Parara North structure.

Balleny Basin

The only closures observed in the Balleny Basin cluster about the Puysegur North basement high. Most are small and rely on faults for closure. They are almost all tensional rollovers formed by listric faulting of the margins of this basement block. Some degree of compressive reactivation may be present but is not obvious. The largest cover areas of 15 to 20 square kilometres. They range in age from Eocene to Late Miocene.

It is unlikely that all possible structures have been mapped in this basin as the seismic grid is very loose and data quality is often poor. The seismic coverage in the Balleny Basin may be one of the prime limitations to locating structural leads as many structures could be lost in the loose grid currently available.

Best Prospect?

In the Waiiau Basin, the TQL 10 structure (Figure 4) has all of the attributes of a good prospect. It overlies the inferred

kitchen area, contains sandstone-rich Eocene and Oligocene sequences and should be well-sealed by the abundant Oligocene and Miocene mudstone.

Offshore, the Hautere North structure is relatively large and has closure at several horizons which probably contain good sands. It should be well-sealed by Miocene mudstones; it overlies the inferred kitchen, and does not rely on fault closure, although such fault closure would extend the structure. Its history of formation is well-documented by modern seismic data and a possible gas plume is imaged by one line (Figure 5). This structure would be the authors' prime target in the area.

Parara North and South have possibilities as do the other Hautere structures. The Waitutu Basin with its larger inferred kitchen should not be ignored, and the Balleny Basin needs modern seismic data and a sequence stratigraphic approach.

Modern seismic data will be essential in predicting the presence of reservoir and seal in the structures mapped to date, and particularly in determining the geographical extent of the basins. The southern limits of thick sedimentation is not yet known, although the northern culmination of a basin containing more than 5 kilometres of sediments has been mapped. Water depths reach more than 1500 m in the study area, but deep-water drilling is more commonplace now than when exploration started in the 1970s. The presence of large basins to the south would be an added attraction.

Conclusions

- Western Southland is a "target-rich" exploration environment.
- Parara-1 was "dry" because the well missed the structure. Parara North may have received the hydrocarbon charge which would have overflowed Parara-1.
- Solander-1 was dry because it is hydrostatically disconnected from the inferred kitchen.
- The oil show in Parara-1 indicates that oil has been generated and expelled from the inferred kitchen.
- Of the undrilled structures, Hautere North seems to have the best prognosis, and onshore the TQL 10 structure is most promising.

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