

STRATIGRAPHIC AND STRUCTURAL EVOLUTION OF THE WEST SOUTHLAND SEDIMENTARY BASINS

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Seismic reflection data from onshore Western Southland have been used for subsurface mapping for the Western Southland Cretaceous and Cenozoic Project. Seismic stratigraphy was controlled using outcrop geology in the first instance and was largely confirmed by two recent wildcat wells in the region.

The Te Anau and Waiau basins are structurally and stratigraphically complex. They developed initially as Cretaceous tensional rifts. In the late Oligocene, uplift and erosion is locally important near the basin axes. This unconformity, though not entirely explained structurally, marks the onset of regional compression which continues to the present day. Subsidence and sedimentation continued throughout the Neogene and was probably driven by the strong compression.

In the offshore region, three basins are recognised; the Balleny, Waitutu and Solander basins. Their history is similar to that of the onshore basins although the effects of compression decrease to the south and west.

The region's hydrocarbon potential remains unknown. Only four modern wells have been drilled in the 12 000 square kilometres covered by the basins. However, the model of structural evolution proposed here indicates two new plays which have yet to be tested.

INTRODUCTION

Location and setting

This paper stems from the regional seismic and geological mapping carried out as part of the New Zealand Geological Survey's Western Southland Cretaceous and Cenozoic Project (CCP). Fig. 1 shows the location of the five sedimentary basins that have been recognised within the region (e.g. Norris and Carter, 1980). They are the Te Anau, Waiau, Solander, Waitutu and Balleny basins. They cover an area of approximately 12 000 square kilometres, or 75% of the Western Southland CCP region, with the larger part offshore. The offshore basins continue southwards below the deep water of the Solander Trough, about which little is known.

The Fiordland basement complex forms the western margin of the onshore basins. Converging with Fiordland from the southeast is the arcuate outcrop of the Permian to Jurassic terranes of the Southland orocline (Wood, 1960). Almost bisecting the two basement masses, and generically part of the latter, is the discontinuous basement high of the Takitimu, Woodlaw, Longwood and northern Stewart Island blocks. The study area lies largely to the west of this Permian remnant volcanic arc.

To date, seismic mapping of the onshore basins has been completed, and the offshore part of the project has started. Observations presented on the offshore region are based on an assessment of earlier work, and the regional model is influenced by the tectonic style observed onshore.

Stratigraphy and structure

As more than 1000 km of modern seismic data were shot in the Waiau Basin (Cendrowski and van Nieuwenhuise, 1987) and more outcrop information is available from this basin than from Te Anau, sub-surface mapping for the Western Southland CCP was completed in the Waiau Basin first.

Published outcrop geology maps of the Waiau Basin (e.g. Wood, 1960, 1969) show sediments as old as Eocene cropping out at the basin margins. Sediments of Cretaceous age crop out only in the Ohai Depression. The overall structure is synclinal with the youngest rocks occupying the centre of the basin (Fig. 2, Table 1).

Several structures are visible in outcrop. In the north are the Monowai, Blackmount and Bellmount fault systems, with their associated en echelon folds. Hump Ridge brings Eocene and basement rocks to outcrop in the southwest and the Tuatapere Anticline is conspicuous at the eastern side of the basin. Seismic sections also show a broad synclinal pattern across the basin. It is only when outcrop geology is used to date the seismic reflectors that the full structural complexities of the basin are revealed.

A total of seven mapped horizons were necessary to describe adequately the structure of the Waiau Basin. These were seismic basement, possible top Cretaceous, top Eocene, top Oligocene, early Miocene, top Miocene and mid-Pliocene.

The possible top Cretaceous reflector is undated and could represent any time from end Cretaceous to mid-Eocene. For convenience it is referred to as possible top Cretaceous.

WEST SOUTHLAND BASINS Seismic Data Base

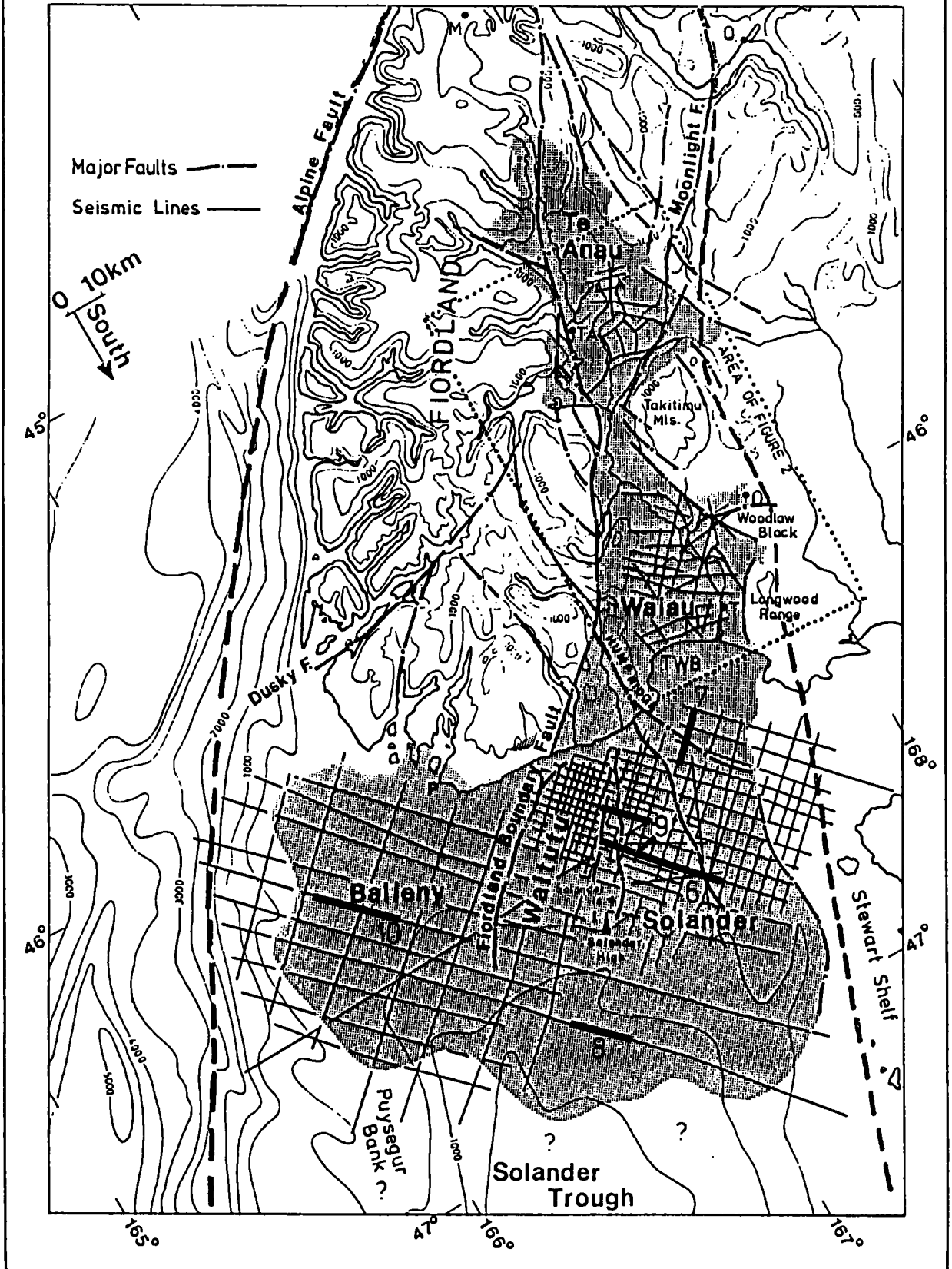


Fig. 1: Location of the West Southland Cretaceous and Cenozoic basins. Dashed lines are CCP boundaries, the Alpine Fault is traced offshore only as far as 45° South. M-Milford, TA-Te Anau, O-Ohai, T-Tuatapere, TWB-Te Waewae Bay and P-Puysegur Point. Major basement-involved faults are shown. Contours every 500 m, above m.s.l. on land and below m.s.l. off-shore. Contours taken from van der Linden *et al.*, 1972. Some seismic lines omitted for clarity offshore. Also shown are locations of Figures 6 to 9.

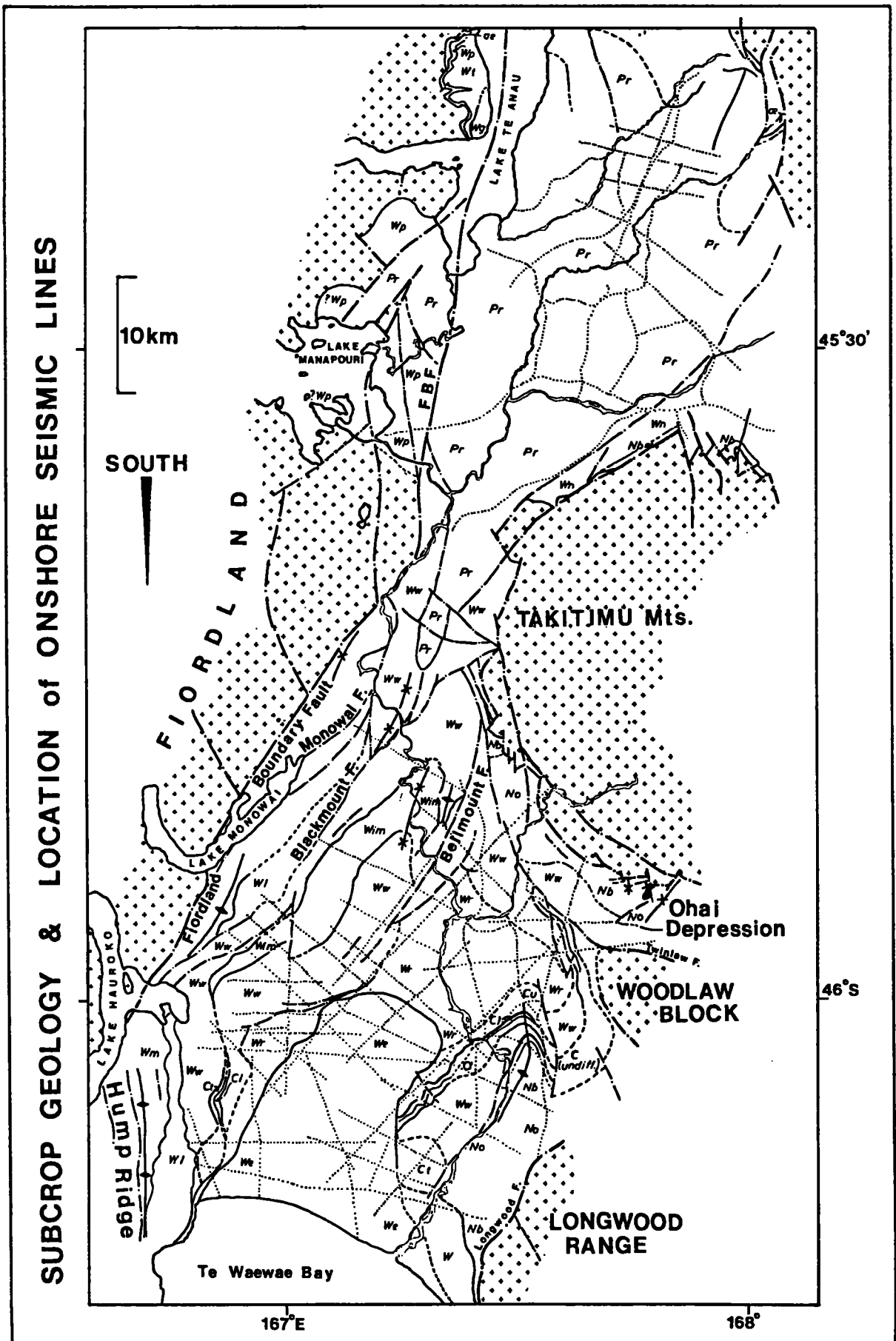


Fig. 2: Onshore basins. Outcrop geology and location of seismic lines (dotted). Shaded regions are undifferentiated basement. For explanation of formation names, see Turnbull *et al.*, 1989 and Table 1 (this paper).

The top Eocene reflector is tied to outcrop along the eastern side of the basin where the Orauea Formation (No, Fig. 2, Turnbull *et al.*, 1989) crops out in the core of the Tuatapere Anticline and along the banks of the Waiau River.

Oligocene sediments crop out widely around the Waiau Basin. On its eastern side, the base of the Te Karara Formation, dated at latest Oligocene (end Duntroonian, Edwards *et al.*, 1988) is tied into the seismic data set at several locations (Figs. 4d, 4e). The same lithostratigraphic unit occurs in the southwest part of the basin and to the north it merges with the base of the McIvor Formation.

The top of the McIvor Formation is contemporaneous with the top of the Forest Hill Formation in the east. These units together form a strong Early Miocene seismic marker horizon.

The base of the Rowallan Sandstone (Wr) is of Late Miocene age. It unconformably overlies earlier Miocene and Oligocene rocks in the southwest and is separated from the Te Waewae Formation by an angular unconformity of mid-Pliocene (Wood, 1969). Both of these unconformable surfaces were mapped to help elucidate Miocene and Pliocene tectonics.

Results from the Waiau Basin were extrapolated first northwards into the Te Anau Basin, then southwards into the offshore region. This paper attempts to show how a better understanding of the Waiau Basin was gained and how this helped in assessing the rest of the region. Attempts are made to highlight and explain similarities and differences and to fit them into a regional tectonic scheme. Finally, some comments on petroleum prospectivity are included.

SEISMIC DATA

Onshore

Apart from some poor-quality single-channel seismic data acquired in the Waiau Basin between 1963 and 1973, the first exploration data were shot by NZ Petroleum in 1982, 1984 and 1985. In 1985 and 1986, when Amoco acquired a further 1047 line km, a good-quality seismic grid became available for the Waiau and Te Anau basins. Amoco additionally reprocessed much of the earlier data and it is this data set, lodged with NZGS in 1986, which forms the basis of the onshore part of this study (Fig. 2). Under current regulations, this data base will remain confidential until 1991 or until the exploration licence is relinquished. However, the current licence operator, Petrocorp, has kindly allowed incorporation of results in this paper.

The 1985/86 programme included both dynamite and vibroseis lines. The former followed surveyed routes while the latter followed roads. Nominally, the dynamite lines are 80-fold and the vibroseis lines are 120-fold. Both data sets were processed to migration.

Offshore

The first offshore seismic surveys in the Southland region were conducted by oil companies as part of their exploration programmes and were concentrated in coastal waters (New Zealand Petroleum, 1970; Hunt International Petroleum Co. (HIPCO), 1970). They were closely followed by regional lines shot by Mobil and Gulf as part of their respective reconnaissance surveys of the New Zealand region from 1971 to 1973 (Mobil International Oil Co.,

1979; Australian Gulf Oil Co., 1973) and by the regional reconnaissance shot by Hunt as part of their exploration programme between 1971 and 1972 (HIPCO, 1973a, 1973b). In total, Hunt collected approximately 3000 km of seismic data in their Petroleum Prospecting Licence (PPL) which was originally awarded as PPL 863 in 1969 and re-awarded as PPL 38013 before being relinquished in 1977.

Following Hunt's relinquishment of PPL 38013, Seahawk operated the licence until 1982. They shot 104 km of seismic data, but relinquished the licence before processing it. The licence was then awarded as PPL 38206 in 1982 to a consortium of BP, Shell, Amoco, Todd, Stewart, Solander and Texas Gas, who shot a further 1100 km in what they saw as the most prospective region at the heads of the Waitutu and Solander basins in 1984 and 1986.

As the data set was acquired over a period of fifteen years, its quality varies. Much of the early Hunt data was reprocessed to modern standards, although acquisition parameters were less stringent when the data were shot, and later data are of better quality.

A total of 4200 km of seismic data of various vintages are now available for the offshore basins (Fig. 1). In addition two wells have been drilled (Fig. 3), Parara-1 in 1975/6 (HIPCO, 1976) and Solander-1 in 1985 (Renton, 1986). All of this data now has *open-file* status as the licence was relinquished by Amoco, the final, and sole licensee, on 1 May 1989.

INTERPRETATION

At the start of the interpretation project, no useful wells had been drilled in the onshore regions. The only controls therefore were ties to outcrop. For this, good geological maps are essential. Maps of variable vintages were used to compile a reasonably reliable map (Fig. 2). Much of the Te Anau Basin is covered by Pleistocene and Recent sediments. Little outcrop information is available in mid-basin, where most of the seismic lines are located, and no boundaries cross seismic lines. Conversely, the Waiau Basin seismic lines cross several geological boundaries. Additionally, the Early Miocene Clifden Limestone (Cl) and the correlative McIvor Formation (Wim), on the western side of the basin, together act as a good seismic marker horizon. The decision was taken to interpret the Waiau Basin data first. Many lessons were learned about interplay between structure and stratigraphy and the Waiau Basin mapping then provided a comparative model which was used to interpret the Te Anau and offshore basins.

Waiau Basin

Despite the fairly straightforward synclinal form of the Waiau Basin at outcrop, there are many suggestions of complexity at the surface. For example, rocks of the Rowallan Sandstone (Wr) show as many as three generations of thrust faulting, and small reverse faults are observed in the coastal cliffs of Te Waewae Bay. These two examples suggest a compressional regime operating recently enough to deform rocks of Pliocene age.

Seismic data suggests that basin architecture is complex. The first regional influence was a tensional regime, but many of the originally normal faults have been reversed by subsequent compressive episodes. Careful correlation of dated boundaries at outcrop with seismic reflectors en-

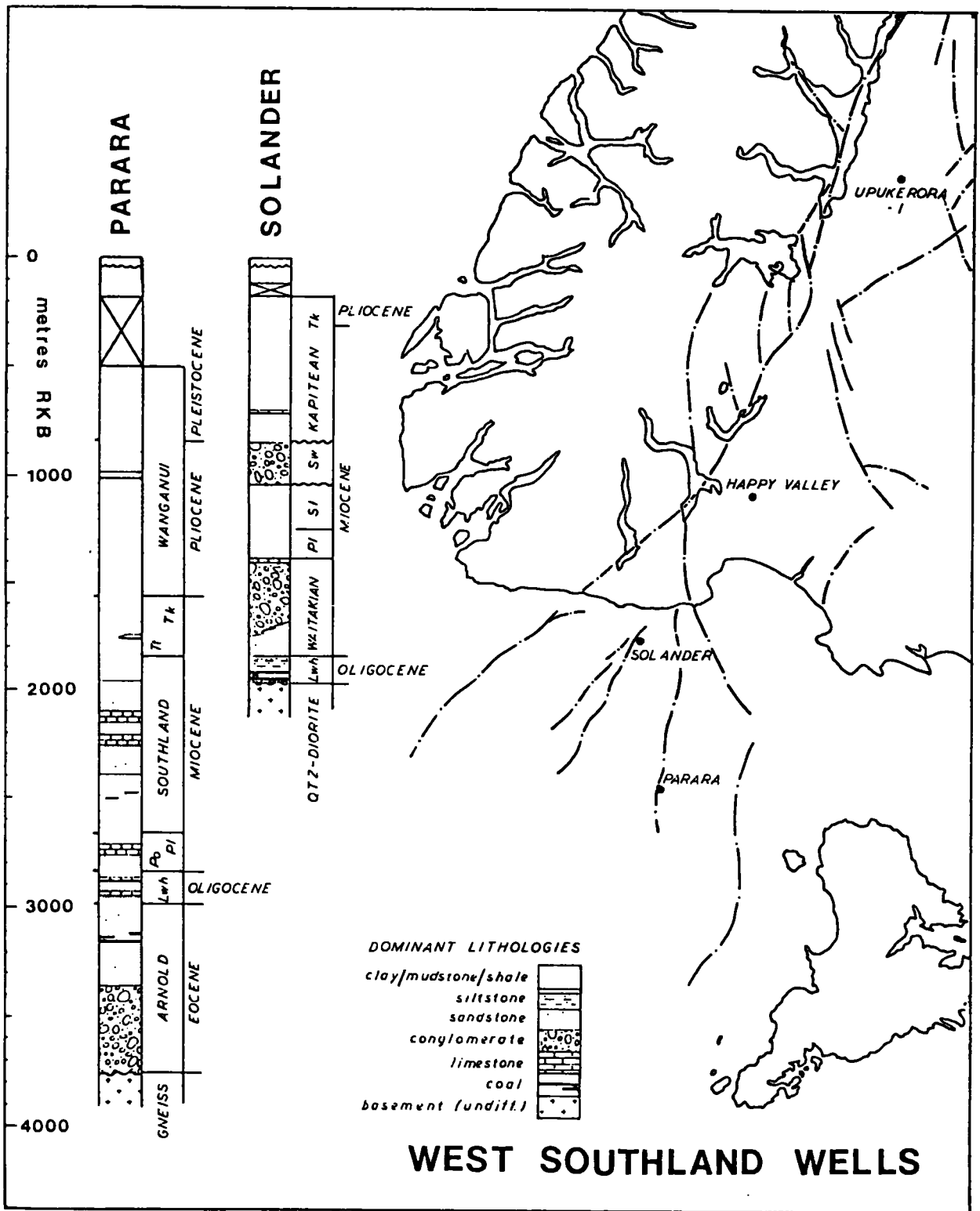


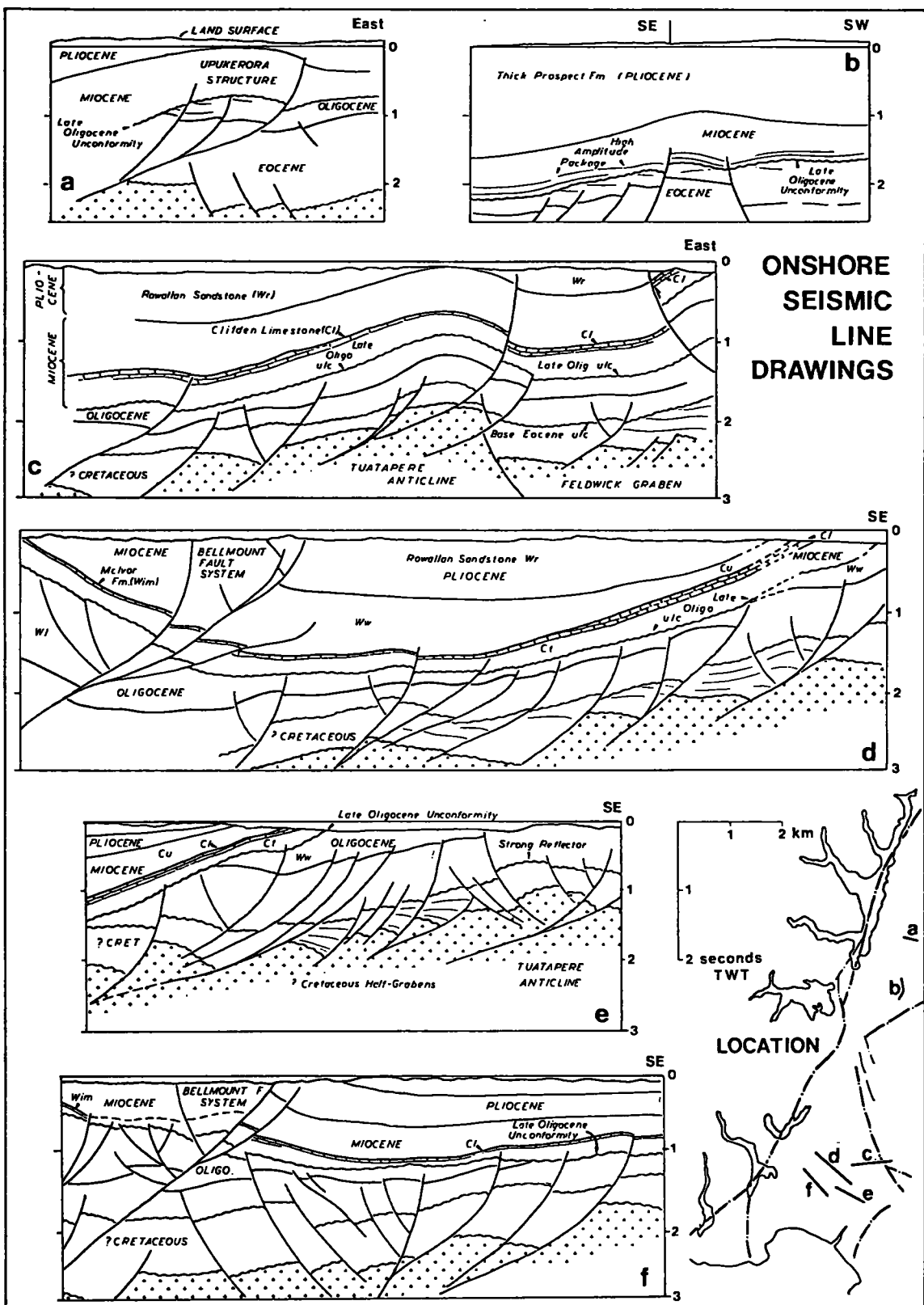
Fig. 3: Location of petroleum wells in Western Southland and generalised lithological logs for the offshore wells.

abled many of these events to be recognised, classified and dated.

Seismic basement Four lines cross basement outcrop allowing basement to be mapped in the sub-surface along the eastern margin of the Waiiau Basin. Elsewhere, structural complexity and inconsistent seismic character necessitate the use of other criteria to map the basement. In some regions, a strong seismic event immediately underlies the

deepest observed sedimentary reflectors and this is often assumed to be seismic basement. In other regions, recognisable sedimentary sequences occur below the apparent basement reflector (Figs. 4d, 4e). In these regions, seismic basement is defined where reflections lose their coherence.

Where sediments are locally derived, they often consist of coarse clastics with a similar composition to the underlying



**ONSHORE
SEISMIC
LINE
DRAWINGS**

Fig. 4: Line Drawings of representative seismic lines from the Waiau and Te Anau basins. Basement shown by cross-pattern, Eocene section shaded. Locations shown on inset map. 4a: Line over the Upukerora structure showing the late Oligocene unconformity, thick Eocene section and basin eversion. 4b: Line from southern part of Te Anau Basin. No apparent compression, note the unconformity below the high amplitude package, thick Prospect Formation and drape over fault blocks. 4c: This line crosses the northeast part of the Waiau Basin. It shows a possible Cretaceous sequence, tensional faulting into the Oligocene, compressional faulting from late Oligocene times to at least Pliocene and strong reverse faulting of the Clifden Limestone marker. 4d: Regional line across the central Waiau Basin showing stronger compression to the northwest and uplift of western part of the basin. 4e: The late Oligocene unconformity is traced from outcrop into the subsurface on this line. 4f: The late Oligocene unconformity in the centre of the basin truncates the top Eocene reflector.

basement. In such circumstances, any acoustic impedance between the basement rock and locally derived sediment is likely to be small, and the amplitude of a reflector originating at such an interface would be negligible.

Seismic basement lies at more than 4 seconds TWT in the north of the basin, deeper than processed seismic sections. Fig. 4d shows that basement lies at greater than three seconds TWT in the centre of the basin. It rises towards the coast and forms a core in the Tuatapere Anticline (Figs. 4c, 4e), as suggested by Anderson (1980).

It is not possible to differentiate basement terranes on the basis of seismic character. Other geophysical methods are also ineffective. Gravity anomalies arise from density contrasts between the shallow sedimentary layers, and magnetics mainly delineate the boundaries between basement and sediment outcrops.

Early Tensional Phase: Cretaceous Although no seismic lines cross Cretaceous outcrop near Ohai, three lines cross part of the Ohai Depression, and the basal sedimentary sequence here has been assumed to be of Cretaceous age (Fig. 4c). The possible Cretaceous sequence can be mapped into the main body of the Waiiau Basin, although not without ambiguity, as correlation across major faults is uncertain. In some places (Fig. 4c) the possible Cretaceous sequence is separated from the overlying Eocene sediments by a distinct angular unconformity while in others (Fig. 4f) no such unconformity is observed.

Evidence for Cretaceous faulting is limited at the surface to thickening sedimentary wedges, splitting of coal seams and sedimentary intrusions which indicate tectonic activity (Sykes, 1989). In the subsurface, however, the basal sedimentary sequence is clearly seen to be faulted.

At the eastern margin of the basin, possible Cretaceous sequences infill small, half-graben depressions bounded by listric-normal faults (Gibbs, 1987). Further west, towards the centre of the basin, the half-grabens coalesce into larger structures (Fig. 4c). The basement steps down towards the deepest part of the basin, the northwest sector below Blackmount.

The possible top Cretaceous reflector has a strong seismic character as may be expected of a regional unconformity representing an hiatus of 20 million years. It is likely that this surface was peneplained. By analogy with the Cretaceous rocks of Ohai, the possible Cretaceous sequence is expected to consist entirely of terrestrial sediments. Following cessation of faulting near the end of the Cretaceous, the basin may have been a relatively flat fluvial plain. The region appears to have been tectonically inactive until the Late Eocene. No sediments of Palaeocene age have yet been reported, and it was not until the second tensional phase that extensive deposition was renewed.

Late Tensional Phase: Late Eocene to Late Oligocene Late Eocene sediments overlie the possible Cretaceous sequence wherever it is mapped. Along the eastern flank of the basin, from the Ohai Depression to the Longwood Range, they are represented by the terrestrial Beaumont Formation (Nb, Turnbull *et al.*, 1989) and the lacustrine to shallow marine Orauea Formation (No). The top of the Orauea Formation is tied to the seismic data on several lines and is mapped as the top Eocene reflector.

During this period, syn-depositional tensional faulting resumed. In many cases, old faults of the early tensional phase were re-activated. The Bellmount Fault System appears to have been a tensional flower structure suggesting initial wrench motion along its trend (Fig. 4d, 4f). It must therefore have been initiated during a tensional phase, with subsequent reactivation as a compressional feature. It may have been this reactivation which gives the system its present westerly dip.

Deposition took place in a regionally subsiding basin accompanied by tensional faulting. Late Eocene and Oligocene tensional faulting was concentrated along the western part of the basin, and a structural high, perhaps the shoulder of a major fault block, occupied the centre of the basin (Fig. 4d). Elsewhere, displacement on many of the reactivated early faults was minimal. The basin deepened during the Oligocene, and the lacustrine to marginal marine Orauea Formation was succeeded by the deeper marine mudstone-dominated facies of the Waioce Formation (Ww).

In the western part of the basin, coarse clastic sediments were shed from the emergent Fiordland block throughout the late Eocene and Oligocene. They crop out along the Hump Ridge, where they immediately overlie basement rocks, and between Lakes Hauroko and Monowai where they were deposited as the submarine fans forming the Hump Ridge (Wm), Kaherekoua (Wk) and Blackmount (Wl) Formations. The younger fans were deposited into the bathyal muddy background of the Waioce Formation.

Late Oligocene unconformity To map the top Oligocene surface in the basin, the base of the Te Karara Formation (Ct), dated as latest Oligocene (Turnbull *et al.*, 1989) was traced from outcrop into the sub-surface. Although conformable at outcrop, it forms a strongly angular unconformity with the underlying Oligocene and Eocene sequences in the centre of the basin. There, it truncates the top Eocene reflector and part of the underlying sequence (Figs. 4e, 4f). This implies differential uplift of the central region of the basin which may have had a thermal component as well as marking a change in tectonic regime.

This reflector marks a change from a transtensional to a transpressive stress regime as the pole of rotation of the Pacific plate relative to the Australian plate drifted southwards (Stock and Molnar, 1987). This new date for the onset of transpressional faulting is considerably earlier than the mid-Miocene age suggested by Carter and Norris (1976), perhaps as much as ten million years.

Compressive Phase: Late Oligocene to Recent Following the late Oligocene unconformity, marginal marine sediments of the Te Karara Formation (Ct) were deposited on the eastern side of the basin near Clifden. They were succeeded by the shelf limestones of the Forest Hill Formation (Cl=Clifden Limestone) along the eastern and southwestern margins of the basin at Clifden and Helmet Hill. The McIvor Formation (Wim), which crops out along the northwestern margin of the basin, is believed to be a deeper water equivalent. It consists of calc-flysch sequences, derived from the east, perhaps from the shallow Clifden region or from the extensive coeval carbonate basin to the east (Invercargill Basin, Hutson and Smith, 1987). The top Clifden Limestone/McIvor Formation reflector is a high amplitude reflector which can be traced over much of the basin. It is dated as Early Miocene (Turnbull *et al.*, 1989).

The Early Miocene reflector can be mapped from outcrop into the sub-surface (Fig. 4d) where it is displaced by the Bellmount Fault System. The deeper water calc-flysch sequence was uplifted and thrust towards the centre of the basin. Similarly, the Late Miocene reflector can be mapped from outcrop into the subsurface, where it also is displaced by the Bellmount Fault System.

Throughout the compressive phase, the centre of the basin continued to subside and fill with marine sediments. The depocentres moved gradually eastwards and southwards as the thrust systems uplifted the western and northern parts of the basin. Successive unconformities testify to the sporadic nature of the tectonic events. In the southern part of the basin, the Early Miocene reflector truncates the Late Oligocene unconformity. Here it appears as a large channel-like feature which strikes approximately north-south and plunges northwards towards the deep part of the basin (Fig. 5). The Late Miocene reflector in turn truncates the Early Miocene reflector and is truncated by the end Miocene reflector. Each of these truncations represents a compressive pulse which progressively uplifted the southern part of the basin, culminating in the present shoreline.

The westward-dipping fault planes of the Blackmount and Bellmount fault systems suggest that they owe their orientation to compression along the Fiordland Boundary Fault. The Fiordland Block appears to be riding up over the Waiiau Basin from the northwest and the Takitimu and Woodlaw Blocks are together thrust over the northeastern part of the Waiiau Basin. One compelling line of evidence for such thrusting lies in the outcrop patterns of the Early Miocene Forest Hill Formation. From outcrop in the vicinity of Clifden, the limestone reflector can be mapped into the sub-surface in the Feldwick Graben (Fig. 4c). The northeastern flank of the graben was uplifted by a reverse fault which carried the Clifden Limestone to the surface, a vertical displacement of approximately 1000 m. With both the Fiordland and Takitimu blocks over-riding the northern part of the Waiiau Basin, it had to respond by subsiding and filling with sediment.

From Late Oligocene times, the Waiiau acted as a foreland basin (Beaumont, 1981). Subsidence was at least partially a response to loading by basement overthrusts. The foreland basin model may explain other features. The Longwood Range occupies the position of a commonly observed basement swell which separates the deeper, deformed part of the foreland basin immediately adjacent to the mountain front from the shallower, less deformed remote section of the foreland basin. This latter region could be represented by the Invercargill Basin to the east of the Longwood Range.

Te Anau Basin

Much of the Te Anau Basin is blanketed by Quaternary sediments. Of the outcrops observed in the central basin region, most are the fluvial gravels and cobbles of the Prospect Formation (Pr). This thick, coarse-grained fluvial sequence scatters seismic waves, making acquisition of good-quality seismic data difficult. As a result, a total of only 600 km of seismic data were shot in this basin, and very few of these lines crossed major geological boundaries at outcrop. However, the Upukerora-1 well had been drilled before interpretation for this study commenced, and it was possible to tie several reflectors to the well.

Basement Basement rocks surrounding the Te Anau Basin have been classified into at least eight groups and numerous sub-groups and formations. These have been subdivided on the basis of age, lithology and interpreted environments of deposition or emplacement (Grindley, 1978). For example, the eastern and southern basement blocks represent components of a Permian to Mesozoic island arc system (Suggate, 1978).

Various basement units were important contributors of sediments to both the Te Anau and Waiiau basins (Turnbull *et al.*, in prep.). The Caples terrane was a major sediment source in the Te Anau Basin but the Takitimu and Humboldt groups were locally important. On the west side of both basins, Fiordland contributed much sediment, particularly close to the Fiordland Boundary Fault.

No seismic lines cross basement outcrops in the Te Anau Basin and the lowest coherent reflector is generally assumed to be basement.

Cretaceous to Eocene No rocks of Cretaceous or Palaeocene ages have been described from the Te Anau Basin. The main depocentres for Cretaceous rocks lay to the south in the Waiiau Basin and the onshore parts of the Balleny Basin between Puysegur Point and Te Waewae Bay (Bishop, 1986) and offshore. Cretaceous faulting either by-passed the Te Anau Basin or the region remained a structurally positive feature during the Cretaceous and Palaeocene.

Late Tensional Phase: Eocene to Late Oligocene Eocene rocks are represented in the Te Anau Basin by the Annick Group which is subdivided into the Sandfly Formation (as) and Earl Mountain Sandstone (ae). The Annick Group ranges from Middle Eocene at the base to latest Eocene. In contrast with the correlative Nightcaps Group of the Waiiau Basin whose basal units are terrestrial, these units were deposited in a tectonically-active, mainly marine basin. The Sandfly Formation consists of massive conglomerates with minor coarse sandstones, typical of a submarine fan facies. This contrasts with the overlying Earl Mountain Sandstone consisting of coarse, fluvial sands at the base, grading into marginal marine and then fully marine sands by the end of the Eocene.

The main Oligocene units in the Te Anau Basin are the Point Burn (Wp) and Tunnel Burn (Wt) formations and a Waioce Mudstone equivalent, the Garden Point (wg) Formation. Although outcrops of Turret Peaks Sandstone (Wu) are not present in the vicinity of the seismic lines, this unit is considered a basin-wide submarine fan unit, similar to the Blackmount Formation of the Waiiau Basin, and is entirely of early Oligocene age.

Seismic and stratigraphic data suggest that the Te Anau Basin developed as a tensional feature during the Eocene and early Oligocene (Figs. 4a, 4b). It is unknown whether the basin was active prior to the Eocene, but it crosses the line of the Fiordland Boundary/Moonlight Fault system and it oversteps the Fiordland Boundary Fault. As such, it may have developed along pre-existing faults, possibly of Cretaceous age. By the middle of the Oligocene, extensive marine mudstone deposition suggests that the Te Anau and Waiiau Basins were fully connected. It has also been suggested that there was a connection between the South-

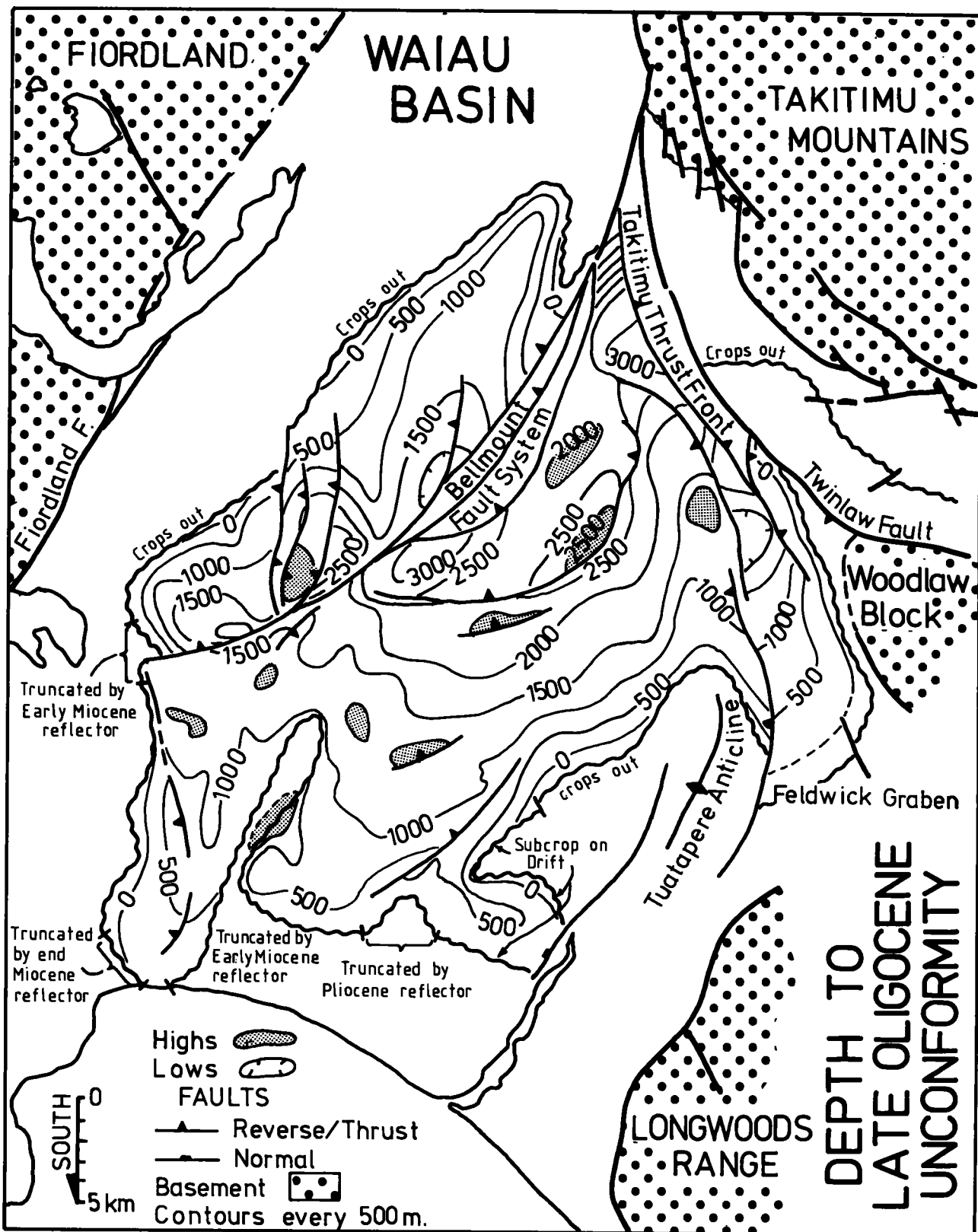


Fig. 5: Depth contours on late Oligocene unconformity. Multiple truncations of southern margin are indicative of successive compressive pulses and resultant uplift.

land and Westland basins (Kamp, 1986) at this time, although the only sediments observed in the intervening region are the Bob's Cove beds of marginal to shallow marine limestones and conglomerates.

Late Oligocene unconformity A basin-wide unconformity underlies a high-amplitude seismic package which may represent a sequence containing sandstones of the Point Burn Formation and limestones of the Tunnel Burn Formation (Figs 4a, 4b). This high-amplitude package can be mapped over most of the data set. As in the Waiiau Basin,

the unconformity marks the onset of uplift and compression and, by analogy with the Waiau Basin, it may be of Dunroonian age. The limestones suggest shallow water conditions.

Compressive Phase: Late Oligocene to Recent The main representative of Miocene sediments (Fig. 2) is the Horse-shoe Mudstone (Wn, Turnbull, 1985), now called Waioce Formation (Turnbull *et al.*, 1989), which is dominated by deep marine mudstones similar to those of the Waiau Basin. It includes thinly bedded, grey, distal turbidite sandstones, a northerly and westerly derived time equivalent of the McIvor Formation of the Waiau Basin.

The Prospect Formation (Pr) is partly latest Miocene in age but mostly Pliocene. It overlies much of the Te Anau Basin and consists mainly of conglomerates. It includes clasts derived from Fiordland in the west, the Caples terrane in the north and the Takitimu Mountains in the south. Many subordinate lithologies are present including lignites, carbonaceous mudstones, massive claystones, angular fanglomerates, fine sandstones and cyclical sand-mud sequences. Its environment of deposition was mainly terrestrial. Fluvial systems flowed into swampy and lagoonal regions, and some deltaic sedimentation is apparent. It is considered a lateral equivalent of the marine Rowallan Sandstone of the Waiau Basin.

The most spectacular structure in the basin, the Upukerora rollover (Fig. 4a) brings the base of the Prospect Formation to within 130 m of the surface. This horizon can be traced over much of the basin, and as much as 3 km of Prospect Formation may be present in the southern constriction of the basin between Fiordland and the Takitimu Mountains. The Prospect Formation can be sub-divided, on seismic criteria, into a lower *chaotic* and an upper *well-bedded* seismic facies.

Seismic data suggests that compression continued until at least Pliocene times in the centre of the basin. However, at the southern edge, where the Prospect Formation reaches its greatest thickness, little compression is apparent. On the contrary, it appears that most faulting remained tensional. This localised tensional regime may result from tensional wrench faulting along the northwest flank of the Takitimu Mountains.

The offshore basins

The CCP mapping project for the offshore part of the Western Southland basins has recently been started. The first part of this project was an assessment of previous work in the region, and the following observations stem mainly from this initial investigation.

Previous workers, with only the early Hunt data to work from, interpreted seismic basement as a highly irregular surface (Grant, 1985) but were unable to explain its mode of origin. Norris and Carter (1980) recognised little difference in tectonic style between the various basins. They observed near-vertical faults separating discrete highs from basement depressions. These they map as linear features which continue for many tens of kilometres. However, examination of several lines in the light of results from onshore work and from more recent offshore seismic surveys suggests that offshore structural style is more complex. As in the onshore region, initial tensional listric

normal faulting was later re-activated by compressional stress.

Considering the highly compressive tectonic nature observed onshore, it would be surprising if the offshore region were not affected by the same stress field. Compression is observed offshore, most spectacularly along the eastern flank of the Solander High, where a listric normal fault system has been reactivated to form a 50 km anticline. However, strong reverse faulting is not observed to the west of the Fiordland Boundary Fault (Fig. 1).

Solander Basin Of the offshore basins, the stratigraphy of the Solander Basin is known best as two exploration wells have been drilled there. The first was Parara-1 (Fig. 3), drilled by the Sea Hunt Group in 1975/76. This penetrated a thick marine Neogene sequence grading down into Oligocene limestones and muds and marginal marine Eocene sands and terrestrial sequences before drilling gneissic basement at 3 779 m. The second well, Solander-1, was drilled by BP in 1985. This well tested the shallowest, and closest inshore, of the closures along the Solander anticline. It penetrated some 1800 m of Neogene marine mudstones, sands, conglomerate and limestone. This graded into an Oligocene terrestrial sequence, including some coals at the base, before bottoming in quartz-diorite basement at 2017 m (Dearnie and Wilson, 1986; Renton, 1986). There is some suggestion that the quartz-diorite was a basal granite wash.

The Solander Basin is characterised by several compressive structures at depth such as the Parara reversal and the major rollover at its western edge, the Solander High (Fleming *et al.*, 1987, Fig. 6). The northern and eastern margins of this basin are of interest as the Waiau Basin shallows dramatically to the south to bring the dioritic and granitic basement of Mid-Bay reef, in Te Waewae Bay, to the surface. Similar basement rocks crop out at the southern end of the Hump Ridge (Wood, 1969).

To the southwest, basement drops sharply to a depth of at least 3 km. This drop was previously explained by a large normal fault which converges with Hump Ridge (Gearson, 1982). However, a northeasterly-dipping thrust is equally compatible with the seismic data (Fig. 7). Just as the Takitimu Mountains have been thrust over the Waiau Basin, the southern Waiau Basin is being thrust over the Solander Basin via the Hump Ridge thrust. These thrusts developed as a result of the compressive component of strike-slip motion (Harding, 1974) initiated in the late Oligocene. The nature of the wrench faulting is not as simple as suggested by Norris and Carter (1980), as several wrench faults share the total movement.

Several compressional rollovers are observed in Solander Basin, one of which is the Parara High. They converge northwards with the Hump Ridge near the coast and are eversion structures of earlier listric tensional faulting. Compression and reversal of these early eastward-dipping normal faults decrease southwards where older half-grabens show little sign of eversion.

The western boundary of Solander Basin is the Solander Ridge, striking northeast from Solander Island, it can be traced as far as the coast near Hump Ridge. Along its eastern flank is the Solander High. This large antiform is sited

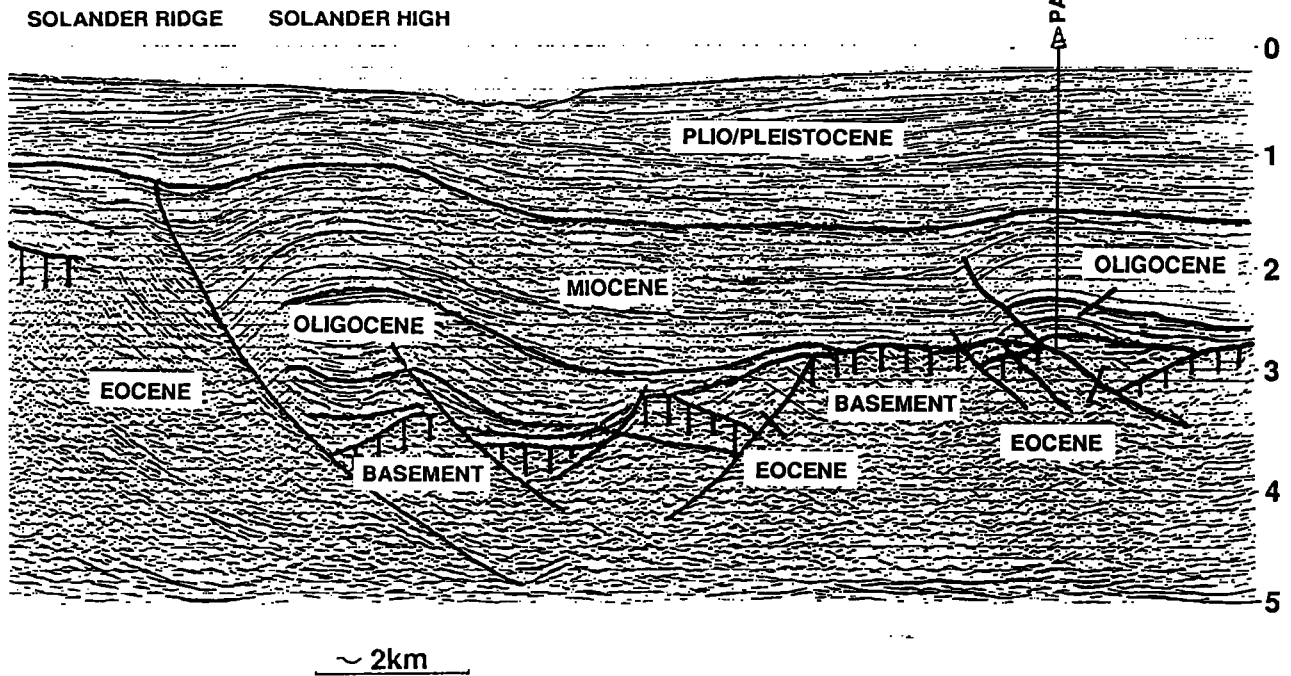
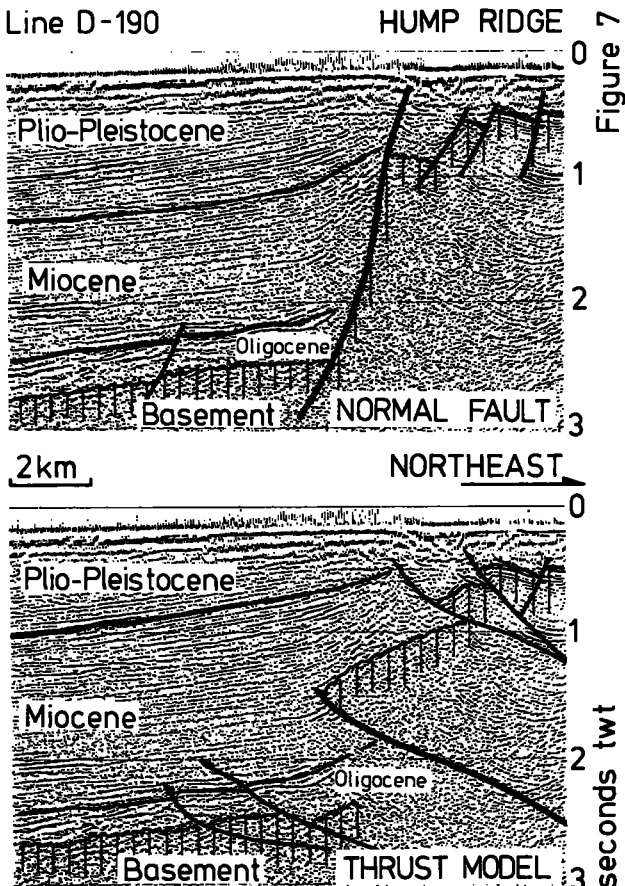


Fig. 6: Seismic section across part of the Solander Basin running northwest through the Parara well. For location, see Fig. 1.



along a system of listric normal faults which were reactivated by compression and, as for the smaller structures within the basin, compression decreases to the southwest until the Solander structure is represented by a large half-graben (Fig. 8). Within the Miocene sequence above the Solander structure, a westward-dipping sediment wedge is recognised. This indicates a phase of normal faulting on that section of the Solander Ridge. Within a short distance, the wedge thins northwards to a narrow, parallel-sided sequence and is reversely faulted relative to a reference horizon (Fig. 9). This is strong evidence for Miocene wrench faulting along the East Solander Fault.

Balleny Basin The structural style of the Balleny Basin differs significantly from that of the other basins, as compression is much less important. On the contrary, the predominant structural style is that of a rifted margin such as the Bay of Biscay (de Charpal *et al.*, 1978) with large-scale fault blocks and intervening basin areas. The basal units consist of easterly-dipping and fanning sequences which were deposited in half-grabens during a major extensional phase (Fig. 10). This series of fault blocks and basins may represent an early rifted margin which has since been uplifted, perhaps by subsequent subduction of the Australian plate below Puysegur Bank.

PETROLEUM POTENTIAL

Onshore

In the Te Anau Basin, the Upukerora-1 well was sited on the most promising structure but it is uncertain whether the

Fig. 7: Alternative interpretations of the offshore extension of the Hump Ridge. Top: Earlier model of Grearson (1982), Grant (1985) showing normal faulting. Bottom: The Hump Thrust model of the present paper. Fig. 1 for location.

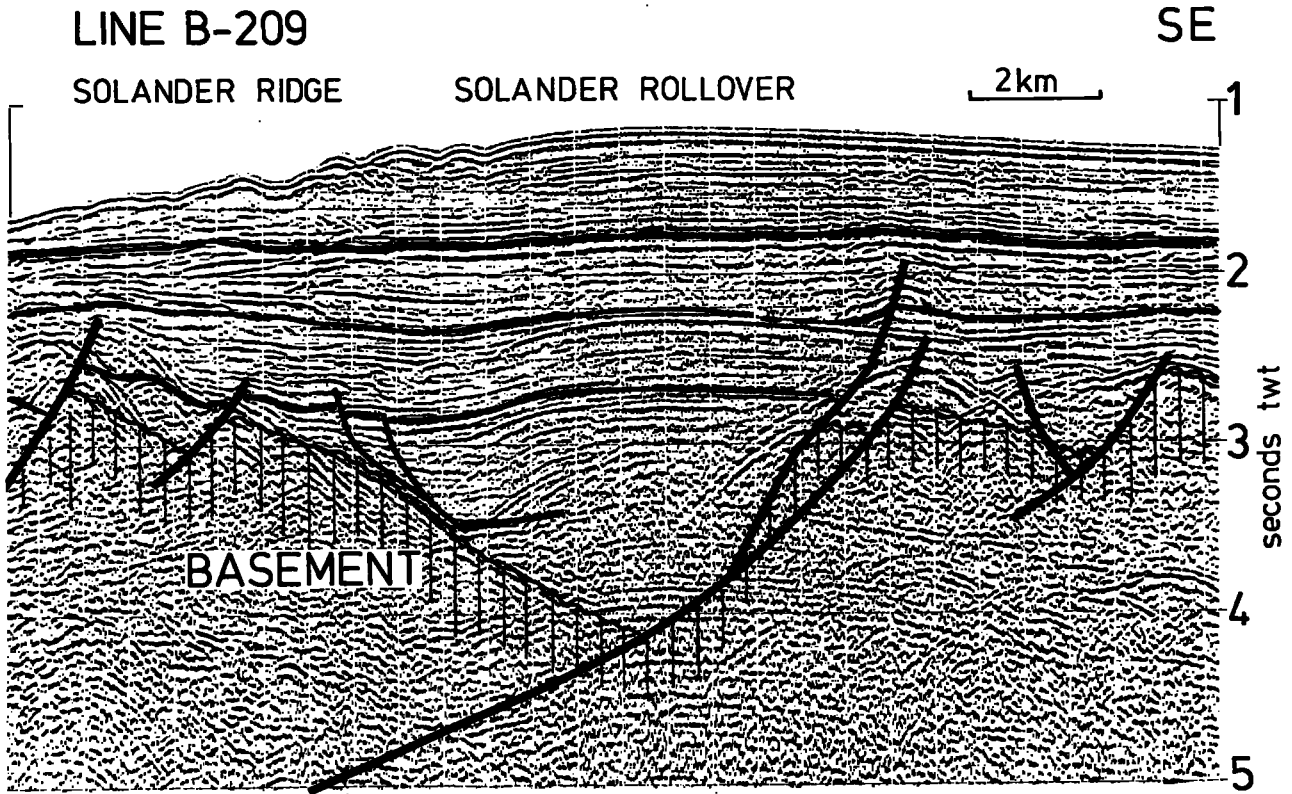
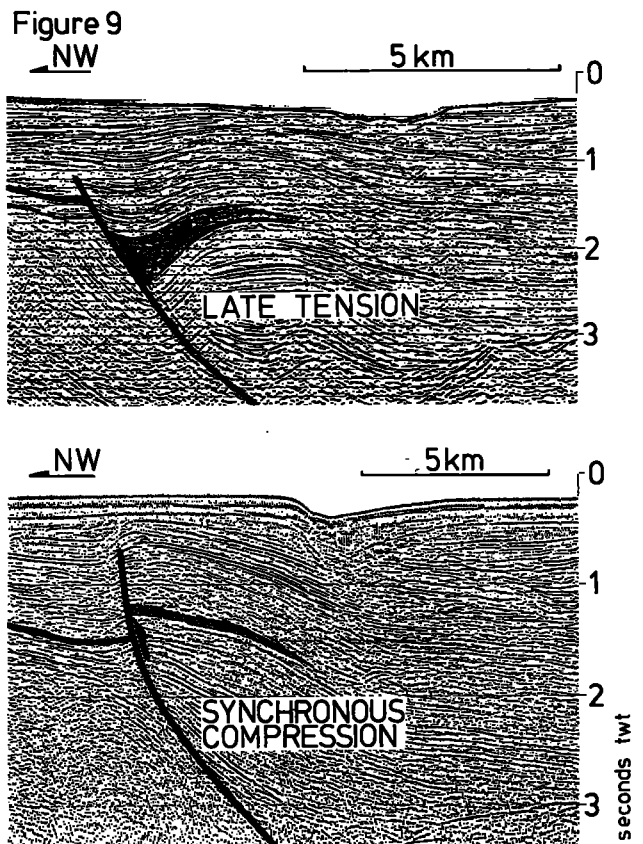


Fig. 8: Section across southwestern end of the Solander rollover. Both Solander Ridge and the rollover have greatly differing in style between this southern region and the more northerly area closer inshore. This section shows very little compression. See Fig. 1 for location.

target horizon was drilled. No hydrocarbons were reported, and any closure below the drilled interval would be very small. Only one other lead has been documented (the Danby Lead of Hutson and Smith, 1987) and further seismic data would be needed to confirm closure at any level. No potential source rocks have been reported. The Eocene marine sequence may include mudstones in mid-basin but this remains speculative.

Two hydrocarbon indicators have been observed in the Waiiau Basin. A gas seep in the Hindly Burn is close to the location of the Happy Valley-1 well and the Orepuki oil shale crops out in the south-eastern corner of the basin (Wood, 1969). If the oil shale proves to be more extensive, it may be a good source rock. Other possible source rocks may include coals of Ohai Group equivalents and coals from Eocene sequences. Adequate reservoirs were drilled by both onshore wells, and sandstones with very good reservoir qualities have been described in the Waiiau Basin (Hutson and Smith, 1987). Seal is abundant. The marine

Fig. 9: Sections across the Solander rollover approximately 5 km apart showing strong evidence for wrench faulting along the Solander Ridge. The lines are tied by cross-lines and the major fault has been mapped as the same feature by all previous workers. Top section: shaded region shows a sediment wedge deposited against an active normal fault scarp. The reflector west of the fault is a reference believed to be of the same age. Bottom section: the wedge is not present, instead, the attenuated sequence is reversely faulted relative to the reference reflector. Fig. 1 shows location.



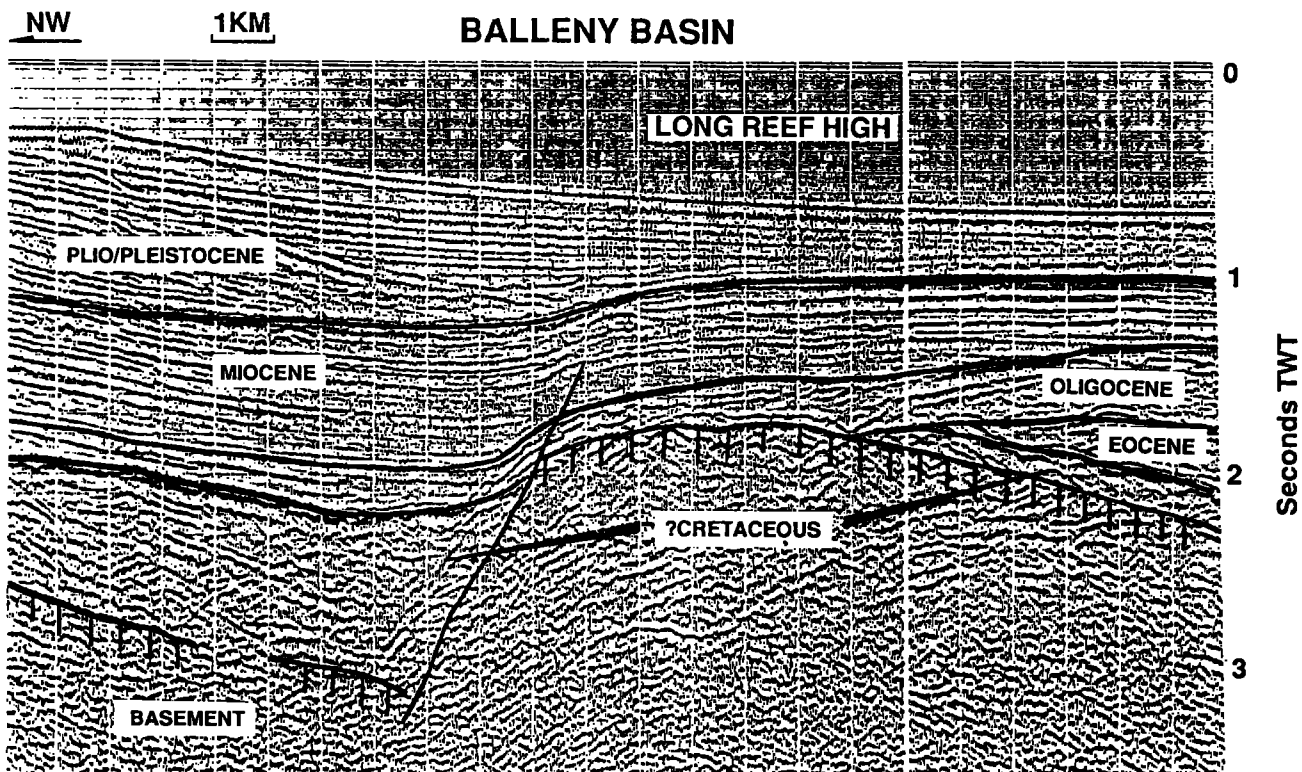


Fig. 10: Seismic line from the Balleny Basin showing dominant tensional tectonics and drape over fault blocks. Fig. 1 for location.

mudstones of the Waioce Formation are extensive and are so tight that the Happy Valley-1 well experienced severe engineering problems.

The Happy Valley-1 well stopped short of possible Ohai Group equivalents so the extent of the Ohai Group, which includes possible source rocks, remains conjectural. The Waiau Basin contains many more mapped closures at Top Eocene and deeper levels, at least some of which should be tested before the basin could be considered non-prospective.

Offshore

Offshore, the Parara-1 well tested a small reverse-faulted anticlinal structure in the Solander Basin. This well was abandoned dry. There were thin coals in the Eocene sequence which may have had source potential but one reason that Parara-1 was dry may be its remoteness from the major potential source area, the possible Cretaceous sequence in the deepest part of the basin, adjacent to the Solander Ridge.

The Solander-1 well was also abandoned dry. It too was situated some distance from the main potential source area, some 15-20 km along strike to the southwest. This well was more a test of particular migration pathways than of petroleum generation. It proved only that hydrocarbons which may have been generated in the deep Solander Basin did not migrate into the structure tested. Both of the above wells penetrated good-quality reservoir sequences and the abundant marine mudstones would have provided good seals.

The remaining basins are yet to be drilled. Of the two, the Waitutu Basin is considered to have the greater potential, as it contains a thicker sedimentary sequence and several mapped closures. The basal units are also believed to

consist of Cretaceous sediments, possibly including oil-prone coal measures. However, the Balleny Basin should not be dismissed, as some syn-rift sequences are deep enough to have reached the oil window. Potential traps include drape across the shoulders of basement blocks. Tensional rollovers and stratigraphic traps are also likely. Little is known about this basin, as only the early Hunt reconnaissance data has been collected from the area.

Solander Trough

The Solander Trough is the deep water continuation of the near-shore basins and it ranges from shelf depths in the north to more than 4000 m depth near Auckland Island, 400 km to the south. The few seismic lines available for the basin suggest that the whole structure contains a considerable volume of sediment (Katz, 1974). Although for economic reasons it is not considered prospective at present, the Solander Trough merits investigation to assess future potential.

CONCLUSIONS

- (a) When outcrop geology and stratigraphy are integrated with seismic data, three tectonic phases are recognised throughout the region: an early tensional phase (late Cretaceous), a late tensional phase (late Eocene to late Oligocene) and a compressive phase (late Oligocene to Present).
- (b) Sediments of the early tensional phase, the Ohai and Puysegur groups, were deposited in half-grabens and contain thick coal measures which are potential hydrocarbon source rocks. Seismic data suggests that sediments of similar ages and facies may form the basal units of the Waiau, Solander, Waitutu and Balleny basins.
- (c) The late tensional phase reactivated many of the half-grabens and deposition extended across the whole region.

Terrestrial sediments were initially deposited in all basins except for Te Anau, where the earliest Eocene rocks are marine sandstones. By the end of the Eocene, all of the basins had subsided as a result of the tensional regime, and by the Early Oligocene they were deep marine depressions with tectonically active margins.

(d) Initial uplift in Late Oligocene times (Duntroonian) is recorded by a widespread unconformity, by extensive shelf limestones and calc-flysch sediments in the onshore basins, and by terrestrial sediments in the Solander-1 well offshore.

(e) The compressive phase commenced with the Late Oligocene unconformity and is expressed by reversal of normal faulting and basin eversion. Structures such as the Parara and Solander rollovers offshore, the Upukerora and Tuatapere anticlines onshore, and many other structures in both regions result from the episodic compression which continued at least into the Pliocene. Compression was initiated at least ten million years earlier than previously thought.

(f) The Moonlight/Fiordland Fault system originated as a splay or several splays from the Alpine Fault in the north (Carter and Norris, 1976). The compressive component imparted by the southwards movement of the pole of rotation of the Pacific plate resulted in the generation of major northwest-southeast trending thrust splays. These faults successively transfer at least part of the strike-slip motion of the Alpine Fault between an increasing number of wrench faults in the southern part of the region. Total offset along this system is distributed between these faults until little reactivation is observed in the more distant regions to the south and west. The dominant structural style in the south and west of the offshore region remains as tensional block faulting.

(g) Major thrust splays form basin margins and are intimately associated with basin evolution. The eastern margin of the Te Anau Basin seems to have been over-ridden by the adjacent basement regions. The northeastern margin of the Waiiau Basin has been over-ridden by the Takitimu Mountains. This assisted the Fiordland thrusts to depress the northern part of the Waiiau Basin which developed as a foreland basin throughout the compressive phase. Similarly, the Hump Ridge Fault extends offshore, where it over-rides the Solander Basin causing uplift of the southern half of the Waiiau Basin and the three post-Oligocene unconformities observed in that region.

(h) Petroleum potential can be better assessed in the light of the above conclusions. Onshore, the timing of compression and its association with development of the *foreland* basins suggests that the northern part of the Waiiau Basin may be prospective as possible source rocks may have reached the petroleum window as the structures were forming. Previously unmapped structures in the southern part of the basin may have been charged at the same time and these should also be tested. Drilling such structures would not be expensive, as the southern part of the basin has been uplifted by the Hump Ridge Thrust. The uppermost Eocene now lies within 1 km of the surface in this region.

(i) Offshore, at least two different tectonic environments should be tested for hydrocarbon potential. The compressive features within the Waitutu Basin and other discrete highs southwest of the Solander-1 well along the Solander rollover are likely targets. Also, block faulting in the mid-

Waitutu Basin, the southern parts of the Solander Basin and in the Balleny Basin may provide opportunities for trapping hydrocarbons in drape structures and stratigraphic traps.

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