OIL PLAYS IN TONGA
SOUTHWEST PACIFIC

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SUMMARY

Tonga is located in the Southwest Pacific as part of a long Tertiary island-arc chain which extends from Papua New Guinea to New Zealand. Within large parts of this trend there are a number of basins which contain Tertiary reef developments with commercial oil and gas accumulations and shows, giving these areas the potential to become hydrocarbon fairways.

The Tonga Ridge is a migratory arc system and contains a major forearc basin. This basin covers nearly 70 000 sq km and has sediment thicknesses of up to 4000 metres. Extensive areas with water depths less than 400 m occur along the length of the ridge making them attractive from the point of view of production technology and economics.

During the last 20 years, exploration by oil companies and government organisations has resulted in the acquisition of over 14 000 km of multichannel seismic, gravity and magnetic data. However, drilling activity has been confined to the island of Tongatapu, where five wells were drilled near oil seeps, based on gravity/magnetic data or poor quality seismic data. None of these wells reached their targets of Eocene reef limestone.

Hydrocarbon charge is proven by oil seeps which geochemical analysis shows are sourced from marine carbonates of Tertiary age. Burial analysis indicates that undrilled Eocene reef reservoirs have been within the oil window since the Early Miocene. Oil kitchens are believed to be in Eocene rocks south and west of Tongatapu where sediments in excess of 3400 m thick have been mapped using seismic data.

A re-interpretation of well data and recently reprocessed seismic data give rise to several untested structural and stratigraphic play concepts: Eocene and Miocene reefal mounds sealed by overlying pelagic shales; and reworked detrital carbonates and shelf carbonates in anticlines and tilted fault blocks. As none of the dry holes tested the very deepest Tertiary sediments the potential for commercial accumulations of oil in Tonga continues to be considered as good.

Several drillable prospects have been identified in Eocene reef targets in the shallow-water 'Eua Channel and a structural lead on the island of Tongatapu. Other prospective reefal and structural leads are outlined, some of which are associated with flat spots on seismic lines. Most of the vast area of the Tonga Ridge is covered only by a very widespread seismic grid. Consequently, there is considerable scope for more prospects to be identified.

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INTRODUCTION

Regional Setting

Tonga is located in the Southwest Pacific at the north-eastern corner of a sinuous island-arc system (Figure 1) which begins in North Papua New Guinea and ends several thousand kilometres away in New Zealand. Tertiary limestone deposition is widespread in Irian Jaya, Papua New Guinea, the Solomon Islands, Fiji and Tonga (Figure 2) and several basins contain reefs identified by drilling or seismic interpretation. Some of these areas have the potential to become hydrocarbon fairways, with oilfields, oil and gas shows, and seeps being widely distributed (Figure 1).

The Tonga Ridge is a migrating island arc system (Wessel, 1986). It is situated along the active plate boundary between the over-riding Australia-India Plate and the subducting Pacific Plate (Figure 3). The present-day configuration as highlighted by the bathymetry (Figure 4) and sediment isopach maps (Figure 5) is the result of 50 million years of plate motion since the Eocene. Since it is in collision with the Pacific Plate, it might be expected that the Tonga Ridge should exhibit compressional tectonism; instead, seismic data show the sedimentary section of the forearc to be within an extensional domain with horst and graben structures, tilted, rotated fault-blocks, and numerous normal faults with minor displacements.

Exploration History

The first geological mapping in Tonga of any significance took place on the island of 'Eua (Hoffmeister, 1932). The sequence comprises Eocene platform limestones and younger volcanic rocks overlain by Pliocene limestones, all resting on a basement of early Eocene or pre-Eocene intrusives and volcanics.

Oil seeps had been reported in Tonga over a period of 30 years in both the main islands of Tongatapu and 'Eua when, in 1968, they were sampled and analysed by several oil companies. The results confirmed that these were genuine oil seeps (Tongilava & Kroenke, 1975), and oil companies started exploration. Two exploratory wells, Kumifonua-1 and -2 (Figure 6) were drilled in 1971 to 1600 m on Tongatapu by Shell and partners proving the existence of much thicker sequences of Pliocene and Miocene volcaniclastics than are exposed on 'Eua. The wells were located in close proximity to the oil seeps and were drilled without seismic data. The main target of Eocene limestone was not reached due to limited rig capacity. Subsequently, the same group acquired 2190 km of multichannel seismic and magnetic data in the area north of Tongatapu, as far as Vava'u, and conducted a geological reconnaissance survey over all the islands of Tonga (Mulder & Nieuwenhuizen, 1971).

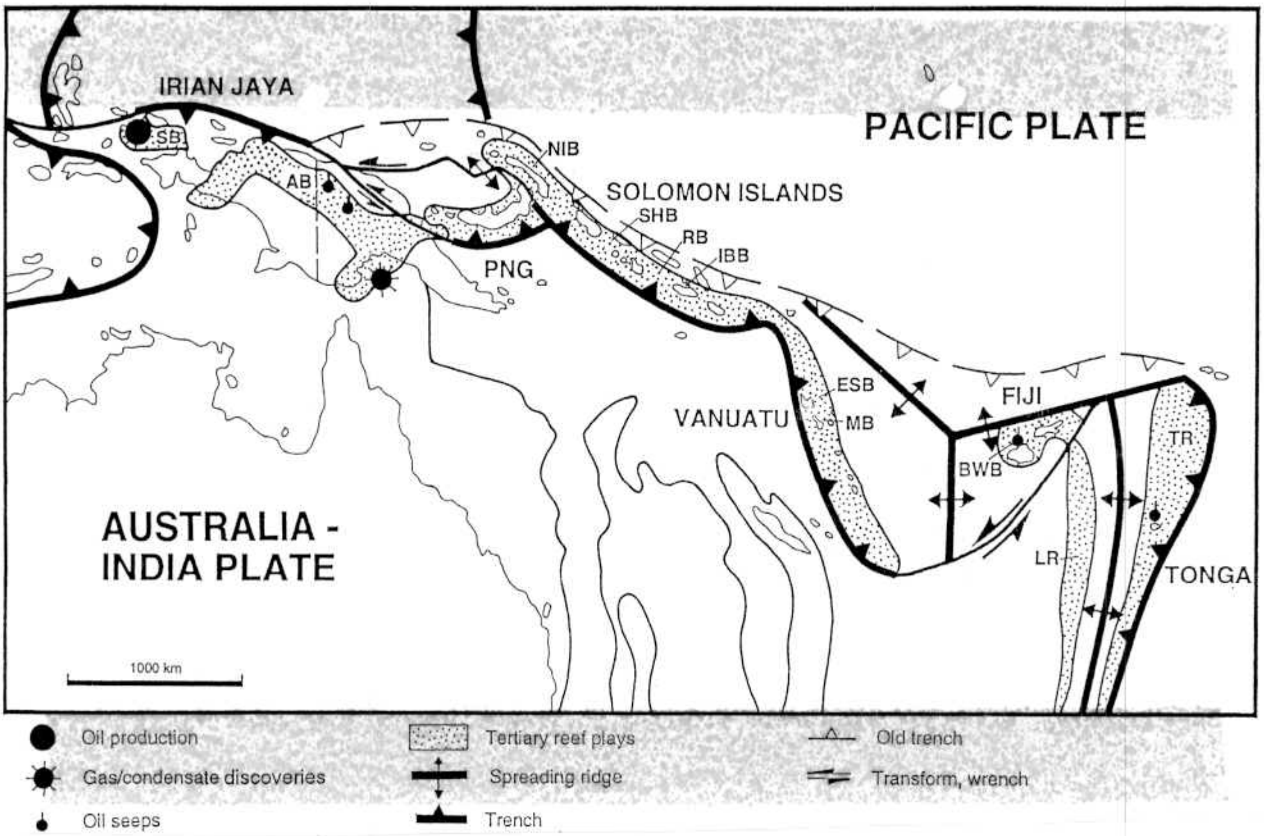

Figure 1. The regional tectonic setting of Southwest Pacific island-arc countries, the Tertiary reef play (stippled), and petroleum occurrences; oil, gas & condensate, and oil seeps (arrows) (Rodd, 1993).
Basins: SB = Salawati AB = Aitape NIB = New Ireland SHB = Shortland RB = Russell
IBB = Iron Bottom ESB = East Santo MB = Malekula BWB = Bligh Water
Ridges LR = Lau TR = Tonga

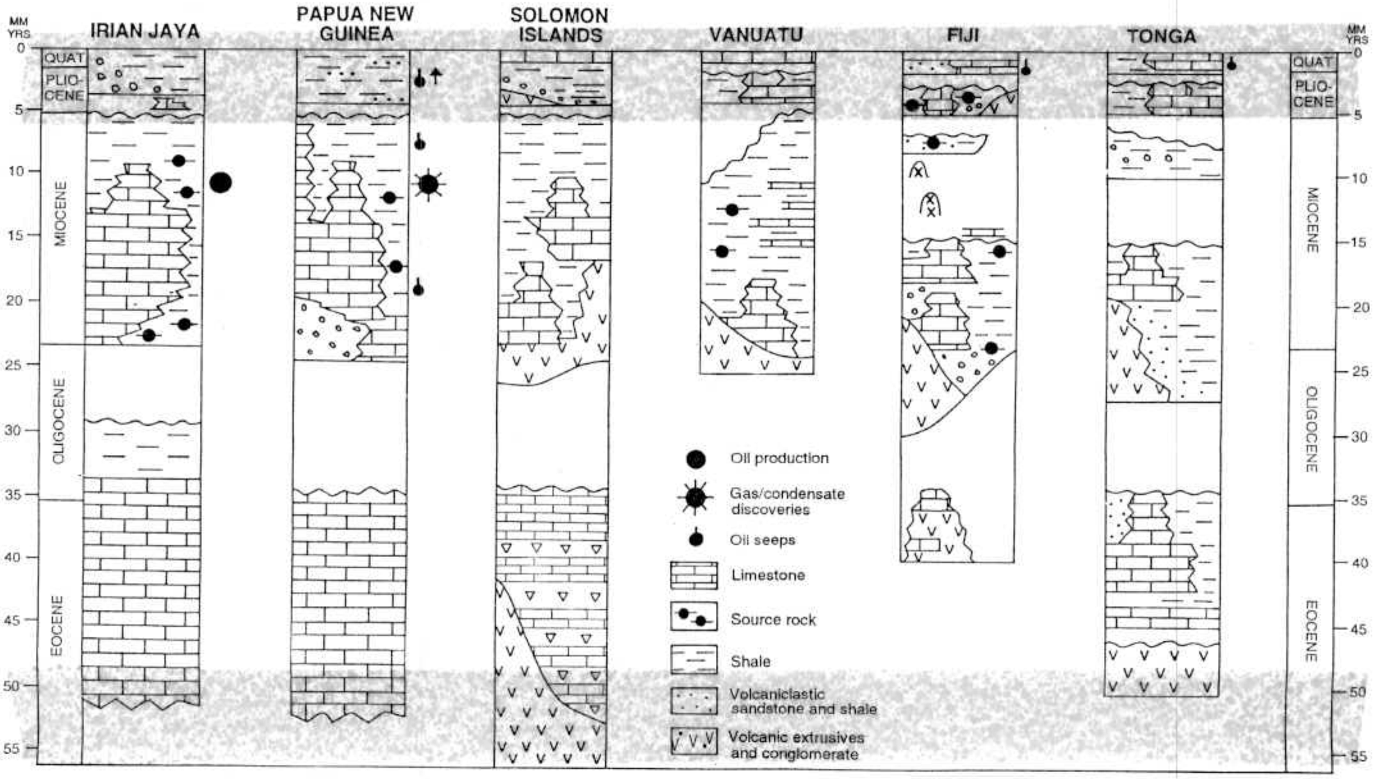

Figure 2. Regional Tertiary stratigraphy of the Southwest Pacific.

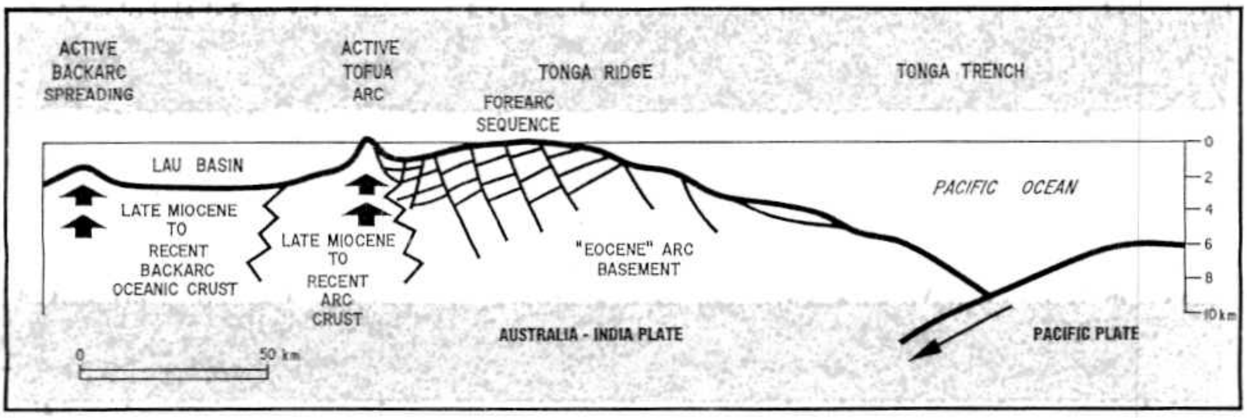

Figure 3. Cross section across the Tonga Ridge forearc (Gatliff 1989).

In 1972 Mobil Oil conducted a regional seismic survey in the area of the North Tonga Ridge, collecting some 2700 km of 6-fold multichannel data. These were used by Austin et al. (1989) to describe the seismic stratigraphy.

The granting of a new concession in 1976 to a group headed by Webb Resources resulted in 283 km of vibroseis data being recorded on Tongatapu, 919 km of multichannel seismic data being shot in the 'Eua channel, and 3 wells being drilled on Tongatapu, Kumimonu-1,-2 and -3. The deepest was drilled to 2635 metres and bottomed in Late Oligocene volcaniclastics. None of the wells penetrated their Eocene reef targets and subsequent seismic mapping shows that only one well, Kumimonu-2, tested a valid structural or stratigraphic trap. Details of the well results have been reported by Barney (1981), Maung et al. (1981), Maung (1984), and Cunningham and Anscombe (1985). In his report for the successor company to the Webb group Barney (1981) confirmed that the wells had not penetrated reef targets and proposed a total of eight new prospects with projected unrisked recoverable reserves of 3.8 billion barrels. Despite this encouragement, and although the concession was continued until 1993, no wells have been drilled since Kumimonu-3 was abandoned in July, 1978.

Consequently, in spite of the drilling of five dry holes on Tongatapu, the Eocene reef play has not been tested.

The Australia-New Zealand-USA Tripartite programmes of 1982 and 1984 resulted in the collection of 2400 km of 24-fold multichannel seismic data, sonobuoy refraction data, seafloor and surface outcrop samples, gravity, magnetics, and bathymetry profiles on the Tonga Ridge south of Tongatapu.

Results of the 1982 and 1984 Tripartite surveys are given in Scholl and Vallier (1985) and SOPAC (Stevenson et. al.) respectively. These publications include relevant studies on the structure and

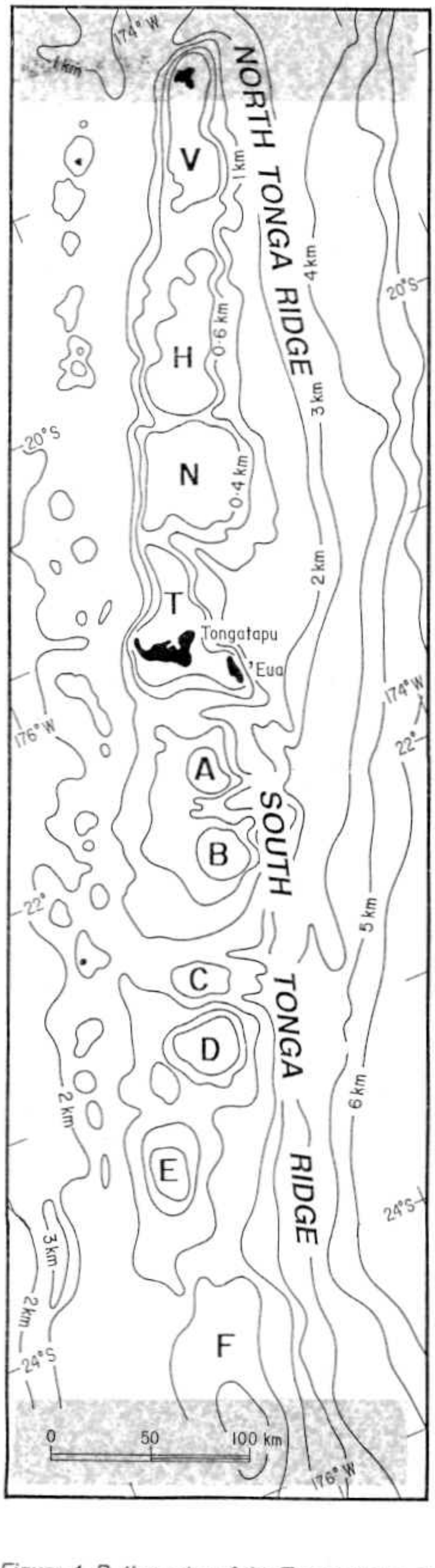

Figure 4. Bathymetry of the Tonga Ridge. The bathymetric highs result from pronounced NW trending faults normal to the subducting Pacific plate (Gatliff 1989).

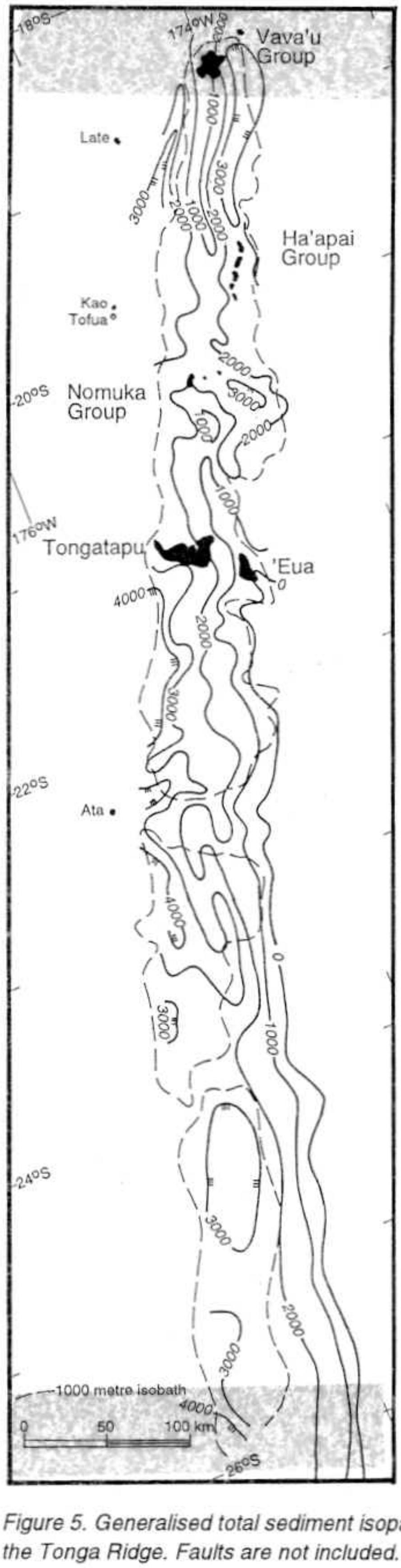

Figure 5. Generalised total sediment isopach map for the Tonga Ridge. Faults are not included. The dashed line is the 1 000 m isobath (after Gatliff 1989).

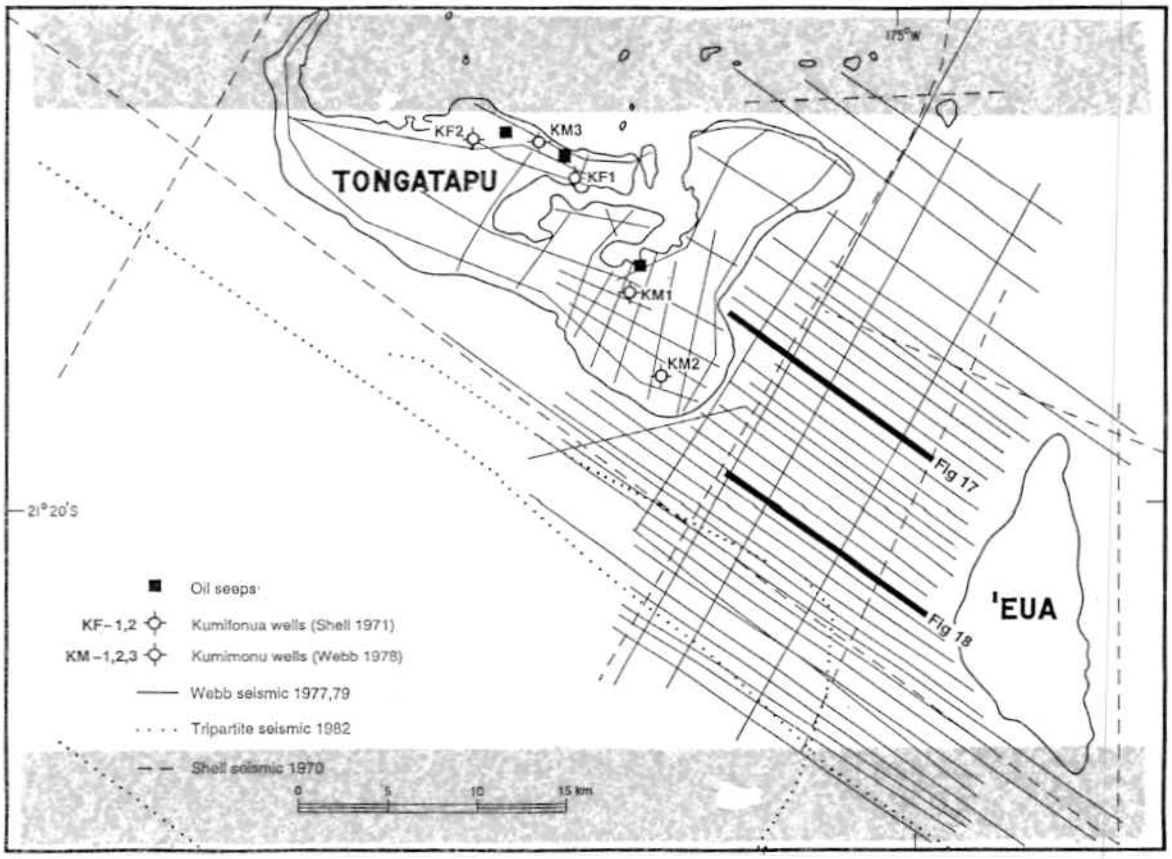

Figure 6. Oil seeps, wells, and seismic coverage in Tongatapu and the 'Eua Channel. Locations of seismic reef prospect lines of Figures 17 and 18 are highlighted (Gatliff 1989).

hydrocarbon potential of the South Tonga Ridge (Herzer and Exon, 1985, and Scholl et al. 1985), the onshore stratigraphy of the Tonga Ridge (Cunningham and Anscombe 1985), and the geochemistry of Tonga oil seeps (Sandstrom 1985). Later work on the oil seep geochemistry has been published by Summons et al. (1992) and Fowler (in press).

Data were collected on the northern Tonga Ridge near Vava'u in 1984 by the Geological Survey of Japan. Approximately 1300 km of 6-fold multichannel seismic and gravity profiles were collected, and dredging and coring stations were completed (Kitekei'aho et al., 1985).

Figure 7 shows the current offshore multichannel seismic coverage for the area.

This paper is based on an evaluation by the South Pacific Applied Geoscience Commission (Pflueger and Havard, 1989) together with more recent work. It integrates all available geophysical and well data from the Tonga Ridge. Earlier summaries of the original work have been given in publications by the Ministry of Lands, Survey and Natural Resources and SOPAC (1989), Gatliff (1990) and Khanna and Helu (1992).

GEOLOGY

Regional Tectonics and Structure

The Tonga Ridge is currently located on the leading edge of the Australia-India Plate. The ridge originated in the Middle to Late Eocene as part of the continuous Outer Melanesian Arc which extended from Papua New Guinea, through Solomon Islands, Vanuatu, Fiji and Tonga to New Zealand and formed as a result of westwards subduction of the Pacific Plate beneath the Australia-India Plate (Austin et al. 1989, Falvey et al. 1991).

From the Early to Late Oligocene, the South Fiji Basin opened as one of a number of back-arc basins westward of the Outer Melanesian Arc. Back-arc spreading resulted in eastward migration of the arc away from the Australian continental crust.

Collision of the Ontong-Java Plateau with the arc in the Late Miocene (10 Ma) was largely responsible for subsequent fragmentation of the arc. This was accomplished by reversal in the direction of subduction beneath the Solomons Arc and New Hebrides Arc, the consumption of the old back-arc basins beneath these arcs, the opening of the North Fiji Basin and clockwise rotation of New Hebrides Arc away from the Fiji-Tonga Arc (Falvey et al. 1991).

Consequently, there was continued subduction of the Pacific Plate only beneath the Tonga-Fiji Arc. Back-arc spreading commenced once again along this section of the arc in the Pliocene. Opening of the Lau Basin, separating the Tonga Ridge from the Lau Ridge, continues today (Kroenke 1984). Initial spreading was accompanied by uplift and erosion along the entire Tonga Ridge (Herzer and Exon 1985). Today, the Pacific Plate is actively being subducted under the ridge (Figure 3) at a rate of about 17-18 cm/year (Lonsdale 1986).

Flexure of the Tonga Ridge above the descending Pacific Plate has created a series of major NW-trending faults which extend across the ridge, dividing it into several large blocks (Figures 4 and 8). A second set of NE-trending cross-cutting faults has created numerous rotated half grabens and horsts over much of the ridge. This faulting appears to have been most intense during the Late Miocene, coinciding with the break-up of the Outer Melanesian Arc. From the Pliocene to the present, subduction of seamounts of the Louisville Ridge on the Pacific Plate has both given rise to further faulting and has controlled the depocentres (Dupont and Herzer et al. 1985).

The bulk of the Tonga Ridge has water depths less than 1000 m and can be conveniently divided into major structural units. The North Tonga Ridge is characterised by four bathymetric highs each shallow enough to be capped by island groups, and by sedimentary sections ranging up to 3000 m thick. The South Tonga

Ridge continues far south into the Kermadec Ridge. Its northern end has several broader bathymetric highs, is in deeper water with no distinct island groups, and has distinctly thicker sedimentary sections, in places well over 4000 m.

The South Tonga Ridge

The present-day topography of the South Tonga Ridge is characterised by a series of large bathymetric highs (A to F; Figure 4) separated by deep canyons which extend into the Tonga Trench immediately to the east. The segmentation of the ridge topography defines a sequence of large fault blocks. Regional dip at all levels is to the west-northwest, normal to the regional trend of the ridge. Along the western edge of the ridge, acoustic basement is at a depth in excess of 5000 m below sea level (bsl) with a sediment thickness of at least 4700 m.

Within the large fault block themselves, the sedimentary section and basement of the forearc are also faulted. Several very large normal faults affect the basement; these are either downthrown to the east or are associated with canyons which cut the trench side of the ridge. Because of the widespread nature of the seismic grid, it is not possible to reliably map all the faults. From acoustic basement upward, mapped horizons successively fill the largest basement half-grabens, then eventually over-ride and drape the basement highs. Dips become more gentle with decreasing age.

A regional high with either an absent or a very thin Eocene section, separates the Tongatapu-'Eua

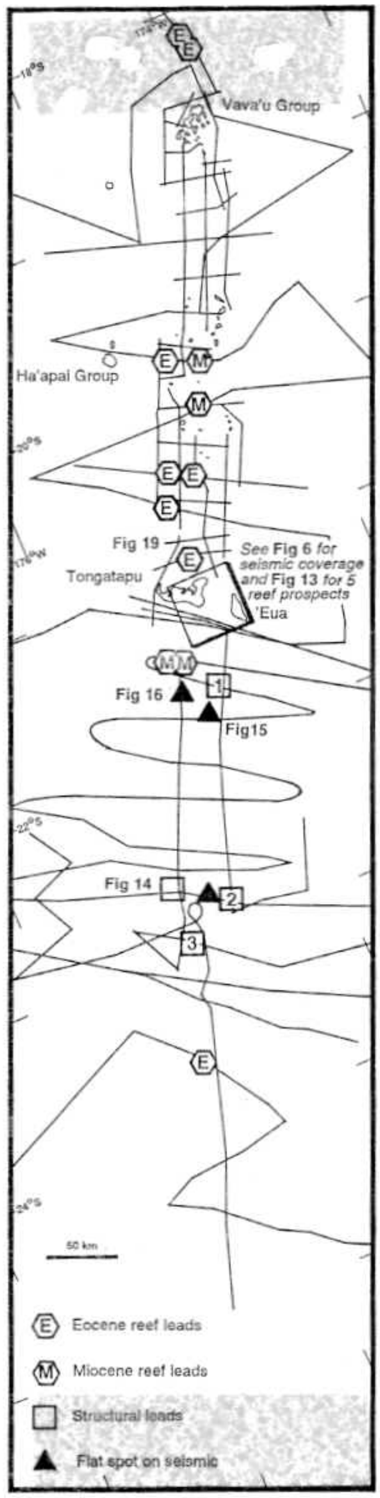

Figure 7. Tonga seismic coverage with reef, structural and flatspot prospects, and leads. Locations of seismic line Figures 14 through 16, and 19 are shown.

Channel depocentre from the other depocentres further to the south (Figure 8). Although the Eocene reflection mapped in the 'Eua Channel may be present on some seismic lines in the south, it discontinuous and cannot be mapped.

The North Tonga Ridge

This major structural unit begins in the extreme north with the Vava'u Group and ends in the south with the Tongatapu-'Eua Islands.

The most northern block (V, Figure 4) extends from the Vava'u islands south to lat. 19 deg 20 min south. A small block straddles lat. 19 deg 30 min South separated by a narrow seafloor channel from a large block which forms the substrate for the Ha'apai group of islands. A deep canyon oriented normal to the ridge axis south of the islands of Tungua and 'Oua bounds this block on the south.

The next block to the south (N, Figure 4), a square bathymetric feature, is the platform for the Nomuka group of islands. Water depths between these islands generally range from 50 to 100 m. A large portion of this block, as well as a large part of the adjacent block to the north, cannot be properly defined because of the sparse coverage of seismic data.

'Eua Island forms the southern termination of a discontinuous, north-trending basement high (T, Figure 4), at an oblique angle to the ridge axis (Figure 8). The basement high marks the eastern edge of a triangular fault block which includes the islands of Tongatapu and 'Eua. It may continue with a left-lateral offset into the next block if the inter-block canyon is a wrench fault. To the west of the basement trend, north of Tongatapu, the sedimentary section rapidly thickens to over 1200 m.

Stratigraphy

Eocene

The most extensive Eocene exposures are found on the island of 'Eua (Figure 9). The basement complex of Middle Eocene age is the oldest exposed on the Tonga arc, contains basaltic and andesitic intrusive and extrusive rocks which represent the early stages of island-arc volcanic development, and is cut by dikes which are dated as Early Oligocene to Early Miocene. Photogeological mapping reveals that the eastern side of 'Eua is highly faulted and the stratigraphic sequence in this area may be incomplete or deformed.

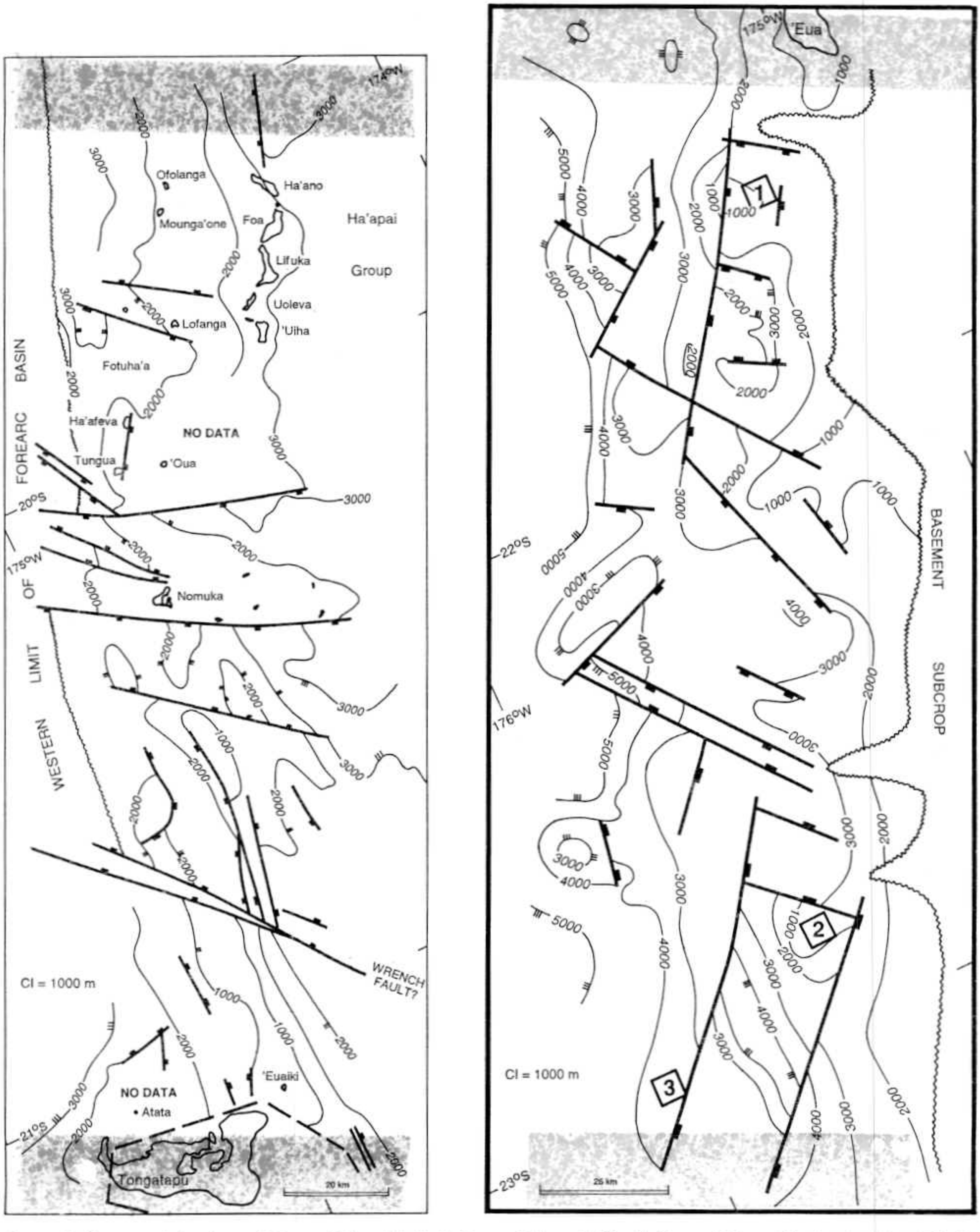

Figure 8. Basement structure of Tonga Ridge: (a) North Tonga Ridge, (b) South Tonga Ridge with structural leads 1, 2, & 3 at higher stratigraphic levels.

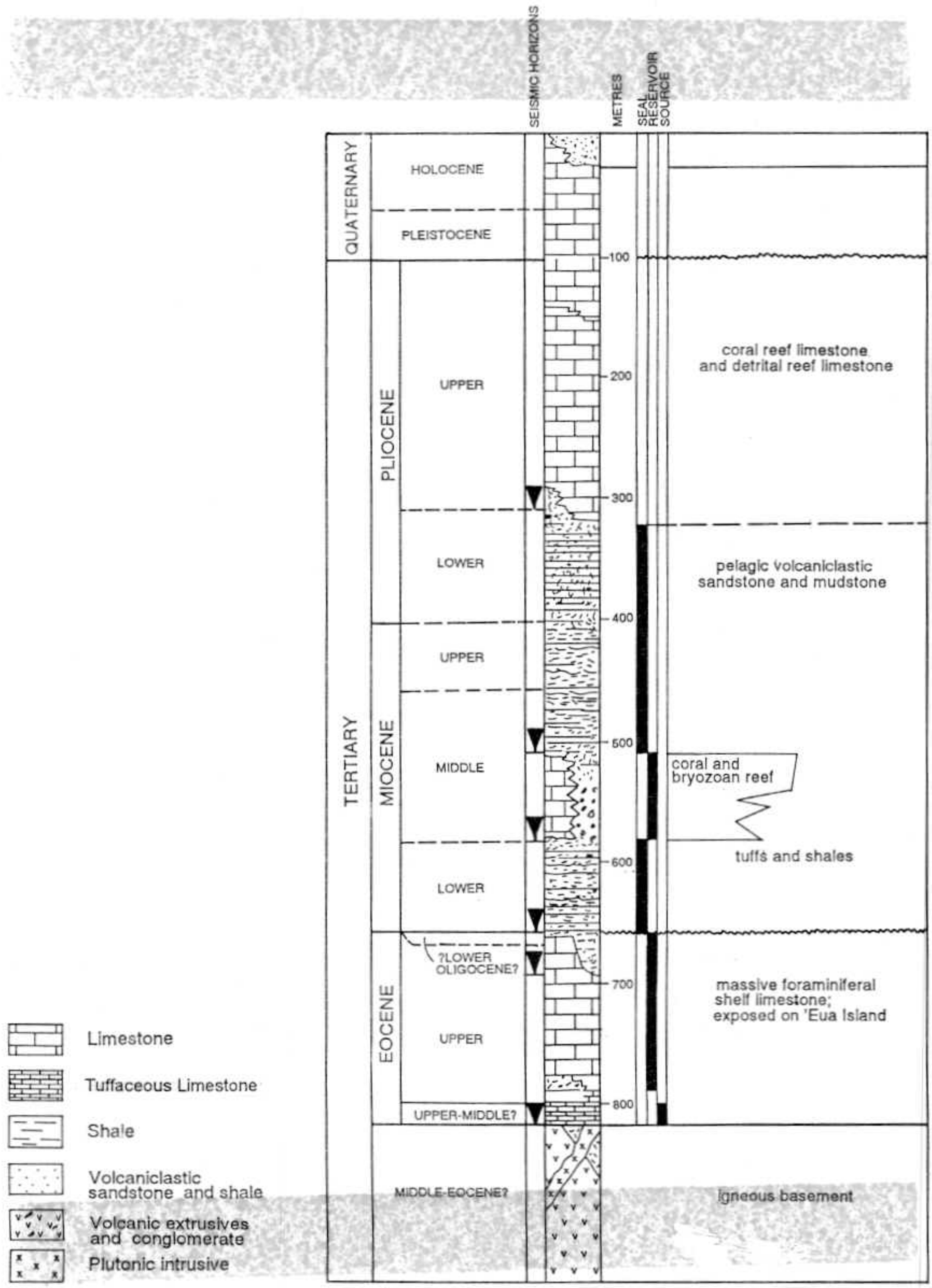

Figure 9. Stratigraphic column of 'Eua (after Cunningham and Anscombe 1985). Principal seismic reflectors, potential seals, reservoirs, and source rocks are highlighted.

Overlying the basement on 'Eua is a thin basal conglomeratic limestone of Middle Eocene age (Mulder and Nieuwenhuizen, 1971; and Chaproniere, in press). This is overlain by approximately 100 metres of massive, bioclastic, algal limestone of Late Eocene age. Chaproniere (in press) suggests that the Eocene limestones were deposited in tropical, sheltered situations in normal marine salinities, at depths of less than 50 m with access to the open sea.

Seismic data from 'Eua channel show that the Eocene interval thins towards 'Eua indicating a shallowing to the east and probable transgression over basement in that direction. Thicker sequences of Eocene and possibly older rocks occur on the southern Tonga Ridge with the thickest, up to 2750 m, being preserved on the downthrown sides of half grabens. The Eocene limestones were uplifted sometime before or during the Pliocene and karstified, resulting in the formation of extensive cave systems. No dolomitization has been reported.

Oligocene

Although no Early Oligocene rocks outcrop in Tonga, seismic interpretation indicates that substantial thicknesses of Lower Oligocene rocks are preserved in the deeper basin areas.

The regional Middle Oligocene unconformity present on the Tonga Ridge resulted from a major eustatic lowering of sea level (Vail & Hardenbol, 1979) and the opening of the South Fiji Basin (Malahoff et al., 1982). A number of half-grabens which formed in the Eocene to Early Oligocene became inactive during the Oligocene and erosion has removed much of the section from the most uplifted areas. Lense-shaped anomalies evident on seismic data in 'Eua Channel and on Tongatapu at this level are interpreted to be the remnants of submarine channels which cut down into the underlying section. These channels are thought to be filled with volcaniclastic turbidite channel deposits and turbidite lobes which give rise to the lense-shaped geometry.

Upper Oligocene volcaniclastic sediments up to 180 m in thickness have been reported from wells Kumimonu-1,-2 and -3 on Tongatapu (Maung et al., 1981; Maung, 1984). A large eroded volcanic edifice showing evidence of reef development in the overlying strata occurs at this level on the southern Tonga Ridge. This is referred to as the 11/14 structure and is described in more detail by Pflueger and Havard (1988).

Miocene

The Lower Miocene section in the wells on Tongatapu is 500 to 600 m thick and is composed of volcaniclastics deposited in deep water (Robertson Research, 1975). The islands of Mango and Tonumea in the Nomuka Group north of Tongatapu have outcrops of turbiditic deep-water volcaniclastic and carbonate sediments. The island of Nomuka has outcrops of shallow water foraminiferal packstones (Muller & Niuwenhuizen, 1971) indicating that some of the present-day islands formed shallow water topographic highs during this time.

Other than on the island of Fonoifua, the Upper Miocene sediments seem to be restricted to a relatively small area around Tongatapu and the area to the southwest. They are 500 m thick in the wells on Tongatapu and consist of volcaniclastics which continue up into the Lower Pliocene section. Robertson Research (1975) indicated that the water depth had shallowed by this time.

Subsequent uplift and erosion has removed most of the Upper Miocene and Lower Pliocene sediments over the Tonga Ridge leaving only a thin veneer in most areas. Many dredge hauls have recovered volcaniclastic sediments and deep-water marls of this age (Tappin, in press).

Pliocene and Pleistocene

A major unconformity separates the Upper Pliocene and Pleistocene from the older sediments. This coincides with the uplift of the Tonga Ridge prior to the opening of the Lau Basin to the west. In addition, some of the vertical movements may be attributed to the subduction of the Louisville Ridge during the past 2 Ma.

The uplifted islands are often capped with porous reefal and shelf limestones of this age which can reach up to several hundred metres in thickness in the Vava'u area. Today's deeper water areas were probably also deeper water areas during the Late Pliocene and Pleistocene. Dredge hauls from these areas show sediments to consist mainly of chalk, marl and tuff.

HYDROCARBON POTENTIAL

Hydrocarbons, Source Rocks, Maturation and Kitchens

Hydrocarbon seeps occur in three separate areas (Figure 6) on the north side of the island of Tongatapu. Samples (Figure 10) have been analysed by a number of companies with encouraging results. The oil on

Figure 10. The Pili oil seep, Tongatapu. Irridescent oil floats on water in a freshly dug shallow ditch. The oil seeps from fractures in the Pleistocene limestone bedrock. (Photograph).

Tongatapu is a thermally mature biodegraded crude oil (Sandstrom 1985, Sandstrom and Philp 1983, Summons et al. 1992, Fowler, in press).

Fowler (in press) analysed samples from Pili and found from gas chromatagraph charts (Figure 11) that the presence of C_{12} and C_{13} n-alkanes, and C_6-C_8 n-alkanes in the gasoline-range fraction, implied mixing of biodegraded hydrocarbons and light unbiodegraded hydrocarbons. He suggested that the seep is currently active with the addition of hydrocarbons from a more mature source than that of the biodegraded portions.

The source of the seeps or any other suitably organic-rich rocks in the Tonga region have yet to be identified. The highest total organic carbon (TOC) content recorded in the Tongatapu wells is 0.42 % in the Early Miocene from the Kumimonu-2 well (Buchbinder & Halley 1985). The same authors also found very low TOC content in outcrop samples from 'Eua. These values are too low to be considered as potential source rocks. Fowler (in press) has interpreted the active Pili seep oil to be from a marine carbonate source of Tertiary age. Summons et al. (1992) reported similar findings.

Maturation profiles for the Tonga Ridge have been modelled using an average temperature gradient of 3^{o} C per 100 m for the five wells on Tongatapu. A maturation model for these wells shows that the deepest one (at 2400 m) did not reach the top of the oil window which is predicted at 2800 m. However, a model in a

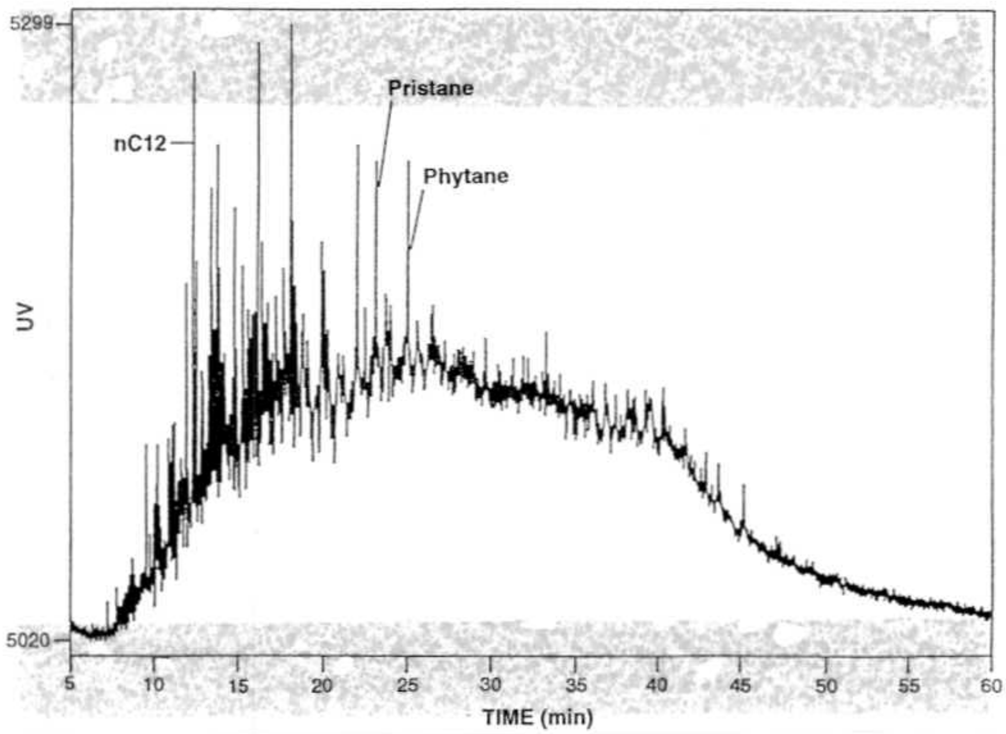

Figure 11. Saturate fraction gas chromatogram of Pili oil seep (Fowler 1993).

deeper part of the basin (Figure 12) shows that Eocene and Lower Oligocene sediments are within the oil window and have been since the Early Miocene. This has important implications in terms of potential migration and filling of traps, as a very long time interval has been available for these processes to occur.

Reservoirs and Seals

Palaeontological evidence and plate-tectonic reconstruction shows that the Tonga region has been in a tropical to sub-tropical environment from the Eocene to the Recent (Chaproniere, in press). Therefore any islands which emerged during this time might reasonably be expected to be associated with fringing or barrier reefs. Indeed, exposures of Eocene platform limestone on 'Eua contain fragments of reef-derived material (Cunningham and Anscombe 1985). Similar platform limestones ranging in age from Eocene to Pliocene occur throughout the island arcs of the Southwest Pacific (Figure 2).

Interpretation of seismic data from 'Eua Channel shows a trend of possible Eocene reefal features. These occur at a position between the shelf environment exposed on 'Eua and the thicker part of the Eocene section to the west. The regionally dipping Eocene section is interpreted as a carbonate ramp on which the reefal mounds developed. These seismic anomalies form a discontinuous chain (Figure 13) separated by lows thought to be inter-reef lagoons and channels. Reefs such as these are considered to be the main

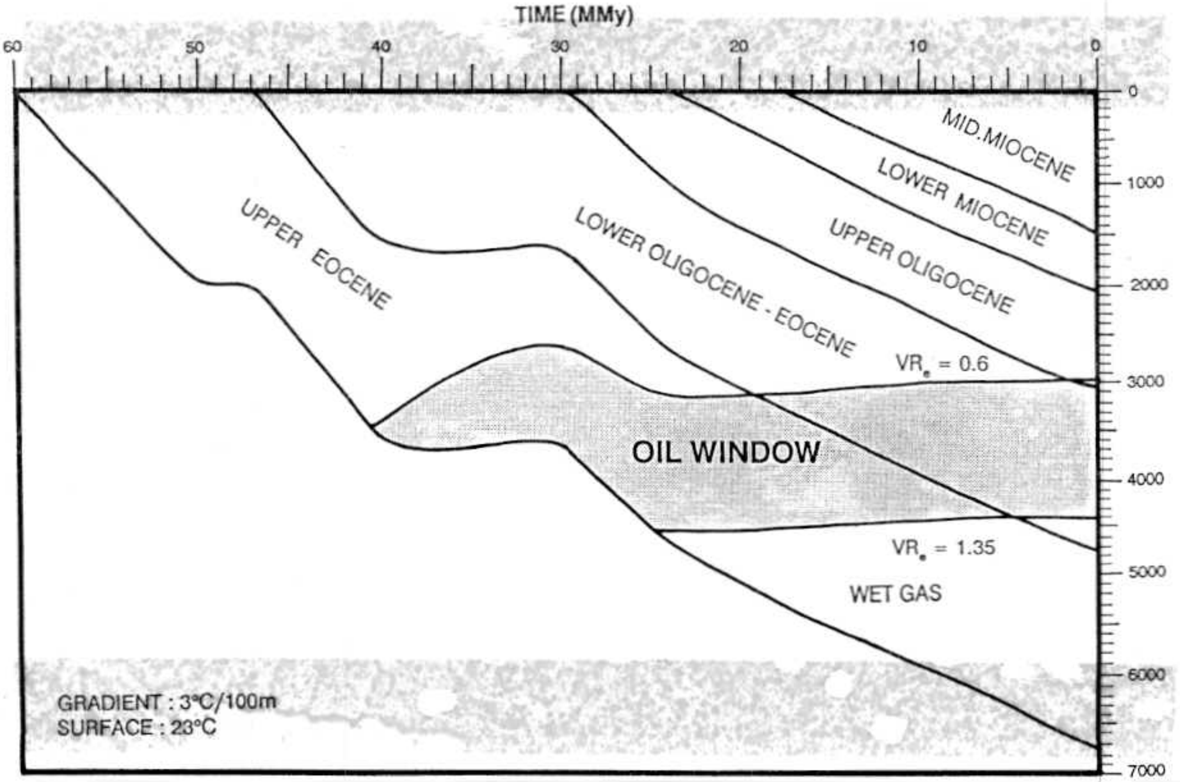

Figure 12. South Tonga Ridge burial and maturation history model using seismic intervals from the deepest part of the South Tonga Ridge Basin. Onset of oil generation would have occurred in Eocene sediments at the beginning of the Miocene deposition and continue in both it and the Lower Oligocene until present. (VR_e = Vitrinite Reflectance estimated).

reservoir targets in Tonga and elsewhere in the region (Exon and Marlow, 1990; Johnson and Pflueger, 1989; Falvey et al. 1992, Barclay et al., 1992; Rodd, in press).

Secondary reservoir targets are fractured and porous shelf limestones. Such limestones of Eocene age occur on 'Eua and are characterised by large solution caverns representing periods of uplift, karstification and vadose solution.

Other reservoir targets are reworked reefal carbonates such as the very porous Middle Miocene calcarenites which outcrop on the island of Nomuka. A few pieces of coral in growth position can also be found in this shallow water sequence (Mulder & Nieuwenhuizen, 1971).

The wells drilled on Tongatapu penetrated a thick sequence of volcaniclastics and shales ranging in age from Late Oligocene to Early Pliocene. Very little porosity was encountered in the sequence and any that was found had very low permeability due to cementation by zeolites. These rocks provide ideal seals. Although there are a large number of normal faults revealed by seismic data, the great thickness of the volcaniclastics and shales should provide good cross-fault seals.

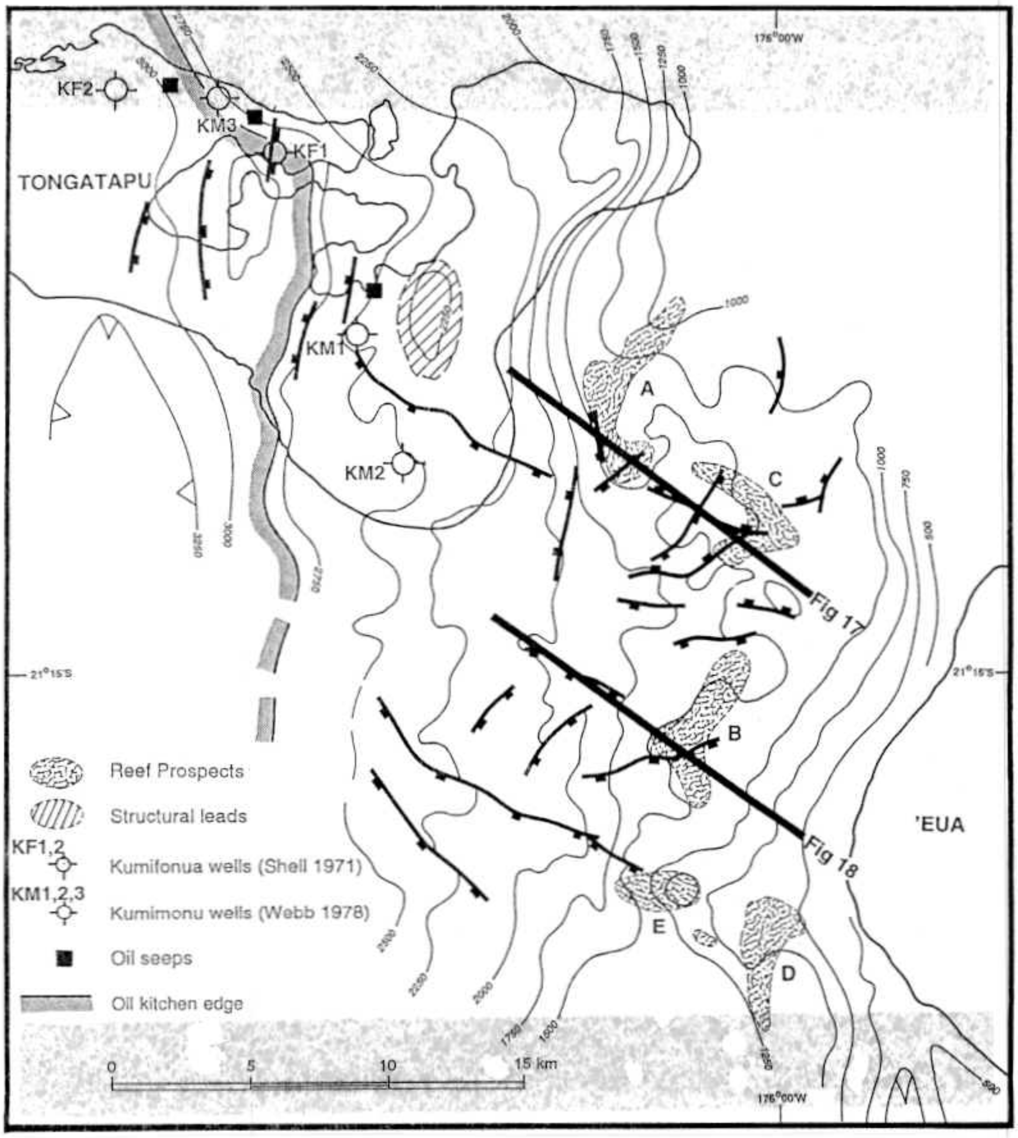

Figure 13. Structure map on an Eocene horizon with the five reef prospects A through E in the 'Eua Channel and a structural lead in NE Tongatapu Island. Note the oil kitchen edge at 2 800 m considerably deeper than the total depth of wells KF1, KF2, and KM3. Locations of the seismic reef prospect lines of Figures 17 and 18 are highlighted.

Traps

The most prospective traps are thought to be reef and shelf limestones sealed by shale and/or volcaniclastics forming combination structural - stratigraphic traps.

Other trap types which exist on the Tonga Ridge are anticlines and tilted fault blocks. This is particularly true on the South Tonga Ridge as demonstrated by Figures 14 and 15. Many half-grabens were formed during the Middle Oligocene breakup of the South Fiji Basin. Later drape over these faults has resulted in a number of structural closures at shallower levels. Flat spots seen on several seismic lines (Figures 15 and 16) on the South Tonga Ridge are associated with fault-controlled basement highs.

PROSPECTS AND LEADS

Seismic data from the 1977 and 1982 marine surveys, and the 1979 Tongatapu land Vibroseis marine survey have been reprocessed and interpreted, together with other data, to produce a consistent set of structure and isopach maps over the entire Tonga Ridge, including the area with the greatest survey detail in the 'Eua Channel. As a result a number of drillable prospects and leads have been developed in three different areas: 'Eua Channel-Tongatapu, the South Tonga Ridge and the North Tonga Ridge.

'Eua Channel - Tongatapu Area

The most prospective part of the area includes the eastern half of Tongatapu and all of 'Eua Channel from Tongatapu almost to the coast of 'Eua Island. Elsewhere, Eocene strata may be too thin for reef development. The Lower Oligocene to acoustic basement interval thins over the western half of Tongatapu and examination of the seismic character suggests that Eocene strata are absent in this area. This interval also thins to the north of Tongatapu and 'Eua. Within the main part of the 'Eua Channel water depths are 100 to 400 m. Southward they increase to over 800 m, limiting the prospective area.

Five reefal anomalies are evident on seismic sections in the Eocene interval. These are possible reef prospects and are indicated on Figure 13 as A to E. Each of the anomalies is defined by a number of the 1 km-spaced seismic lines. For example, prospects A, B and C are shown in Figures 17 and 18.

The anomalies form an arcuate northwest trend across 'Eua Channel which is interpreted to be an area of persistent reef growth established on basement highs. Structural lows between the basement highs later became tidal channels between the reefs and the lagoon situated over 'Eua Island. The channels appear to have persisted through the Early Oligocene, finally becoming filled during the Early Oligocene-Late Oligocene depositional hiatus. Two of these reef prospects, A and B, are described as follows:

Prospect A is located in a water depth of 187 m. The top of the Lower Oligocene is estimated at 1100 m bsl and Eocene seismic horizon between this depth and 1270 m. Acoustic basement is at about 1960 m. The Lower Oligocene-Eocene sediments are 860 m thick, thickest of all the prospects and providing potential for significant reservoir thickness.

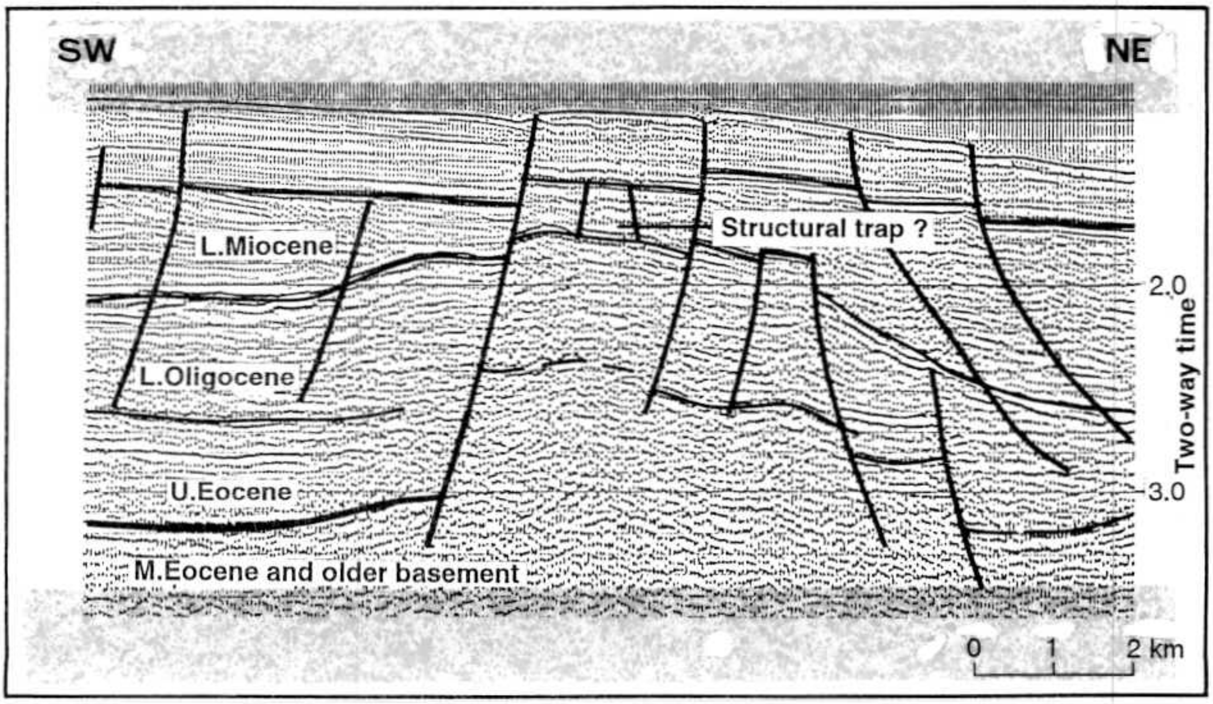

Figure 14. An igneous structure possibly capped with reef material is interpreted on this part of South Tonga Ridge seismic line 82-14. The location is shown in Figures 7 and 8.

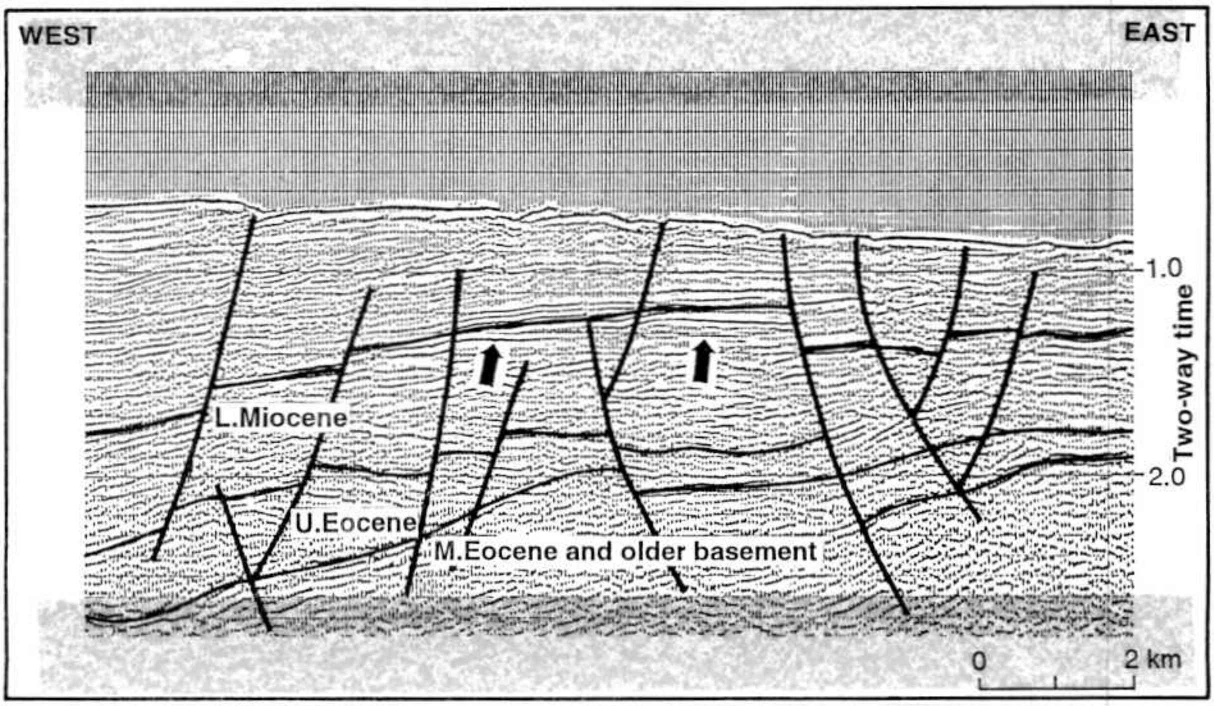

Figure 15. Flatspot anomalies (arrows) associated with a fault block on South Tonga Ridge seismic line 82-6. The location is shown in Figure 7.

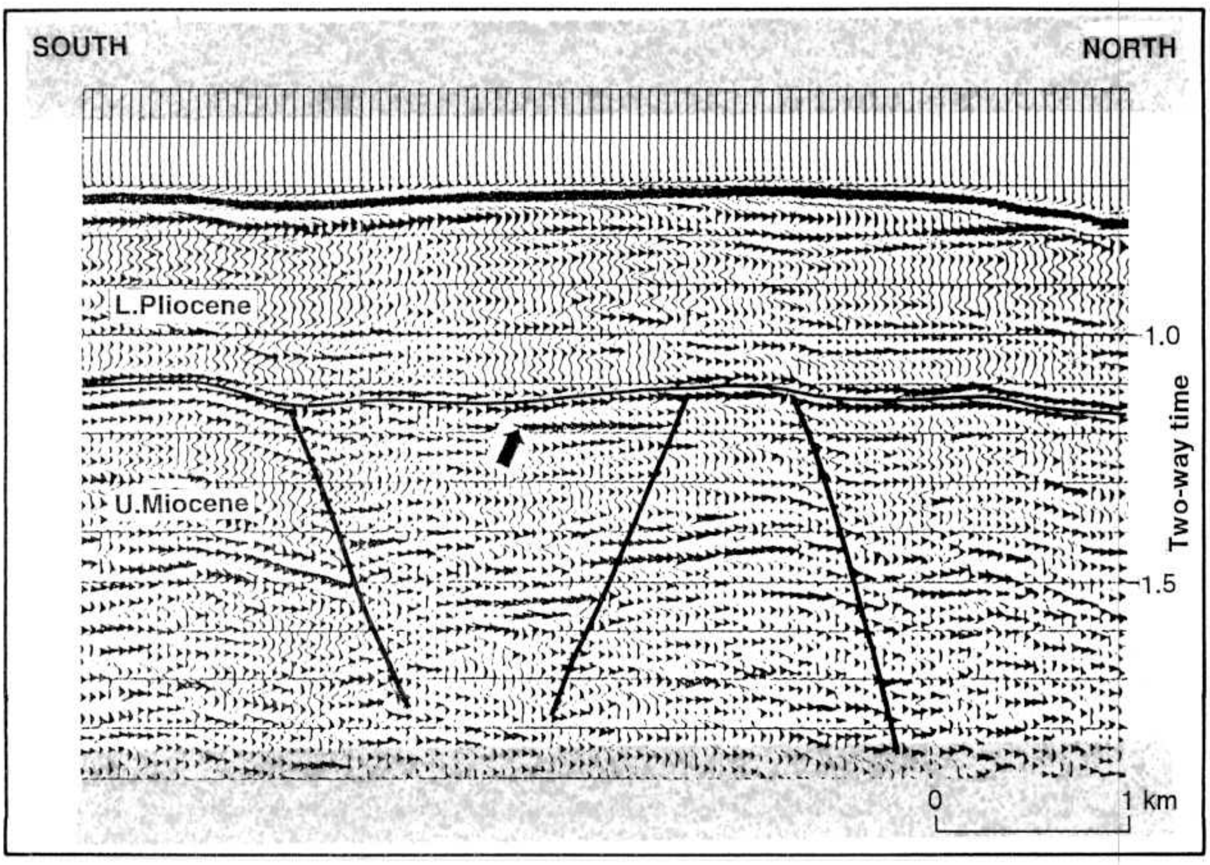

Figure 16. A flatspot anomaly (arrow) on South Tonga Ridge seismic line 82-14. The location is shown in Figure 7.

Reef prospect B (Figures 13 and 18) is located in a water depth of 170 m. The Lower Oligocene is predicted at 1000 m bsl and the Eocene seismic horizon at 1200 m. Acoustic basement is at 1470 m. This prospect is more directly updip from the presumed oil kitchen south of Tongatapu. The Lower Oligocene-Eocene sediments are 470 m thick at this location.

In addition to the reef prospects, a favourable structural lead has been identified in the northeastern area of Tongatapu. This feature (Figure 13) has significant relief, however there is insufficient seismic coverage to demonstrate large closure to the southeast. The depth to the Middle Oligocene unconformity is predicted to be 1700 m bsl, the Eocene horizon at 2180 m and basement at 2730 m. Ground elevation is 20 m.

Other lens-shaped anomalies occur in the 'Eua Channel. These anomalies have erosional bases and are interpreted to be submarine turbidite channels and lobes. One such feature was tested by well Kumimonu-2 and found to comprise volcaniclastic sediments. In view of this result, other similar anomalies are thought to be unprospective.

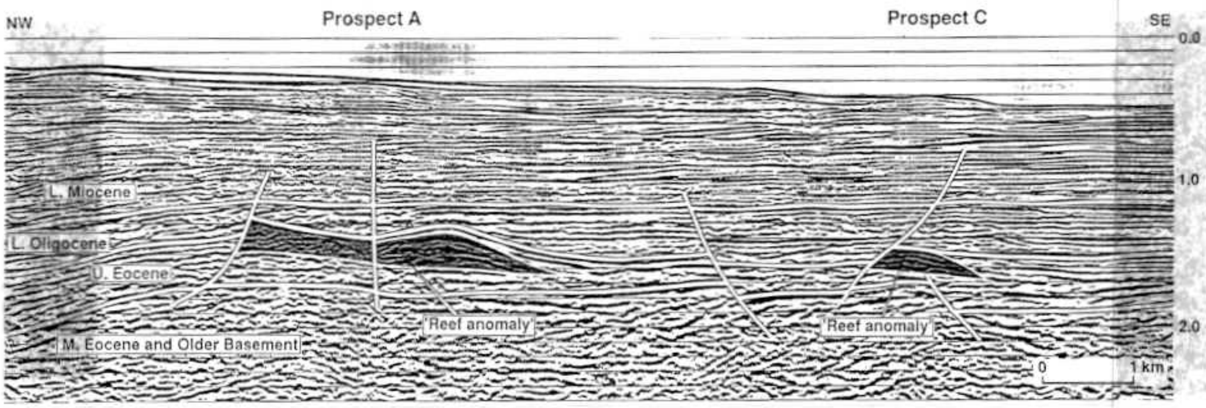

Figure 17. 'Eua Channel Eocene reef Prospects A and C on seismic line 79-24. The location is shown in Figure 13.

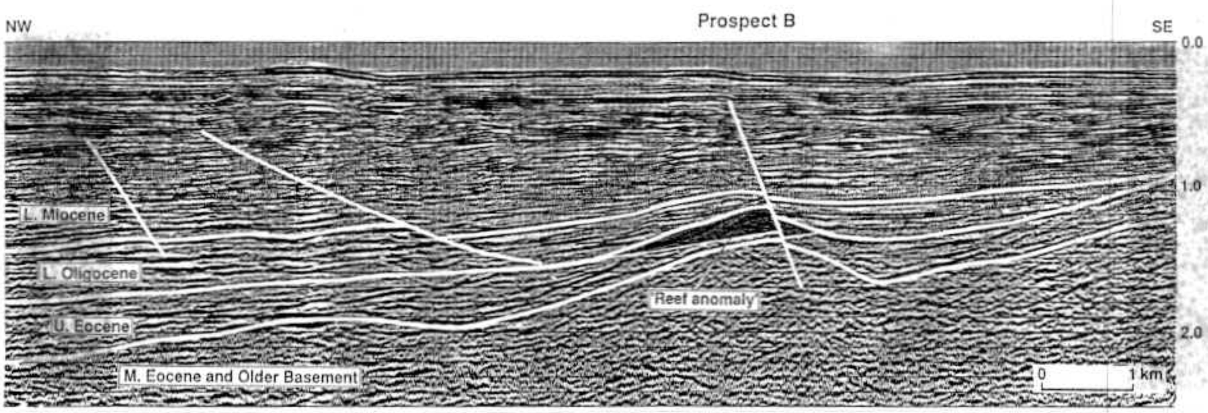

Figure 18. 'Eua Channel Eocene Prospect B on seismic line 79-15. The reef sits on a basement high and is flanked on the W by well-developed foresets. The location is shown in Figure 13.

'Eua Channel: Estimated Possible Reserves

Tonga lies on the same broad play trend of Tertiary reefal limestones that extends from producing oil fields in Irian Jaya and gas-condensate discoveries in Papua New Guinea through the island arcs of the Southwest Pacific (Figure 1). It may expected that reservoir characteristics could be similar throughout this play trend. In developing reserve estimates for the prospects in Tonga, the parameters are drawn from published data on Tertiary reef reservoirs in offshore Papua New Guinea.

Judging from the Miocene reef reservoirs of Pasca and Pandora fields in the Gulf of Papua average porosities of 14%, net to gross pay-zone ratios of 75%, formation factors of 83%, and hydrocarbon saturations of 65% (Durkee 1990) are thought to be reasonable predictions for the Tonga prospects. This is further supported by Eocene and Oligocene wackestones in Tonga well Kumimonu-1, which exhibited porosities in thin section of 10-25% (Exon et al. 1985).

A total oil-in-place of over 1.6 billion was estimated for the five prospects A, B, C, D and E (Table 1). Using a recovery factor of 40%, estimates of unrisked recoverable reserves for individual prospects range from 105 million barrels (MMB) to 150 MMB. The total for all five prospects is about 700 million barrels.

Table 1. Estimates of unrisked recoverable reserves for five reef prospects in 'Eua Channel.

Reef Prospects	Area (km^2)	Maximum Gross Pay of Reef Anomaly (m)	Gross Rock Volume $10^6 m^3$	Oil-In-Place (MMB)	Recoverable Reserves (MMB)
A	8.7	265	1011	360	**145**
B	8.3	278	1014	360	**145**
C	6.5	292	834	300	**120**
D	8.3	288	1051	380	**150**
E	3.8	430	725	260	**105**

As the prospects are in close proximity to each other, it is possible that shared development and production facilities may be feasible thus giving rise to significant cost economies.

South Tonga Ridge

Based on an interpretation (Pflueger and Havard, 1989) of over 1000 km of reprocessed seismic data, structure contour maps have been produced for the Lower Miocene, Upper Oligocene (?), Middle Oligocene Unconformity, and acoustic basement. The seismic character of the interpreted horizons is broadly similar to the 'Eua Channel.

A number of structural traps may be expected in the area, such as anticlinal, drape and faulted dip closures, but the 20 to 30 km seismic grid is too sparse to enable mapping of individual closures. Figure 14 illustrates the north-south aspect of a wave-cut igneous structure at the intersection of lines TRI82-L5-11 and 14 which may be capped by reefal limestone (Pflueger and Havard, 1988). Other structures similar to this feature probably exist between seismic control. Potential reservoirs could be charged from the deeper part of the ridge to the west (Figure 6) where up to 2750 m of Eocene or older sediments have been identified.

Although the total sediment thickness is approximately uniform across the ridge, Eocene rocks constitute a larger proportion of the section in the east, whilst Oligocene-Pliocene rocks are predominant in the west. Consequently, the eastern area may have greater potential for Eocene reefal targets, particularly those structural highs and fault blocks with thicker sections.

Structural leads have been identified on several seismic lines over three blocks (Figure 8) Summary descriptions of three of these are as follows:

Lead 1 is in a water depth of less than 300 m and has a total sedimentary thickness of over 2000 m. The thickness of the Lower Oligocene and Eocene sediments is variable because of extensive faulting, but averages about 400 m.

Lead 2 is in slightly deeper water and has a total section of 1400-1900 m, of which between 400-1000 m are Lower Oligocene and Eocene sediments. This lead exhibits a flat spot at 1.5 seconds two way time (TWT) in the Lower Oligocene-Eocene section. This could be a direct hydrocarbon indication of a gas-water contact.

Lead 3 has water depths up to 400 m, and exhibit the thickest sedimentary section of the three leads with over 3000 m, of which as much as 1400-1800 m could be Lower Oligocene-Eocene.

In addition to structural leads with possible Eocene and Miocene shelf limestone reservoirs, there is also a possibility of Miocene reefs. Tappin (in press) has suggested that shallow waters on the central platform in the Late Early Miocene led to the formation of reefs. Herzer and Exon have identified two possible Miocene reefs southwest of the 'Eua Channel (Figure 7).

North Tonga Ridge

Over 1260 km of seismic data were interpreted on the North Tonga Ridge, north of Tongatapu. The structure here is similar to the southern ridge and exhibits several large but higher fault blocks, separated by relatively deep canyons (Figure 4).

Eocene reefs similar to those identified in the 'Eua Channel may also be present north of Tongatapu along the western edge of the basement high (Figure 8) underlying the bathymetric high T (Figure 4). Anomalies shown on Line G-75 (Figure 19) could be Eocene reefs. Sediment thicknesses of up to 2400 m adjoining the highs could provide kitchens.

There are no seismic data in the shallow water areas around the islands of Nomuka, Mango, and the Fonoifua-Laloma group on the structures underlying the bathymetric high (N, Figure 4). All of these islands have exposures of Lower to Middle Miocene sediments. (Havard, 1989). Interpretation of a 1989 magnetometer survey within this area (Falconer & Handley, 1991) shows that magnetic basement reaches 2000 m bsl. (Havard, 1989) observed cyclic Miocene turbidites which included large coral clasts, implying deep water deposition in close proximity to a shallow reef. Tappin (in press) also suggested Late Early

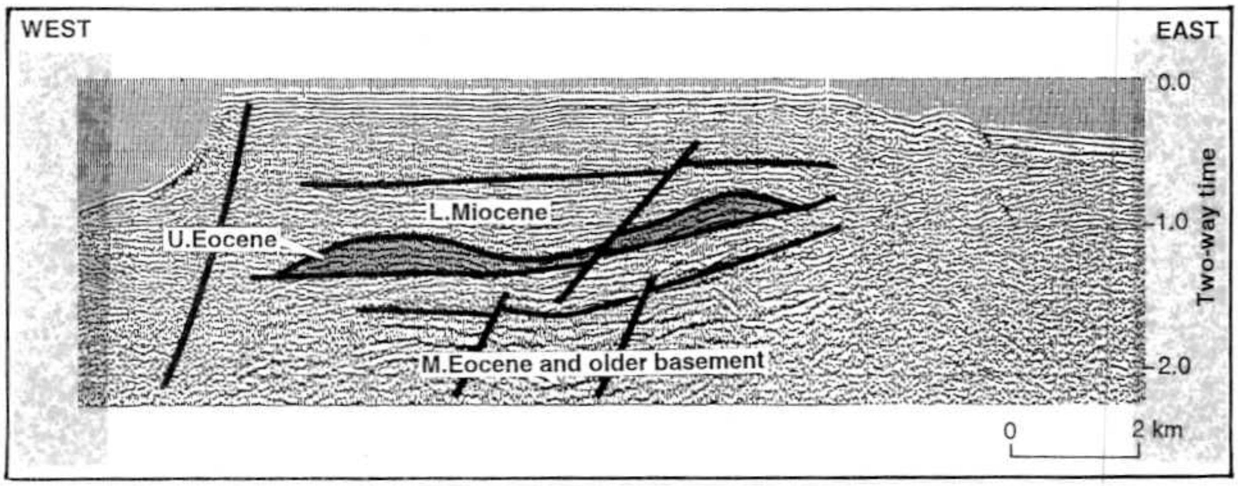

Figure 19. Reef anomaly leads on North Tonga Ridge seismic line G-75. The location is shown in Figure 7.

Miocene formation of reefs. Austin et al. (1989) identified two Miocene reef leads in the Ha'apai and Nomuka areas (Figure 7).

West of the Eastern Ha'apai island group (Lifuka etc.) sediments situated on the flanks of the structure underlying bathymetric high (V, Figure 4) are 1000-2000 m thick, whilst to the north magnetic data show an increase in high-frequency response indicating that igneous basement is generally close to the surface. However, Kitekei'aho (1989) identified possible reefal anomalies within the Eocene interval north of the Vava'u group.

CONCLUSIONS

Tonga exhibits all the necessary characteristics for petroleum potential. These include the presence of hydrocarbons, implying source rocks, maturity, and migration; the presence of porous, permeable reservoir rocks; and the presence of traps with favourable timing of trap formation.

Oil seeps on the island of Tongatapu provide positive evidence that oil is being generated in the offshore forearc basin of the Tonga Ridge. Geochemical analysis shows that these are derived from marine carbonate source rocks. Burial and maturation modelling suggests that oil kitchens may exist both beneath and to the south of Tongatapu, where sediments as thick as 3400 m have been mapped.

Reservoir rocks were not penetrated in any of the five drilled tests, but can be observed in outcrop on 'Eua island. Seismic data in the 'Eua Channel clearly show anomalies which can be interpreted as buried Eocene reefs. None of these features have yet been drilled and so provide an untested play.

Other untested structural and stratigraphic play concepts are Eocene to Miocene shelf limestones sealed by basinal shales forming faulted anticlines and drape-over anticlines.

Given the known and inferred source, reservoir and trap characteristics of the Tonga Ridge, it is believed that there is a good potential for the existence of commercial hydrocarbon accumulations. Five Eocene reef prospects have been identified in the shallow waters of the 'Eua Channel. Estimates of unrisked recoverable reserves are 700 million barrels for these five.

In addition, leads have been identified elsewhere on the Tonga Ridge. These include Eocene and Miocene reef anomalies and several structural leads, including one on the island of Tongatapu.

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