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ASSESSMENT OF PETROLEUM POTENTIAL OF THE SOUTHERN AND NORTHERN PARTS OF THE TONGA PLATFORM

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ABSTRACT

Petroleum potential exists in the reefal buildups of Oligocene–Early Pliocene age which are developed on the Late Middle–Late Eocene limestone platform and are overlain and enclosed by volcaniclastic sediments of Miocene–Early Pliocene age. Three probable reefal buildups having areal extents of 10–20 sq.km and vertical extents of 340-510m are observed in the southern part of the Tonga Platform. Sufficient sedimentary rock thickness and temperature gradient exists for maturation of petroleum. Oil seepages observed on Tongatapu and 'Eua are assumed to be generated in–situ in the reefs and/or behind the reefs in lagoon and to have slowly migrated along fault planes. The reefs are also considered to be both potential reservoir rocks and traps, with the volcaniclastic rocks providing a good seal. Tertiary reefs in general are very porous and permeable and this fact has been confirmed by previous oil company investigations on Oligocene–Lower Pliocene reef outcrops on 'Eua Island in Tonga.

Average water depths over the southern and northern parts of the Tonga Platform are in the range of 500-1000m and 1000-1500m respectively. Technologies for exploratory drilling and production testing for water depths that exist in the southern part of the Tonga Platform are available at present but costly. The cost of an exploratory well in water depths greater than 200m is estimated to be about US$9-20 million. Technologies for production such as the tension leg platform and subsea production systems are still in the experimental stage for water depths of 500 to 1000m and will probably be available in 1984–1990.

The southern part of the Tonga Platform has more petroleum potential in terms of presence of potential source rock, reservoir rock and trap as well as more favourable water depths compared to the northern part of the Tonga Platform. However, there is not much seismic data available on the northern part of the Tonga Platform.

INTRODUCTION

The Kingdom of Tonga is comprised of 170 islands which are scattered over 258,900 sq.km (100,000 sq.mi) of ocean. The main islands are in three groups, Tongatapu, Ha'apai and Vava'u (Fig. 1). West of the three island groups is the north-northeast linear trend of volcanic islands, many of which are active. The most prominent of these are Tofua, Late and Kao.

The Tonga Platform is bounded on the east by the Tonga Trench and on the west by the Lau Basin. For the purpose of this study, the Tonga Platform will be divided into central, southern and northern parts as shown in Figure 2. The Central Tonga Platform is the area bounded on the south by Tongatapu and 'Eua islands, on the north by the Vava'u islands group and in the east and west by the 2000m isobath. This part has been licensed to commercial oil companies since 1970. The Southern Tonga Platform is the area bounded by 2000m isobath south of Tongatapu and north of latitude 26'S. The Northern Tonga Platform is the area bounded by 2000m isobath north of Vava'u islands group and south of latitude 25'S.

The first objective of the present study is to review the existing oil company-generated data to June 1972 on the central Tonga Platform held on open file at the Ministry of Lands, Survey and Natural Resources, Nuku'alofa, in order to aid in the assessment of the petroleum potential of the southern and northern parts of the Tonga Platform. Although a tremendous amount of exploration work and re-assessment of data has been done on the Central Tonga Platform since June 1972 (see for example Kroenke and Tongilava, 1975; Tongilava and Kroenke, 1975; Katz, 1976 and 1980) most of these data are still on confidential file.

The second objective of this study is to review the sediment thickness and possibly the basement and fault trends and particularly to review the petroleum potential of the unlicensed southern and northern parts of the Tonga Platform. The study is based on single-channel continuous seismic reflection profiles obtained between 1977 and 1980 by CCOP/SOPAC and Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM) scientific expeditions.

REVIEW OF OIL EXPLORATION ACTIVITIES IN TONGA

The search for oil in Tonga was initiated after oil seepages were found and brought to the notice of H.M. King Taufa'ahau Tupou in 1968.

The seepages occur in vuggy coral limestone a few feet below the ground surface on Tongatapu, and in the sea off 'Ohonua harbour in 'Eua (Fig. 3). Samples of the oil have been collected and analysed by several oil companies and results show the oil to be genuine weathered crude oil. The results of some of these analyses are included in Appendix A. A reported oil seepage in Vava'u has not been substantiated.

Several oil companies (Shell Development [Australia] Pty Ltd., Australian Aquitaine Petroleum Pty Ltd., Australian Gulf Oil Co., Ampol Exploration Ltd., BP Oil Exploration Co. New Zealand) became interested in the oil potential in Tonga and carried out survey work.

In June 1970 a Petroleum Agreement was signed between the Government of the Kingdom of Tonga and the Tonga Oil Participants consisting of:

Tonga Shell N.V.	=	33.3%
British Petroleurn Co Ltd	=	16.6%
Australian Aquitaine Petroleum Pty Ltd	=	16.6%
Gulf Oil Co of Tonga	=	11.0%
Ampol Exploration Ltd	=	11.0%
Republic International Petroleum Corp.	=	11.0%

Tonga Shell N.V. was appointed as operator. The concession area covered 15,540 sq.km (6000 sq.mi) of the Tonga Ridge from Vava'u in the north to Tongatapu in the south. The agreement was subject to the provisions of the Petroleum Mining Act 1969 and the Petroleum (Income Tax) Act 1969-1970 and covered a period of 40 years.

Shell undertook a geological field survey in 1970 concentrating on 'Eua, but including most of the islands.

A geophysical survey was also carried out in 1970 which covered the whole of the concession area. A total of 2192km (1362 mi) of seismic data was shot by Geophysical Services Incorporated using a 14 litre (860 cu.in) airgun source for 24-fold subsurface coverage. Magnetic and gravity data were recorded simultaneously. The results of these surveys are summarized in Mulder and Nieuwenhuizen (1971).

The Consortium decided to concentrate on Tongatapu, the main island, and carried out a land gravity and magnetic survey in June 1971, in order to determine drilling locations. The results of this survey indicated a basin extending N-S across Tongatapu. Two drilling locations were proposed in August 1971 with the hope of encountering Oligocene/Eocene limestones overlying the volcanic basement, and to determine the provenance of the nearby crude oil seepages. The drilling locations are shown in Figure 3.

The first exploration well in the Kingdom of Tonga, Kumifonua No. 1, was spudded on October 2nd. 1971, southeast of Nuku'alofa. The well failed to reach the targetted lime-stone due to limited rig capacity and was plugged and abandoned at a total depth of 1684m (5525ft.) still in volcaniclastics. The well data are included as Appendix B. A second well, Kumifonua No. 2, drilled in an updip position on the western Flank of the basin near the see-pages of Hofoa, also failed to reach the target within the rig capacity. It bottomed in Miocene volcaniclastics at a depth of 1685m (5529ft.) without encountering any significant oil or gas shows. The well data are included as Appendix C. No radiometric dating was determined for samples from these wells.

These disappointing but inconclusive results caused Shell to withdraw from the Petro-leum Agreement in June 1972, followed soon after by British Petroleum. In July 1972, 5,180 sq.km. (2000 sq.mi.) in the north of the Agreement Area was voluntarily surrendered. The remaining participants unsuccessfully attempted several farm-out proposals in June 1973. Despite the Government of Tonga suspending obligations several times the remaining parti-cipants could not continue and the Agreement terminated late in 1974.

During the following year several other companies showed an interest in the area and finally a Petroleum Agreement between Webb Tonga Inc. and the Government of Tonga was signed in February 1976. This granted Webb Tonga sole exploration rights over the 7,770 sq.km(3000 sq.mi.) of the contract area (the southern half of the original concession area), with an option on the remaining northern 7,770sq.km (3000 sq.mi.). The Third Amendment to the Petroleum Agreement in February 1976 granted Webb the total 15,540sq.km (6,000 sq.mi.).

Webb Tonga re-evaluated all the available data and reprocessed the Shell seismic lines. The results are summarized by Warters (1976). A land seismic survey was carried out on Tongatapu from February-July 1977 in order to map the potentially oil bearing Miocene Oligocene carbonate reefs. The 48 channel, 12 fold seismic survey covered a total of 283km (176 miles) using the vibroseis energy source technique. Three well sites were chosen on the basis of these seismic data. The locations are shown in Figure 3.

The first of the Webb Tonga wells, Kumimonu No. 1, was drilled on the Malapo prospect in February 1978. The well reached a depth of 2,555m (8,373ft.) in presumed volcanic basement and was plugged and abandoned as a dry hole. Kumimonu No. 2 was drilled in April 1978 on the Fua'amotu prospect at the southern tip of Tongatapu. It also proved to be a dry hole after reaching a total depth of 2,295m (6,996ft.) in presumed volcanic basement without encountering any reef section. The final well, Kumimonu No. 3, was drilled in Nuku'alofa in May-July 1978, and reached a total depth of 2,635m (8,643ft.). Although some reefal limestone was encountered there were no significant hydrocarbon shows and the well terminated in volcaniclastics and volcanic conglomerates/breccia.

Potassium-argon dates were determined for ditch cutting samples from 2527-2535m (8290-8302ft.) of Kumimonu No. 1 well and from 2121-2131m (6960-6990ft.) of Kumimonu No. 2 well. The average ages are 13.9 +_ 1 ma (IUGS)i.e., Middle Miocene for the former and 21.3 +_ 0.4 Ma (IUGS)i.e., Early Miocene for the latter. Petrographic analysis of the samples indicates that both samples are dolerite (dyke or sill). No potassium-argon dates were determined for samples from Kumimonu No. 3 well.

After discouraging results of their 3 onshore wells, Webb directed their exploration programme offshore. In October and November, 1979 a marine seismic surveywas conducted in the area between Tongatapu and 'Eua, using an Aquapulse (TM) source, 60-channel, 2 x 24-fold seismic array accompanied by gravity and magnetic instruments with an approximate line spacing of 0.8km (0.5 mi.)

Since July 1980 Samuel Gary Oil Producers Inc. took over the Petroleum Agreement from Webb Tonga. The company is currently assessing the recent marine seismic survey with a view to drilling offshore in 1982.

SUBMARINE PHYSIOGRAPHY

The Tonga Ridge forms a relatively flat-topped feature extending from Latitude 15'S in the NNE, to Latitude 27'S (Fig. 4) where it continues southward as the Kermadec Ridge and then the East Cape Ridge to North Island, New Zealand. The Tonga Platform is roughly outlined by the 2000m isobath in Figure 4, with an average width of about 100 to 120km (63-75 mi.), the highest areas forming the Tongan Island groups of Vava'u, Ha'apai and Tonga-tapu. Extensive areas of the platform have water depths less than 500m. The eastern side of the Ridge drops away steeply into the Tonga Trench which reaches depths of over 10,000m. The trench turns sharply to the west at its northern end at Latitude 15'S and terminates abruptly, probably at a transform fault. The trench marks the site of subduction of the Pacific Plate. East of the trench there is a fairly steep rise into the West Pacific Basin, with average water depths of 5000-6000m. This basin is relatively flat at these depths except for occasional seamounts. The west side of the Tonga Platform drops steeply, but less sharply, into the Tofua Trough which reaches depths of 1750m. This trough separates the main chain of islands from a line of recently active volcanoes, the most prominent of which are Tofua, Kao and Late whose peaks rise above sea level. West of this volcanic chain lies the young Lau Basin with an average depth of 2500m. This is bounded on the west by the N-S trending Lau Ridge which reaches elevations similar to the Tonga Ridge, although the sides are less steep.

Although an Exclusive Economic Zone has not yet been declared by Tonga, it will probably include all the Tonga Platform with water depths of less than 2000m. On this basis, in the south, the 200 mile limit would extend at least to latitude 25'S. On the west and north, median lines have yet to be settled with Fiji and Samoa as the exclusive economic zones overlap. The estimated area of the proposed exclusive economic zone (land area plus offshore area) of Tonga is about 809,000 sq.km.

REVIEW OF GEOLOGY OF TONGA

Outcrop Stratigraphy

The most complete geological succession of the Tongan islands is present in outcrops on 'Eua. Tilting of the island has resulted in basement rocks being exposed on the eastern sea cliffs (Figs. 5 and 6). Although the outcrops probably represent a thinned and condensed sequence, it is invaluable in extrapolating subsurface geology into the basin to the west. A detailed account of the geology of 'Eua was given by Hoffmeister (1932) and subsequent work by various oil companies have not disproved his basic ideas, although more accurate dating has been obtained.

The succession on 'Eua (Figs. 5 and 6) comprises the Following;

Pre Upper/Middle Eocene Basal Volcanics: Lava flows, tuffs and pyroclastic rocks, mainly andesitic in composition are cut by numerous dykes of andesitic and dacitic composition. As no fragments of sedimentary rock have been found within the volcanics, they are assumed to form the basement. Considerable topographic relief existed on the basement rocks.

A footnote in the resume of exploration wells Kumifonua Nos. 1 and 2 by Tonga Shell NV and SIPM The Hague (1972) states that the isotopic age determination of volcanic basement of 'Eua gave an age of 34.7 +_ 3.5 Ma, i.e., uppermost Eocene or lowermost Oligocene. The footnote moreover mentions that this age is probably not older than Eocene and that no great age difference exists with the overlying basal conglomerate and limestones. No references or explanations are given for this date and therefore it must be used with caution.

Late Middle-Upper Eocene Basal Conglomerate and Limestone: In parts of 'Eua a basal conglomerate, up to 23m (75ft.) thick, overlies the volcanic basement. It consists of well rounded to angular pebbles up to 50cm (7.9in.) diameter, poorly sorted and well bedded in a matrix of fine volcanic debris and ;foraminifera (which indicate a late middle Eocene Age). A limestone unit up to 150m (500ft.) thick rests unconformably on these rocks. The limestone is cream coloured, massive to coarsely bedded foraminiferal lime wackestones, with algae, mostly in the form of Oncolites. It has fair to good secondary porosity due to leaching and vugs. The environment of deposition is interpreted as being relatively low energy, middle neritic, protected carbonate shelf with normal salinity.

Oligocene-Lower Pliocene Reef Complex: A reefal development grew extensively on the Eocene platform, probably as an atoll enclosing a central lagoon. The thickness of this complex may be in excess of 305m (1000ft.). The outcrop on the western ridge of 'Eua is interpreted as the high energy seaward front of the atoll with the eastern ridge forming the low-energy leeward edge.

Miocene-Lower Pliocene Clastics: Equivalent in age to the reefal complex, and forming the basinal facies, are detrital, pelagic, in part turbiditic lithic sandstones with siltstones and mudstone intercalations. They are 90-150m (300-500ft.) thick on 'Eua, but the wells drilled on Tongatapu encountered an equivalent section over 1525m (5000ft.) thick which suggests considerable subsidence in the basin at this time.

Upper Pliocene-Pleistocene Reef: A fringing reef facies is developed around 'Eua, and reworked reef detritus in the central valley area is supposedly Pleistocene in age.

The remainder of the Tongan Islands have only limited outcrops. Tongatapu is covered with Pleistocene reef limestone. Farther north, the Nomuka Group have exposures of Miocene volcaniclastic sediments with a possible pinnacle reef facies of similar age exposed on Nomuka itself. Still farhter north the Ha'apai group of islands consist of raised Quaternary coral limestones, some capped with weathered pyroclastics believed to be derived from the eruption of Tofua and Kao volcanoes to the west. The most northerly group of islands, Vava'u, reach an elevation of 185m (600ft.) due to recent uplift, but exposures are of Pliocene-Quaternary limestone. The limestone seems to form 2 units: probable Pliocene foraminiferal and coralline limestones, with dips up to 20', and younger Quaternary coral limestone forming sub-horizontal raised terraces.

West of the main islands of the Tonga Platform, and separated from them by the Tofua Trough (1750m deep), are the chain of younger volcanic islands. They extend from Tafahi in the NNE to Ata in the SSW, some being active within recorded history. Lava flows are mainly vesicular basaltic andesites with some quartz andesites and dacites.

Subsurface Stratigraphy

Knowledge of subsurface stratigraphy is limited, as only five wells have been drilled to date, all on Tongatapu. These wells penetrated a much thicker, sedimentary sequence than is present in outcrops on 'Eua to the east.

Two of the Webb Tonga wells, Kumimonu Nos. 1 and 2, bottomed in what was thought to be volcanic basement. However, potassium-argon dating gave ages of Middle and Early Miocene (13.9 ± 1 Ma and 21.3 ± 1 Ma) respectively, and, as overlying sediments were dated as Late Eocene on the basis of faunal assemblages, the wells probably penetrated dyke or sill rock. The basement under Tongatapu therefore lies at depths exceeding 2620m (8600ft.). The Eocene platform limestone that crops out on 'Eua was not found in the wells. Instead, a basinal equivalent consisting of volcaniclastic sediments, dated as Late Eocene, were encountered in Kumimonu Nos. 1 and 2 wells. The Miocene-Lower Pliocene volcaniclastics which are exposed on 'Eua thicken abruptly into the basin, from 150m (500ft.) in outcrop to over 1525 (5000ft.) in Kumimonu No. 3. None of the wells encountered significant reefal buildups. Only Kumimonu No. 3 penetrated 2 thin intervals of Miocene reefal limestone 15m (50ft.)

and 46m (150ft.) thick. The Pleistocene reefal limestone capping Tongatapu is approximately 150m (500ft.) thick.

Structure

The Tonga Platform is bounded on the north by a transform fault and on the south by a scarp interpreted to be a normal fault, transverse to the ridge axis, with possible minor strike-slip displacement. These normal faults are a common feature of frontal arcs and divide them into blocks which tilt away from the trench thus exposing the oldest rocks on the trench side of the arc summit - as on 'Eua. (See also Marianas, Tracy et.al. 1964; New Hebrides, Obellaine 1958).

The Tonga Platform is gently arched, with down-to-the-east normal faults on the eastern side, and down-to-the-west on the western side. The latter probably developed at the opening of the Lau Basin in the Pliocene (Cherkis, 1980). The west boundary faults, along which the new volcanic chain has formed, have a total displacement of several thousand metres. A NW-SE-trending left-lateral strike-slip fault has been mapped from the Shell seismic data between Nomuka and Tongatapu, with approximately 10km (6 miles) displacement. The WNW trending channels between the island groups may be related to other major strike-slip faults as shown in Figure 7.

Direct observations (Mulder and Nieuwenhuizen, 1971) on 'Eua island reveal an assymetrical N-S-trending anticlinal uplift, probably resulting from faulting. A major down-to-the-east fault zone is inferred off the east coast of this island, also trending N-S. This has resulted in steep easterly dips (20-30') on the eastern coast of 'Eua, but more gentle westerly dips (10-15') on the west. A series of NNE-and-NNW trending faults have been mapped in the central part of the island which are downthrown to the west and probably branch from the major N-S fault.

Direct evidence of faulting on the other islands is limited (Mulder and Nieuwenhuizen, 1971). Fonoifua in the Nomuka group shows small (up to 1m or 3.3ft.) NW-trending faults downthrown to the SW cutting the Miocene volcaniclastics. NNW-trending faults have been inferred from stratigraphic evidence and local steep dips on Mango Island. Photogeological mapping (Mulder and Nieuwenhuizen, 1971) has revealed other linear elements believed to be faults or fractures. These trend NNW with subordinate NNE trends on Tongatapu and 'Eua; NW and NNW trends in the Nomuka group, WNW and E-W trends with subordinate NNW and NNE trends in Ha'apai; and in the Vava'u group WNW and NE trends. Reef terraces also evidence recent tilting on several islands. 'Eua has undergone slight tilting to the NW, Tongatapu to the NNE and Vava'u to the SE.

Geological History

The following account is based on Warters, 1976.

Tonga has been in much the same tectonic setting since early Tertiary; it is part of an island arc under which the Pacific plate is subducting into the Tonga trench on the east. This has caused chains of volcanoes to be formed parallel to the trench, which may have migrated westwards with time. In the early Tertiary, Tonga formed part of the northeastern edge of the Australian continental plate which was over-riding the Pacific plate at the Tonga Trench. This led to volcanic activity in the eastern part of the Tonga Ridge in the 'Eua region, where this volcanic basement presently is exposed.

Middle-Early Late Eocene: This was a period of tectonic unrest during which a volcanic ridge in the vicinity of 'Eua was uplifted and eroded. Subsequently a conglomerate bed was deposited on this irregular surface. Inter mittent quiet periods allowed limestones to develop which were later eroded, and contributed to the conglomerate.

Late Late Eocene: A period of relative quiescence allowed a platform limestone to develop on the shelf to the east (over 'Eua) whilst a more basinal facies of volcaniclastics were deposited to the west (Tongatapu), perhaps indicating that volcanism had migrated westward.

Oligocene: A lowering of sea level during Late Oligocene (due to climatic cooling with a consequent increase in glaciation near the poles) meant deposition continued only in the basinal area (over Tongatapu). A hiatus occurred on the emerged 'Eua Island to the east. By Late Oligocene sea level rose again and reefal development grew on the Eocene platform limestone.

Miocene-Early Pliocene: Volcanic activity was widespread as evidenced by volcaniclastic sediments on Nomuka, 'Eua, and the thick succession encountered by the wells on Tongatapu. The Miocene dolerite dyke or sill encountered in Kumimonu Nos. 1 and 2 probably represent an intrusive phase of the activity. During quiescent periods reefs formed, e.g., on Nomuka and 'Eua, and the thin reefal limestone intervals encountered in Kumimonu No. 3. Considerable differential subsidence took place during this period as evidenced by the thick succession encountered on Tongatapu, as compared with 'Eua only 32km (20 mi.) away.

Late Pliocene: By this time the configuration of the Tongan Platform was much as today, the Lau Basin began to open up, and the volcanic chain moved west to its present position along the western boundary fault of the platform. 'Eua was uplifted and tilted to the west and reef limestone developed around the coast.

Late Pliocene-Pleistocene: A drop in sea level, relative to the present, during the Pleistocene allowed reefs to grow on uplifted areas of the platform such as Tongatapu, 'Eua and Vava'u. These subsequently kept pace with the rising sea level. Some tilting also occurred at this time as evidenced by the reef terraces.

MEASUREMENTS OF SEISMIC AND MAGNETIC PROFILES

Continuous single channel seismic reflection profiles were obtained during R/V MACHIAS cruises TG-79-1 and TG-80-1 in 1979 and 1980, carried out under the CCOP/SOPAC work programme. The seismic traverses were located so as to provide the best coverage of the region in the time allotted for the study. The primary position control was provided by a Magnavox satellite navigation system. Single channel seismic data were continuously recorded using an EPC 4100 graphic recorder, Bolt 0.66 litres (40 cu.in.) airgun, and a Seismic Engineering Co single-channel hydrophone streamer.

Fourteen lines were shot in the southern part of the Tonga Platform south of Tongatapu and north of latitude 24' 10'S with an average line spacing of approximately 22.5km (14 mi.) in 1979. A single tie-line for north-south control was run from latitude 24' 10'S back to Tongatapu along the length of the platform. The total length of the seismic tracks as reported by Gauss (1979) was 2140km (1330 mi.).

Five zig-zag lines were shot across the northern part of the Tonga Platform between latitude 15' 20'S and the Vava'u Islands group in 1980 and reported by Halunen (1980). No north-south control line was run in this part of the Tonga Platform. The total length of the 5 zig-zag traverses was 534km (326 mi.).

The southern part of the Tonga Platform was also traversed by the EVA III scientific expedition in 1977 organized by ORSTOM Centre Geology-Geophysics team of Noumea, New Caledonia. During the cruise, 10 single-channel seismic and magnetic profiles approximately 48 to 64km (30 to 40 mi.) apart were taken. Position control for these profiles was provided by satellite navigation. Moreover, prior to 1977, ORSTOM had conducted two scientific expeditions over the southern and central parts of the Tonga Platform, namely, GEORSTOM III (line No. GEO-321) with airgun as source, and AUSTRADEC (line Nos. 401 and 403) with flexichoc as source. These data have been analysed by Dupont (in press).

The Central part of the Tonga Platform was also traversed by the EVA VII cruise in 1978 carried out as a joint effort by ORSTOM, Cornell University, the University of Texas-Marine Science Institute, and the National Ocean Survey of National Ocean and Atmospheric Administration (NOAA). A series of six refraction lines were recorded in the central part of the Tonga Platform between Ha'apai and Vava'u islands groups using 15-litres (915 cu.in.) capacity airgun source and ocean bottom seismometers for reception. These data have been analysed by Pontoise et. al. (1980).

INTERPRETATION OF DATA

The seismic records of CCOP/SOPAC TG-79-1 and TG-80-1 and ORSTOM EVA III, GEORSTOM, and AUSTRADEC programmes are generally fair to good in quality within the limits of the single-channel seismic system. The quality of the seismic records varies due to the presence of strong multiple reflections from the seabed and interpretation is limited by the multiple to a sub-bottom depth approximately equal to the water depth. On the southern part of the Tonga Platform the water depths are comparatively shallow i.e. less than 500m in most places, and seismic penetration was therefore not great.

Penetration was also limited by the relatively small airgun discharge, repitition rate, and by the analogue heat-sensitive paper recording technique used including sweep rate, to about 0.8 to 1.4 sec. two-way travel time below the seabed, whereas powerful seismic equipment with computer processing to eliminate multiple reflections could have obtained useable reflections from greater depths. This interpretation therefore establishes a minimum estimate of the thicknesses of the sediments.

The seismic profiles recorded under the CCOP/SOPAC programmes were interpreted on photocopies one-half the original size of seismic profiles and presented as cross-sections (line-drawings) in Figures 8 and 9.

The seismic and magnetic profiles recorded under the ORSTOM programmes have been interpreted by Dupont (in press) and the cross-sections with magnetic profiles are reproduced in Figure 10.

Note that the vertical exaggeration of the interpreted sections of CCOP/SOPAC programmes (Figs. 8 and 9) is double that of the interpreted sections of ORSTOM programmes (Fig. 10).

In Tonga no well-velocity data are available, Mulder and Nieuwenhuizen (1971) determined the average velocity for depth prognosis from root mean square velocities in the central part of the Tonga Platform and obtained a velocity of 2700m/s (8860ft./s) the interval of seafloor to basement with possible error of +_ 300m/s (985ft./s). Where thick reefs are suspected a velocity of 3400m/s (11, 155ft./s) was obtained but they stated that the velocity determinations on reefs have very little statistical weight as so few were observed.

Table I is reproduced from Pontoise et. al. (1980). Seventeen velocity determinations were made for the sedimentary rocks from refraction measurements in the central part of the Tonga Platform and the average velocity is 2660m/s (8730ft./s), which is very close to that obtained by Mulder and Nieuwenhuizen (1971). Therefore, in this report the velocity of 2700m/s (8860ft./s) will be used for the sedimentary rocks between the seabed and the basement except for the carbonate reefal buildups or beds, in which case a velocity of 3400m/s (11,155ft./s) will be used.

More seismic information is available for the southern part of the Tonga Platform than for the northern part. The average spacings of the CCOP/SOPAC and ORSTOM traverses, which are in WNW-ESE direction, are about 10 to 25kms (6 to 16 mi). In addition, total intensity magnetic profiles of ORSTOM traverses aid in the interpretation of the Eocene volcanic basement trend ('Eua Ridge) and the Pleistocene-to-Recent volcanic trend (Tofua Ridge) as can be seen in Figure 10.

The western Tofua Ridge, as interpreted from seismic and magnetic data (Figs. 8 and 10), apparently extends from latitude 19' 15'S north of Tongatapu (Fig. 10 AUS. 401) to latitude 24' 30'S (Fig. 10 EVA 302) and in general lies between the 1000 and 2000m isobaths as shown in Figures 11(a) and (b) (hatchured). The northern extension of the Tofua Ridge, to Latitude 15' 30'5, as shown in Figure 11(b) has been reproduced from Dupont (in press) with slight modifications based on the absence of this volcanic trend in the seismic cross-sections (Fig. 9). The eastern 'Eua Ridge as interpreted from seismic and magnetic data (Figs. 8 and 10), extends from latitude 20' 45'S (Fig. 10 EVA 312) to latitude 22" 20'S (Fig. 8 Line G-F) and is shown in Figure 11(a) (cross-hatchured). A patch of 'EuaRidge is drawn between latitude 20'S and 21'S and is based on the interpretation of Mulder and Nieuwenhuizen (1971).

The shallow reflections are in general parallel with the seabed topography which may be due to bubble effects of the energy source. In some sections of the southern part of Tonga Platform (Fig. 8 Lines B-C, F-H, J-K, N-O, and S-T), angular unconformities are observed at about 0.2 sec. or 270m (885ft.) below the seabed generally in the central parts. The dips of the sedimentary beds below the angular unconformity are negligible and in general may be about 1 to 2 degrees only. The thicknesses of the sedimentary rocks north of line G-F as shown in Figure 8 (lines A-B to G-F), are estimated to be 0.8 sec. or 1080m (3545ft.). This estimation is limited by the water depth which is generally about 500m up to this line, and the reflections cannot be observed beyond 0.8 sec. due to interference by seabottom multiples. South of line G-F in places where water depth is deeper than 500m particularly on lines J-K, N-O, S-T, W-X, Y-Z and A'-B' (Fig. 8) thicknesses of the sedimentary rocks are estimated to be 1.2 sec. or 1620m (5315ft.).

The southern part of the Tonga Platform is highly faulted, the majority of the faults affect the topography of the seabed and indicate that the faults have been active up to recent times. The trends of the faults are approximatley NNE-SSW and spacing between the faults varies from 0.5 to 20km (0.3 to 12.5 mi.), as shown in Figure 11(a). Most of the faults appear to be normal and nearly vertical.

A very interesting feature which is of particular importance is observed on line N-O Figure 8(d), between 1700 and 1830 hour lines (latitude 22' 40'S and longitude 176'E) where three probable reefal buildups are observed as shown in Figure 11(a). Depths to the tops of the reefs are about 1080 to 1350m (3545 to 4430ft.) below the seabed. The beds below the reefal buildups cannot be observed due to the presence of seabottom multiples. This portion of the original seismic record is reproduced in Figure 12. The largest and easternmost reefal buildup may possibly be affected by faulting. Generally, reefs tend to grow in a group and it is highly probable that there are reefal buildups on other seismic lines in the vicinity of line N-O which may not be detected due to interference by seabottom multiples and due to limited depth penetration because of small airgun discharge.

The water depths where these reefal buildups are observed are about 750-900m (2460-2950ft.). Assuming a circular shape, the areal extents of these reefal buildups are estimated to be 10–20 sq.km. (3.9–7.7 sq.mi.). They have vertical extents of 340-510m (1115-1675ft.) as estimated from the seismic section of Figure 12 using a velocity of 3400m/s (11,155ft./s). Both these figures are comparable with those of reefal buildups in oil-and-gas producing areas of the world such as the Alberta Basin (for example, the Leduc reef trend, the Rainbow Lake reefs, Beaverhill Lake reefs, and Zama reefs) in Canada; Michigan Basin (Silurian Reef Trends) in USA; Sirte Basin (Paleocene Intisar reefs) in Libya; Salawati Basin (Middle to Upper Miocene pinnacle reefs) in Irian Jaya, Indonesia; Palawan Basin (Lower Miocene Nido limestone reefs) in the Philippines; and Central Luconia Province (Miocene reefal carbonate buildups) in Sarawak, Malaysia.

Because Miocene time was marked by extensive reef growth in Southeast Asia, it is possible that there was also extensive reef growth during Miocene time in the southern part of the Tonga Platform.

Over the northern part of the Tonga Platform, only five widely spaced zig-zag seismic profiles are available. Therefore, interpretation is tentative and represent the current speculations of the authors. According to Mulder and Nieuwenhuizen (1971) Vava'u Island is an extinct volcano of Miocene age on top of which a pinnacle reefal buildup of Pliocene-Pleistocene age was formed. This extinct volcanic trend (Tongatapu Ridge) as interpreted from seismic cross-sections (Fig. 9) appears to extend from Vava'u island to about latitude 15' 30'S to the north as shown in Figure 11(b) (stippled). Two more small volcanic trends are observed, one near latitude 18'S parallel to and east of the abovementioned volcanic trend and another near latitude 15' 30'S and longitude 173' 15'E near the northernmost part of the platform. The southern extension of the Miocene volcanic trend (Tongatapu Ridge) as shown in Figures 11(a) and (b) is based on the interpretation of Mulder and Nieuwenhuizen (1971), and Kroenke and Tongilava (1975). It extends southward to Tongatapu.

The northern part of the Tonga Platform is also highly faulted; most faults also affect the seabed topography. The trends of the faults are approximately N-S and the spacing between the faults varies from 0.5-35km (0.3 to 22 mi.) as shown in Figure 11(b). Most of the faults appear to be normal and nearly vertical.

In a few places (Fig. 9 lines A"-B", B"-C" and D"-E") an angular unconformity is observed at about 0.15 sec., or 200m (655ft.) below the seabed, and the dips of the sedimentary beds are in general very low, in the range of 1 or 2 degrees only. The seismic reflections in the northern part of the Tonga Platform can be observed much deeper below the seabed than those of the southern part due to deeper water depths; the water depths are generally in the range of 1000-1500m. The thicknesses of the sediments are estimated to be 1.4 sec. or 1890m (6200ft.). The areal extent of the sedimentary rocks between the probable northward extension of the Tofua Ridge and the Tongatapu Ridge is observed to be relatively small as can be seen in Figure 11(b).

Except for normal faulting no structural deformation such as folding and major tilting of the sedimentary rocks in both the southern and northern parts of the Tonga Platform is observed on the line drawings of seismic profiles as shown in Figures 8, 9 and 10.

The volcaniclastic sediments composed of mudstones and lithic sandstones of volcanic-derived materials are non-porous and impermeable in the Kumifonua Wells Nos. 1 and 2 and in the surface geology. Therefore, these volcaniclastic rocks are considered as very good sealing rocks but very poor reservoir rocks. Also, even though the fault blocks could be considered as potential petroleum traps, the volcaniclastic sediments do not have the necessary reservoir properties. Hence there is very little possibility of finding petroleum in structural traps in either the southern or norther parts of the Tonga Platform.

On the other hand, the Oligocene–Lower Pliocene coral reef limestone buildups on top of the Eocene Foraminiferal Limestone Platform, observed in 'Eua, are very porous and permeable and would be excellent reservoirs and traps for petroleum provided they occur at considerable depth below the surface on Tongatapu or below the seabed in the offshore areas such as the three probable reefal buildups observed on seismic line N-O (Fig. 12).

PETROLEUM POTENTIAL

The assessment of petroleum potential of any offshore area in general depends on the consideration of the following factors:

1) source rock and available sedimentary rock thickness
2) seal and reservoir rocks
3) type of trap
4) water depth
5) available technologies and economics of exploration and production

Source Rock and Available Sedimentary Rock Thickness

The existence of known oil seeps on Tongatapu and 'Eua is important evidence that sources of oil do exist in the vicinity of Tongatapu and 'Eua. According to Dickey and Hunt (1972), oil seeps still offer the only certain indications that oil exists in the subsurface in an area. Moreover, they stated that: "It is probable that more oil fields have been discovered by drilling on or near seeps than any other prospecting method.".

Also, Link (1952) stated that: "A look at the exploration history of the important oil areas of the world proves conclusively that oil and gas seeps gave the first clues to most oil producing regions. Many great oil fields are the direct result of seepage drilling.".

Though oil seeps do not prove the existence of commercial oil accumulations, they do increase their probability and they do indicate the existence of sources of oil. The Miocene-Lower Pliocene volcaniclastic sediments composed mainly of mudstones and lithic sandstones of volcanic-derived materials cannot be considered as potential source rocks due to the paucity of contained organic matter, as evidenced by the results of source rock analysis in Kumifonua Nos. 1 and 2. The results as reported by Shell N.V. and S.I.P.M., The Hague (1972), indicate that the intervals 1274-1277m (4180-4190ft.) of Kumifonua No. 1 and 1259-1262m (4130-4140ft.) of Kumifonua No. 2 contain marginal source rock for gas, Hardly any vitrinite appears to be present in the samples and a fixed-carbon content of 54 is indicated for the cuttings from both wells. As these samples are taken from the only source-rock layer present, it is considered to indicate the true fixed-carbon content. Also, there were no indications of oil or gas in Kumifonua No. 1, and only very minor chromatograph indications of methane over minor intervals in Kumifonua. No. 2, not considered significant. Wire-line logs confirm the complete absence of petroleum (and reservoirs) in both wells.

The only potential source rock could be either the coral reef complex of Oligocene-Early Pliocene age or the Upper Eocene Massive Foraminiferal limestones observed on 'Eua, provided they are present under Tongatapu and under the seabed in the vicinity of Tongatapu and provided they have been subjected to sufficient depth of burial and sufficient temperature for maturation.

According to Dott and Reynolds (1969), the reef, and the ecology of organisms that build it, define an important environment of the oil forming process because of the following factors:

1) the reef could form an obstruction causing the one-way flow of sea water and plankton in the barred-basin situation,

2) reefs are near-surface features which could produce environments such as shoals areas over which currents pass, i.e. the bank type source beds, and

3) the very existence of reef evidences an environment extremely favourable to organic life, including an abundant supply of nutrients.

Furthermore, Dott and Reynolds (1969) stated that "Geologists enthusiastically disagree on whether, in the reef environment, petroleum is most likely to have originated (1) behind the reef in the lagoon (an example of a silled basin), (2) in front of the reef (euxinic bottom environment), or (3) within the reef itself (in-situ origin).".

Link (1974) in support of the in-situ origin stated as follows: "The majority of geologists think of the surrounding shale and the underlying sediments as the source rock of the oil accumulated in the porous parts of coral reefs or bioherms. Others favour the idea that the hydrocarbons were not only reservoired in the bioherm, but were also generated within the reef itself. When one considers that in coral reefs or bioherms conditions exist, ideal for the growth, death, and accumulation of countless generations of innumerable organisms, why is it necessary to look for outside sources to explain the oil found within them?".

Tissot (1979a) stated that kerogen mostly derived from accumulation of algal and/or microbial lipids has high potential for the genesis of petroleum. Also, Saldivar-Sali (1978) mentioned that the hydrocarbon source potential of the Nido Limestone has been evaluated by Robertson Research for rock samples in the NW Palawan Sub-basin, Philippines, and the algal debris was shown to be the main component of the kerogen. Moreover, he mentioned that this type of kerogen has an excellent oil sourcing potential. Since the overlying and underlying shales do not have oil sourcing potential, Saldivar-Sali (1978) therefore concluded that the carbonate reservoir rock itself is the source rock. This suggests in-situ generation of oil for Nido Limestone reefs (Lower Miocene).

Vincilette (1973), on the other hand, suggested that hydrocarbons have been generated in the Salawati Basin in Irian Jaya, Indonesia and trapped in the pinnacle reefs. Kirkland and Evans (1981) stated that oil in reefs around the Michigan Basin may have originated in dense black carbonate deposited within the basin centre.

The authors' opinion in the case of Tonga Platform is that oil observed in seepages was generated either in-situ in the Oligocene-Lower Pliocene reef and/or behind the reef in the lagoon (since it is observed in 'Eua to be probably an atoll enclosing a central lagoon) and migrated along fault planes. The Eocene Foraminiferal limestones cannot be considered as source rock since there is a distinct unconformity between the overlying formations and these limestones. Any oil that was generated in the Eocene Foraminiferal limestones would be lost due to exposure during the hiatus unless it was formed after the deposition of the sediments overlying the unconformity. Haun (1982 pers. comm) stated that "reefs are well oxygenated and organic matter will be destroyed by bacterial activity". His opinion is that "the petroleum probably comes from organic rich rocks formed from sediments deposited under reducing conditions adjacent to, over, or under the reefs". Bender (1982, pers. comm) is of the opinion that "oil seepages contain much nickel and vanadium indicating carbonate source rocks. The low n-alcane content indicates bacterial degradation. The assumption that oil is formed from carbonates, although in very small quantities, is corroborated by these results". He further stated that "source rocks that sufficiently meet the demands in quality and quantity have neither been encountered in surface exposures nor in wells".

Tissot et. al. (1980) mentioned three successive steps in hydrocarbon generation for each type of organic matter as a function of increasing time, burial and temperature:

" - an immature stage, marked by a decrease of the O/C ratio) and the generation of carbon dioxide and water; little hydrocarbon is generated during this interval of time, except some biogenic methane;

" - the main stage of oil generation, marked by a decrease of the H/C ratio, and the generation of liquid hydrocarbons;

" - the stage of cracking and gas generation, with a further decrease of the H/C ratio and the generation of gas, mainly methane, by cracking of the oil previously formed and also of kerogen."

They also concluded after studying many case histories in Europe, Africa and America, that a large proportion of the presently existing oil and gas fields, amounting to 90% of the petroleum reserves, may have been formed during Cretaceious and Tertiary time and include oil and gas fields derived from Cretaceous and Tertiary source rocks.

The average surface temperatures and temperature gradients of the five exploratory wells on Tongatapu are 25.9'C (78.6'F) and 2.75'/100m (1.51'F/100ft.) respectively. From the above temperature data we will have to derive the burial depth for maturation in the Tonga Platform by analogy with the west Palawan Basin in the Philippines where the reservoir and source rocks are of Miocene age as in Tonga. It is assumed that the amount of subsidence or uplift in both cases were the same or there are negligible differences.

Saldivar-Sali (1978) established the following thermal maturation zone boundaries in West Palawan Basin, based on bottom-hole temperatures of several wells:

Immature zone	66'C	(150'F)
Transition zone (heavy oil and wet gas)	66'-82'C	(150'-180'F)
Mature zone (medium/light oil)	80'-143'C	(180'-290'F)

Tissot (1979b) also stated that the threshhold temperature of oil generation in the Los Angeles Basin (Miocene) and Venture Basin (Pliocene) is 115'C (239'F) but the temperature gradients are 3.91'C/100m (2.15'F/100ft.) and 2.66'/100m (1.46'F/100ft.) respectively. Thus the threshhold of oil generation is at 2400m (7840ft.) in the Los Angeles Basin and 3600m (11,811ft.) in Ventura Basin.

In the case of Tonga, the depths at which maturation temperatures of 82'-143'C occur are approximately 2045-4265m (6710-14,000ft.), using the averages of surface temperatures and temperature gradients of the five wells. The total depths of the first two wells drilled by Shell are 1684m (5525ft.) and 1685m (5529ft.) respectively and did not reach the minimum depth of maturation due to the limitation of the capacity of the drilling rig. The total depths of the latter three wells drilled by Webb Tonga are 2,555m (8373ft.), 2295m (6996ft.), and 2,635m (8643ft.) respectively and were beyond the minimum depth of maturation.

It is estimated from the seismic sections that the sediment thicknesses in the southern and northern parts of the Tonga Platform are 1620m (5315ft.) and 1890m (6200ft.) maximum respectively. The determination as has been pointed out previously is limited by the presence of multiples and by the small capacity of the airgun. If multiples could be eliminated by computer processing and if a powerful seismic energy source could be used, reflections from much greater depths could be obtained and the thicknesses of the sedimentary rocks might be found to be thicker than indicated by the present data. Therefore, it is reasonable to conclude that there may be sufficient sedimentary rock thicknesses in the southern and northern parts of the Tonga Platform to reach temperatures high enough for maturation and generation of oil.

The presence of three probable reefal buildups on line N-O (Fig. 12) at about 135kms (84 mi.) southwest of Tongatapu at depths of 1080 to 1350m (3545 to 4430ft.) to the top of the reefs below the sea bed provides vital evidence that reefal buildups may be present beneath the sediments in the southern part of the Tonga Platform. These could serve as source and reservoir rocks.

Except for a very doubtful oil seepage, reported to occur on the Vava'u Island, which has not been substantiated, no other evidence is present to indicate that there is possible petroleum potential in the northern part of the Tonga Platform. Also, no evidence of reefal buildups is observed in the northern part of the Tonga Platform. In terms of the possible presence of source rocks therefore, the southern part of the Tonga Platform apparently has more petroleum potential. However, there is not much seismic data available on the northern part of the Tonga Platform and with the acquisition of additional data the assessment may have to be revised.

Seal and Reservoir Rocks

The Miocene-Lower Pliocene volcaniclastic rocks composed of mudstones and lithic sandstones of volcanic-derived materials are non-porous and impermeable in the Kumifonua Well Nos. 1 and 2 and in the surface geology. Therefore these volcaniclastic rocks are considered as very good sealing rocks, but very poor reservoir rocks. Carozzi and Ocampo (1976) also mentioned that volcaniclastic rocks provide excellent seals for carbonate reservoirs.

The Oligocene-Lower Pliocene coral reef limestone buildups on top of the Eocene Foraminiferal Platform observed in 'Eua are very porous and permeable and would be excellent reservoirs for petroleum, provided they occur at considerable depth below the surface on Tongatapu or below the seabed in the offshore areas. Reef limestones are inherently porous and permeable. Wilson (1980) commented regarding their diagenesis and porosity as follows:

"Diagenesis and porosity: Organic reefs are recognized by the relative abundance of sessil benthonic colonial animals and plants. Originally high porosity is caused by microporous interior of coral fasciculate structure, by internal cavities in all biotic framework, by rapid growth enclosing and encrusting over large cavities, and by reef growth in large scale pillars. It is common for original porosity to be so great that it cannot be completely filled in by the normal accumulation of internal sediments, bioclastic debris, and lime mud, or by organic and inorganic marine cement. Additional high porosity-permeability is caused by rotting and boring in reefs. High porosity-permeability is also common in adjacent coarse reef rubble derived from buildups in high energy environment."

Generally, high porosity and permeability of high-energy reef reservoirs, particularly reefs of Tertiary age, are preserved intact in the subsurface whereas porosity and permeability are reduced by diagenetic cementation in sandstone reservoirs in either structural or stratigraphic traps.

Type of Trap

Except for extensive vertical normal faults there are no other types of structural traps apparent as the sedimentary rocks exhibit very small or negligible dips. The sedimentary rocks observed on the seismic profiles are assumed to have characteristics similar to the volcaniclastic rocks observed in Kumifonua Wells 1 and 2 and on the surface of 'Eua. Therefore, even though fault blocks could be considered as potential petroleum traps, the volcaniclastic rocks are found to be very poor reservoir rocks.

The only type of potential petroleum trap is likely to be the Oligocene-Lower Pliocene reefal buildups observed on 'Eua and on line N-O buried beneath the volcaniclastics. In general, an ancient reef is a potential petroleum trap from the time it was first buried by overlying sediments and has certain advantages over structural and detrital stratigraphic traps where the timing of deformation is very important. For example, in a stratigraphic trap updip closure against the regional structure is vital to the preservation of oil and is again dependent on the timing of deformation.

Water Depth

The average water depths of the southern part of the Tonga Platform range from 500 to 1000m (1640 to 3280ft.) though there are several small patches with water depths of 250m (820ft.). Extensive areas have water depths of less than 500m (1640ft.).

The average water depths of the northern part of the Tonga Platform range from 1000 to 1500m (3280 to 4920ft.) with many small areas which have water depths of between 500 to 1000m (1640 to 3280ft.). Therefore in view of the deeper water, the northern part of the Tonga Platform has relatively less prospect for petroleum potential at present.

Available Technologies and Economics of Exploration and Production in Deep Water

Since the northern part of the Tonga Platform is less interesting in terms of probable lack of source rock, reservoir rock and traps, small areal extent of the sedimentary basin, and deeper water depth, this discussion will beconfined to the southern part of the Tonga Platform only. For the purpose of exploratory drilling in the southern part of the Tonga Platform, a drillship with dynamic positioning will be required for the water depths encountered.

The dynamic positioning system is a highly sophisticated stationing system whereby computers control multiple propulsion units to enable the drilling vessel automatically to counteract wind, wave and current forces and thereby remain on station in water too deep for conventional anchoring system. The link between the floating drill rig and the wellhead is the marine riser, a steel pipe 41-61cm (16 to 24 inches) in diameter which serves as a guide for drilling tools and pipe strings into the well and provides a return path for the drilling mud.

Special blowout prevention equipment is also required for safety and operational reasons. These must be installed on the seabed rather than on the drilling platform. Blowout preventor stacks consist of a number of valves that can shut off the well when necessary and are controlled remotely from the rig by hydraulic power. They can be up to 12m (40ft.) high and weigh 100 tons. Precise navigation systems such as the satellite navigation system are used to position the floating rig accurately at the chosen drilling site.

There are at least a dozen drillships that are capable of drilling in water depths up to 915m (3000ft.) and 8 of them can operate at water depths of more than 915m (3000ft.) (Ocean Industry, September 1980). Drillships that can operate in water depths from 305 to 1830m (1000 to 6000ft.) are listed in Appendix D.

The record for the greatest water depth for an exploratory well was made by Discoverer Seven Seas off Newfoundland in water depth of 1486m (4876ft.). Another well in a water depth of 1374m (4507ft.) was drilled by the same drillship for BNOC in the North Sea (Ocean Industry, July 1980). In 1979, Esso, Phillips and Hudbay Oil (Australia) Ltd had drilled 7 wells in the Exmouth Plateau off Western Australia in water depths of 841 to 1194m (2759 to 3917ft.). One of Esso's wells in 912m (2992ft.) water depth encountered gas-bearing Lower Cretaceous sandstones but because of water depth this discovery is not considered commercial and the well was abandoned (Durkee, 1980).

The daily operating costs of drillships range from US$100,000 to 130,000 (Whitney, 1980). Segal (1981) mentioned that the cost of a deep offshore wildcat can vary from US$9-20 million on the Exmouth Plateau off Western Australia to US$20-50 million off Labrador. Bhatt (1979) mentioned that an average offshore wildcat well in deep water may cost up to US$15 million. The cost of shallow-water, i.e. 90 to 120m (300 to 400ft.), exploratory well, is about US$8.8 in the North Sea, whereas a development well costs about US$5 million in the North Sea and US$3 million in the Gulf of Mexico (Ocean Industry, October 1979). In Australia and Southeast Asia, the cost of an average delineation well is in the range of US$1-3 million.

The technology for deepwater production testing is also available at present. The deepest-water high-volume oil flowing test was conducted by Chevron at Montanazo D-2 well at 746m (2448ft.) water depth off east coast of Spain. The well flowed at a rate of 1560 cu.m. (9800 bbls) per day (Whitney, 1980). Production testing was also attempted in 554m (1818ft.) of water depth in Browse Basin, Western Australia, for gas-bearing sandstones by Woodside Petroleum Development Pty Ltd (Durkee, 1980).

Therefore, technologies for exploratory drilling and production testing in water depths that exist in the southern part of the Tonga Platform are available but costly.

In the event of discovery of oil in commercial quantities in the southern part of the Tonga Platform, the conventional steel fixed-production platform cannot be used. The deepest-water and heaviest conventional steel fixed-platform in the world was installed in 312m (1028ft.) of water for Shell's Cognac field in the Gulf of Mexico; other deep-water fixed-platform installations are Union Oil's Cerveza field in 285m (935ft.) of water in the Gulf of Mexico and Exxon's Hondo field in 260m (850ft.) of water in the Santa Barbara Channel, off California (Lee, 1981; Segal, 1981).

There are two types of deepwater production technologies in the experimental stage at present and they may become widespread by 1984-1990.

The first type as reported by Ocean Industry July 1979 is the tension leg platform (TLP) or tethered buoyant platform (TBP) which can be designed for water depths of 245-915m (800-3000ft.). Esentially this system consists of a semi-submersible rig held below its natural buoyancy level to restrain vertical motion and anchored by tensioning devices incorporated into the drilling and riser columns. Two types of tethering systems are under study - spiral strand wire and tubular steel. The first type would consist of 125mm (4.9 inches) diameter wire spiral strands in groups of six at each corner. The same system for the tubular steel would consist of 245mm (9.6 inches) diameter joints screwed together. According to Segal (1980), British Petroleum, Amoco, Conoco, British Gas and British National Oil Company have all been involved in the tension-leg platform design and development along with Deep Oil Technology of California, Norway's Aker Group, Vickers and the Arge group.

The second type is the subsea production system (SPS). There are two basic types - wet or dry. Under the wet system, all components are exposed to the sea and must therefore be exceptionally reliable, requiring servicing only rarely. The dry type has all components housed in a chamber, to which men can be brought in a transfer capsule or submersible vehicle to assemble or work on the equipment in normal atmospheric pressure. Control of both types varies from simple hydraulic systems to more sophisticated electro-hydraulics, operated from a nearby surface platform or vessel. The principal subsea equipment includes pollution control systems, Christmas trees, tubing hangars, structures, a remote control for automatic connectors for cables and flowlines. Technological advances in subsea production systems provide savings both in time and money in deepwater and severe environmental areas.

Some 150 subsea production systems have been installed around the world at shallow depth and are connected to nearby platforms. Most of them have been installed where directional drilling from existing platforms was not feasible or where the marginal nature of the field could not economically justify the building of further conventional platforms. The record for subsea production system in deepest water is 190m (620ft.) at Enchova field, off Brazil, installed by Petrobas (Segal, 1981; Ocean Industry October 1979).

Ocean Industry, October 1980 reported projected depths of diverless subsea production systems as follows:

Year	Depth in metres (feet)
1980	305m (1000ft.)
1982	475m (1500ft.)
1984	610m (2000ft.)
1987	762m (2500ft.)
1990	915m (3000ft.)

Also, Ocean Industry (July 1979) claimed that, according to the opinions of the experts in subsea production technology, oil and gas will be produced in 915m (3000ft.) of water by 1985 and the depth range could be extended to 1525-1830m (5000-6000ft.) by 1990. This is also supported by Conoco (Ocean Industry, February 1981) which claimed that production in 1830m (6000ft.) of water could be achievable by 1990.

The costs of developing deepwater fields have been estimated by Segal (1981). He projected a cost of US$3 to 5 billion - plus For potential deepwater Fields such as Western Australia. Also, he mentioned that for deepwater development there will be longer project lead times and heavy front end loading of investment which can mean a gap of perhaps ten years before such projects can pay out - compared to just two years in the North Sea at present.

Petroleum Economist magazine (February 1981) stated that in the opinion of Exon, commercial risks to develop a field in the southwest offshore areas of Ireland (Goban Spur area) in water depths of 655-1600m (2150-5250ft.) are not worthwhile unless the recoverable reserves of at least 40×10^6 cu.m. (250×10^6 bbls) are available. Thus a large recoverable reserve is essential for commercial viability and a discovery or several discoveries together must satisfy these conditions.

It is apparent that technologies for production from water depths that exist in the southern part of the Tonga Platform are still in the experimental stage but may be available commercially by 1984-1990 and the development costs for potential oil fields will be extremely high.

DISCUSSION

A few selected examples of oilfields with reefal buildups as traps and reservoirs from various parts of the world are discussed below.

The Intisar reefs of Paleocene age in Sirte Basin, Libya are composed of 6 reefal build-ups; Intisar A, B, C, D, E, and L out of which only A, C, D, and L are productive. Intisar A and D are both giant oil fields* each with recoverable reserves of 222.5 x 106 cu.m. (1.4 billion bbls) for A and 286.0 x 10^6 cu.m. (1.8 billion bbls) for D. The oil columns for A and D are 305m (1000ft.) and 274m (900ft.) respectively and the production rates of discovery wells of A and D are 6833cu.m. (43,000 bbls) per day and 11,918 cu.m. (75,000 bbls) per day respectively. Average porosity for both A and D is 22% and average permeabilities range from 26-500md. The areal extent of both A and D are 17 sq.km. C and L have relatively Small oil columns of 91m (300ft.) and 15m (50ft.) respectively (Vincelette, 1973 and Brady et. al., 1980).

The Leduc reef trend of Late Devonian age in the Alberta Basin, Canada, is composed of 11 reefal buildups with areal extents ranging from 1.0 to 87.4 sq.km. (0.4 to 33.8 sq.mi.) with an average of 22.4 sq.km. (8.7 sq.mi.). All the reefs are productive. Five of the reefs have thick gas columns ranging from 63.4m to 205m (208 to 673ft.) with large gas reserves. Three of the reefs have recoverable reserves of oil over 31.9 x 10^6 cu.m. (200 million bbls) with oil columns ranging from 11.6 to 193m (38 to 634ft.) with an average of 75m (246ft.). Though all the reefs contain oil, six of the reefs are devoid of gas. The average porosities range from 6 to 10% and the average permeabilities range from 600 to 1900md. The Leduc reef trend contains in the order of 731 x 10^6 cu.m. (4.6 billion bbls) of oil-in-place and 276 billion cu.m. (9.73 trillion cu.ft.) of gas and is a giant oilfield (Barss et. al., 1970; Ball, 1972; and Vincelette, 1973).

The Rainbow Lake reefs of Middle Devonian age in the Alberta Basin, Canada, contain 12 reefal buildups with areal extents ranging from 1.6 to 19.5 sq.km. (0.6 to 7 sq.mi.) with an average of 6.7 sq.km. (2.6 sq.mi.). Oil columns range from 48.8 to 209m (160 to 686ft.) with an average of 112.5m (369ft.). The average porosities range from 5 to 12% and the average permeabilities range from 126 to 1000md. The Rainbow Lake reefs contain in excess of 238 x 10^6 cu.m. (1.5 billion bbls) of oil-in-place and 28.3 billion cu.m. (1 trillion cu.ft.) of gas and is also a giant oil field. The recovery factor range from 20-50% whereas the secondary recovery methods are estimated to boost the ultimate recoveries to 80-95% (Barss et. al., 1970, and McQuillin et. al, 1979).

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* A giant oil field is one containing 79.5 x 10^6 cu.m. (500 million barrels) or more of recoverable oil and giant gasfield has minimum of 99.1 billion cu.m. (3.5 trillion cu.ft.) of recoverable gas (Halbouty et. al., 1970).

The Silurian Reef Trend in Northern Michigan is estimated to contain 63.6 x 106 - 95.3 x 10^6 cu.m. (400–600 million bbls) of oil and 85–142 billion cu.m. (3–5 trillion cu.ft.) of gas. The areal extent of reefal buildups (pinnacle reefs) range from 0.16–2.4 sq.km. (40–600 acres) and the vertical extents increase basinward from the reef shelf margin, reaching a maximum of 185m (600ft.). The porosity of the reef varies throughout the trend ranging from 5-30%. These reefs are generally encountered at depths of 915-2135m (3000-7000ft.) below the surface. (Caughlin et. al., 1976). Production from this reef trend was about 4.0 x 10 cu.m. (25.3 million bbls) of oil and 3.8 billion cu.m. (135 billion cu.ft.) of gas in 1979 (Ells, 1980).

The reefs of Middle to Late Miocene age in the Salawati Basin, Irian Jaya, Indonesia, contain 8 reefal buildups and the combined total average daily production of all the reefs is 11.3 x 10^3 cu.m. (71,055 bbls) of oil and 730 x 10^3 cu.m. (4.6 million cu.ft.) of gas in 1979. Cumulative production of oil up to the end of 1979 is 37.02 x 10^9 cu.m. (283 million bbls) (Fletcher, 1980). The Kasim No. 3 and No. 6 wells, drilled in 1973 (Vinceletee, 1973) tested 3337 and 2746 cu.m. (21,000 and 17,280bbls) of oil per day respectively. The oil column in the Kasim field is 128m (420ft.) and the areal extent is about 17.5 sq.km. (6.8 sq.mi.). The average porosities range from 20 to 25%. Primary recovery factor is 60–75%.

The daily production in late 1979 from the Miocene Nido reef complex in offshore northwest Palawan Basin, Philippines was reported by Hatley and Harry (1980) to be 6356 cu.m. (40,000 bbls) from a pay zone of 183m (600ft.). Cumulative production of oil to the end of 1979 was reported by Fletcher (1980) to be 1.36 x 10^6 cu.m. (8.57 million bbls). Average porosities, according to Saldivar-Sali (1978), range from 8 to 20%.

It is apparent from the above discussion that reefal buildups have the following characteristics:

1) the reefal buildups occur in groups of 6 to 12;
2) the areal extent of the reefal buildups is generally small, approximately in the range of 2 to 22.5 sq.km. (0.8 to 8.7 sq.mi.);
3) pay zones generally are very thick from 75 to 305m (246 to 1000ft.);
4) productivity per well is very high;
5) average porosity for Tertiary reefs is higher than Devonian reefs and is in the range of 20-25%;
6) average permeabilities of the reefs range from 126-1900md;
7) recoverable reserves are generally very large;
8) the primary recovery efficiencies of reefs range from 60–75% for Miocene reefs (Vinceletee, 1973) to 20-50% for Devonian reefs (Barss et. al. 1970), compared to sandstone reservoirs (about 20-35%), are higher, so that a relatively smaller amount of oil-in-place is necessary for reef traps; and

9) at least 6 giant oil fields exist in the world with oil production from reefal build-ups (Halbouty et. al. 1970).

Most of the world's productive reefs are detectable by seismic methods and are generally observed as prominent events on modern type multichannel, multifold (2400% or 4800%) high-resolution seismic recording. Bub and Hatleid (1977) summarized the criteria for recognition of reefs on seismic records. The direct criteria are boundary outline and seismic facies change and the indirect criteria drape, velocity anomalies (velocity pullup), spurious events and basin architecture. Evans (1972) recorded in considerable detail the development of seismic techniques to detect the Zama Reefs (Middle Devonian pinnacle reefs) in Alberta, Canada and Caughlin et. al. 1976) described the detection by seismic methods of the Silurian Reefs in northern Michigan, USA. May and Hron (1978) made studies of synthetic seismic sections of reef models. In the case of the reef model without petroleum, there is overlap of reef crest reflections with deeper reflections, velocity pullup and amplitude change of reflections beneath the reef. If the reef model contains a low-velocity petroleum zone, there is a reduction in the velocity pullup with other characteristics remaining unchanged.

Carbonate reefs, however, are generally difficult to identify in poor quality seismic sections (Evans, 1972; Caughlin et. al., 1976, and McQuillin et. al., 1979). On the Tonga Platform, some of the criteria for recognizing reefal buildups such as drape and velocity pullup may not be detected since the reefs are assumed to be overlain and enclosed by volcaniclastics, whereas in other areas such as Libya, Malaysia, Indonesia and the Philippines, the reefal buildups are overlain and enclosed by shales. Shales are relatively more plastic than the volcaniclastics and produce draping over the reefs. Also, the velocity contrast between shales and reefal limestones is about 1525m/s (5000ft./s) compares to about 700-1000m/s (3000-3280ft./s) for volcaniclastics and reefal limestones so that there will be very little ltive velocity pullup.

All reef-like seismic reflection events do not turn out to be reefs when drilled. One of the seven wells drilled in the southern Philippines tested a reef prospect detected by seismic data and turned out to be a volcaniclastic bed (Saldivar-Sali 1978). The l'Etoile No. 1 well drilled on a seismically interpreted reef by Shell Development (Australia) Ltd in 1973 in the western offshore area of Bougainville Island, Papua New Guinea, terminated in volcanics of Miocene age. Similarly, Goodenough No. 1 and Nubian No. 1 wells drilled on seismically interpreted reef prospects by Amoco Australia Exploration Co in 1975 in the offshore Cape Vogel Basin, Papua New Guinea, terminated in volcanic tuffs and volcaniclastics.

One of the problems encountered in the Palawan Basin, Philippines, during the exploration stage of the Nido reef complex according to Hatley and Harry (1980), was the irregularity of water bottom caused by the presence of surface and near-surface reefs of Pliocene to

Recent age. Interpretation of seismic data was influenced greatly by these shallow features, Similar problems may be encountered in the southern part of the Tonga Platform since the sea bed topography is also very irregular (as can be seen in cross-sections of Figs. 8, 9, and 10), and near surface Upper Pliocene-Pleistocene reefs may also be present.

Furthermore, the Tonga Platform is a forearc basin (Karig, 1970; Hawkins, 1974 Fig. 7 and 1976 Fig. 3; Dickson, 1976 Fig. 9) and according to Fletcher and Soeparjadi (1976), Huff (1980) and Bender (1982, pers. comm.) historically, there are very few oil and gas fields in the forearc basins of the world. For example no commercial quantities of petroleum have been discovered in the forearc basins of Indonesia. The majority of the oil and gas fields in Indonesia are in the foreland basins including the Salawati Basin in Irian Jaya (Fletcher and Soeparjadi, 1976). Haun (1982, pers. comm.) is less concerned about the forearc tectonic position because there has been little exploration in these areas.

On the other hand, except for normal faulting, the southern and northern parts of the Tonga Platform exhibit very little structural deformation. The lack of deformation favours the retention of oil already present in reefal buildups. Most of the areas with reefs which had been affected by structural deformation generally contain no hydrocarbon accumulations (Fletcher and Soeparjadi, 1976).

Another positive aspect is that both Tonga and Fiji are structurally northward divergent extensions of New Zealand where an enormous gas field, located along the North Island's southwest coast - the Maui field, has been discovered. The Maui field is one of the fifteen largest in the world.

CONCLUSIONS AND RECOMMENDATIONS

The oil seepages on Tongatapu and 'Eua, and the three probable reef buildups, with considerable areal and vertical extent, observed on one of the CCOP/SOPAC seismic sections, indicate that there are sufficient positive aspects regarding petroleum potential in reefal buildups in the southern part of the Tonga Platform. It is apparent that the northern part of the Tonga Platform has relatively less petroleum prospectivity at present since the areal extent of the sedimentary basin is smaller and water depths are greater. Also, reefal buildups are not observed on any of the seismic sections, although this may be due to sparse seismic coverage.

The only negative aspect for both areas is that most of the Tonga Platform is now considered as a forearc basin and historically there is very little commercial oil or gas production from this type of basin.

Technologies for exploratory drilling and production testing for water depths that exist in the southern part of the Tonga Platform are available at present but technologies for production systems are still in the experimental stage and will probably be available by 1984-1990.

It is recornmended that a high resolution multichannel and multifold (preferably a minimum of 2400% coverage) seismic survey with a large energy source and close grid spacing be conducted in the area south of Tongatapu (i.e. south of the present oil concession boundary) and to about Latitude 23' 15'S. The specific target of the survey should be in the vicinity of CCOP/SOPAC line N-O with the aim of detecting reefal buildups.

Also, more continuous single-channel seismic and magnetic profiling is recommended in the northern part of the Tonga Platform. The objectives are to detect any possible reefal buildups that may be present and to define the areal extent of the sedimentary basin by delineating the northern extension of the Tofua Ridge. The recommended line spacing is about 30km.

Several refraction profiles are also recommended for more accurate velocity information over both the southern and northern parts of the Tonga Platform. The velocity information available at present is confined to the central part of the Tonga Platform.

Source rock studies on samples of the Oligocene-Lower Pliocene reef complex are recommended to determine the possibility of oil generation in the reefs in-situ or behind the reefs in the lagoon.

Lastly, it is recommended that the Government of Tonga requests Samuel Gary Oil producers Inc. to carry out a well-velocity survey in the offshore exploratory well they plan to drill in 1982. This information will greatly help the interpretation of multichannel, multifold seismic data that will be generated

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ANALYSIS OF SEEPAGE OIL

The following are the results of an examination of a 'crude oil' sample from Tonga collected by Mr. R. de Caen and forwarded under cover of BP (South-West Pacific) Ltd. Memo SG 116, dated 13th November, 1968.

Most of these results were previously reported by telephone on December 13th, 1968 but, on subsequent checking of the nickel and vanadium contents by different techniques, it was found that these were much higher than the original results determined by emission spectroscopy. The revised figures are given in the table and a possible explanation for the marked discrepancy between these and the previous results (vanadium and nickel both less than 5 ppm) is that the bulk of the vanadium and nickel in this oil is present as volatile compounds (porphyrins?) which are lost during the ashing procedure used in the emission spectroscopic technique. Losses of both nickel and vanadium are sometimes observed in emission spectroscopic determinations of these trace elements in crude oils but, losses of this order of magnitude are virtually unknown, and suggest that this oil is of rather unusual character.

No information was received on the likely origin or collection of this sample, or the possibility that it might be contamination and therefore not a genuine seepage oil, so it was examined to see if it had the properties of a fuel oil, waxy sludge or weathered crude oil. The Inspection data given in the attached table, together with the shape of the TBP curve determined by GLC and the n-paraffin distribution, all suggested that the sample resembled a weathered crude oil.

From its chemical nature, the sample appears to be a genuine seepage oil but the possibility of a deliberate 'plant' cannot be rigorously excluded by this evidence alone. The latter possibility does seem rather unlikely however, and may well be obvious from the locations and nature of the seepage. There are a number of properties of this oil which also indirectly support the suggestion that it is genuine in character. The apparently high content of volatile vanadium and nickel compounds is most unusual and the low content of n-paraffins is also noteworthy. The distribution of the latter suggests that the oil is of marine origin which, presumably, would be in agreement with its likely origin.

The properties of this oil closely resemble those of a petroleum which has undergone little 'evolution' in the geochemical sense i.e. it is geologically young and/or has never been deeply buried. If this is so, then the degree of weathering may only be slight and the boiling range of the'original' oil may be little different from that actually observed for the seepage sample.

It will be appreciated that some of the above suggestions are rather speculative and we hope to carry out some further work, for our own interests, on the small amounts of remaining sample. In view of these interests, if an opportunity arises of collecting a further, somewhat larger, sample from this source then we would be most grateful if it could be arranged.

Source: de Caen, 1969

G.C. Speers

CRUDE OIL SEEPAGE SAMPLE

Inspection Data

Specific Gravity	60°F/60°F	0.962
Sulphur Content	%wt	2.01
Asphaltenes	%wt	5.4
Wax Content	%wt	3.8
Wax Melting Point	°F	140
Vanadium	ppm	223
Nickel	ppm	31
Distillation Data (by GLC)		
Distilled at 200°C	%wt	0.5
" " 214°C	%wt	2.0
" " 241°C	%wt	5.0
" " 273°C	%wt	10.0
" " 323°C	%wt	20.0
" " 365°C	%wt	30.0
" " 407°C	%wt	40.0
" " 448°C	%wt	50.0
" " 494°C	%wt	60.0
" " 558°C	%wt	70.0
" " 600°C	%wt	75.0
" " 650°C	%wt	80.0

Source: de Caen, 1969

Normal Paraffin Distribution

Carbon No.	%wt
nC_{14}	0.002
nC_{15}	0.003
nC_{16}	0.006
nC_{17}	0.010
nC_{18}	0.009
nC_{19}	0.008
nC_{20}	0.007
nC_{21}	0.005
nC_{22}	0.004
nC_{23}	0.003
nC_{24}	0.003

Source: de Caen, 1969

GULF RESEARCH & DEVELOPMENT COMPANY

SEEPAGE OIL - TONGATAPU IS. - S. PACIFIC

August 27, 1969

The seepage crude from Location 4 was investigated for identification purposes. It appears to be a weathered crude oil of moderate asphaltic content. The hydrocarbon fraction (83% of the crude) was about equally divided between saturated and aromatic types. A gas chromatogram of the saturated portion indicated sufficient residual amounts of hydrocarbon types present to identify the sample as a crude. The amount of sulfur, 2.2%, and metals (vanadium to nickel ratio = 7.2) accentuate this conclusion.

Complete analytical data are given in the attached table. A gas chromatogram of the saturated hydrocarbons is attached with some identifying peaks labeled.

Signed by

S.C. Camp

Source: Gulf Oil Corporation Report 1970

PROPERTIES AND COMPOSTION OF TONGATAPU, SITE 4 SEEPAGE

Gravity, °API	16.5
Specific Gravity, 60/60 °F	0.956
Refractive Index, Nd 20°C	1.541
Sulfur, % of Crude	2.21
Nitrogen, % of Crude	0.30
Vanadium, PPM	224)
Nickel, PPM	31) Ratio = 7.2

GROSS FRACTIONS OF CRUDE

(% of Total Crude)

Saturated Hydrocarbons	38	(See Attached Figure)
Aromatic Hydrocarbons	45	
Total Hydrocarbons	83	
Asphaltenes and Resins	19	

Source: Gulf Oil Corporation Report 1970

SHELL OIL COMPANY

RESULTS OF CHEMICAL ANALYSIS OF A HYDROCARBON SAMPLE FROM TONGATAPU

by

C.G.J. Nieuwenhuizen

(K.S.E.P.L.)

An analysis was made of a hydrocarbon sample collected by C.J. Mulder at location 4 (EP-41310) on the SE outskirts of Nuku'alofa with the following results:

Asphaltenes content (wt. %)	4.2
Sulphur content (wt. %)	1.9
Water content (wt. %)	24.2

True boiling point distillation (tbp-glc)

temperature (degr. C)	total fraction (wt. %)
137	0
211.5	1.5
244	5.1
274.5	10.2
302	15.3
325.5	20.4
348	25.5
370	30.6
391	35.6
412	40.8
432	45.8
453	50.9
476	56.0
503	61.1
536.5	66.2
557	68.9

Contd...2

Using a correction factor to make up for the water content of 24.2%, the fractions are calculated as weight percentages of the water-free hydrocarbon sample.

COMMENTS

The volatility distribution of the hydrocarbon sample as presented by the tbp-glc data is characterized by the following features:

a. Initial boiling point of about 200° C.

b. About 30% residue over 550°C.

c. Absence of discontinuities.

The hydrocarbon sample is neither a residual diesel fuel/fuel oil (as the initial boiling point is as low as 200°C) nor a distillate diesel fuel (as the asphaltenes content is 4.2%) nor a mixture of distillate and residual products (as no discontinuities in volatility distribution are observed). It is concluded that the hydrocarbon sample is a crude oil from which the volatile hydrocarbons have evaporated to an unknown extent.

The true boiling point curve of this Nuku'alofa sample is attached to this note.

Source: Mulder and Nieuwenhuizen 1971

KUMIFONUA NO.1

Well Data

Operator: Tonga Shell N.V.

Co-ordinates: E9376.53, N7954.20 Tongatapu grid in chains
Date Spudded: 2 October 1971

Date Abandoned: 2 November 1971

Final status: Plugged and abandoned

Derrick Floor Elevation: 35 feet AMSL

Total Depth: 5525 feet (below derrick floor)

Objective: Investigation of tertiary sediments down to basal volcanics. To ascertain the presence, in the deeper part of the basin, of Eocene limestone above volcanic basement. To determine the provenance of the Pili oil seepage.

Results: Eocene limestone and basal volcanics not reached as the succession of volcaniclastics was thicker than anticipated and the rig capacity would not allow deeper penetration.

Cores: 4500 - 4515 feet 100% recovery

5495 - 5525 feet 66% recovery

22 sidewall cores between 1900 and 5487 feet

Hydrocarbon Indications: None

Source Rock Potential: Interval 4180-4190 feet contains a marginal source rock for gas.

Bottom Hole Temperature: 163°F

Surface Temperature: 75°F

Temperature Gradient: 1.6°F/100 feet

Lithology:

11 - 19 feet - Topsoil

19-470 feet - Limestone - leached coral grainstone, packestone and boundstone. White, creamy yellow, hard. Very porous and permeable at the top, decreasing with depth (25%- 10% porosity) Basal development of Foraminiferal limestone

470-5525 feet (TD) - Volcaniclastic sediments. Partly or wholly water laid volcanic detritus dark grey-black to grey-green. Relatively soft, silty clay to extremely course, angular to sub-rounded moderately sorted grains of andesite, dacite, basalt, augite & Feldspar in a clay matrix. Graded bedding, scour and fill.

Generally finer in the middle section. Calcoreous in part due to probably reworked limestone fragments and fine calcite "crusts". Possible lenses of limestone at 2470 and 3470-90.

Porous but not permeable except for the interval 5300-5350

Stratigraphy:

Based on palaeontological investigations of ditch-cuttings and side-wall cores.

0-470'	Plio/Pliestocene
470-600/700'	Lower Pliocene
600/700-2000/2200'	Upper Miocene
2000/2200-3650'	Middle Miocene
3650-5500'	Lower Miocene

Source: Tonga Shell N.V. 1971a

KUMIFONUA NO.2

Well Data

Operator: Tonga Shell N.V.

Co-ordinates: E9126.8, N8030.6 Tongatapu grid in chains
Date spudded: 12 November 1971

Date Abandoned: 28 November 1971

Final status: plugged and abandoned

Derrick floor elevation: 35.75 feet AMSL

Total depth: 5529 feet (below derrick floor).

Objective: To investigate the tertiary succession in an updip position from No. 1 on the western flank of the basin, near to the oil seepage at Hofoa.

Results: Eocene limestone and basal volcanics not reached within the rig capacity.

Cores: 5499 - 5529 82% recovery

27 side wall cores between 2150 and 5451 feet

Hydrocarbon Indications:-

Slight traces of methane - 600', 800-900', 2100-2200' and 3650'

Bituminous material over the interval 4250-4280'

Reacts strongly with chlorethane to give yellow-brown cut and strong whitish-yellow cut flourescence

Source rock patential: Interval 4130 - 4140 contains marginal source rock for gas. Bottom Hole temperature: 177°F

Surface temperature; 80°F

Temperature Gradient: 1.75°F/100 feet or 3.2° C/100 metres

Lithology:

(BDF)

11-20' Top Soil

20-440' Limestone - same as for Kumifonua 1 except for being less leached, with more secondary calcite development. There is no basal development of foraminiferal limestone as in No.1.

440-5529' (TD) - Volcaniclastic sediments

Rapid alternations of coarser and finer beds ranging from agglomerates to claystones much the same as Kumifonua 1, also being generally finer in the middle section which roughly concides with the Middle Miocene. The terminal core contains a probable ash-flow showing flow structures and autometamorphism. Permeable interval from 4383-4742'.

Stratigraphy

0- 440 Plio/Pliestocene

440-2100' Upper Miocene

2100-3700' Middle Miocene

3700-5500' Lower Miocene

The palaeontological correlation between the Miocene strata of Kumifonua 1 and 2 is nearly horizontal.

Source: Tonga Shell N.V. 1971b

LIST OF DEEPWATER DRILLSHIPS FOR PETROLEUM EXPLORATION

NAME OF DRILLSHIP	WATER DEPTH	DRILLING DEPTH	POSITIONING OR MOORING SYSTEM	REMARKS/WORK AREA
DISCOVER SEVEN SEAS	6000ft. (1829m)	25,000ft. (7620m)	Honeywell	Contracted to AGIP Mediterranean
SEDCO/BP 471	4500ft. up to 6000ft. (1372m up to 1829m)	25,000ft. (7620m)	Dynamic Positioning	Contracted to BP Farmout to Wood-side. Australia
NEDRIL I	100ft. to 4000ft. designed up to 6000ft. (30m to 1279m designed up to 1830m)	25,000ft. (7620m)	Dynamic Positioning or anchor. Anchor + D.P. assit	Contracted to Petro-Canada Work Area: World wide (now in Labrador Coast)
PACNORSE I	5000ft. (1524m)	20,000ft. (6096m)	N/A	Contracted to Phillips. Bay of Biscay
SEDCO 472	4500ft. (1372m)	20,000ft. (6096m)	Dynamic Positioning	Contracted to Esso Exploration, Australia
SEDCO 445	3500ft. (1067m)	20,000ft. (6096m)	Dynamic Positioning	Contracted to Shell/BP/Todd New Zealand
CO-950	3300ft. (1006m)	20,000ft. (6096m)	CIT-Alcatel	Under construction in Holland. World wide.
PELERIN	3300ft. (1006m)	20,000ft. (6096m)	CIT-Alcatel	Contracted to Petrocan. Labrador
DISCOVERER 534	3000ft. (915m)	25,000ft. (7620m)	Both Dynamic Positioning and furret mooring system	Contracted to Petrobras, Brazil
BEN OCEAN LANCER	3000ft. (915m)	20,000ft. (6096m)	Dynamic Positioning	Contracted to N/A Canada

NAME OF DRILLSHIP	WATER DEPTH	DRILLING DEPTH	POSITIONING OR MOORING SYSTEM	REMARKS/WORK AREA
GLOMAR ATLANTIC	2000-3000ft. (610-915m)	25,000ft. (7620m)	Dynamic Positioning or anchors	Contracted to Chevron. Work Area N/A
GLOMAR PACIFIC	2000ft. (610m)	25,000ft. (7620m)	Anchors	Contracted to Exxon USA Work Area N/A
DISCOVERER 511	2000ft. (610m)	20,000ft. (6096m)	Anchors	Contracted to Amoshore, Brazil
REGIONAL ENDEAVOUR	1506ft. (459m)	20,000ft. (6096m)	Anchors	Contracted to Wood side Petroleum Development Aust.
INTEROCEAN DISCOVERER	1500ft. (457m)	25,000ft. (7620m)	Anchors	Contracted to Petrobas, Brazil
GLOMAR JAVA SEA	1500ft. (457m)	25,000ft. (7620m)	Anchors	Contracted to Arco Gulf of Mexico
GLOMAR CORAL SEA	1500ft. (457m)	25,000ft. (7620m)	Anchors	Contracted to Exxon California
CANMAR EXPLORER III	1500ft. (457m)	25,000ft. (7620m)	Honeywell. Ask and anchors	Contracted to Dome Petroleum Beaufort Sea
SAIPEN DUE	1500ft. (457m)	25,000ft. (7620m)	Honeywell Ask and DMA with VOITH cycloidal propel-lors and anchors	Contracted to AGIP Mediterranean Sea
PELICAN	1000ft. (305m)	20,000ft. 6096m)	N/A	Contracted to East-can Ltd. E. Canada
DANWOOD ICE	1000ft. (305m)	20,000ft. (6096m)	Anchors	Contracted to Shell Sarawak. E Malaysia
SCAN QUEEN	1000ft. (305m)	25,000ft. (7620m)	Anchors	Contracted to Union S E Asia.
TAINARON	1000ft. (305m)	30,000ft. (9144m)	Anchors	Contracted to Petro-bas for 15 wells. Brazil Garoupa Field Available 1981

TABLE OF CONVERSION FACTORS

To convert non-metric to metric equivalent multiply by conversion factors given:

	Non-Metric Unit	Symbol	Metric Unit	Symbol	Conversion Factor
1.	inch	in.	centimetre	cm	2.54
2.	foot	ft.	metre	m	0.3048
3.	mile	mi.	kilometre	km	1.609
4.	square mile	sq.mi	square kilometre	sq.km	2.589
5.	acres	acres	square kilometre	sq.km	4.04656×10^{-3}
6.	cubic in.	cu.in	cubic centimetre	cc	16.387
7.	cubic in.	cu.in	litre	1	0.016387
8.	cubic foot	cu.ft	cubic metre	cu.m or m^3	0.02817
9.	million cu.ft.	MMcf	cubic metre	" "	28.17×10^3
10.	billion cu.ft.	bcf	" "	" "	28.17×10^6
11.	trillion cu.ft.	tcf	" "	" "	28.17×10^9
12.	US gallon	USgal	litre	1	3.78541
13.	barrel (42USgal)	bbl	litre	1	158.91
14.	barrel	bbl	cubic metre	cu.m or m^3	0.15891
15.	million bbl		" "	" "	158.91×10^3
16.	billion bbl		" "	" "	158.91×10^6
17.	degree Farenheit	^{o}F	degree Celcius	^{o}C	$(^{o}F-32) \times 0.556$
18.	^{o}F per 100ft.	$^{o}F/100ft.$	^{o}C per 100 metre	$^{o}C/100m$	1.8227

Source: based on Miall 1980 with modifications

TABLE 1

Profile No. and Type ( )	Position of Recording Station	Source	Water Depth km	Az.	L km	Sediment (1) V km/s	Sediment (1) T km	Sediment (1) t s	Transition (2) V km/s	Transition (2) T km	Transition (2) t s	Oceanic (3) V km/s	Oceanic (3) T km	Oceanic (3) t s	Mantle (4) V km/s	Mantle (4) T km
						TONGA										
7R12	19°37.3 S	AG 15	6.55		27	2.54	0.76	3.52	4.17	2.55	4.92					
	173°08.8 W								4.82		5.7					
7R13	19°35.9 S	AG 15	4.91		38	2.43	0.91	2.56	4.74	1.30	3.75	7.04		5.26		
	173°21.0 W								5.71	4.02	4.20					
7R14	19°35.2 S	AG 15	3.65		53	1.99	0.3	1.60	6.0	1.20	3.20	6.6	7.39	4.13		
	173°41.8 W					2.68	0.7	2.22				7.6		5.29		
						3.84	1.74	2.87								
7R15	19°27.8 S	AG 15	2.01	S	15	2.27	1.25		4.39	1.28	2.58					
	173°54.9 W					3.38	0.99		5.99		3.20					
			2.01	N	46	2.1	0.72	0.90	4.55	1.51	2.58	6.72	2.84	3.35		
						2.76	1.23	1.57	6.33	0.88	3.21	7.5		3.84		
7R16	19°23.7 S	AG 15	0.51	S	17	2 †	0.35	0.25	5.01		1.51					
	174°31.1 W					2.87	0.83	0.54								
						3.87	1.19	1.00								
			0.51	N	27	2 †	0.39	0.25	4.28	2.33	1.50	7.20		3.20		
						2.67	0.79	0.54	5.97	2.61	2.52					
						3.53	1.19	1.01								
7R17	19°25.5 S	AG 15	2.19	S	50	2.15†	1.46		5.83	1.88	2.68	6.9	2.57	3.08		
	175°12.9 W											7.6		3.50		
			2.19	N	35	2.15†	1.24		5.20	1.73	2.45	6.2	1.04	2.86		
												7.6	1.20	3.37		

Refraction Data in the Central part of the Tonga Platform

After Pontoise et al. (1980).