Natural Resources and Environment

AGRICULTURE • RESOURCES • CONSERVATION • LAND MANAGEMENT

MUSSEL-1

MISCELLANEOUS DATA

1 Folio No	2 Referred to	3 Date	4 Clearing Officer's Initials	1 Folio No.	2 Referred to	3 Date	4 Clearing Officer's Initials

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LOCATION

CAPE OTWAY PROJECT

SECTION 3

WORK PROGRAMME AND EXPENDITURE

PRELIMINARY DISCUSSION

The Mussel platform which occupies the majority of the application area V 79/3 is a major tectonic province of the Otway Basin. A brief discussion of this area, the Otway Basin and the Southern Continental Margins in general is given to highlight the geological assessment of the area for hydrocarbon entrapment.

REGIONAL GEOLOGY OF SOUTHERN BASIN REGION

The sedimentary basins of the southern continental margin of Australia have a gross similarity to those of the western continental margin. Both are related to the break-up and drifting apart of the Gondwana continent. However, on the southern margin, break-up occurred later in time. Final separation of the continents on the western margin was achieved in early Cretaceous, whereas separation of Australia and Antarctica did not occur until the Eocene. Marine transgression by the Tethyan Sea over the rifted western continental margin began earliest in the north. In the same way, on the southern continental margin the post-tectonic marine transgression was from the west.

In the extreme eastern part of the southern continental margin, basin development is related not only to the separation of Australia and Antarctica, but also differential movement between the Australian plate and the Tasmanian sub-plate (Bass and Gippsland Basins) and separation of Australia from the Campbell Plateau, New Zealand and Lord Howe Rise (Gippsland Basin). These events occurred respectively in the Cretaceous to Eocene and Late Cretaceous to Paleocene.

The Great Australian Bight Basin, the Duntroon Embayment and the Otway Basin are essentially similar in type to the Dampier, Beagle and other basins or sub-basins of the North West Shelf, except that the former were developed later in geologic time. On the North West Shelf, Upper Jurassic to Lower Cretaceous seas transgressed over an eroded, rifted pre-tectonic, predominantly continental Mesozoic sequence. Thick shale deposition occurred in the graben areas and this shale constitutes an important petroleum source rock.

PRELIMINARY DISCUSSION - Cont/...

In the southern basins the pre-tectonic continental sequence is Lower Cretaceous, extending down into Upper Jurassic in some areas, and the post-tectonic marine transgressive sequence is Upper Cretaceous in age. Both the Upper Jurassic-Lower Cretaceous on the North West Shelf and the Upper Cretaceous in the Great Australian Bight and Otway Basins appear to have been deposited in a restricted marine environment, with structurally high seaward barriers. Later in time, in both areas, separation of the continents had occurred, the barriers no longer existed and open ocean sedimentation occurred with increasing carbonate content. This open ocean sedimentation commenced in Upper Cretaceous on the North West Shelf and in Lower Tertiary in the Great Australian Bight and Otway Basisn. The Torquay, Bass and Gippsland Basins are of a different type and deposition of a continental coal measures sequence occurred in the Upper Cretaceous and Lower Tertiary. It was not until late Eocene or early Oligocene that the seas transgressed these basins. There are however, minor marine incursions in the late Cretaceous to early Tertiary in the Gippsland Basin, which at this time was open to the Tasman Sea.

THE OTWAY BASIN

GENERAL:

The Otway Basin ia a west-north-west trending trough containing a thick Mesozoic to Tertiary section that extends from Cape Jaffa South Australia, eatward to the Mornington Peninsula Victoria, a distance of some 500Km Continental, paralic and marine sediments exceed 7,500 m thickness in basin depocentres. North-south trending Palacozoic metasediments out-cropping north of the basin, extend south-ward to form economic basement throughout the area. Sedimentation in the basin was greatly influenced by tectonic movements, and all major phases of deposition are recognised in the Mesozoic-Tertiary.

The northern boundary of the basin is largely onshore and is defined by the northern limit of thick Mesozoic-Tertiary sedimentary section. In Victoria this lies just to the south of Paleozoic rocks of the Lachlan Fold Belt. In South Australia the Padthaway Ridge separates the Otway and Murray Basins. The south eastern boundary is the Cape Otway - King Island High. To the south west the basin is bounded by a basement high on the inner edges of the continental slope.

An extension of the King Island High separates the Otway Basin from the Sorell Basin, which extends along the west coast of Tasmania at least as far south as Macquarie Harbour. The basin is little known and extends into deep water. Knowledge of the sedimentary section has been

PRELIMINARY DISCUSSION - Cont/...

derived from one well, Clam No. 1, drilled south of King Island in the area known as the King Island Sub-Basin.

STRUCTURE AND STRATIGRAPHY

The three major sedimentary units recognised are the Upper Jurassic-Lower Cretaceous continental Otway Group deposited in an intra-cratonic basin when Australia and Antarctica were one continent; the transgressive-regressive Upper Cretaceous to Paleocene Sherebrook and Wangerrip Groups deposited as the seas invaded the basin prior to separation; and the Tertiary Nirranda and Heytesbury Groups, deposited in an open marine environment following separation separation. Volcanic activity was widespread in the Otway Basin with the initial volcanics been part of the Otway Group while the other principal periods of volcanism are in the Tertiary. The "Older Volcanics", were extruded over a period of time which may range from pre-Upper Eocene to Middle Miocene and consist principally of various types of basalt. Two phases of extrusion are recognised in the "Newer Volcanics", Plio-Pleistocene and Quaternary. Lithologic types include basalts, trachytes and scoria cones.
The structure of the Otway Basin is dominated by normal faulting, generally downthrown basinwards and aligned sub-parallel to the northern margin. Greatest movement occurred in the Lower Cretaceous with throws decreasing progressively upwards. Major movement appears to have ceased by the end of the Upper Cretaceous although some faults do extend into the Tertiary. Few major dip closures are evident. Such rollover as does occur has been (to date) associated with faulting.

The stratigraphic Units can be separately described as follows. (a statigraphic table is included. Fig 1)

BASEMENT

To the north of the Otway Basin is a variety of rocks ranging in age from Precambrian to Upper Palaeozoic which would be expected to continue as basement beneath the Basin.

True basement has been reached in only one offshore Well, Clam 1 which was drilled in the Sorell Sub basin extension, basement been reached at 1592 m. Out of a total of 12 offshore and 158 onshore, in all 170 wells only 11 other wells have reached basement in the basin. All these with the exception of Fergusons Hill 1 (mid Basin) have been drilled on the northern Margin. The Wells were:-

PRELIMINARY DISCUSSION - Cont/...

Kalangadoo 1	Basement reached	2036 m
Casterton 1	" "	2406 m
Pretty Hill 1	" "	2362 m
Fergusons Hill 1	" "	3453 m
Lake Eliza 1	" "	1460 m
Lucindale 1	" "	929 m
Lake George 1	" "	1361 m
Robertson 2	" "	1448 m
Moyne Falls 1	" "	889 m
Hawkesdale 1	" "	1635 m
Garvoc 1	" "	1424 m

The metamorphic rocks and the weathered lamprophyre (which proved unsuitable for isotopic dating) have been tentatively regarded as Cambro-Ordovician, because they are similar to rocks of that age described from outcrop.

Fractured basement in kalangadoo No. 1 yielded gas which contained 80 or even up to 96% carbon dioxide. The carbon dioxide may be related to the oxidation of hydrocarbons during local volcanic intrusions.

PRELIMINARY DISCUSSION - Cont/...

OTWAY GROUP:

The maximum known thickness of the Otway Group exceeds 3,500 meters in the Crayfish No.1 well. Seismic data indicates total thickness may exceed 4,500 meters in the more basinal areas. A threefold subdivision is recognised in some areas of the basin.

1. BASAL UNIT: (CASTERTON BEDS)

This consists of dark grey to black shales with some interbedded felspathic sandstones and weathered volcanics.
Three conglomeratic bands have been recognized in Casterton No. 1 Their porosity is 14% to 15% and permeability 1 to 2 md. Strong interpenetration of phyllite fragments and interstitial patches of calcite have reduced the porosity in places. The shales are known to be marginal source rocks for gas and light oil in some areas and are interpreted as paludal deposits that accumulated in locally low areas while the rare sandstone interbeds are lensoidal fluviatile deposits. The volcanics are contemporaneous flows and may be assoicated wit the initial downwarping or rifting of the Otway Basin.

ENVIRONMENT OF DEPOSITION

The sediments are paralic and alluvial, derived from an area of high relief and deposited in quiet water.

HYDROCARBON OCCURRENCES.

No oil staining has been observed in the sediments. A drillstem test in Casterton No. 1 over the interval 2098m yielded 270 m of muddy salt water, with a salinity of about 35,000 ppm (as NaCl) calculated from the SP log.

2. PRETTY HILL SANDSTONE:

The Pretty Hill sandstone has a rather sporadic distribution flanking paleo-topographic highs in the north-west and central part of the basin. It comprises porous quartz sandstones with some interbedded carbonaceous shales, siltstones and coals.
This unit is extremely variable in thickness (1,590-135m) and sand/shale content. In Pretty Hill-1,central Otway Basin, the unit is 570 m thick consisting of 94 per cent quartz sand with porosities up to 25 per cent and permeabilities to a few Darcies.

PRELIMINARY DISCUSSION - Cont/...

ENVIRONMENT OF DEPOSITION

Sediments are inner paralic to alluvial: high-energy features alternate with quiet shallow-water features. The occurrence of subgreywacke, containing depositional calcite and mudstone with plant fragments and coal lenses, possibly indicates a transitional environment in which marine and non-marine influences alternated. The lithic constituents suggest that the sediments were derived partly from a regionally metamorphosed source area, and partly from an acid to intermediate igneous source area. The unit contains a good floral assemblage but no marine fauna indicating that deposition probably occurred under terrestrial conditions. Abundant large scale cross bedding, carbonaceous shales, coaly laminations and occasional ripple marks further indicate a fluviatile sedimentary regime.

The appearance of acitarchs in the Geltwood Beach Formation in core 14, 6296 feet, Casterton No. 1 and that of the unicellular organisms 'Gen.et sp. indet. Forma A' in abundance in core 12, 5609 feet, Casterton No. 1 and core 19, 5590 feet, Heathfield No.1 imply a near-marine environment.

HYDROCARBON OCCURENCES

Gassy water in Tullich No. 1 (gases mainly methane and nitrogen). Weak gas shows in Crayfish 1 (offshore) and Robertson 1 along with weak oil shows in Hawkesdale1, Woolsthorpe No 1 and Garvoc, are the only indication of hydrocarbons. However,only 9 wells drilled in the basin and only one offshore well has intersected this formation.

EUMERELLA FORMATION

Thisisa widely distributed sequence of siltstones carbonaceous claystones, fine grained sandstones with abundant volcanic detritus, and minor coal (in seams and lines 1m to 3 m thick).

Because it contains more subgreywacke and therefore has a high average porosity, the upper part of the Eumeralla formation was regarded as a more prospective target for hydrocarbons than the lower part. However drilling of the offshore wells in the late sixties indicated that zeolitisation of the sandstones had destroyed all reservoir quality. It has however produced a thick seal for the relatively clean Pretty Hill Sandstone.

ENVIRONMENT OF DEPOSITION

Conditions of low energy, interrupted by short periods of high energy, prevailed throughout the Basin during the Lower Cretaceous The homogeneity of the sediments indicates a generally consistent pattern of sedimentation.

The region was one of tectonic instability, with shallow-water sedimentation keeping pace with subsidence. In the Mount Gambier area, marginal marine conditions appear to have

PRELIMINARY DISCUSSION - Cont/...

existed, with broad flood plains traversed by stream channels, marshes, mudflats, and localized deltaic fans; large deposits of peat and coal were not formed. In the easternmost part of the basin sedimentation also took place on broad flat plains. A restricted environment developed within the alluvial flats, swamps, and deltas. Coal developed from drift material probably derived from areas around the eastern end of the basin. Some marine inundation occurred in the Port Campbell area.

HYDROCARBON OCCURRENCES.

Flows of gas and salt water with gas in solution have been obtained from the Eumeralla formation; Port Campbell No. 4 produced 36 barrels/day of emulsified crude oil. None of the gas flows was sustained; so the reservoirs were small or restricted. (Heathfield Sandstone Areas?) In fact the Eumeralla has yielded the most hydrocarbon shows - a total of 10. after Port Campbell 4 above Flaxmans 1 yielded 7×10^3 M^3D gas plus 87° API condensate, this gas flow coming from 1200 metres below the tope of the unit, probably from a fractured zone. Obviously as well as a suitable seal, the Eumeralla holds some potential as a source rock particularly in the eastern part of the basin.

B. SHERBROOK GROUP:

1. WAARRE SANDSTONE:

This comprises coarse grained, sometimes argillaceous sandstone, with some interbedded siltstone and carbonaceous shale. It is a non-marine unit which is absent in the Tyrendarra Embayment and probably over local paleotopographic highs. Reservoir properties are generally good. The range of highest porosities measured on available cores is 20-25%, and the maximum measured permeability is 4840 md Thickness have ranged from 60m to 140 m.

Lithological studies of the Waarre formation indicate that part of it was deposited in fresh water and part in salt. Formation waters produced on test also include both fresh and salt. The fresh formation waters produced in Fergusons Hill No. 1 and Sherbrook No. 1 could conceivably be connate, but the high proportions of bicarbonate suggest that a meteoric origin is more likely. If this is so, then at least parts of the reservoir must be continuous over considerably distance.

ENVIRONMENT OF DEPOSITION

A paralic environment is indicated low in the sequence where probable marine or partly marine mudstone and sandstone are interbedded with coaly layers. Higher in the sequence coarser terrigenous sands followed by a conglomerate indicate a subsequent regression of the sea.

PRELIMINARY DISCUSSION - Cont/....

HYDROCARBON OCCURRENCES.

Port Campbell No. 1 produced a substantial flow of gas (117×10^3 M^3D) which was not sustained. Port Campbell Nos 2 and 3 produced gas and salt water. All other wells in the Port Campbell area produced either salty or fresh water. Offshore in the Port Campbell area Pecton 1 produced 4×10^3 M^3 D while Caroline 1 was completed as a CO_2 producer in the Gambier sub basin in the North West.

2. FLAXMANS FORMATION:

The Flaxmans Formation transgresses the basal Waare Sandstone and consists of dark grey marine shales, glauconitic siltstones and minor sandstones.

ENVIRONMENT OF DEPOSITION.

Flaxmans Formation was deposited in a transgressive nearshore shallow marine environment with recurrent high-energy conditions. The nearby landmass supplied detritus from emtamorphic basement and Lower Cretaceous sediments. Volcanic detritus could either be derived from older deposits or represent the last manifestation of the vulcanism which began in the Upper Jurassic and continued spasmodically through the Lower Cretaceous; its source appears restricted to the Port Campbell area.

HYDROCARBON OCCURRENCES.

No evidence of hydrocarbons has been noted; the formation has very low porosity and permeability.

3. BELFAST MUDSTONE:

This unit conformably overlies and interfingers with the Flaxmans Formation, except in the Tyrendarra Embayment where the total Upper Cretaceous section is thin and it unconformably overlies the Otway Group. The lithology is predominantly marine shale or siltstone.

ENVIRONMENT OF DEPOSITION.

Mud,clay, silt and coarser material were deposited contemporaneously with chemical precipitation in a restricted basin of deposition, in calm, slightly alkaline waters, under reducing conditions, with the formation of glauconite and sulphides. The macro- and microfaunal associations are characteristic of such an environment.

HYDROCARBON OCCURRENCE.

No oil staining has been observed in either the cores or cuttings of the Belfast Mudstone. However when the thick marine Belfast Mudstone is at sufficient depth it can be regarded as a potential hydrocarbon source.

PRELIMINARY DISCUSSION - Cont/...

4. PAARATTE FORMATION:

The Paaratte Formation is the regressive phase of the Sherbrook Group and comprises marine to paralic glauconitic quartz sandstones and siltstones. The porosities of the sandstone are generally moderate to high and permeabilities are good although reduced in places by silty material and chemical cements (including chlorite). The amount of cement decreases towards the top of the sequence. Permeabilities up to 2390 md have been recorded in the Paaratte Formation (Mount Salt No. 1)

ENVIRONMENT OF DEPOSITION.

The sediments of the Paaratte are 'marginal marine' or paralic, deposited in deltaic, lagoonal, and shallow neritic areas. Iron silicate, ferruginous chlorite pellets, and, in some parts, ferruginous chlorite cement were formed by flocculation of iron gels produced by climatic-pedogenic processes on a nearby landmass, Similar conditions probably recurred at different times during deposition of the Curdies and Pebble Point Formations.

The sandstone was deposited in oxidizing to slightly reducing conditions with slightly alkaline water and little organic matter.
From the drilling of offshore well Pecten 1A, the Paaratte formation was apparently deposited in shallower water offshore than in the nearby onshore wells, as it has a higher sand content and contains silt rather than shale. Diachronism of the formation previously demonstrated on shore was also shown in Pecten 1A where the lower Paaratte formation is time equivalent to the upper Belfast Mudstone in the onshore wells. (In these correlations the Paaratte is distinguished from sands in the overlying Curdies formation by the presence of abundant green pellets (? chlorite).

HYDROCARBON OCCURENCE

Waxy oil was recorded in Port Campbell No. 1 at 1427 m.

5. CURDIES FORMATION:

Conformably overlying the Paaratte Formation, the Curdies Formation was deposited in a fluviatile environment and consists of quartz sands, also with good reservoir characteristics, coal and minor siltstone. The maximum known combined thickness of the Paaratte and Curdies Formations is 880 meters in Prawn No. 1. In some areas they are absent due to erosion.
The Curdies Formation has high porosity and fair to good permeability (- 3100md Port Campbell No. 4)

ENVIRONMENT OF DEPOSITION.

Inner paralic to alluvial conditions prevailed in the onshore part of the Otway Basin. Thicker sands in the trough areas may be alluvium deposited in stronger energy conditions than in the intervenening flats, where coal formed.

PRELIMINARY DISCUSSION - Cont/...

HYDROCARBON OCCURRENCES.

No hydrocarbons have been reported. Organic matter in sandstone at 1095m and 1266m in Mount Salt No. 1 has been called 'dead oil', but later studies attributes its derivation to bituminous coal.

C. WANGERRIP GROUP:

The Wangerrip Group unconformably overlies the Sherbrook Group and was deposited during the second transgressive-regressive cycle during the Paleocene. It comprises a basal marine sand (the Pebble Point Formation) overlain by the marine to continental Dilwyn Formation. The lower part of the Dilwyn Formation consists of marine siltstone, mudstone and shale, to which the names Pember Mudstone Member, Rivernook Member or Rivernook Formation have been applied. This grades upwards into the more continental sequence of the remainder of the Dilwyn Formation, which is predominantly arenaceous with minor siltstone and coal.

This sedimentary cycle is widespread west of the Otway Ranges, and has an average thickness of about 240 m.

1. PEBBLE POINT FORMATION

The Pebble Point Formation at the base of the Wangerrip is a pebbly pelletal and colitic sandstone, 15 to 120m thick. A belt of foreset sands is predicted from seismic evidence to occur underneath the coastal area west of Port fairy, adjacent to an area of calcarenite rich in ooliths (Eumeralla No. 1) and another more extensive belt of foreset sands occurs along the edge of the continental shelf. (Nautilus 1) the unit contains thick porous and permeable sands over most of the basin and is more than 840 m thick in Heywood No. 1 Bore. Porosity in the sandstone ranges from low to moderate, depending on diagenetic changes. The chemically cemented rocks have low porosity.

ENVIRONMENT OF DEPOSITION.

The formation was deposited in shallow water during a marine transgression. The rounded detrital grains and coliths are indicative of high energy currents. The waters were supersaturated in calcium carbonate and a carbonate cement was precipitated and carbonate ooliths formed; at times drducing conditions prevailed, and siderite and phosphate were precipitated.

HYDROCARBON OCCURRENCES.

No hydrocarbons are known in the Pebble Point Formation. Sands with good porosity and permeability are found in Mount Salt No. 1 and Flaxmans No. 1, but sands in wells appear to be of low permeability.

Results from offshore drilling indicated that the formation has sands with good reservoir characteristics (Nautilus 1 and Murrel 1).

2. DILWYN FORMATION (CHARACTERISTICS)

The formation includes sandstone, carbonaceous sandy siltstone, and shale. The Dilwyn formation contains a thick homogeneous marine siltstone, the Rivernook Member, which is a useful marker horizon.

PRELIMINARY DISCUSSION - Cont/...
ENVIRONMENT OF DEPOSITION

Initially deposited in a paralic environment with marine deposition shown by carbonate-cemented sandstone, glauconite, and isolated marine fossils; small amounts of carbonaceous matter occur in the sediments, possibly in pro-delta deposits.

Desposition then continued during regression under predominantly deltaic conditions interrupted by minor marine incursions. Abundant carbonaceous material lignitic and coaly lenses, plant remains, burrows, pyrite, phosphatic fragments, and glauconite, indicate that the waters were generally reducing or neutral.

The alternation of coarse and fine carbonaceous sediments may be a result of stream migration across deltaic flats.

HYDROCARBON OCCURRENCES.

Cores of the Dilwyn Formation from Mount Salt No. 1 showed some fluorescence of unknown origin.

D. NIRRANDA GROUP:

The Nirranda Group of Eocene age disconformably overlies the Wangerrip Group and is totally marine. It comprises the Mepunga Formation (predominantly Ferruginous quartz sand) and the overlying Narrawaturk Marl which consists of marl, mudstone and argillaceous limestone.

The Eocene strata rest unconformably on the Wangerrip group or equivalents in most parts of the Otway Basin. In the Torquay sub-basin the Eocene rocks consist of the fluviatile Boonah formation, overlain by the Demons Bluff formation which is marine in the upper part. In the western part of the Otway Basin the Eocene rocks are limonitic sands (the Mepunga formation) and limonitic limestones (the Nelson formation) overlain in the Port Campbell Embayment by Eocene marls (the Narrawaturk Marl).

THE MEPUNGA FORMATION

The unit consists of fine-grained sandstone grading into very coarse-grained sandstone; in the Nelson Bore a conglomerate 2 m thick occurs at the base. Chamosite and limonite pellets are common throughout and the cement is mostly dolomite.

The high percentage of dolomite cement is probably related to a primary carbonate cement which has been changed diagenetically. The pellets are thought to have been formed by slight current action on a fine-grained precipitate.

These basal sands have good porosity and permeability, but have probably been flushed in the onshore area.

A thick section 150 m was encountered in Pecten 1A offshore (Port Campbell Embayment area), the equivalent Boonah in Nerita and Snail (Torquay Basin) was relatively thin, as was the Voluta occurence.

ENVIRONMENT OF DEPOSITION.

The limontic sandstone facies reflects a period when the sea transgressed across a still unstable landmass. A basal conglomerate at the bottom of this sequence in the Nelson Bore may be derived from the reworking of an older, possibly Eocene, conglomerate. In the sandstone, pellets of limonite, hematite, and goethite and rounded grains suggest deposition under high-energy conditions in shallow oxygenated waters.

HYDROCARBON OCCURRENCES.

There have been no indications of hydrocarbons.

2. NARRAWATURK MARL

Similar onshore and offshore occurence as the Mepunga.

The unit consists of glauconitic marly limestone mudstone sandstone, and sandy limestone containing glauconitic pellets. In all these rocks, oxidized glauconite, limonite, iron oxide pellets and ooliths, and reworked limenitic rock fragments may occur.

Purplish brown glauconitic marl, containing limonite and glauconite pellets and spots of gypsum associated with pyrite, was encountered in Port Campbell No. 1.

ENVIRONMENT OF DEPOSITION.

The glauconitic marly limestone facies was deposited after a marine transgression over a shallow shelf area. The temperature and salinity were suitable for supporting calcareous organisms. The generally low detrital contents indicates that sedimentation was taking place on a stable shelf area adjoining a low-lying landmass. Sandy limestone gives way to marl and clean limestone towards the tope of the sequence.

HYDROCARBON OCCURRENCES.

No indications of hydrocarbons have been observed.

HEYTESBURY GROUP:

The Heytesbury Group (generally between 150-600m thick) was deposited in the widespread Oligocene-Miocene marine transgression and disconformably overlies the Nirranda Group. The lowermost unit, the Clifton Formation, consists of bryozoal calcarenite and quartz sand. The Gellibrand Marl is predominantly grey marl, with some calcareous clay, siltstone and argillaceous limestone. The Port Campbell Limestone is predominantly calcarenite and calcisiltite. The Heytesbury Group progrades seaward, the maximum known thickness exceeding 1,500 meters at Nautilus No. 1. There sediments become the Torquay Group in the Torquay Embayment (and are relatively thinner).

ENVIRONMENT OF DEPOSITION

From the rounded and very coarse nature of the quartz grains and bioclastics, the lack of clay matrix, and the presence of carbonate cement, the upper sediments appear to have been deposited in a shallow sea in a high energy environment; earlier, in the Portland area, quieter conditions prevailed.

HYDROCARBON OCCURRENCES.

No hydrocarbon occurrences are known despite high porosity and permeability in the sandy sections.

EXPLORATION HISTORY:

The near coastal areas of western Victoria and southern South Australia have attracted attention with respect of petroleum search since the later part of the 19th Century. Early interest was influenced by the prospects of a thick section of Tertiary sediments and was stimulated by reported oil seepages and the observed stranding of inspissated oil along coastal beaches. The first well drilled for oil in Australis was the Alfred Flat Bore, drilled in 1982 in the Coorong area (near the Padthaway Ridge in South Australia, part of the northern margin of the Otway Basin). The first deep holes within the basin were water bores drilled by the Victorian Department of Mines. The Robe No. 1 Bore was drilled to 373m feet in 1915 by the South Australian Oil Wells Company who subsequently drilled wells at Tantanoola, in the Hundred of Caroline, and near Anglesea. These, and some of the subsequent wildcat wells, were based on surface indications of structure. Mount McIntyre No. 1 was drilled to ascertain whether any oil had accumulated through distillation of organic matter in carbonaceous beds by volcanic intrusion or by the folding of the beds as a result of the intrusion. After the drilling of numerous shallow wells which failed to produce significant showings of hydrocarbons, interest waned and the theory developed that much of the thick Tertiary section was of continental origin and therefore unattractive from the petroleum viewpoint. The Nelson bore was commenced in 1941 by joint Commonwealth and State Authorities and abandoned at a depth of 2227m in November 1945. This well indicated the considerable thickness of sediments present but no significant hydrocarbons were encountered. In the ensuing years government authorities maintained interest in the area but investigations were restricted mainly to fact geological mapping. Evaluation studies carried out for various interests by overseas consultants and local geologists were inconclusive due to the paucity of subsurface information.

The first application of geophysics to oil prospecting in the Otway Basin (to ascertain the nature of a structure which was about to be drilled for oil) was in 1930, when J.M. Rayner conducted a magnetometer survey on Knights Dome in southeastern South Australia.

The subsequent drilling of the dome was, unfortunately, stopped before the whole of the Tertiary section had been penetrated, and results were inconclusive.

An airborn magnetometer survey carried out by the Zinc Corporation in 1949 over the western parts of the area indicated the probably landward limits of the basin and outlined areas of thick sedimentation in the Mt. Gambier and Portland areas. B.M.R then did some gravity and magnetometer surveying in 1949-50 in southwestern Victoria and the South Australian Department of Mines ran gravity surveys in southeastern South Australia from 1950 to 1954.

The discovery of oil at Rough Range in Western Australia in 1953 created a renewed interest in petroleum exploration through Australia. After that the Frome-Broken Hill Company Pty. Ltd., commenced active interest in the investigation of the sub-coastal basins of South Australia and Victoria.

In following years other exploration companies have carried out investigations within this province. These include General Exploration Company of Australia Lt., Beach Petroleum N.L., South East Oil Syndicate, Oil Development N.L. Planet Oil N.L. and Haematite Explorations Pty. Ltd., A gravity survey carried out by the S.A. Mines Department in southern South Australia in 1954 have further support to the premise that sedimentary and structural conditions favourable with respect to petroleum search were present. Interest in the area was stimulated in 1959 when the Belfast No. 4 bore drilled by the Victorian Mines Department at Port Fairy intersected marine Cretaceous sediments.

Later in the same year the first well drilled by Frome-Broken Hill Company at Port Campbell discovered a strong initial flow of rich petroleum gas with condensate and traces of oil associated with marine Cretaceous sediments. Modern exploration in the Otway Basin then commenced. Since then approximately 45 wells have been drilled, including 12 offshore wells. Of these 18 have recorded hydrocarbon shows, generally from the Waarre Sandstone or the Otway Group. The four most significant shows are from Port Campbell No. 1 and No. 4, Flaxmans No. 1 and Pecten No. 1A, all in the Port Campbell-Peterborough area of the Port Campbell Embayment.

Port Campbell No. 1 produced gas at a maximum rate of 4.36 MMCFD with 6 barrels per day of 65° API condensate in a drillstem tests of the Waarre Sandstone. On production test flow rates and pressures steadily declined and the well began to produce salt water, indicating a very limited reservoir. Port Campbell No. 2 produced gas and gas cut water from the Waarre Sandstone. Port Campbell No. 3 yielded a small gas flow and salt water from the Otway Group. Port Campbell No. 4 produced small amounts of oil (Max. 5BPD) and gas from two drillstem tests of Otway Group sandstones. API gravity was 35° to 38° and production was accompanied by brackish water. Flaxmans No. 1 had gas shows in the Paaratte Formation, Waarre Sandstone, and Otway Group.

A small amount of 51° API condensate was also produced from the Otway Group. Pecten No. 1A flowed 90 - 145 MCFGD and 615 BWPD on a drillstem test of the Waarre Sandstone. In South Australia Caroline No. 1 produces commercial carbon dioxide (0.3 BCF per annum) from the Waarre Sandstone. The gas is almost pure carbon dioxide with about 1% hydrocarbons.

The principal operators in recent times have been the Frome-Broken Hill-Shell Group (onshore and near offshore Victoria) Esso-BHP (offshore South Australia and further offshore Victoria) and Alliance Oil Development, General Exploration of Australia - Beach Petroleum (onshore South Australia and Victoria) Planet Oil Company and Pursuit Oil Companies.

A large amount of geophysical exploration has been done. There is aeromagnetic coverage over the entire basin and gravity coverage of the onshore. There is moderate onshore seismic coverage over the areas of thicker section, but much of the data is poor quality. There are considerable problems in obtaining usable data in areas of volcanics, sand dunes and cavernous limestones.

Offshore seismic coverage is fairly dense varying from 2 to 10 kilometers line spacing on most of the continental shelf, with sparse coverage of the continental slope. The earlier shooting commenced in 1966 and much of this is poor quality and inadequate for reliable mapping. The more recent surveys include those done close inshore in 1973 and 1975 by Interstate. Record quality was much improved compared to earlier data and structure could be mapped down to the lower part of the Otway Group. Two structures were indicated in the offshore part of the Port Campbell Embayment but these have not been drilled.

Hematite shot three surveys totalling 4,500 km of 24 to 72 fold data in 1972, 1973 and 1974. The results showed considerable improvement over earlier surveys but good quality data was seen only down to the base of the Tertiary. Extensive faulting was evident within the Cretaceous on the Mussel Platform, but mapping of Cretaceous structures was inhibited by multiples from the Tertiary.

PETROLEUM PROSPECTS:

This section will briefly discuss the petroleum prospects of the Otway Basin. Fig 1 illustrates the statigraphical distribution of hydrocarbon shows encountered in onshore and offshore exploration to date and also grades the lithological units with respect to their Reservoir, source and seal potential.

(a) SOURCE

Popular opinion seems to regard the source potential of the Otway Basin as poor, this opinion having been expressed by the BMR and Shell. The reasons appear to be alleged low total organic carbon content in post-Otway sediments, predominance of humic content suggesting gas-prone source, and immaturity. However, the reputation appears undeserved. The Otway Basin has produced a number of significant gas condensate shows and some oil shows, indicating that generation has occurred. There are some indications from recent work that the classic ideas on the level of maturity required to generate hydrocarbons may have to be revised downwards. Alternatively, in the Otway Basin, as in so many other basins, generation could have occurred at deeper levels and migrated into reservoirs which are within the immature zone.

By reference to the Statigraphic column shown in Fig 1, the following formations have source rock potential.

LOWER CRETACEOUS:	Casterton Beds Eumeralla Formation	(Major)
UPPER CRETACEOUS:	Flaxman Formation Belfast Mudstone Paaratte Formation	(Major)
TERTIARY:	Eastern View. Member Pember Mudstone Narrawaturk Marl	(Major)

Strandings of coastal bitumen along the southern coast of Australia have been well documented for over 100 years. In all but one case they found that the samples represented naturally occurring oil and not fuel oil or crude oil sludge discharged at sea by tankers. The pour points were all high, indicative of a high wax content which characterises crude oils derived from non-marine higher plants. Furthermore, two distinct families of bitumen were seen. One family, the lighter, was highly paraffinic to paraffinic in composition.

The heavier group had a paraffinic to naphthenic base. The first group had a strong similarity in composition with the crude oil recovered in Port Campbell No. 4.

Source rock reports on the Otway Basin are Contradictory. However, if one were to accept the conclusions reached, the overall impression would be that the Otway Group contains fair source rocks for gas, with in some cases possibility for oil; that the Upper Cretaceous contains poor to fair gas sources, but unlikely for oil; and that in most onshore areas the sediments are immature.

In evaluating these conclusions several factors need clarification. Firstly the reports by the companies are ten years or more old, and do not incorporate the later ideas and techniques.
Secondly, the number of samples, particularly in the Upper Cretaceous, is relatively sparse, and usually confined to cores. Even so, the figures for total organic contents in most Upper Cretaceous samples are relatively high, generally over 1.0% which considering this criteria alone, would rate as a good hydrocarbon source rock. Some samples of Upper Cretaceous showed total organic carbon contents of 3 to 8% which would constitute excellent hydrocarbon source. Thirdly, and perhaps most significant of all, the great mass of Upper Cretaceous section in the Voluta Trough has been tested by one well only, Voluta No. 1, and even that failed to reach the base of the Upper Cretaceous. Much of the Upper Cretaceous section that has been penetrated has been onshore and relatively close to the shoreward margin of the basin, near the regressive end of the transgressive-regressive cycle. Therefore it could be expected to contain a higher proportion of land derived plant material.
The Upper Cretaceous marine transgression in the Otway Basin, is comparable with the Upper Jurassic marine transgressions on the North West Shelf and in the North Sea. Its source potential has not been tested and it could be a significant source of oil.
TO SUM UP:-The Lower Cretaceous Otway Group appears to be a proven source for both gas and oil. Nearly all of the hydrocarbon shows and the coastal bitumen strandings appear to have been derived from the Lower Cretaceous and two distrinct families have been recognized possibly from two different source horizons. Support for this concenpt is seen in the distinct difference in the condensate types between the Port Campbell No. 1 and Flaxmans No. 1 wells. The Lower Cretaceous appears immature in some of the areas where shows have been obtained,which is indicative of migration from the deeper basin.

The Upper Cretaceous has a potential for gas and could prove to have a significant potential for oil.
In many of the areas where it has been penetrated, the Upper Cretaceous has been described as immature. The present day theremal gradient varies from about 2.5° C/100 metres offshore to about 4.0° C/100 metres near

the northern margin of the basin. Shell has noted that a higher gradient appears to exist in the Upper 1,200 metres of the section. The value of 2.5° C/100 metres is comparable with the Dampier Sub-Basin of the North West Shelf. It is clear that the Upper Cretaceous is mature in the deeper parts of the Voluta Trough.

Practically no figures are available for total organic carbon in the Tertiary. In the marine section at least they could be expected to be low. The Tertiary however, is possibly immature throughout the basin, and therefore low with respect to a potential source.

(B) RESERVOIR AND SEAL:

By reference to Fig 1. The following reservoirs and seals are postulated for the Otway Basin.

AGE	RESERVOIRS	SEALS	GRADING
Tertiary	Port Campbell Limestone		
	Clifton Formation	Gellibrand Marl	
	Mepunga formation	Narrawaturk Marl	Good
	Dilwyn Formation	Narrawaturk Marl	Fair
	Pebble Point Formation	Pember Formation	Fair
Upper Cretaceous	Timboon Sand	Pember Formation	Fair to Good
	Paaratte Formation		Fair to Good
	Nullawarre Greensand	Belfast Mudstone	
	Flaxman Formation	Belfast Mudstone	Fair
	Waarre Formation	Belfast Mudstone	Good
Lower Cretaceous	Eumeralla	Belfast or Eumeralla	Good
	Heathfield Sandstone	Eumeralla	
	Pretty Hill Sandstone	Eumeralla	Good

Although several wells have had substantial shows of gas, no commercial hydrocarbon accumulation has yet been found in the Otway Basin. Good initial flows of gas were obtained in Port Campbell No. 1 (4.2 MMcf/ from the Waarre Formation), Flaxmans No. 1. (250 Mcf/ from the Eumeralla Formation) Port Campbell No. 4 (160 to 219 Mcf/day from the Eumeralla Formation, and Pecten 1a 4×10^3 M^3D from Eumeralla).
None of these flows was sustained, and in each case the reservoir pressure fell rapidly, indicating that the zones tested were very small.

In all, from 170 wells drilled in the Otway Basin, 50 of these have had hydrocarbon or CO_2 indications from the following potential reservoirs ranked in order of present hydrocarbon shows.

Eumeralla)
Waarre)
Pretty Hill) - 90% of shows have occurred in these formation
Paaratte
Timboon
Pebble Point
Dilwyn

C. STRUCTURE:

The majority of the wells drilled in the search for oil since 1959 have been sited on closed anticlines or fault traps defined by seismic exploration, although Fergusons Hill No. 1 and Sherbrook No. 1 were sited to test possible pinch - out of sediments against an uplift, Anglesea No. 1 was an off-structure stratigraphic well.
The location of viable structural traps is probably the most difficult phase of further exploration in the Otway Basin. Continental breakup has given rise to major structural movement, mostly down to the basin normal faulting. However, except in certain (Torquay Basin) areas, movement on the faults had largely ceased by Tertiary time. This has resulted in a paucity of closed Tertiary structures, which would be required for entrapment in the topmost Upper Cretaceous and the Lower Tertiary reservoirs. Seismic definition beneath the Tertiary has not been good so that Cretaceous structures have been hard to define. All this notwithstanding, structural traps do exist, as evidenced by carbon dioxide accumulations at Caroline and Kalangadoo. It is likely that most structures defined will be dependant on fault closure. However, dip closed anticlines associated with transcurrent faults are also likely to exist. Stratigraphic traps are undoubtedly present but hard to locate with present seismic definition.
The most prominent structural features in the Otway Basin are horsts and grabens or half-grabens produced by tension, and transcurrent faults and short en echelon fractures produced by shear. Although many of the faults are post-depositional, some were contemporaneous with sedimentation.

Fault traps or pinch-outs which have formed as a result of 'down-to-basin' faulting are to be expected. Stratigraphic traps may occur in areas of rapid clastic sedimentation where floods of coarse detritus produce localized or blanket-type sand lenses.

Folds are more common in the eastern half of the basin than in the west. The nature of many of the folds is difficult to determine because of inadequate seismic control, but some are certainly compressional. Some of the subsurface features are confined to sediments older than the Sherbrook Group, others persist into the Sherbrook and Wangerrip Groups, and the most persistent affect the Heytesbury Group. Some of the anticlinal structures appear to plunge towards the long axis of the basin. Elongated folds may show closure at one or more places along their axes; the extensive feature through Flaxmans No. 1 is typical.

Anticlines or monoclines may be associated with 'down-to-basin' faulting at the edges of troughs.

Seismic records show dome-like structures in certain younger sediments, in the areas where vulcanism is known; they are perhaps caused by basaltic intrusion or extrusion. Traps could be created by updoming by the intrusions or by draping over rises caused by the intrusions and extrusions. The latter might be expected in earlier sediments associated with the Upper Jurassic to Lower Cretaceous (?) vulcanism, or in the eastern part of the basin where the 'older (Oligocene) Volcanics' occur.

Traps may occur below angular unconformities around the southern and eastern margins of the basin. However, throughout much of the Otway Basin sequence, most unconformities are followed by marine transgressions and the deposition of coarsegrained generally porous sediments which would not provide a seal. Traps could be developed offshore along the edges of shallow basement features such as the Warrnambool Ridge and south of Cape Otway.

The large foreset structures shown in seismic records in the area west of Warrnambool and offshore could supply excellent reservoirs.

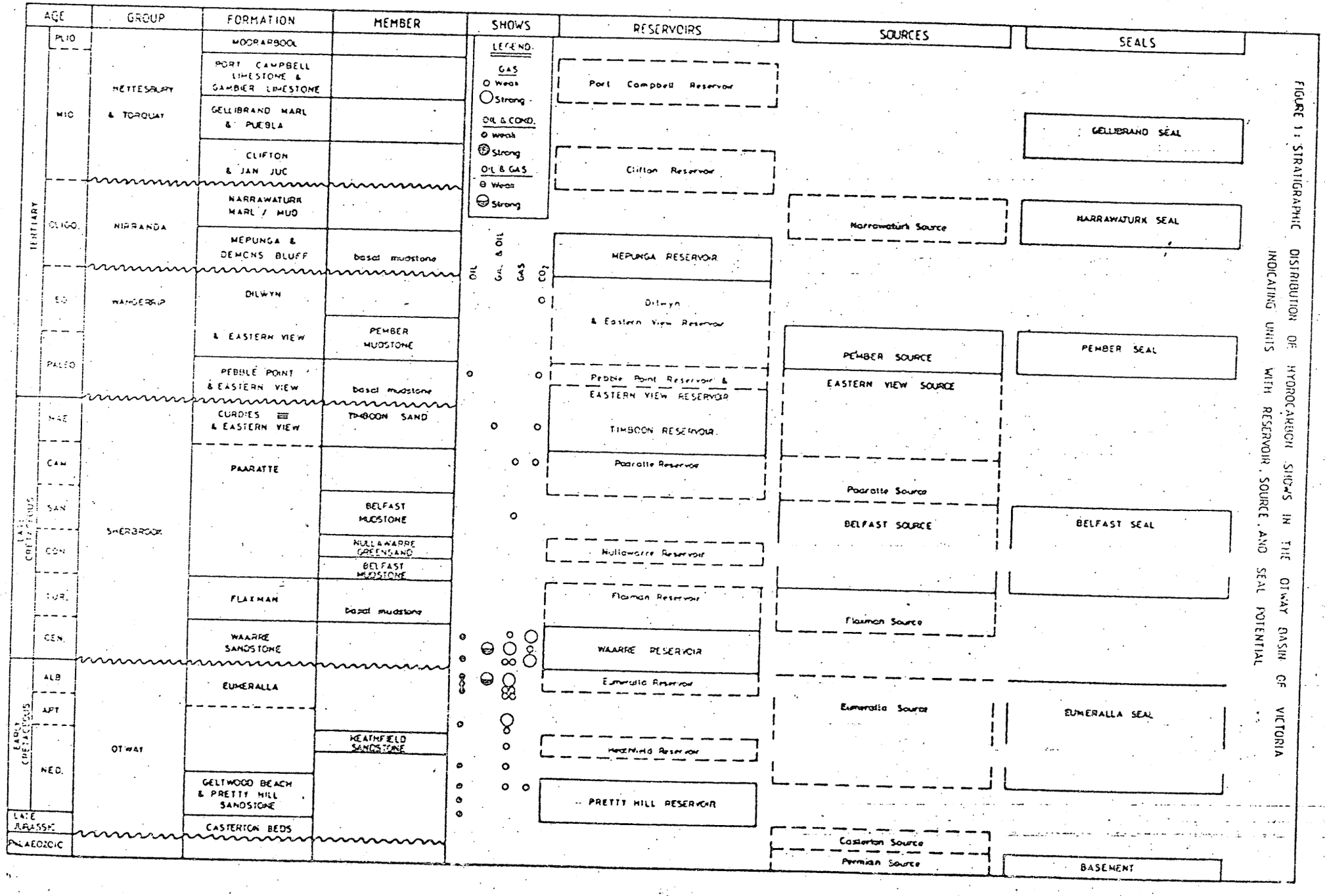

FIGURE 1: STRATIGRAPHIC DISTRIBUTION OF HYDROCARBON SHOWS IN THE OTWAY BASIN OF VICTORIA INDICATING UNITS WITH RESERVOIR, SOURCE, AND SEAL POTENTIAL

CAPE OTWAY PROJECT

SECTION 5 (CONTINUED)

CAPE OTWAY AREA (PERMIT AREA V79-3)

1. Sea Floor Configuration

Permit Area V79-3 encompasses the Victorian waters on the continental shelf to the south-west of Cape Otway and extending eastwards into Bass Strait. It thus includes the offshore region between Port Campbell and Lorne, an area of 4485 km^2 of which all is above the -200 m sea-floor contour.

Though several infilled channels are recognizable in deeper waters beyond the south-west boundary of the permit area, these become masked or disappear as they approach the axis of the Cape Otway-King Island High to the north-east

A prominent submarine ridge extends across the permit area in a southwestward direction from Cape Otway and is probably the surface expression of a shallow continuation of the Otway Ranges High.

The sea floor to the east of the Cape Otway-King Island High slopes gently towards a central basin depression situated to the south of Torquay and Anglesea.

2. Basin Development

The region covered by the permit area includes two major basinal units that are separated partially by a positive tectonic element whose axis lies between the Palaeozoic high of King Island and the Mesozoic high of the Otway Ranges. Seismic records reveal that there is a corridor across this axis connecting the Port Campbell Embayment and the Torquay Embayment.

These two basin units have undergone three main stages in their development which are related to initial movement and final drifting apart of the Australian and Antarctica continental plates.

(1) A proto-rifting stage from Late Jurassic to mid-Cretaceous times during which the nonmarine Otway Group sediments were deposited in an intercratonic basin extending through the Otway, Bass, and Gippsland Basins.
Denham and Brown (1976) believe that instead of a single rifted basin, the Otway and Strzelecki Groups were formed in a series of intermontane basins which bear no relationship to the Late Cretaceous and Tertiary of the Bass Strait region.

(2) A rifting stage during the Late Cretaceous and Early Tertiary, when the marginal marine and deltaic Sherbrook and Wangerrip Groups respectively accumulated in two superimposed and lapping basins. Denham and Brown (1976) consider that the Sherbrook Group sedimentation in the Late Cretaceous occurred in discrete basins separated by the Cape Otway-King

Island High which terminated with a precipitous eastern edge as expressed by the north-south Sorell Fault.

This interpretation of seismic data implies that Upper Cretaceous sediments are absent from the corridor connecting the two major basin units. However, marine deltaic and fluvio-deltaic sediments of the Lower Tertiary Wangerrip Group were apparently deposited throug this corridor.

(3) A separation stage during the Middle and Late Tertiary introduced widespread open marine conditions across both embayments and resulted in a laterally continuous cover of carbonate-rich sediments.

3. Petroleum Prospects

The connecting corridor between the Torquay and Port Campbell Embayments appears to have been in existence since earliest Tertiary times. A simple palaeogeographic model is here suggested for the Cape Otway area so that the scarce basic data can be more purposely arranged towards petroleum search

The tectonically negative belt linking the Torquay and Embayment and its extension into the Port Phillip Graben is regarded as having provided the trunk drainage channel for the central Victorian hinterland throughout Early Tertiary times. Although some outflow into the land-enclosed Bass Basin may have occurred over the King Island-Mornington Peninsula Ridge, it seems probable that the main outlet was through the Cape Otway corridor and across the Mussel Platform to the ocean to the west. This major trunk river system has been responsible for deposition of the fluvio-deltaic sediments of the Eastern View Formation in the Torquay Embayment and their marine deltaic equivalents in the Dilwyn Formation on the Mussel Platform. Both formations consist of dominantly sandy beds with intercalated carbonaceous shales and minor coals. (Abele, 1979).

Stratigraphic traps are likely to be present as there are a great variety of facies present. The sequence is broadly sealed by such Middle to Upper Tertiary argillaceous units as the Narrawaturk Marl, the Gellibrand Marl, and the Puebla Formation.

There are source rocks in this deltaic complex with enough maturation to be capable of generating hydrocarbons in locations with sufficient depth of burial and geothermal gradients.

These include the black carbonaceous marine Pember Mudstone and the equivalent of the Anglesea coal measures in the thick Eastern View Formation.

Favourable comparisons with the depositional environment of the Latrobe Group in the Gippsland Basin, and the similar age of petroleum occurrences there, are not unreasonable.

Previous exploration wells in the Torquay Embayment (Nerita-1 & Snail-1) and on the southern Mussel Platform (Prawn-1) were not sited along the main depositional axis of the deltaic system outlined above. Only traces of hydrocarbons were found in these wells (White, 1968; McPhee, 1976)

The permit area also contains potential for petroleum search in the Upper Cretaceous sequence on the Mussel Platform. The Belfast Mudstone must everywhere in the Otway Basin be regarded as a significant source rock for both oil and gas. Although the Waarre Sandstone is the most probable reservoir for hydrocarbons migrating from the Belfast Mudstone, the stratigraphically higher Timboon Sand should also be investigated. Further to the east, the latter unit passes without significant lithologic break into the overlying sands of the Eastern View Formation.

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