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A COMPARISON OF THE OTWAY AND GIPPSLAND BASINS

by

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SUMMARY

This paper compares the results of the B.M.R. review of the Otway Basin (1963 to 1966) with the data available for the Gippsland Basin, and makes some reference to the Bass Basin.

Petrological studies of the subsurface material from the western and Port Campbell areas of the Otway Basin have shown that most parts of the section can be correlated, and tied to the reduced section shown by Anglesea No. 1 Well in the Torquay area. Although a direct correlation of the lithostratigraphic units of the Otway Basin with those in the Gippsland Basin is not possible, a comparison may be made indirectly using the results of drilling in the Bass Basin.

The top of the lithological succession in each Basin is a mainly carbonate sequence. In the Gippsland Basin, the carbonate sequence overlies the important Lakes Entrance Formation composed of marl, glauconitic sand, and gravel - the marl forming the cap rock for hydrocarbon accumulations. The direct correlate in the Otway Basin (based on palaeontology) is more of a sandy limestone facies with little cap rock potential, but a marl formation does occur in the underlying Nirranda Group, known only from the Port Campbell area. The Nirranda Group is correlated with part of the Demons Bluff Formation (of the Torquay area) which is tied, in turn, to a siltstone unit in the Bass Basin; these are marine units and cannot be traced, as such, to the Gippsland Basin where the Latrobe Valley Coal Measures were apparently being deposited. The lower beds of the Coal Measures and the underlying Upper Cretaceous in the Gippsland Basin are mainly sandstone and are represented in both the Bass and Otway Basins. In the Otway Basin, these sandy beds with coal occur as the Eastern View Coal Measures and the upper formations of the Sherbrook Group. The lower beds of the Sherbrook Group are marine mudstone and sandstone units which are so far unknown in the Gippsland Basin. The Otway Group is similar lithologically to the Strzelecki Group of the Gippsland Basin; although both are mainly interbedded mudstone and tight lithic greywacke to sandstone, some permeable sandstone beds and lenses occur, particularly in the Otway Basin. An older formation, known informally as "Unit T", and composed of mudstone and lithic sandstone to conglomerate is found at the base of the Otway Basin succession in limited areas.

The structural and geological histories of the Otway and Gippsland Basins are similar. The development of both basins appears to have begun in the Mesozoic (?Jurassic) at a time of regional crustal expansion. Both basically started as graben or half-graben structures, with tensional forces directed to the south-west in the western part of the Otway Basin, and south-easterly in the Bass Strait region. Contemporaneous vulcanism probably resulted from the additional strain produced by the orthogonal arrangement of the predominant tensional forces. By the end of the Lower Cretaceous, prominent horst and ridge-like structures had formed or had been initiated, and available evidence suggests a stress reversal at this time or in the early Upper Cretaceous. The principal stresses in the Cainozoic appear to have been derived from the east and culminated in the Kosciuskan Orogeny.

At least two structural provinces are apparent in the Otway Basin:

(1) the part of the basin west of a feature called the Warrnambool Ridge, where faulting is the main structural influence, folding is subordinate, and trends are mainly north-west to south-east;

(2) the eastern part where fold-like features (as shown in seismic records) are more common and, together with the faulting, show predominant north-east to south-west trends.

Three Basin-wide unconformities are recognized, and a cycle of marine transgression and regression occurs above each unconformity. Considerable faulting took place in parts of the Otway Basin during some intervals of sedimentation, and migration of the main axes of deposition occurred from time to time.

In the western part of the Gippsland Basin, north-east to south-west trends are observed which parallel those of the eastern part of the Otway Basin, and both areas show some evidence of thrust movements to the north. From east of Woodside to about Rosedale and extending off-shore to the Tasman Sea area, a change in trend to more nearly east-west is noted. Major breaks occur in the Gippsland Basin succession at much the same levels as the upper two unconformities of the Otway Basin, and there is evidence of movement during deposition.

The distribution of the Cainozoic volcanics appears to be controlled by the structural provinces, with the "Older Volcanics" more or less confined to the western Gippsland and eastern Otway provinces, and the "Newer Volcanics" affecting only the northern margin and western province of the Otway Basin.

The best reservoir rocks in the Gippsland Basin are the glauconitic sand at the base of the Lakes Entrance Formation, and sandstone in the Latrobe Valley Coal Measures and the underlying Upper Cretaceous unit. In the Otway Basin, good reservoir sands exist in the lower Tertiary Wangerrip Group, the Curdies, Paaratte and Mount Salt Formations of the Sherbrook Group, the Waarre Formation and other sandstone bodies of the Otway Group, and in the unnamed Unit T.

Gas Fields (Barracouta and Marlin) have been found in the Gippsland Basin off-shore, and an oil flow has been recorded from the Marlin Field. Small quantities of heavy oil, and gas rich in methane and nitrogen were obtained from fields in the Lakes Entrance area. Although some wells have had substantial shows of hydrocarbons in the Otway Basin, a commercial reservoir has yet to be found. Good sustained flows of carbon dioxide gas, however, have recently been reported from Caroline No. 1 Well in the western part of the Otway Basin.

Although the Otway and Gippsland Basins have the same form, and partly similar geological histories, an apparent difference is shown in the distribution of the hydrocarbons:

(1) those in the Gippsland Basin are concentrated below the marl of the Lakes Entrace Formation, in the Latrobe Valley Coal Measures, and in the Upper Cretaceous unit (but a gas show is recorded also from the Strzelecki Group in North Seaspray No. 1);

(2) in the Otway Basin, they occur mainly in reservoirs of limited extent in the Otway Group (although small gas shows have been noted in the Upper Cretaceous Paaratte Formation). No concentrations have been found in sediments correlated with the upper beds of the Latrobe Valley Coal Measures, even though a similar cap rock to the marl of the Lakes Entrance Formation (but not a correlate) occurs in the Port Campbell area.

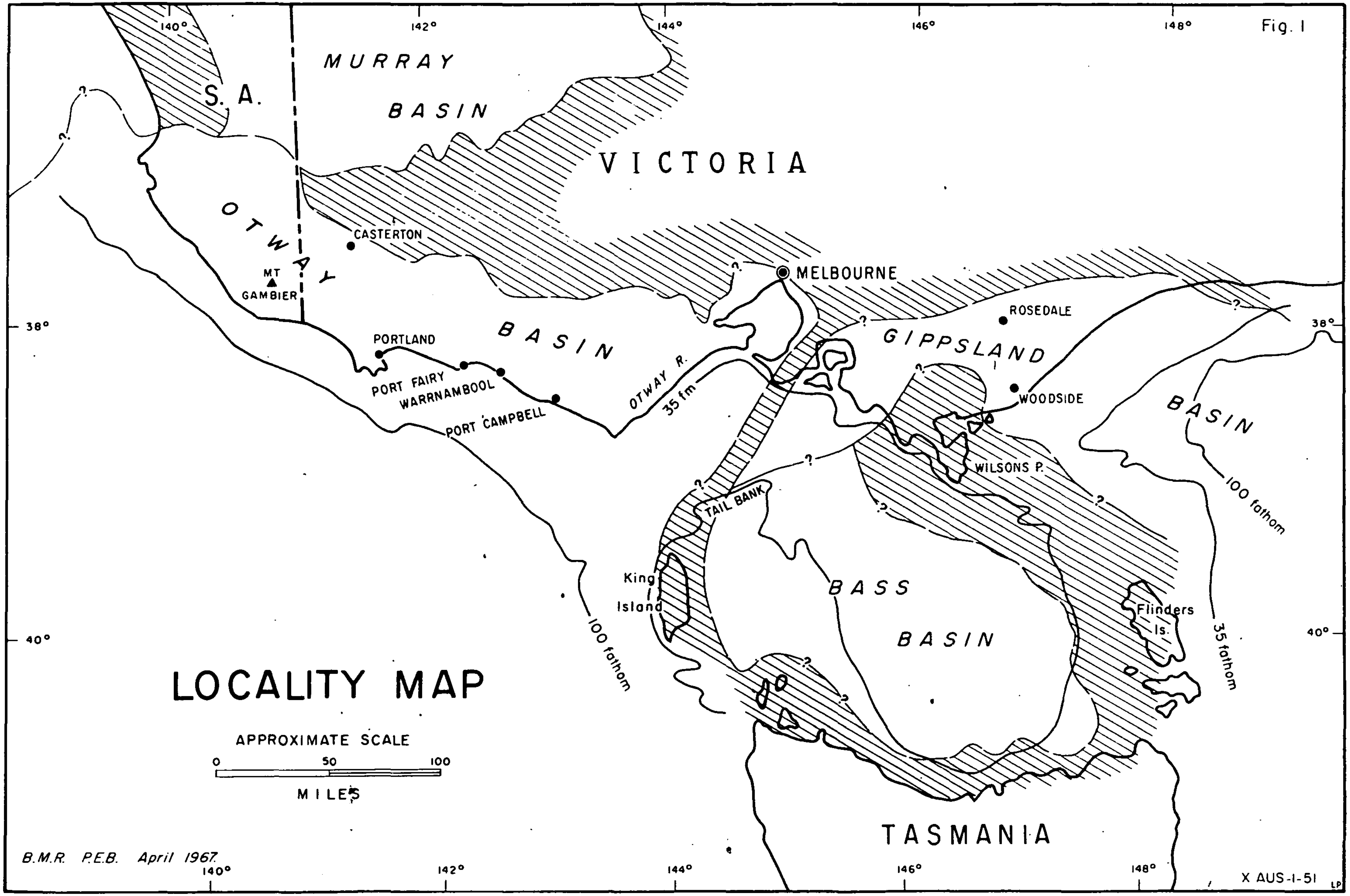
Fig. 1
MURRAY BASIN
S. A.
VICTORIA
OTWAY BASIN
CASTERTON
MT GAMBIER
MELBOURNE
ROSEDALE
GIPPSLAND BASIN
PORTLAND
PORT FAIRY
WARRNAMBOOL
PORT CAMPBELL
OTWAY R.
35 fm
WOODSIDE
WILSONS P.
TAIL BANK
100 fathom
King Island
BASS BASIN
Flinders Is.
35 fathom
LOCALITY MAP
APPROXIMATE SCALE
0 50 100
MILES
TASMANIA
B.M.R. P.E.B. April 1967
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INTRODUCTION

A review of the Otway Basin was begun in October, 1963 by the Sedimentary Basins Study Group, BMR, and completed in 1966. The methods used by the Group were outlined by Condon and Reynolds (1965) and are explained in more detail in the introduction to the report on the Otway Basin review (BMR, 1966). Petrological and palynological studies made as part of the review showed that a number of distinct lithological units could be traced across the Basin. Some units were restricted to certain parts of the Basin, or interfingered with other units. Three important basin-wide unconformities were recognized and it was subsequently possible to tie these horizons to levels of good reflection in seismic records. As part of the geophysical contribution to the Basin review, the three horizons were contoured and isochron contours were drawn for the major units between the horizons. A map using seismic data and incorporating other geophysical results was prepared to show the main structural trends. This work, and the data obtained from the other avenues of study allowed certain conclusions to be formed on the structure and geological hisotry of the Basin, and provided some ideas on the hydrocarbon potential. BMR officers who participated in the preparation of the review report were:

P.J. Hawkins and J. Dellenbach (Petrology and Geology)
P.R. Evans (Palynology)
A.L. Bigg-Wither and R.P.B. Pitt (Geophysics)
R. Bryan (Structure and Provenance)
J.D.T. Scorer (Reservoir Engineering)
M.A. Reynolds (Structure, Geological History, Economic Geology, Bibliography).

The results of the review are here compared with the data available on the Gippsland Basin in the more recent papers by Webb (1961), Boutakoff (1964), Hocking and Taylor (1964), and in completion reports on some of the subsidized operations between 1963 and 1966.

The Gippsland and Otway Basins are aligned from east to west across southern Victoria and the Otway Basin continues to the west-north-west into south-eastern South Australia. Both basins extend on to the Continental Shelf. On-shore the two basins are separated by the Mornington Peninsula south of Melbourne; off-shore across Bass Strait, they are separated by a subsurface divide (determined by geophysical means) extending to King Island. The margins of the basins, and their relation to each other and to the Bass Basin, are shown in Fig. 1. On-shore margins follow the known limits of Lower Cretaceous and, in some places, Tertiary rocks whereas the off-shore margins have been determined on the results of geophysical (mainly aeromagnetic) surveys.

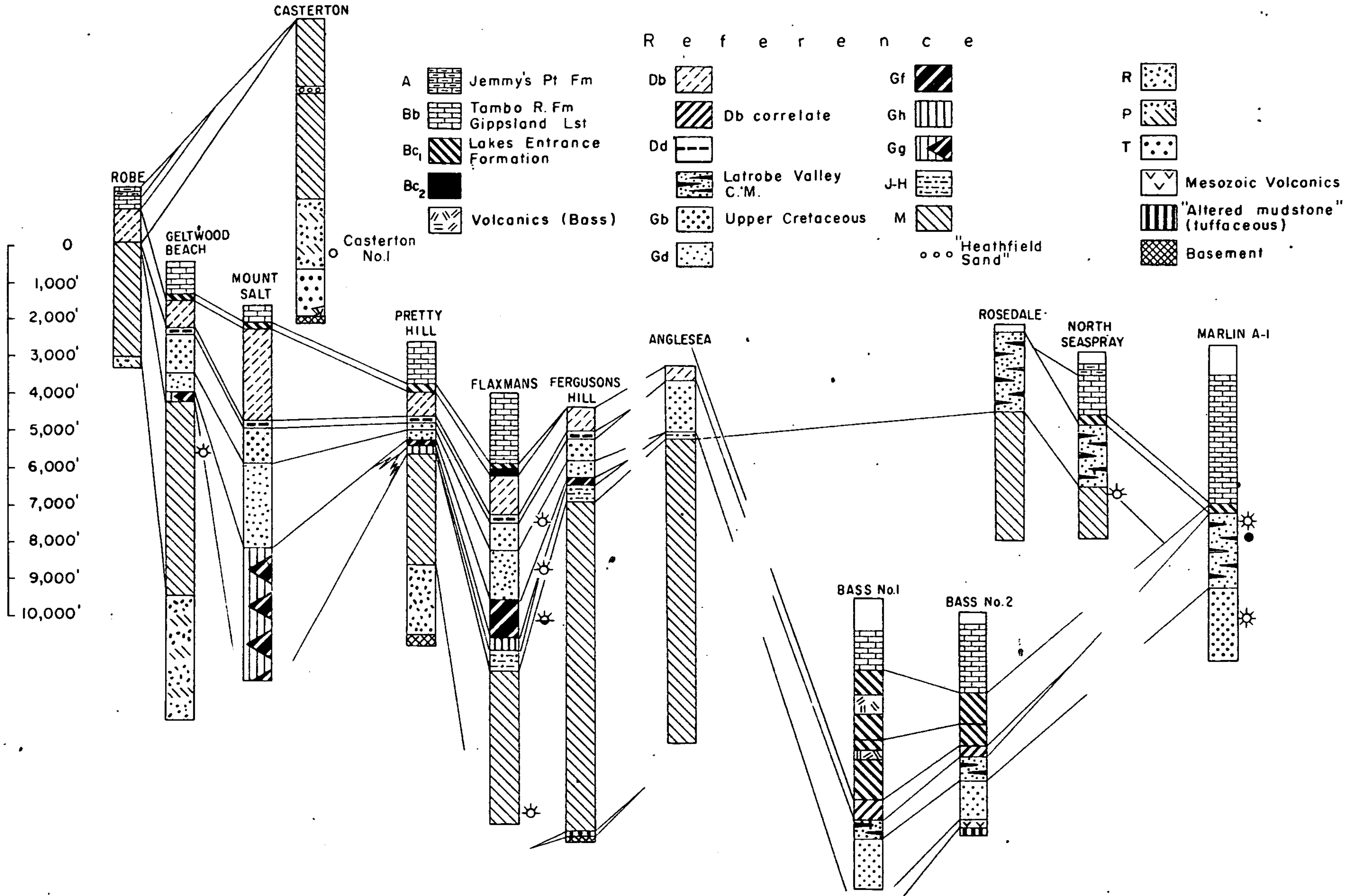
STRATIGRAPHY

Basement rocks in both basins are probably Palaeozoic rocks similar to those along the northern margins, and which form part of the Tasman Geosyncline of eastern Australia. Precambrian rocks may continue south from Fleurieu Peninsula in South Australia, and west from King Island and north-western Tasmania, to form part of the southern off-shore marginal area of the Otway Basin.

To the north of the Otway Basin, the Palaeozoic rocks include dark shale and greywacke with basic intrusions, mildly metamorphosed in parts, and partly fossiliferous sandstone and conglomerate, with intrusions

GENERALIZED LITHOLOGICAL CORRELATIONS

Fig. 2



B.M.R. P.E.B. April 1967.

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of granite and porphyry. Similar rocks occur north of the Gippsland Basin with the addition of some carbonate rocks - including reef facies - in the Lower to Middle Devonian sequence. The Wilson's Promontory basement inlier between the Gippsland and Bass Basins, is mainly granite with a belt of Middle Devonian fossiliferous limestones over Cambrian greenstone near the western edge.

Permian outcrops, including deposits of glacial origin and marine sediments, occur as outliers in small areas north of the margin of the Otway Basin, and they are known to exist in the subsurface both in the Otway Basin (Yalimba Bore, Spencer-Jones, 1965) and in the Gippsland Basin (Duck Bay No. 1, A.L. & W., 1964).

The various lithologies recognized by BMR in the subsurface of the Otway Basin were initially subdivided into informal units and identified by a set of letter-number symbols (see Table I). Some of the units were subsequently allocated existing stratigraphic names, and some of the Cretaceous units were given new names (Reynolds, Evans, Bryan and Hawkins, 1966). The BMR informal units are shown in the accompanying chart together with the main stratigraphic units of the Otway and Gippsland Basins. The Gippsland Basin nomenclature follows Hocking and Taylor (1964), and correlation is based mainly on Carter (1964). The diagonal line marking the upper limit of the Latrobe Valley Coal Measures is not intended to signify thinning, but that the upper part of the formation in the western, on-shore half of the Basin has no correlate in the east.

Detailed petrology such as that done for the Otway Basin has not been done by BMR for rocks in the Gippsland Basin, and a direct correlation of lithological units, other than the Strzelecki Group with Unit M and the Gippsland Limestone with part of Unit Bb, has not been possible. However, an indirect approach is provided by the Bass Nos. 1 and 2 Wells in which several lithological units have been recognized (E.E.A., 1966c), and for which palaeontological evidence is available (Taylor, in E.E.A., op.cit.). A suggested correlation between stratigraphic units in the Otway and Gippsland Basins using the Bass Nos. 1 and 2 Wells is shown in Fig. 2.

The top of the lithological succession in each basin is a mainly carbonate sequence which was divided in the Otway Basin into Units Ab and Bb.

Unit Ab is a thin limestone unit, up to 150 feet thick, mainly restricted to part of south-eastern South Australia and western Victoria; the corresponding unit shown on the Chart for the Gippsland Basin is the Jemmy's Point Formation, fine-grained sandy marl (250 feet thick in North Seaspray No. 1).

Unit Bb is one of the most widespread units in the Otway Basin, and at the western end overlaps the northern margin and continues into the Murray Basin; it is 2700 feet thick in the Portland area. The unit is correlated on lithological evidence with the upper part of the Torquay Group at the eastern end of the Basin and with 1900 feet of coarse calcarenite in the Bass Basin (although the upper 600 feet of this section may be separate stratigraphic unit). In the Gippsland Basin, calcareous lithic sandstone, argillaceous calcarenite, sandy marl and marl, more than 3500 feet thick in Marlin A-1, are equated with Bb.

TABLE I: SUMMARY OF LITHOSTRATIGRAPHIC UNITS OF OTWAY BASIN

GROUP	FORMATION	BMR UNIT.	LITHOLOGY
		Ab	C-grd sdy calcarenite, biocalcarenite, sdy limestone. Unconformity
		Bb	Limestone (polyz, partly dol.), marly limestone, spic marl, chert in parts.
		Bc_1	Glauconitic marly limestone (sdy in part). Unconformity
		Bc_2	Brn. glauc. & limonitic marl; limonitic sandstone and conglomerate. Unconformity
WANGERRIP	Dilwyn Formation	Db	F.-grd. carb. sandstone/subord. siltstone; c. argill. sandstone to f.-grd. qtz sandstone, siltstone and shale.
WANGERRIP	Pebble Point Formation	Dd	Pebbly sandstone, pelletal & ool. chamositic sandstone, siderite. Unconformity
SHERBROOK	Curdies Formation	Gb	Argill. c.-grd. sandstone/coal frags & stringers.
SHERBROOK	Paaratte Formation	Gd	Sandstone & siltstone, chloritic in part; chlorite pellets; carbonate cement (lower part), kaol. mtx. (upper part).
SHERBROOK	Belfast Mudst.	Gf	Gf - massive glauconitic mudstone
SHERBROOK	Mount Salt Formation	Gg	Gg - interbedded sandstone and shy siltstone (of Gf and Gh lithologies).
SHERBROOK	Flaxmans Formation	Gh	Gh - sandstone & sandy mudstone; cham. to sideritic ool., minor phos., some volc. dtr. Unconformity
OTWAY	Waarre Formation	J-H	Quartz to chlor. lithic sandstone carb. mudstone and coal; calc. cmt. (lower part); no volc. dtr. Unconformity
OTWAY	Eumeralla Formation	M	Chlor. mudstone & shale/coaly lenses; subord. greywacke to subgywk and volc. sandstone; diagenetic calc. sid., zeo., and clay.
OTWAY	Geltwood Beach Formation "Pretty Hill sandstone"	P-R	P - lith. sandstone/Unit M sediments; volc. & meta.dtr. R - lith. sandstone/kaol. & sid. cmt.; both sandstones rich in garnets. Unconformity
	Unnamed	T	Cglc lith. (phyllite frags) sandstone/thn mudstone; sid. (lower part), & shale. Unconformity

The carbonate sequence of the Gippsland Basin overlies the important Lakes Entrance Formation composed of marl, glauconitic sand, and gravel - the marl forming the cap rock for oil and gas accumulations. The direct correlate in the Otway Basin (based on palaeontology) is Bc_1, a limestone which is sandy in part, and generally less than 100 feet thick. (The section at this level in the Bass Basin appears to be much thicker - 1400 feet in Bass No. 2, 3000 feet excluding volcanics in Bass No. 1 - and is composed of calcareous mudstone, silty sandstone, and silty micaceous mudstone).

An older unit, Bc2, occurs below Bc_1, in parts of the Otway Basin, and in the Port Campbell area forms the Nirranda Group which is mainly marl, sandstone and conglomerate (and is thus similar lithologically to the Lakes Entrance Formation). Bc2 is correlated on stratigraphical evidence with the upper part of the Demons Bluff Formation in the Torquay area.

The lower part of the Demons Bluff Formation, which was drilled in Anglesea No. 1 Well, was tied during petrological studies to Unit Db, the Dilwyn Formation, which together with the Pebble Point Formation (Dd) forms the Wangerrip Group; the Group is over 2500 feet thick in the Otway Basin. A siltstone unit in the Bass Basin section is lithologically similar to Unit Db in Anglesea No. 1 and has been correlated with Db (Fig. 2). Taylor and Apthorpe (in E.E.A., 1966c) also note the similarity of the siltstone unit to the Demons Bluff Formation, although they give it an Upper Eocene age which would place it stratigraphically nearer the upper beds of the Demons Bluff Formation and Unit Bc_2. Units Bc_2, Db, Dd, and the Bass Basin correlate are marine units and cannot be traced, as such, to the Gippsland Basin where the Latrobe Valley Coal Measures were being deposited.

The older (off-shore) beds of the Latrobe Valley Coal Measures and the underlying Upper Cretaceous in the Gippsland Basin are mainly sandstone, and similar sediments are present at about the same stratigraphical levels in both the Bass and Otway Basins. The Marlin A-1 section in the Gippsland Basin includes quartz sandstone with shale, coal, and dolomitic beds in the Latrobe Valley Coal Measures (2000 feet thick); interbedded fine-grained quartz sandstone, siltstone and shale with some coal and dolomitic beds form the underlying Upper Cretaceous (at least 2000 feet thick). In the Otway Basin, sandy beds with coal occur as the Eastern View Coal Measures and Curdies Formation, and sandstone and siltstone are interbedded in the underlying Paaratte Formation. A tentative correlation is also made in Fig. 2 with the lower units of the Bass Basin.

The lower beds of the Upper Cretaceous Sherbrook Group in the Otway Basin are marine mudstone and sandstone units which are so far unknown in either the Gippsland or Bass Basins. They are divided into the Belfast Mudstone and Flaxmans Formation in a restricted basin in the Port Campbell area (combined thickness up to 2300 feet), and interbedded in the western part of the Otway Basin where they form the Mount Salt Formation, at least 3500 feet thick in Mount Salt No. 1.

The Otway Group is similar in general lithology to the Strzelecki Group of the Gippsland Basin and contains mudstone and tight lithic greywacke to sandstone; some permeable sandstone beds and lenses occur in the Otway Basin and possibly in the Gippsland Basin. The Otway Group thickness varies from 4000 feet (Kalangadoo No. 1) to 9000 feet (Fergusons Hill No. 1), and the Strzelecki Group from 500 feet (Duck Bay No. 1) to almost 9000 feet - base not reached (Wellington Park No. 1). The permeable sandstone beds in the Otway Group occur in the lower part,

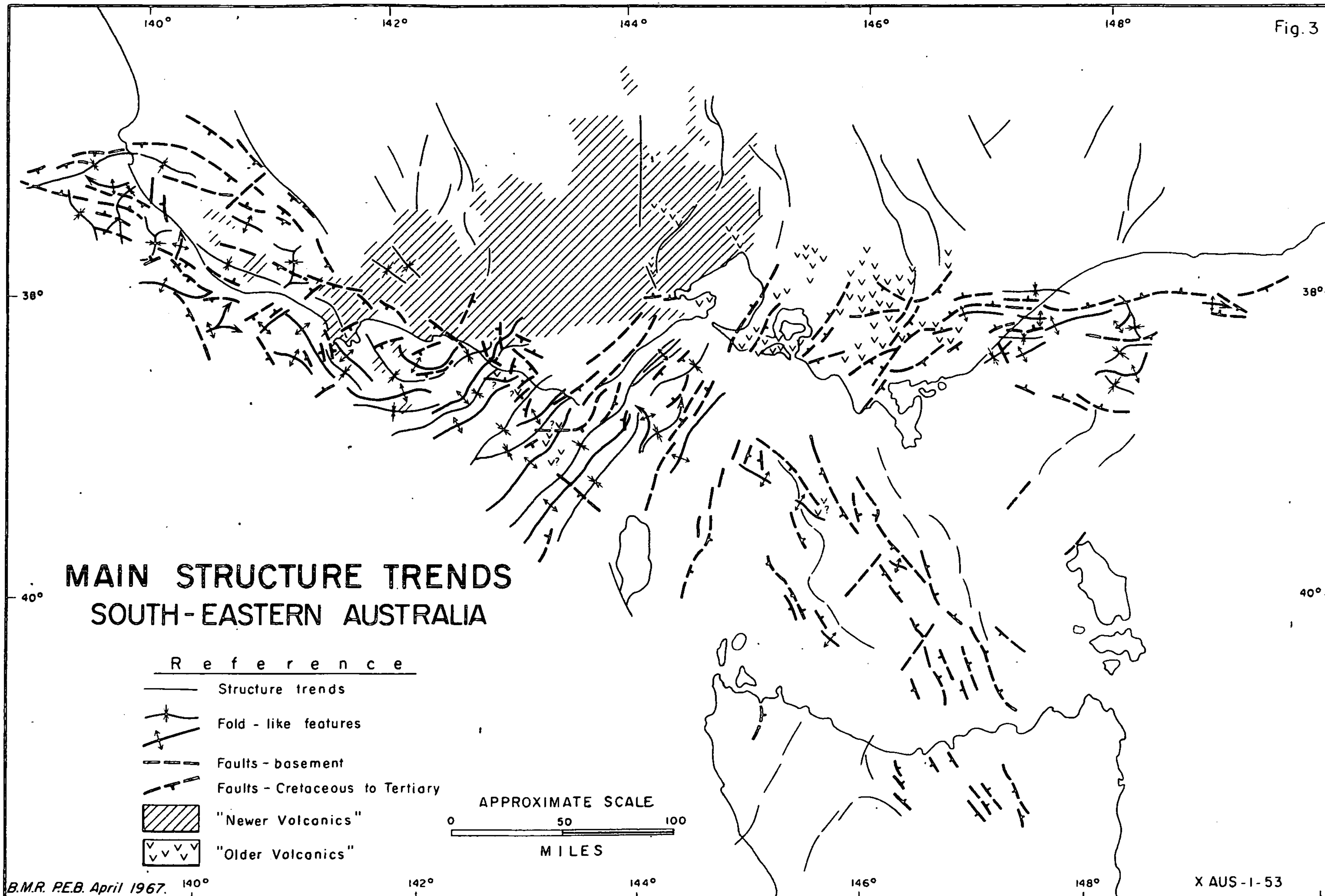
Fig. 3
MAIN STRUCTURE TRENDS
SOUTH-EASTERN AUSTRALIA
Reference
Structure trends
Fold - like features
Faults - basement
Faults - Cretaceous to Tertiary
"Newer Volcanics"
"Older Volcanics"
APPROXIMATE SCALE
0
50
100
MILES
140°
142°
144°
146°
148°
38°
40°
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LP

interbedded with mudstone in the Geltwood Beach Formation and in the "Pretty Hill sandstone", or as lenses such as the "Heathfield Sand" higher in the section near the northern margin; these sands are known only from the western part of the Otway Basin. In the eastern part of the Otway Basin, the Waarre Formation is a sandy unit at the top of the Otway Group; its maximum thickness is 550 feet (Flaxmans No. 1). Unit H in Anglesea No. 1 of the Torquay area is correlated with the Waarre Formation.

An older formation, known informally as "Unit T", and composed of mudstone and lithic sandstone to conglomerate is found at the base of the Otway Basin succession in Casterton No. 1 where it is 1250 feet thick; 23 feet of sandstone between basement and Otway Group in Fergusons Hill No. 1 is lithologically similar to Unit T.

Basement rocks which have been met in drilling in the Otway Basin are slightly metamorphosed mudstone in Kalangadoo No. 1, schist (Fergusons Hill No. 1 and Casterton No. 1), and a dark green crystalline altered igneous rock in Pretty Hill No. 1. Basement has been drilled near the northern margin of the Gippsland Basin below 1000 feet of ?Permian volcanics and sediments in Duck Bay No. 1 (slate and indurated siltstone and sandstone), and in South-west Bairnsdale No. 1 (sedimentary rocks of the Upper Devonian Avon River Group).

STRUCTURE AND GEOLOGICAL HISTORY

The structure and geological history of the Otway and Gippsland Basins are similar in many respects, and both are aligned more or less across the regional strike of the Palaeozoic rocks of the Tasman Geosyncline of eastern Australia.

The basins appear to have formed during the Mesozoic (?Jurassic) as graben-like structures showing extensive control by north-west and north-east lineaments. Their development may have occurred during a period of major crustal expansion which affected most of eastern Australia (Reynolds, in BMR, 1966).

Two main structural provinces are recognized in the Otway Basin:

(1) the part of the Basin west of a subsurface feature called the Warrnambool Ridge, where faulting is the main structural influence, folding is subordinate, and trends are mainly north-west;

(2) the eastern part where fold-like features (as shown in seismic records) are more common, and, together with the faulting, show predominant north-east trends.

In the western part of the Gippsland Basin, north-east trends are observed which parallel those of the eastern part of the Otway Basin. From east of Woodside to about Rosedale and extending off-shore to the Tasman Sea area, a change in trend to more nearly east-west is noted in the Gippsland Basin. The main trends are shown in Figure 3.

Both the Otway and Gippsland Basins are thought to have started as graben or half-graben structures, and the structural provinces suggest that the tensional forces were directed to the south-west in the western part of the Otway Basin, and south-easterly in the Bass Strait region. Contemporaneous vulcanism probably resulted from the additional strain produced by the orthogonal arrangement of the predominant tensional forces. The influence of the vulcanism is seen in the lava extrusion in "Unit T" of the Otway Basin, the large amount of volcanic detritus in the sediments of the Otway and Strzelecki Groups (and possibly the dolerites of Tasmania and basal volcanics of the Bass Basin).

The bulk of the sediment of Upper Jurassic (?) - Lower Cretaceous age is of the mudstone and greywacke facies, and several authors have expressed the idea of a land mass to the south for the provenance in the Otway Basin. Reynolds and Bryan (BMR 1966) support this hypothesis and link the land mass with King Island and Tasmania; sandstone beds in "Unit T" and in the Otway Group are attributed to a northern provenance. The distribution of the sandstone beds suggests that the Warrnambool Ridge exerted an influence at an early stage in the development of the Otway Basin; although its structural configuration is unknown, the Ridge is thought to be a shallow basement feature.

The link between the Otway and Gippsland Basins during the Lower Cretaceous is not clear, although the similarity of the sedimentary pile suggests a common source, and a connection across the Mornington Peninsula is indicated by Bock and Glenie (1965). Another possibility is suggested by the work of Jennings (1959); he shows (in his Fig. 4) a north-east trending "Otway Depression" between the Otway Ranges and the "Tail Bank", a bathymetric feature extending north-easterly from King Island (and separate from the subsurface aeromagnetic anomaly which defines the eastern margin of the Otway Basin). The "King Island Rise" adjoins the south-western end of the "Tail Bank" but extends south-south-east from it, as does the "Bassian Depression". Although the bathymetric features described by Jennings are recent, they could reflect basement configuration. If his "Otway Depression" is extended into the western part of the Gippsland Basin, an avenue for continuous sedimentation between the Otway and Gippsland Basins becomes apparent. A link between the "Tail Bank" and the Wilson's Promontory inlier could have formed part of the northern margin of the postulated southern land mass of Lower Cretaceous time. (See Fig. 1). This could also explain the continuation of the prominent north-east structural trend from the eastern side of the Otway Basin into the western half of the Gippsland Basin (Fig. 3).

At the end of the Lower Cretaceous and probably extending into the early Upper Cretaceous, a short period of marked tectonic activity occurred, but it has not been possible to date closely the events. The following features associated with this activity were noted in the Otway Basin:

(1) the ridge along the Selwyn Fault lineament (between King Island and Mornington Peninsula) became established;

(2) the Otway Range structure formed as a horst, and faulting uplifted the Casterton area - presumably along the Kanawinka lineament;

(3) some rotation of pre-Unit G trends took place along or around the Warrnambool Ridge;

(4) the influence of the southern land mass became less evident, and a land mass of Otway Group rocks probably formed the southern margin of sedimentation in the Upper Cretaceous;

(5) vulcanism declined.

Some type of stress reversal to the north-west after the early Cretaceous expansion is suggested at this time. Regional dextral transcurrent movement is envisaged. This would explain the apparent "squeezing up" of a wedge of Otway Group sediments to form the Otway Range structure, rotation around the Warrnambool Ridge, and the foundering of the old land mass north-west of Tasmania. From this time onwards, the Palaeozoic land masses to the north, and the areas of uplifted Lower Cretaceous provided the main provenance of detrital sedimentation.

Blocks of Strzelecki Group sediments were possibly also uplifted during this period of stress reversal near the end of the Lower Cretaceous, but the extent to which this activity and subsequent movements during the Upper Cretaceous and Cainozoic, have affected the Gippsland Basin could not be fully assessed without detailed studies of the type done for the Otway Basin review. The subsequent geological history and structure development in the Otway Basin has been summarized, therefore, and is compared with the available information on the Gippsland Basin.

The review of the Otway Basin showed that at least three basin-wide unconformities, which can be traced in seismic records, were developed:

(a) at about the end of the Lower Cretaceous;

(b) between the Upper Cretaceous and Tertiary;

(c) and above the Palaeocene-Middle Eocene succession.

A cycle of marine transgression and regression occurs above each unconformity. The Upper Cretaceous cycle is represented by the Sherbrook Group and the next is clearly shown by the Wangerrip Group. The Upper Eocene transgression ocurred in two phases:

a Unit Bc_2 cycle of limited extent which ended with local regression in some parts and with erosion in other parts, and,

a much wider Bc_1 - Bb transgression followed by sharp regression at the end of Bb time.

Two main structural provinces have developed and these are divided by the Warrnambool Ridge. Initial influence in the Upper Jurassic (?) - Lower Cretaceous was tensional, but subsequent stress pulses have produced compressional and shearing effects. The net results have been:

(1) to produce horst-graben structures with predominant north-west trends in the western province with folds subordinate; faulting contemporaneous with sedimentation has occurred. As well as subordinate compressional type folds, en echelon folds due to shearing along fault zones, and drape or monoclinal structures due to "down-to-basin" faulting could be expected. An abnormal north-east trend of faulting is noted west of Portland, and another prominent feature with north-east trend is shown by O'Driscoll (1960) in his contours on the upper surface of the Knight Group (Unit D);

(2) to produce fold-like features (most prominent in the subsurface in the off-shore area) and faulted structures with north-east trends in the eastern province; minor overthrusting has been noted. The Warrnambool Ridge and the shelf area south and south-east of Cape Otway may represent shallow basement features;

(3) to cause migration of the main axes of troughs and depressions of sedimentation at various times;

(4) to produce at least three volcanic episodes; dome-like structures (seen in seismic records) which effect certain younger sediments but not older units may be due to volcanic intrusion or extrusion;

(5) to cause fracturing in older lithological units.

In comparison, the Gippsland Basin has at least two basin-wide unconformities which have been recognized in seismic records throughout the eastern half of the Basin. They are at the same general stratigraphical positions as the upper two in the Otway Basin, but the conditions of deposition which followed varied between the two basins. The lower of the two unconformities occurs at a petrological and palaeontological break between the unnamed Upper Cretaceous unit and the Latrobe Valley Coal Measures. On-shore, the Coal Measures were deposited directly over the Strzelecki Group in a widespread paludal environment. Marginal marine deltaic conditions were develped in the eastern off-shore area. There was no widespread initial marine transgression followed by regression such as occurred above the corresponding unconformity in the western and Port Campbell areas of the Otway Basin. In fact, the depositional history from late Upper Cretaceous to early Tertiary in the Gippsland Basin was apparently more like that for the Torquay area at the eastern end of the Otway Basin.

The upper unconformity in the Gippsland Basin was followed by the marine transgression which led to deposition of the Lakes Entrance Formation. This unconformity corresponds to the break between the Wangerrip Group and Unit B in the Otway Basin. However, the Lakes Entrance Formation transgression commenced later than the basal sub-unit Bc_2 time, and is correlated with the overlying Bc_1 marine invasion.

Comparison of structure effects shown in the Gippsland Basin with those in the Otway Basin is hampered by the lack of seismic coverage in the western half of the Gippsland Basin. However, some similarities have been noted:

(1) horst-graben structures occur throughout the basin and faulting contemporaneous with sedimentation occurred in the eastern part. This eastern area shows some folding parallel with the faulting (Fig. 3), but other folds are irregularly aligned; the fault-fold pattern is similar to that in the western part of the Otway Basin;

(2) the faulting in the western part of the Gippsland Basin has the same north-east trend as the folding and faulting in the eastern Otway province; faulting with downthrow to the north occurs near the northern margin in each area.

HYDROCARBON PROSPECTS

1. Hydrocarbon occurences:

Gas fields (Barracouta and Marlin) have been found in the Gippsland Basin off-shore, and an oil flow has been recorded from the Marlin Field. Small quantities of heavy oil, and gas rich in methane and nitrogen were obtained from fields in the Lakes Entrance area. Although some wells have had substantial shows of hydrocarbons in the Otway Basin, a commercial reservoir has yet to be found; in each case tested, the initial flows were not sustained and the zones tested were apparently of limited extent. However, good sustained flows of carbon dioxide gas have recently been reported from Caroline No. 1 Well in the western part of the Otway Basin.

Many reports have been made of strandings of asphaltic material along the shores of western Victoria and South Australia, and of some seepages both on-shore and off-shore. Most of these have been referred to by R.C. Sprigg in various reports from 1952 to 1964; he supports earlier suggestions of off-shore seepages for the strandings. Possible loci for seepages could be faulting within the basin area, or along the continental slope in the area where the postulated pre-Upper Cretaceous southern land mass might have foundered.

2. Properties of the sediments:

The sediments of Unit T at the base of the Otway Basin succession are mudstone and sandstone with porous sand bodies in the upper 450 feet; a drillstem test of Unit T in Casterton No. 1 yielded 900 feet of muddy salt water with a salinity of about 35,000 p.p.m. (Na Cl) calculated from the S.P. log.

Both the Otway and Strzelecki Groups are composed mainly of mudstone and greywacke to volcanic sandstone with some more quartzose sand bodies in parts of the Otway Basin. Good sands with high porosity (22%) and permeability (up to 2700 millidarcys) occur in the "Pretty Hill sandstone" but generally do not extend to the Geltwood Beach Formation in the western half of the Otway Basin; diagenetic cementation has diminished the reservoir potential of some sandy intervals. Improved reservoir conditions are most likely near the margin of the Basin where conglomerate and coarser sands occur. Thin sandy wedges are found in the dominantly mudstone sequence of the Eumeralla Formation and in the Strzelecki Group although their extent in the Gippsland Basin is not known; those in the Otway Basin are from 20 to 120 feet thick and extend from Penola in south-eastern South Australia to Casterton. The top of the Otway Group in the Port Campbell area contains the porous and permeable sand of the Waarre Formation; a possible equivalent - "Unit H" - was drilled in Anglesea No. 1. The Waarre Formation, with porosities of 8 to 27% and measured permeabilities of up to 2985 millidarcys, is regarded as one of the best reservoir prospects. Known occurrences of oil and gas do not appear to be at any particular level in the Lower Cretaceous sediments and the main gas flow (initial rate 250,000 cub.ft./day - not sustained) in Flaxmans No.1 came from 4500 feet below the top of the Otway Group, probably from a fractured zone.

Impermeable strata occur in the basal beds of the overlying Sherbrook Group in the Otway Basin. The tight sandstone and sandy mudstone of the Flaxmans Formation and dark glauconitic mudstone of the Belfast Mudstone in the Port Campbell area are represented west of the Warrnambool Ridge by the composite Mount Salt Formation of interbedded sandstone and siltstone. However, the sands in the Mount Salt Formation show some porosity and permeability (up to 955 md) in Mount Salt No. 1. No equivalent formations are known from the Gippsland Basin. The Paaratte and Curdies Formations form the upper beds in the Sherbrook Group and both have some porosity and show fair to good permeability to over 2000 md. Only the Curdies Formation is known to continue east from the Port Campbell area to the Torquay area, although it seems likely that some of the older units of the Sherbrook Group are represented in the depressions shown by seismic evidence east of the Otway Ranges and west of King Island. The Sherbrook Group contains possible source rocks, and good reservoir and cap rocks in the on-shore part of the Otway Basin, and it is surprising that so few shows of hydrocarbons have been located. The unnamed Upper Cretaceous unit which has yielded commercial deposits of gas in the off-shore part of the Gippsland Basin appears to be a correlate of the Curdies Formation and part of the Paaratte Formation, (based on lithological and palaeontological evidence). The Upper Cretaceous unit has fair to good porosity from 15 to 21%, and low to moderate permeability (up to 600 md): good pressure was maintained during testing of the 600 foot gas zone in Marlin A-1 Well.

Good porosity and permeability occur in the basal bed (Pebble Point Formation, Dd) of the Wangerrip Group in the Otway Basin, although only low permeability has been noted in some parts of the Basin. The Pebble Point Formation is overlain by the Dilwyn Formation (Db) which contains thick porous and permeable sands over most of the Otway Basin. Areas of foreset sands are indicated in the Wangerrip Group by seismic records in a narrow belt beneath the coastal area west of Port Fairy, and more extensively along the edge of the continental shelf south of Port Fairy. No signs of hydrocarbons, other than some fluorescence in Mount Salt No. 1, have been found in the on-shore wells in the Wangerrip Group. In contrast, commercial gas and a flow of oil have been obtained in the Gippsland Basin from the Latrobe Valley Coal Measures which are correlated in part with the Wangerrip Group. The Coal Measures also contain thick porous (up to 30%) and highly permeable quartz sands (as much as 5000 md). Although they show deltaic deposition in the eastern part, they have been formed mainly in a paludal to lacustrine environment, and do not exhibit the marine influence as in the Wangerrip Group. Higher in the succession, the Coal Measures do interdigitate with marine beds (Hocking and Taylor, 1964), but at the time of the much later Lakes Entrance Formation transgression. Sedimentation in the Torquay area at the eastern end of the Otway Basin shows an apparently intermediate environment during the Unit D time interval with coal measures at the base and a marine pulse developing in the overlying Demons Bluff Formation.

Two main transgressions occur in the Unit B phase of sedimentation in the Otway Basin, the first represented by Sub-Unit Bc_2 - limonitic sandstone and conglomerate, overlain in the Port Campbell area by marl - and, after a sharp regression, the second and widest landward transgression represented by Bc_1 and Bb. The latter, and the formations above the Lakes Entrance Formations in the Gippsland Basin are generally porous with no widespread impermeable cap rock, so that there would be little possibility of hydrocarbons being trapped. The Lakes Entrance Formation, however, which is correlated with Bc_1 on palaeontological evidence, provides the important cap rock for some of the hydrocarbon accumulations in the Gippsland Basin; it represents a marine transgression with basal gravel and glauconitic sand overlain by micaceous marl. Because of its cap rock potential, Unit Bc_2 of the Otway Basin is also important. Bc_2 has a basal sand overlain by marl in the Port Campbell area, and equivalent sediments occur in outcrop along the Aire and Anglesea coastal areas.

3. Petroleum Traps:

The commercial fields in the Gippsland Basin are closed structures and the majority of deep wells drilled since 1959 in the search for oil in the Gippsland and Otway Basin have been on closed structures defined by seismic exploration. However, both Ferguson Hill No. 1, and Sherbrook No. 1 in the Otway Basin were located to test possible pinch-out of sediments against an uplift, and off-structure stratigraphic wells have been drilled in both basins.

Folds and fold-like features are present in both basins in the subsurface and rarely in outcrop. The nature of many of the fold-like features is difficult to determine because of limited seismic control, particularly in the off-shore area, but at least some are probably compressional. Studies in the Otway Basin showed that some of the subsurface features are confined to pre-Unit G sediments, others persist into the times of deposition of Units G and D, and the most persistent or latest movement affected Unit B. Some of the anticlinal types appear to plunge towards the long central axis of the Basin. Others that are more elongated may show closure at one or more places along their axes. Some fold-like features, particularly those confined to earlier units, could be due to draping over elongated basement ridges, and Fig. 3 shows that some of the anticlines follow the basement trends closely.

Other types of folds are as follows:

(i) Small en echelon folds with low dips on the limbs attributed by Sprigg (1962) to basement shearing at depth. These are probably most common in the western half of the Otway Basin.

(ii) "Down-to-basin" faulting (Weegar, 1960) occurs contemporaneously with sedimentation and produces anticlinal or monoclinal types of folds at the margins of the active troughs. Movements contemporaneous with sedimentation are known to have occurred in both basins, particularly in the western half of the Otway Basin, but the off-shore Torquay area, and north-eastern (Lake Wellington Trough) part of the Gippsland Basin were also probably affected in this way.

(iii) Dome-like structures are shown at various levels in seismic records in areas where vulcanism is known, and may be due to basaltic intrusion or extrusion. Traps could possibly be formed by updoming of strata by intrusions, or intrusions and extrusions could have formed rises over which draping has subsequently occurred.

In addition to normal fault traps, pinch-outs could be expected as a result of "down-to basin" faulting. Further seismic surveys across the possible shallow basement feature called the Warrnambool Ridge, and the shallow basement indicated south of Cape Otway by aeromagnetic surveys might indicate trends worth exploring for stratigraphic traps. In the Gippsland Basin, the off-shore extension of the Lakes Entrance Platform (Hocking and Taylor, 1964) might offer similar possibilities.

4. Possible source rocks for hydrocarbons:

Although the Otway and Gippsland Basins are probably of similar origin and have the same form, and show some similarities in their geological history, an apparent difference occurs in the distribution of the hydrocarbons:

(i) those in the Gippsland Basin are concentrated mainly in the basal sands of the Lakes Entrance Formation, in the Latrobe Valley Coal Measures below the Lakes Entrance Formation, and in the Upper Cretaceous unit (although a gas show is recorded from the Strzelecki Group in North Seaspray No. 1);

(ii) in the Otway Basin, the hydrocarbons occur mainly in reservoirs of the Otway Group (although small shows have been noted in the Upper Cretaceous Paaratte Formation). No commercial concentrations have been found in sediments correlated with the upper beds of the Latrobe Valley Coal Measures or the Upper Cretaceous unit of the Gippsland Basin, even though a similar cap rock to the marl of the Lakes Entrance Formation (but not a correlate) occurs in the Port Campbell area.

An examination of the source rock potential and possible access to reservoir rocks at different stratigraphic levels within the basins might provide some reason for the differences. Several possible sources can be suggested for the carbon dioxide gas in fractured basement at the base of Kalangadoo No. 1 Well in the Otway Basin. Provided that sufficient oxygen is available in sediments or formation water, oxidation by igneous intrusion into a hydrocarbon reservoir is one of the many possibilities for carbon dioxide formation. Unit T, in the graben north-east of Kalangadoo, which shows marine influence by its salt water content and has been intruded by basic igneous rock, could have been a source of the carbon dioxide gas; but it is also conceivable that the sediments of the overlying Otway Group provided the gas. Evidence that older sediments of the Otway Basin may provide a source of hydrocarbons is shown farther east in Flaxmans No. 1; here, also, the reservoir is provided by fracture porosity. Other shows of hydrocarbons (such as the small supply of emulsified crude oil from the Eumeralla Formation in Port Campbell No. 4 and the gas with initial flow of 4.2 MM c.f.d. from the Waarre Formation in Port Campbell No. 1) which came from higher in the Otway Group, and the one from the Strzelecki Group are further evidence for suggesting primary sources of hydrocarbons within sediments of Lower Cretaceous age. As noted earlier, permeable sands are associated with the sediments of the Otway Group, and access to reservoirs might also be provided by fracture porosity.

The Belfast Mudstone of the Upper Cretaceous succession in the Otway Basin, and similar mudstone beds in the Mount Salt Formation, are dark, fossiliferous, and glauconitic. Their properties suggest that they were deposited in an anaerobic environment well-suited for the preservation of organic material in a form which would allow the development of hydrocarbons. Access to reservoirs is provided by the porous and permeable sands in the overlying Paaratte Formation, and in the permeable sands within the Mount Salt Formation.

In the on-shore part of the Gippsland Basin, Boutakoff (1964) suggested that the Lakes Entrance hydrocarbons were derived from brown coal in the Latrobe Valley Coal Measures and were trapped beneath marl in the basal sands of the overlying Lakes Entrance Formation under the influence of an hydrodynamic gradient directed southwards. This explanation cannot be accepted at this stage for the origin and trapping of the oil and gas in the off-shore fields. First, the gas in the Barracouta Field is of different composition to that produced in the Lakes Entrance area. Secondly, from the small number of pressure readings available from the Barracouta and Marlin fields and on-shore wells, it would appear that the present hydrodynamic gradient in the basin is small and directed towards the on-shore (J. Scorer, pers. comm.). Some suggested sources for the hydrocarbons in the off-shore fields are:

(i) a possibly more marine facies down-dip in the Latrobe Valley Coal Measures;

(ii) an older off-shore source, such as beds similar to the Belfast Mudstone and not yet penetrated;

(iii) an older source, but possibly near the on-shore or marginal areas - (even from beds within the Strzelecki Group in faulted zones) - and migrations upwards and in the off-shore direction under palaechydrodynamic influences.

The latter suggestion is prompted by Jennings' (1959) observation that the marked bevelling in the Bass Strait at depths of from 30 to 35 fathoms may be due to sea-level withdrawal during a Pleistocene glaciation. Sprigg (1952, and pers. comm.) and Gill (in Jennings, op. cit.) have also given evidence of falls in sea-level due to eustatic effects in the Pleistocene. The possible development is envisaged of hydrodynamic gradients directed off-shore during periods of lower sea-level.

Both the Lakes Entrance Formation in the Gippsland Basin, and the marl at the top of Bc_2 in the Otway Basin could be regarded as possible source rocks, but reservoir prospects appear to be lacking because overlying sediments are generally porous and crop out over wide areas.

5. Conclusions:

Some similarity between the Otway and Gippsland Basins has been indicated, and this leads to the hope that commercial accumulations of hydrocarbons, similar to those found in the off-shore Gippsland Basin Fields, may be found in the Otway Basin.

Some of the conclusions reached in the review of the Otway Basin (BMR, 1966) are as follows:

(i) The Otway Basin should be assessed not so much by its prospects on-shore compared with off-shore, as by the differences which exist in the western and eastern halves on either side of the Warrnambool Ridge.

(ii) In the western half, Unit T, and permeable sand units in the Otway Group and Mount Salt Formation offer the best targets. Structural features are mainly north-west tensional and shear faulting, with subordinate folding. Some doming may be due to basic volcanic intrusions. Late Cainozoic upwarp and possibly some associated faulting have affected south-eastern South Australia and south-western Victoria, and produced north-east trending structure.

(iii) In the eastern part, all units to the top of Unit Bc_2 can be regarded as possibly prospective for hydrocarbons if they extend off-shore from the Port Campbell area, and if the marl at the top of Bc_2 is widespread as suggested by the occurrence of similar clayey beds of the same age in coastal outliers near Cape Otway. However, some reduction of the Upper Cretaceous section occurs to the east of the Port Campbell area. Fold-like features with north-east axes that continue for long distances are predominant in the structure of the area, but faulting is common in the Port Campbell area. Doming due to basic intrusions is suspected in some parts; in the eastern half of the Basin, however, the phase of intrusion is due to the "Older Volcanics" and not to the "Newer Volcanics" as in the west. Good fracture porosity may occur in faulted areas (throughout the Basin). Pinch-outs appear to offer some prospects along basement features such as the Warrnambool Ridge, and the edge of a shelf thought to extend south from Cape Otway.

(iv) The marginal belt north of the Port Campbell area and extending eastwards may offer reservoir prospects if sands similar to Unit T occur at the base of the section or marginal sands are developed within the Otway Group. If permeable sands do exist here or farther east in the Port Phillip Bay area, the possibility of the existence of suitable reservoirs for gas storage, as well as the hydrocarbon prospects, could be considered an added incentive for exploration.

While other structural and stratigraphic features may offer prospects for hydrocarbon accumulations in the Gippsland Basin, the success of drilling closed anticlinal structures in the off-shore area, and the existence of other similar structures for testing would indicate that fold-like subsurface structures offer the best prospects for the immediate future. Although the source of the off-shore Gippsland hydrocarbon accumulations will probably be sought in Upper Cretaceous to Tertiary marine facies to the east, ample evidence that Lower Cretaceous sediments may provide hydrocarbons has been seen in the Otway Basin review, and these sediments should not be disregarded in exploration.

The possibility that hydrocarbon migration has been influenced by palaeohydrodynamic gradients during Pleistocene glaciations might be worth further consideration. A down-dip hydrodynamic gradient from on-shore to off-shore through extensive permeable strata with sparse folds (such as the Latrobe Valley Coal Measures) could cause down-dip migration of hydrocarbons, and their entrapment in the crests of the folds. If Gussow's "spill-over" theory (Levorsen, 1958, p.555) also applied under these conditions, the ratio of oil to gas would be greater in the lower, down-gradient structures.

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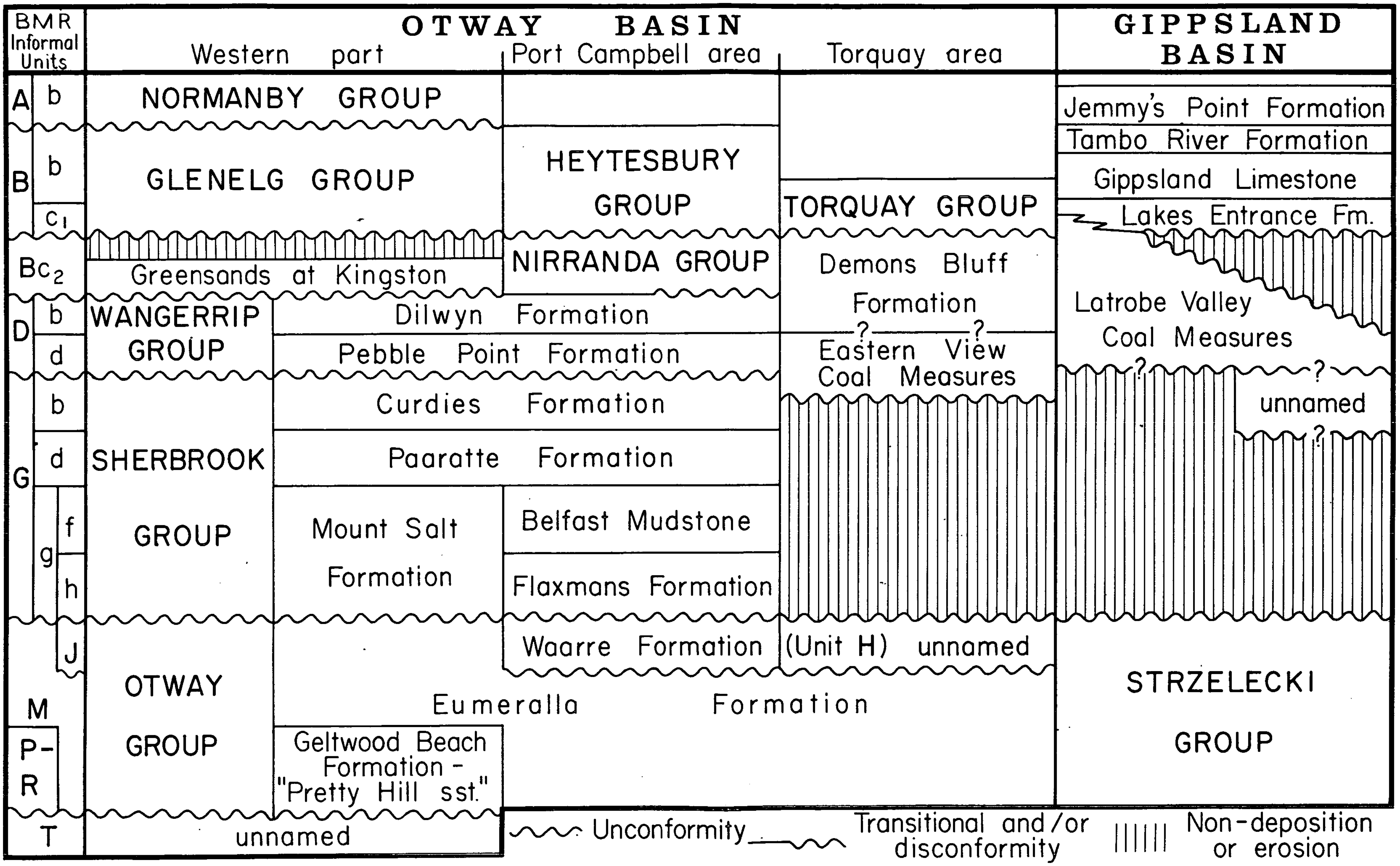

CORRELATION OF LITHOLOGICAL SEQUENCES IN PARTS OF THE OTWAY BASIN & THE GIPPSLAND BASIN