1:250 000 GEOLOGICAL SERIES—EXPLANATORY NOTES

PENDER

WESTERN AUSTRALIA

SHEET SE/51-2 INTERNATIONAL INDEX

DEPARTMENT OF RESOURCES & ENERGY
BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

DEPARTMENT OF MINES, WESTERN AUSTRALIA
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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COMPILED BY D. L. GIBSON

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Explanatory Notes on the Pender 1:250 000 Geological Sheet

Compiled by D. L. Gibson

The Pender 1:250 000 Sheet area lies in northern Western Australia between latitudes 16° and 17°S and longitudes 121°30′ and 123°E. The northwestern part of the Dampier Peninsula occupies about 10% of the Sheet area in the southeast; the remainder is part of the Indian Ocean. Geologically, the Sheet area falls in the northernmost part of the Phanerozoic Canning Basin; a small area in the north-eastern offshore part of the Sheet area may be part of the Precambrian Kimberley Basin.

Permanent centres of population are Beagle Bay and Lombadina Missions, a lighthouse station at Cape Leveque, and a small pearling station at Catamaran Bay. Coastal areas have been used for cattle grazing in the past, but Pender station and most wells and bores seen were abandoned when the Sheet area was visited in 1977.

A formed natural-surface road links the Cape Leveque lighthouse station with Broome to the south, and roads and tracks connect this road with population centres, wells, and bores. The roads and tracks are generally impassable during the wet season. There are landing strips at Lombadina and Beagle Bay Missions (the Beagle Bay strip is just south of the Sheet area) and at the lighthouse station.

The vegetation of the Sheet area is characterised by Pindan, which is essentially a grassland wooded by a sparse upper layer of trees and a dense, thicket-forming middle layer of phylloidal acacias (Beard, 1967). The middle layer is frequently destroyed by fire, but regenerates from seed. Supratidal mudflats are sparsely covered with halophytic shrubs and groundcover, and mangroves fringe bays and inlets.

Aerial photographs and base maps

Vertical aerial photographs at an approximate scale of 1:80 000 (RC-9 series) were flown by the RAAF in 1967; 1:50 000 scale photos (K-17 series) were flown in 1949. The Royal Australian Survey Corps prepared a 1:250 000 topographic map from the 1949 airphotos in 1963, and three 1:100 000 contoured topographic maps covering the areas of land in the Sheet area in 1972 from the 1:80 000 airphotos.

History of investigations

The first geologists to work in the Sheet area were D. J. Guppy and A. W. Lindner of the Bureau of Mineral Resources (BMR) who visited Cape Leveque and other coastal localities in 1948 (Guppy & Lindner, 1949). This work was followed by a more exhaustive survey of the area in 1950 by R. O. Brunnschweiler (BMR) and H. Smith (consulting geologist for Ampol Petroleum Ltd) (Brunnschweiler, 1951, 1957; Smith, 1951).

Geophysical surveys in and near the Sheet area began in the 1950s with gravity surveys carried out by BMR as part of an Australia-wide gravity coverage (Flavelle & Goodspeed, 1962; Flavelle, 1974). West Australian Petroleum Pty Ltd (WAPET) began geophysical surveying as part of its search for oil in the Sheet area in 1965 with the Dampierland Gravity Survey (WAPET, 1965a) and the Offshore Canning Magnetic Survey (WAPET, 1965b). These surveys were followed by the Dampierland Seismic Survey (WAPET, 1966b), the King Sound Aeromagnetic Survey (WAPET, 1966a), the Bedout Marine Seismic Survey (WAPET, 1969), the Canning Marine Seismic Survey (WAPET, 1970a) and the Pender Seismic Survey (WAPET, 1970b).

Following these surveys, two petroleum exploration wells were drilled—WAPET Tappers Inlet 1 (WAPET, 1971) and WAPET Pender 1 (WAPET, 1972). The former had insignificant oil shows in tight Devonian and Ordovician limestones; the latter was dry.

The Burmah Oil Company of Australia Ltd (BOCAL) also conducted several offshore seismic surveys in and around the Sheet area. These include the Northwest Shelf (BOCAL, 1964), the Montebello-Mermaid (BOCAL, 1965), the Legendre-Marie (BOCAL, 1969a) and the Adele-Scott (BOCAL, 1969b) Marine Seismic Surveys. In 1970, BOCAL drilled the offshore wells Leveque 1 and Lacepede 1 & 1A, respectively 28 km north and 12 km south-southwest of the Sheet area (BOCAL, 1970a, 1970b). Mid-Eastern Oil carried out the Rowley Shoals, Scott Reef and Sahul Banks Aeromagnetic Survey in 1963 (Mid-Eastern Oil, 1963).

BMR carried out offshore geological reconnaissance studies (dredge sampling, seismic reflection, and sea-floor photography) in 1967 (Jones, 1973) and a detailed offshore geophysical survey (seismic, gravity, and magnetics) in 1968 (Whitworth, 1969) in and around the Sheet area.

In 1973, BMR began a detailed basin study of the Canning Basin, the results of which are reported by Gorter & others (1979), and Forman & Wales (1981).

Several geophysical surveys have been carried out in the Sheet area since 1973. Most results of these are confidential, but raw data from offshore surveys which come under the Petroleum (Submerged Lands) Act are available at BMR and the Western Australian Department of Mines, generally five years after completion.

These Explanatory Notes and accompanying map are based on field mapping carried out by a combined BMR/Geological Survey of Western Australia (GSWA) team in 1977 (Towner & Gibson, 1980) as part of a project to map the entire Canning Basin at 1:250 000 scale (Towner & Gibson, 1983). Vehicle and helicopter-assisted traverses were made in the Sheet area during this survey. The offshore section on the map is partly based on information provided by Gorter & others (1979) from seismic and magnetic data.

Since the fieldwork was carried out, Esso Exploration and Production Australia Ltd has carried out seismic work in the Sheet area, and drilled and abandoned the petroleum exploration well Moogana 1 about 5 km northeast of Beagle Bay Mission in early 1980. Some information on the section penetrated in this well was made available to the author by courtesy of Esso and its Fitzroy Joint Venture partners.

PHYSIOGRAPHY

The climate of the Sheet area is hot and seasonally wet. Average annual rainfall is about 700 mm and most of this falls between December and March. Normal daily maximum and minimum temperatures are about 32° and 25°C in January, and 29° and 14°C in July, and the average annual evaporation is about 2250 mm (these figures have been estimated from Bureau of Meteorology contour maps).

Most of the land in the Sheet area is made up of a gently undulating, well-vegetated sandy plain which reaches about 110 m above sea level (Fig. 1). Watercourses across the plain are choked with alluvium and contain flowing water only

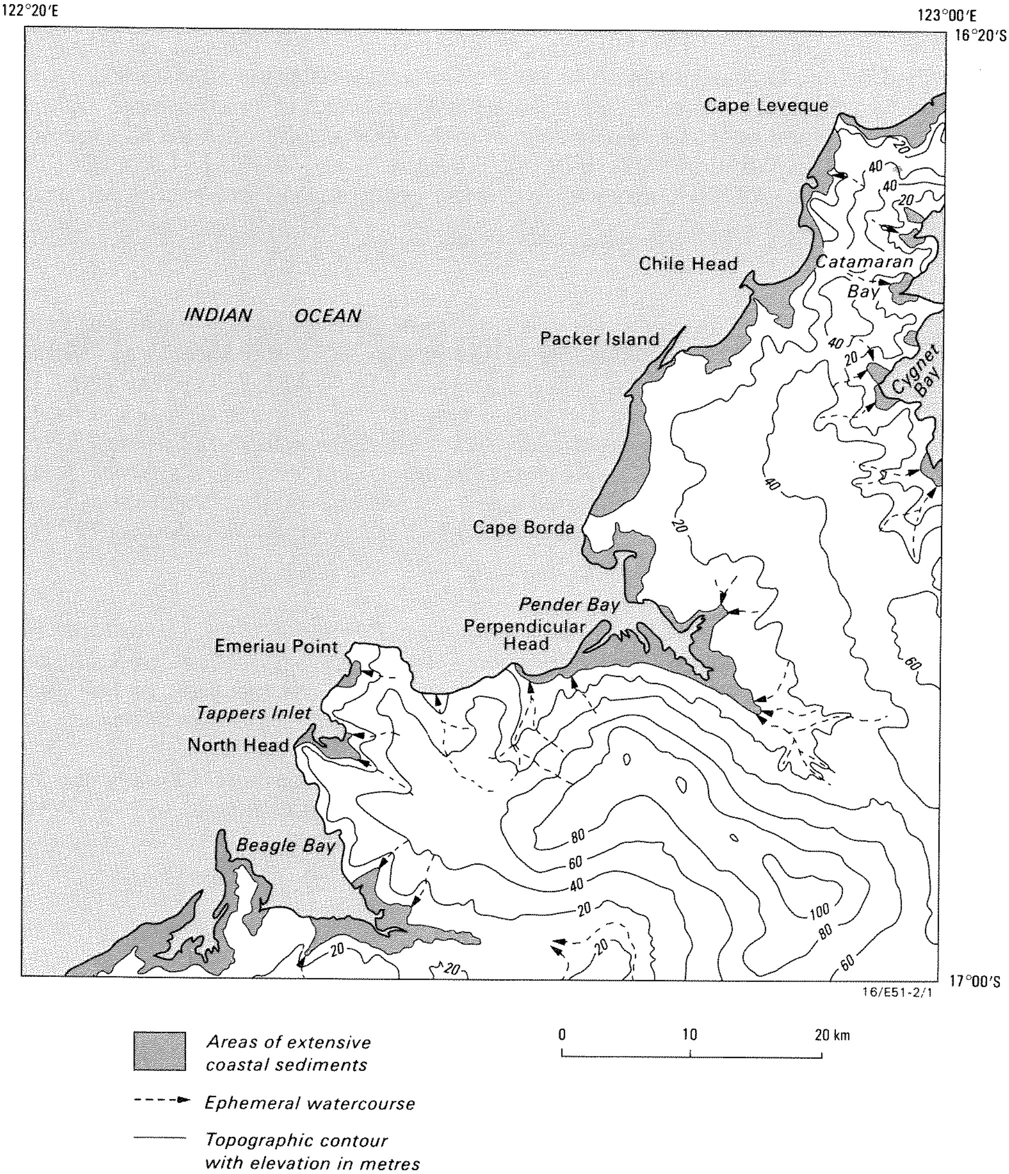

Fig. 1. Physiography.

after heavy rainfall. Land within about 5 km of Cygnet and Catamaran Bays is slightly more rugged and is characterised by incised creeks and rocky outcrops. Coastal areas are characterised by large areas of aeolian dunes, platforms of lithified Quaternary sediment, and extensive supratidal and intertidal mudflats bordering inlets and bays.

Offshore, the continental shelf slopes gently to the north and northwest to a maximum water depth of about 90 m in the Sheet area. Shallow northwest-trending depressions occur on the sea-floor.

STRATIGRAPHY

The stratigraphy of the Sheet area is summarised in Table 1 and briefly described below. Onshore, units beneath the Cretaceous Broome Sandstone are not known to crop out; however, all have been intersected in one or more of the petroleum exploration wells. An insight into the stratigraphy offshore is given by the petroleum exploration wells BOCAL Leveque 1 and BOCAL Lacepede 1A (BOCAL, 1970a, 1970b), respectively 28 km north and 12 km south-southwest of the Sheet area.

PRECAMBRIAN

Basement rocks of Precambrian age (p€) underlie the Canning Basin and may subcrop beneath Cainozoic sediments in the northwest of the Sheet area. Metabasalt, mica schist, and gabbro were intersected in WAPET Tappers Inlet 1, WAPET Pender 1, and BOCAL Leveque 1 respectively (Forman & Wales, 1981). Esso Moogana 1 bottomed in interbedded graphitic shales and metadolerite (Esso, written communication, 1980). At Apex Island, 5 km east of the Sheet area, medium to coarse-grained, well-sorted quartz sandstone of the Proterozoic King Leopold Sandstone crops out (Brunnschweiler, 1957; Gellatly & Sofoulis, 1973).

ORDOVICIAN

Two Ordovician units, the basal *Nambeet Formation* (Ot; Johnstone *in* WAPET, 1961) and the *Willara Formation* (Ow; McTavish *in* Playford & others, 1975) are here recognised in WAPET Tappers Inlet 1 on the basis of lithology and age as determined from conodonts and palynomorphs. Both formations are of Early Ordovician age (McTavish & Legg, 1976).

Ordovician units are present throughout most of the onshore Canning Basin, but it is not known how far offshore these extend. They are thought to have been deposited in a shallow epicontinental sea (McTavish & Legg, 1976).

MIDDLE DEVONIAN TO EARLY CARBONIFEROUS(?)

Rocks of Devonian to Early Carboniferous age (DC) were intersected in WAPET Tappers Inlet 1. A lower unit of very fine to fine-grained calcareous sandstone 65 m thick is interpreted to be the Poulton Formation of Playford & others (1975) on the basis of its lithology and age (as determined by palynology—Givetian/Frasnian), and an upper unit of limestone and calcareous shale 418 m thick is interpreted to be part of a reef complex (Towner & Gibson, 1980). Esso Moogana 1 intersected 45 m of Late Devonian (Frasnian) carbonates, overlain unconformably by 67 m of Early Carboniferous sandstone and siltstone assigned to the Anderson Formation of McWhae & others (1958) (Esso, written communication, 1980).

Offshore, Gorter & others (1979) and Forman & Wales (1981) recognise Carboniferous rocks in BOCAL Lacepede 1A, apparently on the basis of lithology. However, Permian palynomorphs have been identified in sidewall cores from these rocks (BOCAL, 1970b), and hence they are here considered to be Permian. This does not rule out the possibility, as shown in cross section AB, that Carboniferous and older rocks are present below the depth reached by that well (2286 m).

It is probable that equivalents of many of the Middle Devonian to Early Carboniferous units which form reef complexes and associated deposits along the northern margin of the Canning Basin are present in the Sheet area (see Derrick

& Playford, 1973; Playford & Lowry, 1966; Playford & others, 1975; Playford, 1976; Playford & Cockbain, 1976; Druce & Radke, 1979; and Playford, 1980 for details of these units).

Late Carboniferous and Permian

Rocks of the *Grant Group* (Pg; Guppy & others, 1958; Crowe & Towner, 1976) have been intersected in all petroleum exploration wells in the Sheet area. No attempt has been made on the section to distinguish the basal, sandy Betty Formation, the shaley Winifred Formation, and the upper, sandy Carolyn Formation of Crowe & Towner (1976), which have been recognised in WAPET Tappers Inlet 1 and WAPET Pender 1 (Towner & Gibson, 1980). The Betty and Carolyn Formations are thought to have been deposited under cold-water or glacial marine conditions. The Grant Group is generally regarded as being Sakmarian in age, although it extends down into the Late Carboniferous in WAPET Pender 1 (WAPET, 1972).

The *Poole Sandstone* (Pp; Guppy & others, 1952) overlies the Grant Group. Crowe & others (1978) showed that the contact is an angular unconformity in the Grant Range (Mount Anderson and Derby 1:250 000 Sheet areas to the south-east), but angularity has not been demonstrated in the Pender Sheet area. No attempt has been made on the section to show the lower, calcareous Nura Nura Member (Guppy & others, 1958) and the upper, sandy Tuckfield Member (Crowe & Towner, 1976) as these units are too thin to show individually. The Poole Sandstone is of Sakmarian to Artinskian age, and is probably of shallow-marine to lagoonal origin.

The overlying *Noonkanbah Formation* (Pn; Wade, 1938; Guppy & others, 1952) is of Artinskian age, and is made up of fine-grained shallow-marine deposits.

The Noonkanbah Formation is conformably overlain by the *Liveringa Group* (Pl; Guppy & others, 1952; Yeates & others, 1975), which was intersected in Esso Moogana 1. No attempt has been made to divide the Group into its constituent formations and their members because of the limited information afforded by the one intersection of the unit in the Sheet area. It is a shallow-marine to deltaic deposit.

Rocks of Permian age are seismically definable offshore, and it is possible that the units recognised onshore extend to the western margin of the Sheet area. BOCAL Lacepede 1A intersected 186 m of very fine to fine-grained sandstone, grading into siltstone with minor shale, overlain by 87 m of siltstone and in turn overlain by 15 m of shale, all of which are assigned a Late Permian age, and a non-marine origin (BOCAL, 1970b). It is possible that these rocks could be equivalent to part of the Liveringa Group.

Early Triassic

The *Blina Shale* (Rb; Reeves, 1951; Brunnschweiler, 1954) is of Early Triassic age, and was deposited in a shallow restricted sea. It has been intersected only in Esso Moogana 1.

Triassic rocks are not known offshore in the Sheet area.

Jurassic to Cretaceous

The *Wallal Sandstone* (Jl; McWhae *in* WAPET, 1961) consists of sandstone with minor siltstone and lignite in WAPET Tappers Inlet 1, WAPET Pender 1, and Esso Moogana 1; conglomerate is also known from this unit in wells outside

TABLE 1. STRATIGRAPHY OF PENDER SHEET AREA

Age	*Rock unit*	*Maximum Thickness (m)*	*Lithology*	*Stratigraphic relationships*	*Fossils*	*Comments*
QUATERNARY	Qa	10?	Sand, silt, clay, minor gravel	Superficial deposit		Alluvial and lacustrine
	Qs	10?	Sand, silt, minor gravel	Superficial deposit		Mixed alluvial and aeolian
	Qcs	5?	Clay, silt, sand, minor salt	Superficial deposit		Supratidal mud flat
	Qci	5?	Silty clay, black organic clay	Superficial deposit		Tidal flat and mangrove swamp
	Qcd	20?	Calcareous sand, partly oolitic	Superficial deposit		Coastal aeolian sand dunes: includes reworked Qpb
	Bossut Formation Qpb	20?	Fine to coarse calcareous and quartzose sandstone, calcilutite, oolite; cross-bedded in part	Unconformably overlies older rock units	Bivalves, gastropods, forams	Coastal
TERTIARY(?)	Borda Sandstone Tb	5	Fine sandstone, minor mudstone; basal conglomerate	Unconformably overlies Kb		Only recognised at Cape Borda; ferruginised Kr clasts in basal conglomerate; probably fluvial
EARLY CRETACEOUS	Emeriau Sandstone Kr	30?	Fine to coarse, poorly sorted sandstone, minor conglomerate; cross-bedded; commonly has iron oxide matrix	Disconformably overlies Kb, Km, probably with very minor time break		Fluvial to deltaic; probably equivalent to Aptian Frezier Sandstone of southwest Canning Basin
	Melligo Sandstone Km	40?	Fine to medium, well sorted, thin-bedded to laminated sandstone; pebbly in places; partly silicified	Conformably to disconformably overlies Kb; disconformably overlain by Kr	Belemnites, bivalves	Regressive beach
	Broome Sandstone Kb	300?	Fine to very coarse sandstone, some mudstone, minor conglomerate; ripple-marked, cross-bedded; bioturbated in part	Conformably overlies JKr; possibly unconformably overlies pЄ; overlain conformably to disconformably by Km, disconformably by Kr, unconformably by Tb	Plant fossils, bivalves, microfossils; dinosaur footprints outside Sheet area	Includes 'Leveque Sandstone' and 'Jowlaenga Formation' of Brunnschweiler (1957); regressive shallow-marine (tidal)
LATE JURASSIC TO EARLY CRETACEOUS(?)	Jarlemai Siltstone JKr	73 in WAPET Tappers Inlet 1	Siltstone, claystone, sandstone	Conformable between Ja or Jl and Kb; possibly unconformably overlies pЄ	Bivalves, gastropods, ammonites, microfossils	Shallow-marine (subtidal)
LATE JURASSIC	Alexander Formation Ja	50 in Esso Moogana 1	Interbedded fine to coarse sandstone and mudstone	Conformable between Jl and JKr	A wide range of shelly fossils known from outside Sheet area	Shallow-marine (tidal) transgressive
EARLY(?) TO LATE JURASSIC	Wallal Sandstone Jl	213 in WAPET Tappers Inlet 1	Sandstone; minor siltstone, conglomerate, lignite	Unconformably overlies Rb, Pl, Pn, Pp, Pg, pЄ; conformably overlain by Ja, JKr	Microfossils, plant fossils	Continental to shallow-marine
EARLY TRIASSIC	Blina Shale Rb	78 in Esso Moogana 1	Mudstone, sandy in places	Unconformable between Pl and Jl	Ostracods, vertebrates, brachiopods known from outside Sheet area	Shallow restricted marine

Age	*Rock unit*	*Maximum Thickness (m)*	*Lithology*	*Stratigraphic relationships*	*Fossils*	*Comments*
EARLY TO LATE PERMIAN	Liveringa Group Pl	207 in Esso Moogana 1	Sandstone, mudstone; minor limestone, conglomerate, coal	Conformably overlies Pn; unconformably overlain by Rb, Jl	Bivalves, gastropods, brachiopods, ammonoids, plant fossils, microfossils known from outside Sheet area	Shallow-marine to deltaic
EARLY PERMIAN	Noonkanbah Formation Pn	287 in WAPET Tappers Inlet 1	Calcareous mudstone, fine sandstone, limestone interbeds	Conformably overlies Pp; overlain conformably by Pl and unconformably by Jl	Brachiopods, bryozoans, corals, crinoids, bivalves, gastropods, ostracods, and microfossils known from outside Sheet area	Unrestricted shallow-marine
	Poole Sandstone Pp	49 in Esso Moogana 1	Very fine to fine sandstone; interbedded mudstone, minor limestone at base	Unconformably(?) overlies Pg; overlain conformably by Pn, unconformably by Jl	Brachiopods, bryozoans, ammonoids, molluscs, conodonts, crinoids, ostracods, plant fossils, and microfossils known from outside Sheet area	Shallow-marine to lagoonal
LATE CARBONIFEROUS TO EARLY PERMIAN	Grant Group Pg	826 in Esso Moogana 1	Fine to coarse sandstone, mudstone, minor conglomerate	Unconformably overlies DC, Ow, Ot, p€; overlain unconformably by Jl and possibly Pp	Bivalves, gastropods, brachiopods, bryozoans, crinoids, fossil wood, microfossils known from outside Sheet area	Marine, partly glacial-marine
MIDDLE DEVONIAN TO EARLY CARBONIFEROUS(?)	DC	483 in WAPET Tappers Inlet 1	Limestone, dolomite, shale, siltstone, fine sandstone	Unconformably overlies Ow, p€; unconformably overlain by Pg	Palynomorphs, conodonts; a wide variety of fossils known from outside Shtet area	Reef complexes and equivalents of Poulton Formation (Playford & others, 1975); marine
EARLY ORDOVICIAN	Willara Formation Ow	187 in WAPET Tappers Inlet 1	Limestone, partly dolomitic; interbedded shale, siltstone	Conformably overlies Ot; unconformably overlain by DC, Pg	Palynomorphs, conodonts; a wide variety of fossils known from outside Sheet area	Shallow-marine
	Nambeet Formation Ot	632 in WAPET Tappers Inlet 1	Shale; interbedded limestone and fine sandstone	Unconformably overlies p€; overlain conformably by Ow, unconformably by Pg	Palynomorphs, conodonts; a wide variety of fossils known from outside Sheet area	Shallow-marine
PRECAMBRIAN	p€		Igneous, metamorphic, and sedimentary rocks	Unconformably overlain by Ot, DC, Pg, Jl; possibly overlain unconformably by JKr, Kb		Kimberley Basin, and basement to Canning Basin; metabasalt and mica schist known from Sheet area; quartz sandstone 6 km east of Sheet area

the Sheet area. It is probably of continental to shallow-marine origin. It is not well dated in the Sheet area, but is probably of Middle to Late Jurassic (Oxfordian) age (Playford & others, 1975), although there are indications that it may extend down into the Early Jurassic in the southwest Canning Basin (Towner & Gibson, 1980).

The overlying *Alexander Formation* (Ja; Brunnschweiler, 1954) is recognised in Esso Moogana 1 and WAPET Tappers Inlet 1, but identification is uncertain in WAPET Pender 1 (Towner & Gibson, 1980). It has been dated as Oxfordian, and possibly Kimmeridgian, from intersections outside the Sheet area.

The *Jarlemai Siltstone* (JKr; Brunnschweiler, 1954) has been dated as possibly Oxfordian or Kimmeridgian to Tithonian outside the Sheet area, but may extend into the Early Cretaceous (Crowe & others, 1978). This unit was deposited at the height of the Jurassic-Cretaceous transgression in the Canning Basin.

The *Broome Sandstone* (Kb; Reeves, 1951) as used here, includes the 'Leveque Sandstone' and the 'Jowlaenga Formation' of Brunnschweiler (1957). Field examination of the 'Leveque Sandstone' at Cape Leveque (the only place where it was mapped by Brunnschweiler) showed that it is a coarse-grained part of the Broome Sandstone (Towner & Gibson, 1980). The 'Jowlaenga Formation' as mapped by Brunnschweiler (1957) underlying the Melligo Sandstone (see below) about 6 km east of the Sheet area in the One Arm Point area, and in the Broome and Derby Sheet areas to the south and southwest, is also considered by Towner & Gibson (1980) to be part of the Broome Sandstone. Small amounts of fine-grained heavy minerals are present in sandstones at the top of the Broome Sandstone in the Perpendicular Head area, and also in the One Arm Point area.

The *Melligo Sandstone* (Km; Brunnschweiler, 1957; McWhae & others, 1958) overlies the Broome Sandstone disconformably in the Perpendicular Head area, and conformably in the One Arm Point area (Towner & Gibson, 1980). Brunnschweiler used the presence of silicification as a requisite for recognising the unit, but Towner & Gibson identify unsilicified Melligo Sandstone in the Perpendicular Head area on the basis of sedimentary structures and fabric.

The good sorting and rounding of the constituent grains (some of which are heavy minerals) coupled with thin bedding, flat to low-angle cross-bedding, and parting lineation indicate that it is a beach deposit, laid down as the sea in which the Broome Sandstone was deposited, regressed. The disconformity in the Perpendicular Head area is probably due to minor reworking of the sediments of the Broome Sandstone during regression.

The age of the Melligo Sandstone is well documented as it contains the key Aptian bivalve, *Fissilunula clarkei.*

The *Emeriau Sandstone* (Kr; Brunnschweiler, 1957) disconformably overlies the Broome Sandstone where the contact is exposed at Emeriau Point. Towner & Gibson (1980) equate this unit with the Aptian Frezier Sandstone of the western Canning Basin, rather than giving it a Tertiary age as Brunnschweiler (1957) did. The 'Pender Bay Conglomerate', considered by Brunnschweiler to be a lateral equivalent of the Emeriau Sandstone, was found by Towner & Gibson (1980) to be a thin Cainozoic lag gravel of clasts of ferruginised Emeriau Sandstone, and was not considered a mappable unit at the scale of the accompanying map.

Offshore, Jurassic to Cretaceous rocks are probably present over almost all of the Sheet area. BOCAL Leveque 1 (BOCAL, 1970a) penetrated latest Jurassic to Early Cretaceous (Albian) marine rocks, which rest directly on basement. This sequence consists of 164 m of argillaceous sandstone, shale, and claystone, disconformably overlain by 311 m of claystone with minor interbedded argillaceous siltstone and sandstone. This is unconformably overlain by a Late Cretaceous (Santonian to Maestrictian) sequence of calcisiltite and calcilutite 81 m thick, which is probably a deep-water deposit. It is unconformably overlain by Tertiary carbonates.

BOCAL Lacepede 1A (BOCAL, 1970b) intersected 1695 m of Jurassic to Cretaceous rocks. The basal part of the sequence consists of 658 m of non-marine sandstone with interbedded shale and minor coal of Early Jurassic to Oxfordian age, conformably overlain by 67 m of Oxfordian to Tithonian marine sandstone with interbedded shale. This is overlain, probably with minor disconformity, by a sequence of 187 m of claystone (open marine at base, grading up to nearshore marine) of Tithonian age, conformably overlain by 181 m of nearshore marine sandstone and siltstone of Tithonian to Neocomian age. Another probably minor disconformity separates this from 532 m of marine grading up to nearshore-marine sandstone, siltstone, and claystone of Neocomian to Aptian age.

A major break separates this from 78 m of Late Cretaceous siltstone, marl, and claystone which is unconformably overlain by Tertiary carbonates.

The lowermost disconformity in BOCAL Lacepede 1A may correspond to the 'breakup' unconformity, a major break encountered in offshore wells in the Canning, Browse, and Carnarvon Basins. It marks a change from predominantly continental deposition and erosion to marine deposition which commenced with the breakup of Australia from a landmass to the northwest (see Powell, 1976). This unconformity has not been recognised onshore in the Canning Basin, but the boundary between the Wallal Sandstone and Alexander Formation may correspond to it.

CAINOZOIC

The *Borda Sandstone* (Tb; Brunnschweiler, 1957) is only known to crop out at Cape Borda in the Sheet area. It contains clasts of ferruginised Emeriau Sandstone (Towner & Gibson, 1980). Hence the Borda Sandstone is considered to be much younger than the Emeriau Sandstone, and is most probably of Tertiary age.

The *Bossut Formation* (Qpb; Traves & others, 1956; Lindner *in* WAPET, 1961) as used here includes the 'Chimney Rock Oolite' and 'North Head Limestone' of Brunnschweiler (1957), which are considered by Towner & Gibson (1980) to be local variants of the Bossut Formation. A minor deposit of fossiliferous silicified limestone overlying the Broome Sandstone at Cape Leveque (mentioned by Brunnschweiler, 1957, p. 9), is here considered to also be part of the Bossut Formation. The Bossut Formation is considered to be of Quaternary age because of its occurrence at or close to the present day shoreline.

Coastal aeolian sand deposits (Qcd) form high dunes along much of the coastline. The dunes are now inactive, and many are well vegetated.

Tidal flat and mangrove swamp deposits (Qci) up to 2 km wide flank inlets and tidal creeks.

Supratidal mud flat deposits (Qcs) usually occur landward of the tidal deposits. These are inundated only by spring tides, although they may be flooded by fresh water during the wet season.

Most of the land in the Sheet area is covered by a veneer of sand and silt (Qs) which is probably of *mixed alluvial and aeolian* origin.

Alluvial and lacustrine sediments (Qa) floor claypans and the valleys of larger creeks.

Offshore, the Cainozoic is represented by a wedge of carbonates thickening to the west. BOCAL Leveque 1 penetrated 33 m of Early Tertiary (Eocene or Oligocene) dolomite and interbedded fine-grained sandstone, unconformably overlain by 215 m of Miocene and younger calcarenite, calcilutite, recrystallised limestone, and fine-grained sandstone. BOCAL Lacepede 1A intersected 235 m of Cainozoic rocks, but no samples were obtained except for the basal 3 m (dolomite) because of lost circulation. It is expected that most of the missing section is made up of carbonates, as these predominate in the Cainozoic sections of all offshore wells in the Canning Basin (Gorter & others, 1979; Forman & Wales, 1981).

STRUCTURE

Structural interpretation is based wholly on the results of geophysical surveys and drilling, as the onshore part of the area is covered by a veneer of virtually undeformed Mesozoic rocks. Some idea of structure in Ordovician rocks is given by WAPET's onshore seismic surveys (WAPET, 1966b ; 1970b); offshore, there is no non-confidential seismic information on horizons lower than the Permian. A simplified presentation of structure within the Sheet area is given in the schematic sections and simplified geology sketch on the accompanying map.

The offshore northeastern margin of the Canning Basin is taken to be the limit of subcrop of Jurassic to Lower Cretaceous sediments (Forman & Wales, 1981). Its approximate position is shown on the simplified geology sketch. Precambrian rocks of the Kimberley Basin subcrop to the northeast of the Canning Basin in the Sheet area.

The Canning Basin is divided into three structural subdivisions in the Sheet area, based on basement morphology: Lennard Shelf, Leveque Shelf, and Fitzroy Trough.

The Lennard Shelf is an area of shallow basement in the northern onshore part of the Sheet area. It is overlain by mostly gently dipping Canning Basin rocks generally less than 2000 m thick.

Some folds have been mapped seismically in the Permian sequence on the Lennard Shelf in the area south of Pender Bay (see simplified geology sketch). However, the underlying Ordovician-Devonian rocks are much more strongly deformed (see Section CD—information provided by Esso Australia Ltd, 1980). No attempt has been made to show their structure on the map, as non-confidential information is sketchy and of poor quality.

Offshore, the Lennard Shelf grades into the Leveque Shelf, a broad area of shallow basement, generally overlain by less than 1000 m of Phanerozoic sediments. It has sometimes been considered to be part of the Browse Basin, which is contiguous with the Canning Basin (e.g. Allen & others, 1978), but the northern margin of the Canning Basin is here taken to arbitrarily follow 16°S (the top edge of the Sheet area), following the definition of the Canning Basin by Gorter & others (1979) and Forman & Wales (1981).

To the south of these shelves is the Fitzroy Trough, a northwest-trending graben which was initiated probably in the Middle Devonian when movement occurred along its bounding faults; the Beagle Bay Fault System forms the northern boundary of the trough in the Sheet area. Further movement along the Beagle Bay Fault System during deposition in the Late Devonian and Early Carboniferous resulted in much greater thicknesses of sediment being laid down in the Trough than in adjacent areas. Limited seismic information in the onshore part of the

Sheet area suggests that downthrow along the Beagle Bay Fault System is in the order of thousands of metres.

Many east-trending en-echelon folds are present in the Fitzroy Trough, and it has been proposed that these were generated probably in the Late Triassic or Early Jurassic by right-lateral shear along its bounding faults (Rattigan, 1967; Smith, 1968; Rixon, 1978). A syncline in the Trough in the southern onshore part of the Sheet area probably originated during this phase of deformation.

GEOLOGICAL HISTORY

In Precambrian times, sediments were laid down, igneous rocks intruded them, and metamorphism took place. These rocks, part of the Kimberley Basin, and basement to the Canning Basin, were eroded to a near peneplaned state prior to Early Ordovician times, when a shallow sea transgressed the southern part of the Sheet area. Mud, sand, and carbonates (Nambeet and Willara Formations) were deposited in this sea.

A long period of emergence and minor erosion followed until Middle or Late Devonian times when the sea again entered the southern part of the Sheet area, probably coinciding with movement (down to the south) along the Beagle Bay Fault System. Clastic sediments and carbonates accumulated in this sea, and limestone reefs grew in areas of shallow water near the fault system. Deposition of clastic sediments and non-reef carbonates, and movement along the Beagle Bay Fault System continued into the Carboniferous. Emergence in Carboniferous times resulted in partial erosion of the Devonian, Carboniferous, and Ordovician rocks.

The sea again transgressed the southern part of the Sheet area in latest Carboniferous or Early Permian times, but possibly reached farther north than before. Sand and mud (Grant Group) were deposited under cold-water conditions in this sea. A minor period of emergence and erosion may have followed, then sand and mud (Poole Sandstone) were deposited under warm-water conditions. Transgression continued, and mud and carbonate (Noonkanbah Formation) were laid down. Regression in Early to Late Permian times resulted in deposition of sand and mud, with some peat (Liveringa Group).

Emergence and minor erosion followed until mud of the Blina Shale was deposited in the Early Triassic in a shallow sea which extended across the southern part of the Sheet Area.

After Triassic deposition ceased, the area was subjected to a major period of tectonism and erosion. Right-lateral shear probably induced folding in the Fitzroy Trough.

Deposition re-commenced, possibly in Early Jurassic times, when continental to shallow-marine sand and minor mud (Wallal Sandstone) were deposited. Transgression in the Late Jurassic led to deposition of sand and mud in a marine environment (Alexander Formation, Jarlemai Siltstone, and unnamed sediments offshore), and by latest Jurassic times, most of the Sheet area was covered by the sea.

Regression in Early Cretaceous times resulted in deposition of sand and mud in a shallow-water environment (Broome Sandstone, onshore). By Aptian times, the sea had regressed from the land part of the Sheet area, beach sands (Melligo Sandstone) being deposited as this happened. Fluvial sand (Emeriau Sandstone) was then deposited. Offshore, the sea regressed entirely from the area by Albian times, and minor erosion followed.

The sea transgressed across the western part of the Sheet area in Late Cretaceous (probably Santonian) times, and fine-grained carbonates and mud were deposited in a deep-water environment. The sea then regressed entirely from the area in Maestrictian times, and again, minor erosion followed.

A short-lived transgression in Eocene or Oligocene times resulted in deposition of carbonate and sandstone, at least in the northwestern part of the Sheet area. Further erosion followed, and younger Tertiary (Miocene and younger) carbonates and minor sand were then deposited over the western part of the Sheet area.

Onshore, probably in Tertiary times, sandstone and gravel were deposited probably in a large river channel (Borda Sandstone).

In Quaternary times, a variety of thin sediments of shoreline, alluvial, lacustrine, and mixed aeolian and alluvial origin were deposited on the onshore part of the Sheet area. Offshore, carbonates and sand continued to accumulate in a marine environment.

ECONOMIC RESOURCES

Petroleum

Traces of oil and gas have been found in only one of the three petroleum exploration wells in the Sheet area. WAPET Tappers Inlet 1 encountered traces of oil bleeding from tight fractures and stylolites in Devonian and Ordovician limestones and traces of gas from Ordovician shales. No hydrocarbons were found in WAPET Pender 1 and Esso Moogana 1.

Burne & Kantsler (1977) concluded that the zone of oil generation in the Canning Basin lies between the 50° and 75°C isotherms; this relatively low temperature range reflects the prolonged burial of the Palaeozoic rocks. They show that rocks of Ordovician to Permian age in the southern onshore part of the Sheet area lie within this temperature window at present, and that present temperatures are close to the maximum reached by these rocks in the past. Burne & others (1979) list the Lennard Shelf and Fitzroy Trough as being amongst the areas having greatest potential for the commercial discovery of hydrocarbons, and consider that source rock analyses favour oil generation in Ordovician rocks. However, porosity in the Ordovician rocks is very low, as is porosity in the Devonian reef complex carbonates encountered in WAPET Tappers Inlet 1. The porosity in sandstone of the underlying Poulton Formation in Tappers Inlet 1 was found to be much higher (20%), with a permeability of 66 md.

The presence of source rocks in the Ordovician, and potential reservoirs in dolomitised Devonian reefs near the Beagle Bay Fault System, point to reasonable petroleum prospects in the onshore part of the Sheet area.

Offshore, to the south-southwest of the Sheet area, BOCAL Lacepede 1A encountered minor gas shows in Permian and Jurassic rocks. The Leveque Shelf area has little petroleum potential as the sedimentary sequence on it is very thin. The offshore Fitzroy Trough area would appear to have reasonable petroleum potential.

Coal

Lignite encountered in the Wallal Sandstone in the petroleum exploration wells in the Sheet area is likely to be of little economic significance.

Coal is known from the Liveringa Group outside the Sheet area (Towner, 1981; Gibson & Crowe, 1982) but, if present in the Sheet area, its depth (e.g. over 700 m in Esso Moogana 1; Esso, written communication, 1980) would make exploitation unlikely in the near future.

Water

Claypans and creeks in the Sheet area contain water after heavy rain in the wet season. Groundwater from Quaternary sediments and the Broome Sandstone is tapped by wells and bores. Poor quality artesian water is obtained from the Alexander Formation, Wallal Sandstone, and Jarlemai Siltstone at Broome to the south of the Sheet area, and it is expected that large quantities of sub-artesian water would be present in these formations in the Sheet area.

Heavy minerals

Farrand (1965) reported that heavy minerals are distributed throughout quartz dune sands in the Cape Leveque, Lombadina Point, and Emeriau Point areas, and Brunnschweiler (1952) records the presence of 'blackish sands' in the Beagle Bay and Pender Bay areas. Farrand lists opaques, zircon, tourmaline, rutile, kyanite, staurolite, and epidote as being present.

Details of heavy-mineral concentrations in the Broome Sheet area to the south are given by Stillwell (1953), Baxter (1977), and Towner & Gibson (1980). These are probably very similar to the occurrences in the Pender Sheet area.

Heavy minerals are present in places at the top of the Broome Sandstone and in the Melligo Sandstone in the Sheet area, and it is probable that the heavy minerals seen in the dune sands are derived from these units. As areas of heavy-mineral sands are small, and concentrations are low, they are probably of no economic significance.

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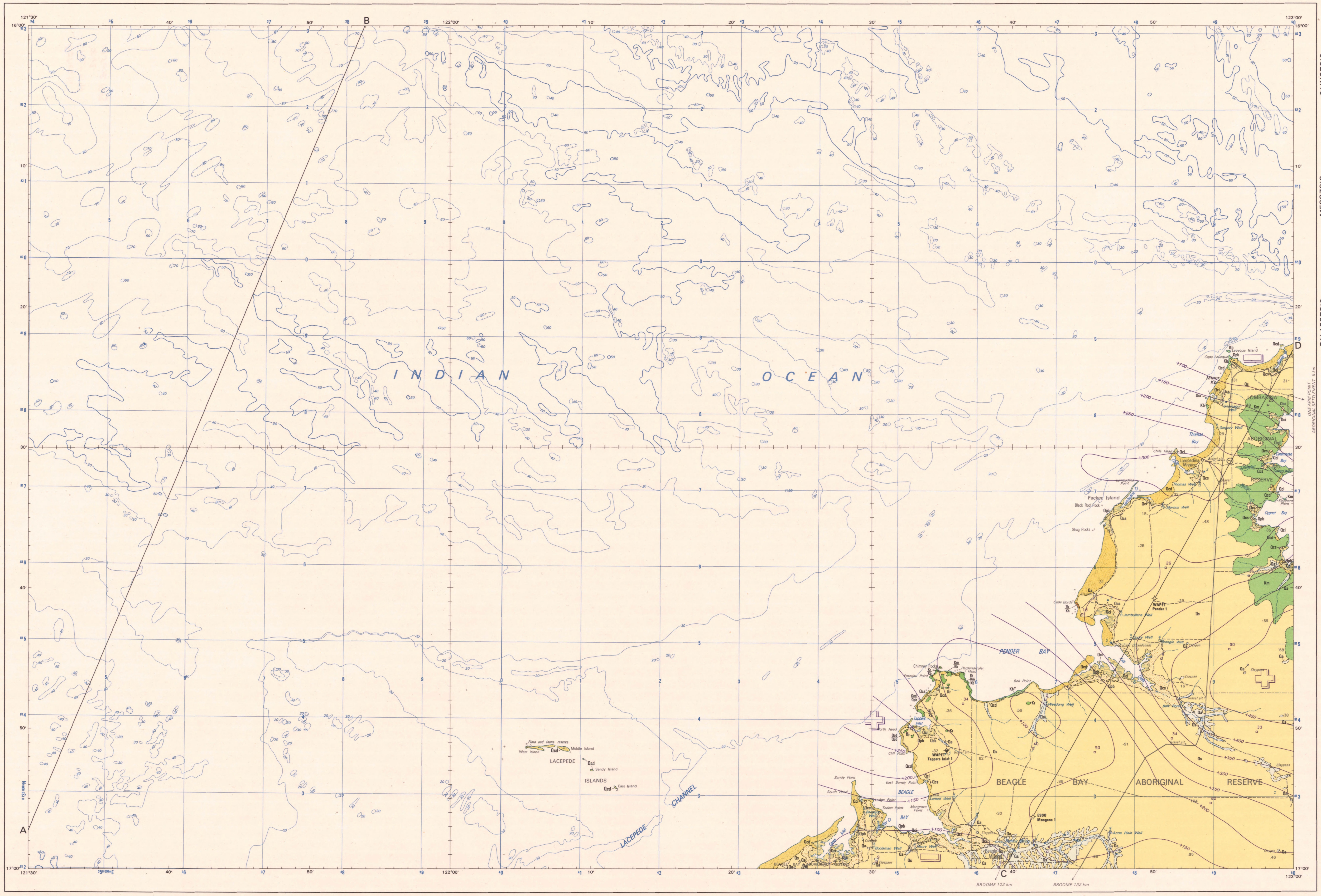
PENDER

WESTERN AUSTRALIA

AUSTRALIA 1:250 000 GEOLOGICAL SERIES

SHEET SE 51-2



Era	Period	Formation	Symbol	Description
CAINOZOIC	QUATERNARY		Qa	Sand, silt, clay; minor gravel: alluvial and lacustrine
			Qs	Sand, silt; minor gravel: mixed alluvial and aeolian
			Qcs	Clay, silt, sand; minor salt: supratidal mud flat
			Qci	Silty clay, black organic clay: tidal flat and mangrove swamp
			Qcd	Calcareous sand, partly oolitic: coastal aeolian dunes (includes reworked Qpb)
		Bossut Formation	Qpb	Calcareous and quartzose sandstone, fine to coarse; calcilutite, oolite; cross-bedded in part: coastal
	TERTIARY?	Borda Sandstone	Tb	Sandstone, fine; minor mudstone; basal conglomerate: fluvial?
MESOZOIC	EARLY CRETACEOUS	Emeriau Sandstone	Kr	Sandstone, poorly sorted; minor conglomerate; cross-bedded: fluvial to deltaic
		Melligo Sandstone	Km	Sandstone, fine to medium, well-sorted, pebbly in places; laminated to thin-bedded; silicified in part: beach
		Broome Sandstone	Kb	Sandstone, fine to very coarse; mudstone in part; minor conglomerate; ripple-marked, cross-bedded; bioturbated in part; plant fossils: shallow marine
	LATE JURASSIC TO EARLY CRETACEOUS?	Jarlemai Siltstone	JKr	Siltstone, claystone, sandstone: marine
	LATE JURASSIC	Alexander Formation	Ja	Sandstone, fine to coarse; interbedded mudstone: shallow marine
	EARLY? TO LATE JURASSIC	Wallal Sandstone	Jl	Sandstone; minor siltstone, conglomerate, lignite: continental to shallow marine
	EARLY TRIASSIC	Blina Shale	Rb	Mudstone, sandy in places: shallow marine
PALAEOZOIC	EARLY TO LATE PERMIAN	Liveringa Group	Pl	Sandstone, mudstone; minor limestone, conglomerate, coal: shallow marine to deltaic
	EARLY PERMIAN	Noonkanbah Formation	Pn	Mudstone, calcareous; fine sandstone, limestone interbeds: marine
		Poole Sandstone	Pp	Sandstone, very fine to fine; interbedded mudstone; minor limestone at base: shallow marine to lagoonal
	LATE CARBONIFEROUS TO EARLY PERMIAN	Grant Group	Pg	Sandstone, fine to coarse; mudstone; minor conglomerate: marine, partly glacial
	MIDDLE DEVONIAN TO EARLY CARBONIFEROUS?		DC	Limestone, dolomite, shale, siltstone, fine sandstone: marine
	EARLY ORDOVICIAN	Willara Formation	Ow	Limestone, partly dolomitic; interbedded shale and siltstone: shallow marine
		Nambeet Formation	Ot	Shale, grey to green; interbedded limestone and fine sandstone: shallow marine
PRECAMBRIAN			p€	Igneous, metamorphic, and sedimentary rocks

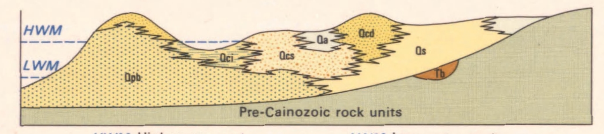
section and rock relationship diagram only

Geological boundary
Fault
Where location of boundaries, folds and faults is approximate, line is broken; where inferred, queried; where concealed, boundaries and folds are dotted, faults are shown by short dashes
Petroleum exploration well, dry, abandoned
Petroleum exploration well with show of oil, abandoned
Bore
Well
WH Waterhole
Windpump
S Water storage
Spring
30 50 Bathymetric contours in metres; closed depression
Rock awash; rock submerged
Cliff

Minor road
Vehicle track
Landing ground
Pender Homestead
Building
Yard
Minor administrative boundary
Trigonometrical station
.25 Elevation in metres
182 Selected gravity station with elevation in metres
+100 Bouguer anomaly contour (micrometres sec^{-2}), computer-plotter produced
Gravity anomaly — relative high
Gravity anomaly — relative low

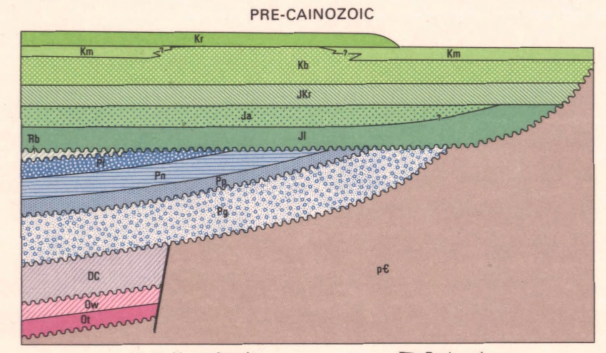
DIAGRAMATIC RELATIONSHIP OF ROCK UNITS

CAINOZOIC



HWM High water mark LWM Low water mark

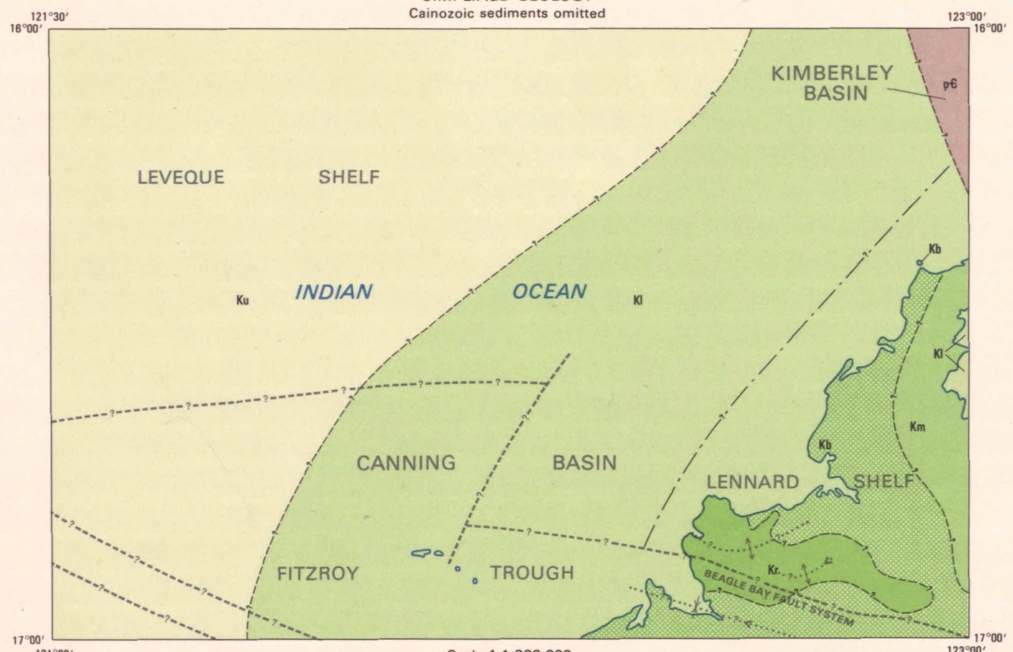
PRE-CAINOZOIC



Unconformity Facies change

SIMPLIFIED GEOLOGY

Cainozoic sediments omitted



Scale 1:1 000 000

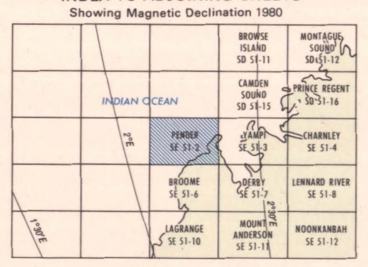
Symbol	Description
Ku	Undivided Late Cretaceous rocks; includes siltstone, marl, and claystone
Kl	Undivided Kb, Km, Kr

Tectonic feature boundary
Anticline, showing trend of plunge
Syncline, showing trend of plunge
Fault
concealed and inferred (from seismic data)

Published by the Bureau of Mineral Resources, Geology and Geophysics, Department of National Development and Energy. Prepared in collaboration with the Geological Survey of Western Australia. Issued under the joint authority of the Minister for National Development and Energy and the Minister for Mines, Western Australia. Base map supplied by the Division of National Mapping, topographic information shown is correct to 1979

INDEX TO ADJOINING SHEETS

Showing Magnetic Declination 1980



UNIVERSAL GRID REFERENCE

GRID ZONE DESIGNATION: 51K

100 000 METRE SQUARE IDENTIFICATION

TO GIVE A STANDARD REFERENCE ON THIS SHEET TO NEAREST 1000 METRES

SAMPLE POINT: Balk Bore

1 Read letters identifying 100 000 metre square in which the point lies: VB

SAMPLE REFERENCE: VB8842

If reporting beyond 18° in any direction, prefix Grid Zone Designation, as: 51KVB8842

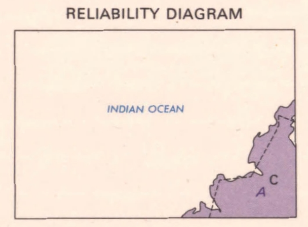
SCALE 1:250 000

5 0 5 10 15 20 25 Kilometres

BLUE NUMBERED LINES ARE 10 000 METRE INTERVALS OF THE AUSTRALIAN MAP GRID, ZONE 51

TRANSVERSE MERCATOR PROJECTION

RELIABILITY DIAGRAM



Geology C General reconnaissance: few traverses, mainly airphoto interpretation

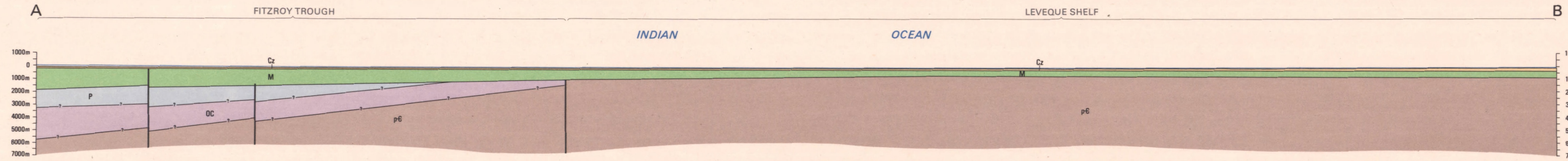
Helicopter traverse

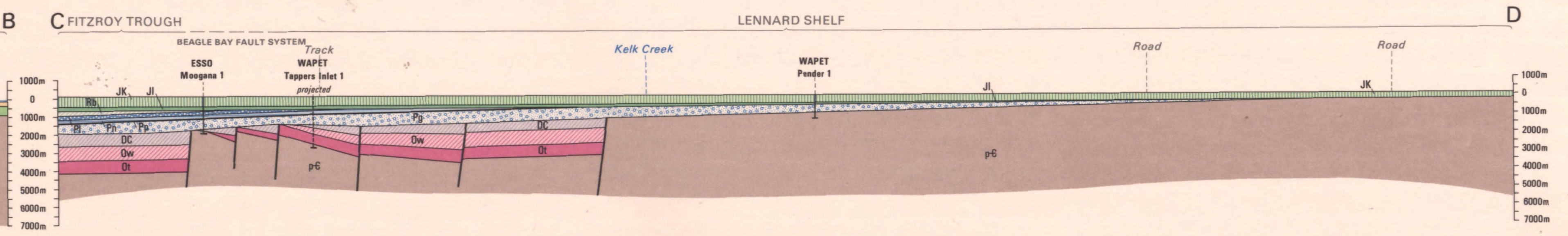
Gravity A Detailed survey

Geology 1948 by D.J. Guppy, A.W. Lindner BMR
1950 by R.O. Brunnschweiler BMR
1977 by D.L. Gibson, R.R. Towner BMR; R.W.A. Crowe GSWA
Compiled 1978 by D.L. Gibson, D.G. Walton BMR
Edited 1981 by J. Mitchell, A.S. Mikolajczak
Gravimetry 1956-65 by private companies
Design by Cartography Section, BMR
Drawn by Capital Drafting Consultants Pty Ltd
Printed by Mercury-Walch, Hobart, Australia

SCHEMATIC SECTIONS

Scale $\frac{V}{H} = 1$





Symbol	Description
Cz	Undivided Cainozoic rocks. Includes carbonates and fine sandstone
M	Undivided Mesozoic rocks. Includes Early Jurassic to Late Cretaceous rocks. Includes sandstone, siltstone, shale, claystone and fine detrital carbonates
P	Undivided Permian rocks. Includes sandstone, siltstone, shale
DC	Undivided Ordovician to Carboniferous rocks. Lithologies unknown
JK	Undivided Ja, JKr, Kb, Km, Kr

PENDER

SHEET SE 51-2

FIRST EDITION 1983