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Petrological and petrophysical study of Permian arenites for potential subsurface storage of natural gas, Sydney basin, New South Wales, Australia

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PETROLOGICAL AND PETROPHYSICAL STUDY OF PERMIAN ARENITES
FOR POTENTIAL SUBSURFACE STORAGE OF NATURAL GAS,
SYDNEY BASIN, NEW SOUTH WALES, AUSTRALIA

VOLUME I

A thesis submitted in (partial) fulfilment of the
requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

from

THE UNIVERSITY OF WOLLONGONG

by

STANLEY OZIMIC[✓] B.Sc.

Department of Geology
1980

I DEDICATE THIS THESIS

TO THE

OZIMIC[✓] AND KONECKI FAMILIES

*... and may the Lord help those
who help themselves.*

*(After: George Herbert,
1593-1633)*

Author's Statement

I declare that the research described in this thesis is my own except where the work of others is specifically acknowledged.

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ABSTRACT

The highly populated and industrialised areas of New South Wales are the "have-nots" with respect to natural gas reserves but are one of the largest markets for natural gas in Australia. Natural gas supplies are brought to these areas by a 1300 km long pipeline from the Cooper Basin in the northeast corner of South Australia. The expanding natural gas market in New South Wales will require, in the next decades, guaranteed supplies even in the event of insufficient deliverability through the Moomba-Sydney Pipeline or cut-off of the pipeline. Subsurface storage of natural gas in natural reservoirs near the market area offers one solution for guaranteeing supplies to this increasing market.

Petroleum exploration wells drilled between 1910 and 1973 in the Sydney Basin near Sydney tested the petroleum potential of the Permian Nowra Sandstone, Muree Sandstone and Snapper Point Formation. The present petrological, wireline log, structural and reservoir engineering study of water-bearing arenites in these formations resulted in the delineation of seven potential natural reservoirs near Sydney, suitable for storage and retrieval of natural gas. The structures of these reservoirs include both faulted and unfaulted gently folded anticlines, and an irregular dome. The areal extent and vertical closure range from 1 to 45 km² and 15 to 225 m respectively. The cap rocks to the seven reservoirs are Permian impermeable arenites, siltstone, claystone and shale beds of the Berry Formation, Mulbring Siltstone, Wandrawandian Siltstone, and Snapper Point Formation.

In spite of the growth of authigenic quartz, calcite, and siderite which has considerably reduced the primary intergranular porosity, the quantitative evaluation of wireline logs indicates the remaining average porosity for potential reservoirs in the Nowra and Muree Sandstone to be from 5.5 - 12.2 percent and from 5.4 - 6.8 percent in the Snapper Point Formation. Permeabilities to dry nitrogen gas for the Nowra and Muree Sandstone range from 1.0 to 23.4 millidarcies and for the Snapper Point Formation from 1.5 to 98.5 millidarcies.

A total potential storage capacity for the seven reservoirs is estimated to be $21\,342 \times 10^6 \text{ m}^3$ of natural gas.

Dural South

Nowra Sandstone reservoir	$8\,878 \times 10^6 \text{ m}^3$ of natural gas
---------------------------	---

East Maitland

Muree Sandstone reservoir	$4\,994 \times 10^6 \text{ m}^3$ of natural gas
---------------------------	---

Kurrajong Heights

Snapper Point Formation reservoir	$4\,730 \times 10^6 \text{ m}^3$ of natural gas
-----------------------------------	---

Kurrajong Heights

Berry Formation - Nowra Sandstone reservoir	$1\,546 \times 10^6 \text{ m}^3$ of natural gas
---	---

Mulgoa

Nowra Sandstone reservoir	$922 \times 10^6 \text{ m}^3$ of natural gas
---------------------------	--

Stockyard Mountain

Snapper Point Formation reservoir	$180 \times 10^6 \text{ m}^3$ of natural gas
-----------------------------------	--

Woronora

Nowra Sandstone reservoir	$92 \times 10^6 \text{ m}^3$ of natural gas
---------------------------	---

Their respective deliverability potential ranges from 0.041

$0.256 \times 10^6 \text{ m}^3$ of natural gas per day per well.

The potential storage reservoirs delineated in this study are favourably situated to the New South Wales gas markets of Sydney Metropolitan Area (Dural South, Mulgoa and Kurrajong Heights); Wollongong - Port Kembla and the South Coast (Woronora and Stockyard Mountain); and Newcastle - Hunter Valley (East Maitland). These reservoirs are also favourably situated relative to the existing pipelines: Moomba - Sydney (Wilton, 'City Gate'); Wilton, 'City Gate' - Wollongong, as well as to the proposed gas pipeline from Wilton, 'City Gate' to Newcastle.

Apart from their primary function as natural gas storage reservoirs for peak shaving and security of supply, they could also be used for storing gas manufactured from coal.

Of the three alternatives (duplication of Moomba - Sydney gas pipeline, building of liquid natural gas plants or development of subsurface gas storage) for adequate supply of gas to the New South Wales market, it would appear that the development of subsurface storage in natural reservoirs would be by far the most economically viable.

I

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INTRODUCTION

General statement

A petrological and petrophysical investigation of water-bearing arenites of the Permian Shoalhaven and Maitland Groups of the Sydney Basin, New South Wales, Australia, enabled delineation and evaluation of nine potential subsurface reservoirs for storage of natural gas.

Background

The highly populated and industrialised areas of New South Wales (N.S.W.) are the "have nots" with respect to natural gas reserves, even though these areas are one of the largest markets for natural gas in Australia. The natural gas supplies are brought in to these areas by long-distance pipeline (Moomba-Sydney) 1300 km from the Cooper Basin in the northeast corner of South Australia (Fig. 1). Of the 5 million N.S.W. inhabitants, 75% live in three centres along the narrow coastal strip between Newcastle (8%), Sydney Metropolitan Area (62%) and Port Kembla-Wollongong (5%).

As the estimated daily demand for natural gas in N.S.W. expands from 3.8 to $13.9 \times 10^6 \text{ m}^3$ in the years from 1980 to 1995 and beyond (Fig. 2, Table 1, The Pipeline Authority, 1976), the situation that is most likely to develop would be an insufficient deliverability through the Moomba-Sydney pipeline, to meet the projected demand.

Producing Fields ○

- 1 Roma area
- 2 Gippsland Shelf
- 3 Cooper Basin
- 4 Dongara/Mondarra/Yardarino
- 5 Barrow Island area

Pipelines —

- a Roma (Wallumbilla) to Brisbane
- b Gippsland Shelf to Longford
- c Longford to Melbourne
- d Longford to Western Port
- e Melbourne to Wodonga
- f Melbourne to Ballarat
- g Cooper Basin to Sydney/Wollongong
- h Cooper Basin to Adelaide
- i Dongara area to Perth, Kwinana, Pinjarra

XAUS-7-190

Fig.1 Australia: Gas producing fields and pipelines.

Fig.2 New South Wales : Natural gas supply, demand and pipeline capacity .

Table 1

Assessed demand for natural gas to the year 2000 in
New South Wales (After The Pipeline Authority, 1976)

Year	Low Demand $10^9 \text{ m}^3/\text{a}$	High Demand $10^9 \text{ m}^3/\text{a}$	Best Estimate $10^9 \text{ m}^3/\text{a}$
1976	.05	.05	.05
1977	1.06	1.06	1.06
1978	1.14	1.23	1.20
1979	1.23	1.42	1.30
1980	1.32	1.66	1.40
1981	1.42	1.91	1.59
1982	1.53	2.21	1.80
1983	1.65	2.56	2.05
1984	1.78	2.96	2.32
1985	1.91	3.43	2.64
1986	2.00	3.65	2.82
1987	2.08	3.89	3.01
1988	2.15	4.14	3.20
1989	2.22	4.41	3.43
1990	2.29	4.70	3.66
1991	2.35	5.00	3.91
1992	2.41	5.33	4.17
1993	2.46	5.68	4.45
1994	2.52	6.05	4.75
1995	2.56	6.44	5.07
1996	2.56	6.44	5.07
1997	2.56	6.44	5.07
1998	2.56	6.44	5.07
1999	2.56	6.44	5.07
2000	2.56	6.44	5.07

The expansion of the natural gas market in N.S.W. represents projected demands to supply northern N.S.W. through a proposed pipeline from Wilton "City Gate" to Newcastle. Lateral pipelines to Wagga Wagga, Cootamundra and the N.S.W. provincial centres Cowra, Orange, Bathurst, Lithgow, Goulburn, Young, Yass and Queanbeyan, and the Australian Capital Territory, have been proposed, and some are in the process to be build.

Because natural gas is used primarily for industrial and household heating, its consumption is subject to considerable annual, weekly and daily variation. A pipeline large enough to cope with the peaks of a highly variable demand would be very costly. Therefore a pipeline of economic size can only be feasible if it operates at or near capacity throughout the year, and if suitable large storage of natural gas near markets is available to support it.

Subsurface storage of natural gas is one of several means that may be employed to meet the peak demands of fluctuating load. Variations in the peak demands may occur in any one of the following patterns:

- Annual demand pattern (due to seasonal changes)
- Weekly demand pattern (due to industrial shut-down from Friday to Monday)
- Daily demand pattern (due to variations in the domestic market but to a lesser extent in the industrial).

For the natural gas distributor organisation there are several means available to meet the demand patterns.

For the annual demand pattern

- a - Subsurface storage
- b - Excess supply availability through duplication of pipeline
- c - Restriction to consumers

For the weekly and daily demand pattern

- a - Subsurface storage
- b - Excess supply available through duplication of pipeline and/or liquid natural gas plants
- c - Restriction to consumers

The problems of deliverability in N.S.W. will probably be experienced soon after year 2000 (Fig. 2) when the total projected demand will still be below the pipeline capacity; however annual, weekly and daily peak demands for natural gas may well exceed the capacity of the fully pressurised pipeline. To overcome the problems of deliverability in N.S.W. the following alternatives are available:

- duplication of pipeline,
- building of liquid natural gas plants,
- storage in subsurface natural reservoirs, or
- restriction of natural gas supply to consumers.

Purpose and objectives

The purpose of this study is to delineate potential subsurface natural gas storage reservoirs within the water-bearing Permian arenites of the Sydney Basin by petrological, petrophysical, reservoir engineering and structural methods. The objectives of the investigation were threefold.

The first objective was concerned with a study of Sydney Basin literature on regional geology, the history of petroleum exploration and the selection of petroleum exploration wells, drilled on structural closures for detailed petrological, petrophysical and structural analysis.

The wells selected are: Stockyard Mountain-1, Farmout Drillers No Liability (F.D.N.L.), 1963; Woronora-1, Australian Oil and Gas Corporation Ltd (A.O.G.), 1963; Kirkham-1, (A.O.G.), 1964; Dural South-1, Shell Development (Aust.) Pty Ltd (Shell), 1966; Kurrajong Heights-1, Exoil N.L., 1962; Mulgoa-2, (A.O.G.), 1960; and East Maitland-1, Planet Exploration Company Pty Ltd (Planet), 1963 (Figure 3).

The second objective involved a study to develop a methodology which would be appropriately applied to solve specific problems for delineation of potential subsurface natural gas storage reservoirs.

AUS 1-779

Fig. 3 Sydney Basin: Rock unit correlation (after Mayne et al. 1974)

The methods of approach employed for achieving these objectives were:

- (a) megascopic core study
- (b) petrological analysis
- (c) wireline log study
- (d) reservoir engineering analysis
- (e) structural analysis.

Details of methods employed are discussed in
Chapter II

The third objective was to determine the storage capacities and possible deliverability of the delineated potential subsurface natural gas storage reservoirs as well as their relationship to the future supply and demand of natural gas in the Sydney Basin area in the next decades.

The conclusions drawn for the reservoirs are developed in a concluding chapter (ChapterVII) to indicate the costs and ways in which the potential gas reservoirs could be developed for commercial use.

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Keywords definitionArenite:

A sedimentary rock consisting of sand grains more or less firmly united by some cement (silica, carbonate, iron oxide, etc).

Cap Rock:

A comparatively impervious stratum immediately overlying a reservoir.

Closure:

A closed anticlinal or domal structure.

Natural gas:

Raw gas - a mixture of hydrocarbons and nonhydrocarbons, which is recoverable at a well from an underground reservoir and is gaseous at the conditions under which its volume is measured or estimated (i.e. at standard conditions).

Condensate - Low-vapour-pressure products that are contained in the vapour phase in natural gas in the reservoir, and become liquid at standard field separation conditions.

Liquefied petroleum gases (LPG) - High-vapour-pressure products which are contained in natural gas. LPG contains only propane, isobutane, and normal butane.

Sales gas - A mixture of methane and ethane, and containing less than 3 percent CO_2 . Sales gas is raw gas that has been processed to remove condensate and LPG and any CO_2 in excess of 3 percent.

Porosity:

The ratio of the volume of all pore space to total bulk volume of a given rock sample.

Permeability:

The permeability of a porous substance is the ability of this substance to permit flow of fluid through its network of interconnected pore spaces. The total volume of the interconnected pore space is called the effective porosity; in clastic rocks it is generally equal to total or absolute porosity.

Reservoir:

A natural subsurface container of liquid or gas.

Reservoir rock:

Any rock with adequate porosity or fractures to permit liquid or gaseous hydrocarbons to be contained.

Shale volume:

Is the fraction of shale present in the total rock.

Spill point:

The lowest level of the closed contour.

Standard conditions:

The standard base conditions are 60°F (15.56°C) and 14.73 psia.

Structure:

A feature produced in the rocks by movement after deposition in which entrapment or storage of liquid or gas may occur.

Wireline logs:

Records obtained by lowering geophysical instruments into boreholes and recording continuously some physical properties of the rock.

Abbreviations and symbolsSydney Basin rock units

Rw	Wianamatta Group
Rh	Hawkesbury Sandstone
Rn	Narrabeen Group
Pi	Illawarra Coal Measures
Ucm	Upper Coal Measures
Pt	Tomago Coal Measures
Psg	Gerringong Volcanics
Psb	Berry Formation
Pmm	Mulbring Siltstone
Psn	Nowra Sandstone
Pmms	Muree Sandstone
Psw	Wandrawandian Siltstone
Pmb	Branxton Formation
Pgc	Greta Coal Measures
Pdfr	Farley-Rutherford Formations
Pdal	Allandale-Lochinvar Formation
Pssp	Snapper Point Formation
Pspb	Pebbly Beach Formation
Pswh	Wasp Head Formation

General

A	Area
A.S.L.	Above sea level
API	American Petroleum Institute
BBL	Barrels
bbl	"
B.C.L.	Below collar level
B.F.L.	Below floor level
Bg	Gas formation volume factor
B.K.B.	Below kelly bushing
B.M.R.	Bureau of Mineral Resources
B.R.T.	Below rotary table
CA	Caliper
cm	Centimetre
Cp	Centipose
D	Day
D.S.T.	Drill stem test
ES	Electrical log survey
F	Formation factor
FT	Foot
ft	"
Gsc	Gas initially in-place at standard conditions
Gps	Gas produced at standard conditions
Grm	Gram
GR	Gamma ray
h	Thickness
ITT	Interval transit time
K	Spontaneous potential coefficient
k	Permeability

k/h	Permeability/thickness
km	Kilometre
LL	Laterolog
N.S.W.	New South Wales
ML	Microlog resistivity
m	Metre
md	Millidarcy
mm	Millimetre
N	Number of wells
NaCl	Sodium chloride
Pi	Initial pressure
Ppc	Pseudo-critical pressure
ppm	Part per million
Pr	Reservoir pressure
Psc	Pressure at standard conditions
Psia	Pressure pound per square inch absolute
Psi	Pressure pound per square inch
Pwf	Well flowing pressure
Q	Flow rate
Rmf	Resistivity of mud filtrate
Rmfe	Resistivity of mud filtrate equivalent
Ro	Formation resistivity when 100% water saturated
Rt	True formation resistivity
Rw	Resistivity of formation water
Rwe	Resistivity of formation water equivalent
SP	Spontaneous potential
Sw	Water saturation
(I-SW)	Gas saturation
std	Stock tank barrel

Ti	Initial temperature
Tpc	Pseudo-critical temperature
Tr	Reservoir temperature
Tsc	Temperature at standard conditions
Twf	Well flowing temperature
t	time
V	Volume
Vw	Viscosity of water
W	Well
Z	Gas deviation factor
Zi	Initial gas deviation factor
$^{\circ}\text{F}$	Degrees Fahrenheit
$^{\circ}\text{C}$	Degrees Celsius
$^{\circ}\text{R}$	Degrees Rankine
μ	Viscosity
Δt	Sonic interval transit time
Δh	Time lapse
$\emptyset$	Porosity
%	Percent

Metric conversions

All measurements given in the company well completion and seismic survey reports used in this study were given in non-metric units. The following conversion factors were used.

<u>Non-metric units</u>	<u>Metric units</u>	<u>Conversion factor</u>
Foot	Metre	x 0.3048
Square foot	Square metre (m^2)	x 0.093
Cubic foot	Cubic metre (m^3)	x 0.02831685
Barrel	Cubic metre (m^3)	x 0.1589875

CHAPTER I

SYDNEY BASIN, N.S.W.

PART I - REGIONAL GEOLOGICAL SETTINGIntroduction

The Reverend W.B. Clarke, who arrived from England in 1839, is generally credited with being the first trained geologist to work in Australia. However, Berry, in 1822, gave the first geological account of Permo-Carboniferous strata on the south coast of N.S.W. and briefly described the rocks in the vicinity of Batemans Bay and the newly discovered Clyde River. The Reverend W.B. Clarke was the first to recognise the Sydney Basin as a geological entity: in 1847 he predicted that the coal seams cropping out around the margins of the basin were part of a single sedimentary unit that is present at depth beneath Sydney. The occurrences of coal measures close to Sydney inspired many of the early geological investigations in the Sydney Basin, both by officers of the Geological Survey of N.S.W. (established in 1855) and by individuals and mining companies. The resulting well documented observations of W.B. Clarke, F.W. Booker, T.W.E. David, L.F. Harper, L.J. Jones, H.G. Raggatt, and T.L. Willan, in particular (Mayne and Raine, 1972) provided basic geological information.

Limits of the Basin

Sydney Basin is part of a larger structure known as the Sydney-Bowen Basin which extends from Batemans Bay, N.S.W. north into Queensland (Fig. 4). This structure occurs as a downwarp within the Tasman Geosyncline between the Lachlan Geosyncline along the western and southern margins of the basin and the New England Geosyncline in the north and northeast. This structural basin is divided into northern and southern parts by a structural high near Narrabri, N.S.W. The southern part is further subdivided by the Mount Coricudgy Anticline into the Gunnedah Basin in the north and the Sydney Basin in the south (Fig. 5). Sydney Basin's western margin occurs where a series of erosional plateau surfaces of Permian sedimentary rocks unconformably intersect lower and middle Palaeozoic sedimentary rocks, lavas and batholites of the cratonized Lachlan Geosyncline. The north-eastern boundary of the basin is a partly faulted, partly conformable and locally unconformable contact with Carboniferous and Lower Triassic basement rocks of the New England Geosyncline.

The Sydney Basin (Fig. 5, Plate I) contains about 5900 m of Permian and Triassic sediments, which cover an area of about 36 000 km² onshore and about 16 000 km² on the continental shelf in N.S.W.

The Permian and Triassic sediments of the Sydney Basin were deposited as a result of fluctuating marine transgressions and regressions. The sedimentation of the basin was both initiated and controlled by tectonism. Therefore, sedimentation from Late Carboniferous is best discussed within the tectonic framework.

XAUS-7-198

Fig.4 Sydney - Bowen Basin (after Brown et al. 1968)

Fig. 5 Sydney Basin: Basin outline and structures containing closures.

Scheibner (1976) proposed a system of five tectonic stages (Table 2) during which varying types of sedimentation took place. In this thesis, discussion of the history of deposition will be limited to the Currabubula and Hunter Tectonic Stages which resulted in the Currabubula, Greta, Snapper Point and Nowra-Muree Depositional Episodes. History of deposition in the Sydney Basin is summarised in Figure 6.

Table 2

Sydney Basin tectonic stages

(after E. Scheibner, 1976)

Age	Tectonic stage	Depositional episode
Triassic	Hawkesbury	Wianamatta Hawkesbury Upper Narrabeen Middle Narrabeen Lower Narrabeen
Permian	Bowen	Newcastle Upper Tomago Lower Tomago
	Hunter	Nowra-Muree Snapper Point Greta
Late Carboniferous	Currabubula	Currabubula

Fig.6 Depositional history of the Sydney Basin (after Mayne and others,1974)

History of deposition

Currabubula tectonic stage

During the Late Carboniferous, Sydney Basin did not exist as a structural entity. The sediments within the area of the potential Sydney Basin comprised thick fluvial and glacial conglomerates which were restricted to valleys surrounded by highlands of moderate elevation (Fig. 7). Terrestrial and shallow marine sediments were deposited to the north on a broad shelf (Kullatine Shelf) and deep-water flysh sediments were deposited between the emergent New England Arch and a terminating subduction zone to the east (Figs. 7 and 8). Sediments were supplied to the Kullatine Shelf from both the active Ayr Volcanic Rift zone and from the New England Arch.

In the latter part of the Currabubula Tectonic Stage, Jadboro and Tallong Conglomerates, (Wasp Head Formation) were deposited in the southern part of the basin. Contemporaneous volcanic activity in the northeastern part of the basin resulted in deposition of a thick basaltic and rhyolitic sequence (Lochinvar Formation) during the Sakmarian Period (Table 2, Fig. 9).

Hunter tectonic stage

As the volcanism of Currabubula Tectonic Stage ceased subsidence and marine deposition continued into the succeeding Hunter Tectonic Stage. The Hunter Tectonic Stage deformed the New England Arch during Early Permian, causing the New England Fold Belt and the eastern margin of the Lachlan Fold Belt slowly to subside and form a more extensive continental shelf (Shoalhaven Shelf)

Fig. 7.
PALAEOGEOGRAPHY OF NORTHEASTERN NEW SOUTH WALES
(After Branagan et al., 1979)

Late Carboniferous

Early Permian

Late Permian to Middle Triassic

REFERENCE

Fig. .8.

TECTONIC DEVELOPMENT OF THE
SYDNEY BASIN

(After Branagan, et al. 1979)

REFERENCE

- Formation boundary
- Unconformity, disconformity or hiatus
- Terrestrial sediments, including coal
- Marine, near-shore and shoreline sandstone
- Marine siltstone and laminite, shallow marine, prodelta and delta front
- Volcanic flows, tuffs, breccias, etc., some sediment

Fig. .9.

CROSS SECTION OF THE SYDNEY BASIN
SHOWING SCHEMATIC STRATIGRAPHIC
RELATIONSHIP OF THE PERMIAN
SEQUENCE

(After Branagan, et al. 1979)

than had existed before (Figs. 7 and 8). Sediments deposited on this shelf were mainly sand and silt and are equated to lower Shoalhaven, Dalwood and lower Maitland Groups (Table 2, Fig. 9).

During the latter part of the Greta Depositional Episode (Table 2) a thick terrestrial sedimentary wedge, the Greta Coal Measures (Figs. 6 and 9) were deposited.

After the Greta Depositional episode subsidence resulted in a basin-wide marine transgression which expanded the depositional area almost to the presently defined limits of Sydney Basin.

In the north, the Greta Coal Measures were transgressed by marine Cessnock Sandstone. In the southern part of the basin, however, deposition of thick quartz-rich transgressive marine arenites of the Snapper Point Formation took place. Northward trending longshore currents distributed the sand over much of the southern, western and central part of the basin (Fig. 8, Table 3).

Following the Greta and Snapper Point Depositional Episodes fine-grained, fossiliferous, shallow marine silts of the Wandrawandian Formation and correlative Branxton Formation were deposited (Fig. 9).

An additional diastrophic episode resulting in a significant marine regression and subsequent transgression in the late Kunguriam and early Kazanian resulted in deposition of quartz-rich nearshore fossiliferous Nowra and Muree Sandstone formations; fine grained sands and silts of the overlying Berry Formation in the southern, western and central part of the basin and the Mulbring Siltstone in the northern part of the basin (Fig. 9).

				Interval	WESTERN AREA	NORTHERN AREA	CENTRAL AREA	SOUTHERN AREA				
								ILLAWARRA DISTRICT	CLYDE RIVER COALFIELD			
TRIASSIC	LOWER AND MIDDLE			14	WIANAMATTA GROUP			WIANAMATTA GROUP				
				13	Hawkesbury Sandstone			Hawkesbury Sandstone				
		NARRABEEN GROUP	GROSE SUB-GROUP		NARRABEEN GROUP	GOSFORD FORMATION	NARRABEEN GROUP	GOSFORD FORMATION				
			CALEY SUB-GROUP			CLIFTON SUB-GROUP		CLIFTON SUB-GROUP				
PERMIAN	UPPER	TATARIAN	7 - 11	ILLAWARRA COAL MEASURES (Western and Southwestern Coalfields)		SINGLETON COAL MEASURES WOLLOMBI COAL MEASURES (UPPER HUNTER) WITTINGHAM COAL MEASURES (UPPER HUNTER) NEWCASTLE COAL MEASURES (LOWER HUNTER) TOMAGO COAL MEASURES (LOWER HUNTER)	ILLAWARRA COAL MEASURES (Central Coalfield)	ILLAWARRA COAL MEASURES (Southern Coalfield)				
		KAZANIAN	6	Berry Formation	MAITLAND GROUP	Mulbring Siltstone	Budgong Sandstone	Budgong Sandstone				
			5	Megalong Conglomerate ? ? ?		Muree Sandstone	Nowra Sandstone	Nowra Sandstone				
			4			Branxton Formation	Wandrawandian Siltstone	Wandrawandian Siltstone				
	LOWER	KUNGURIAN	3	SHOALHAVEN GROUP	GRETA COAL MEASURES		Snapper Point Formation	Snapper Point Formation				
		ARTINSKIAN	2		DALWOOD GROUP Skeletal Formation and Gyarran Volcanics (MUSWELLBROOK)	Farley Formation	Pebbly Beach Formation	Pebbly Beach Formation				
			SAKMARIAN			1	Rutherford Formation	SHOALHAVEN GROUP CONJOLA SUB-GROUP		Wasp Head Formation	Wasp Head Formation	
							Allandale Formation					Clyde Coal Measures ? ?
							Lochinvar Formation					

Table 3 Time correlation of Permo-Triassic rocks. (after Mayne et al., 1974)

This diastrophic episode corresponding to the Hunter Tectonic Stage took place before the major mid-Permian diastrophism changed the Sydney Basin to its present configuration.

A marine regression in the late Kazanian brought dominance of marine sedimentation in Sydney Basin to an end (Fig. 6). This regression allowed coal swamps to spread from the northern to central part of the basin. The southern part of the basin however remained covered by shallow sea.

After the mid-Permian Hunter diastrophism, during the Bowen and Hawkesbury Tectonic Stages, the Sydney Basin evolved as a foredeep. Initially, sediments were rapidly shed from the elevated New England Fold Belt and transported in the southwesterly direction across the axis of the basin and deposited as regressive molasse wedges equated to Late Permian coal measures and basal Narrabeen Group. During the early Triassic deposition took place in less energetic streams flowing down the axis of the basin in a southerly direction. The major deposition of the basin terminated during the Middle Triassic (Branagan et al., 1979).

Structure

The structural history of Sydney Basin is poorly understood as it is not always possible to tell the time when particular structures developed. It is, however, assumed by numerous authors that the major structural features of the Sydney Basin were developed during three main periods of diastrophism: late Permian Hunter-Bowen Orogeny; possible late Triassic movements; and probable late Cainozoic epeirogenic movements (Wellman, 1979).

The structural history and tectonism of the Sydney Basin has been described and discussed in some detail by many authors including: David (1907), Raggatt (1938), Osborne (1950), Voisey (1959 a & b), Booker (1960), Bembrick et al., (1972), Mayne et al., (1974), Cook (1969), Scheibner (1976), and Branagan et al., (1979).

The structural features containing closures suitable for hydrocarbon accumulations are the: Hunter Valley Dome Belt; Kulnura, Mount Murwin and Woronora Anticlines; Lapstone and Nepean Monoclines; and Dural Dome (Fig. 5). Mayne et al., (1974) describes history and diastrophism of these structures in some detail. A number of wells have been drilled for hydrocarbons on the structures listed, however no large petroleum accumulations have been discovered.

Regional stratigraphy

The central region of Sydney Basin is covered by Triassic rocks whereas the Permian rocks outcrop in separate areas around the edges of the basin. Three different stratigraphic nomenclatures have evolved for separate areas within the basin in particular for the Permian sequences. Correlation of Permian rocks in recent years has been considerably improved as the result of data obtained from petroleum exploration wells, geophysical surveys and palaeontological studies.

The correlation of rock units in the basin (Table 3) by Mayne et al., (1974) is based on lithology, lateral continuity, roles of superposition, palaeontological and geophysical data. This correlation is related to the geological time scale on the basis of fossil evidence.

PART II - HISTORY OF PETROLEUM EXPLORATION

Introduction

The search for coal and its exploitation in the Sydney Basin led to the discovery in 1885 of natural gas in arenites of the Triassic Narrabeen Group in two wells: Narrabeen No. 1 and No. 2.

These and other occurrences of gas in rocks of Permian and Triassic age led to an intensive programme of exploration for hydrocarbons in Sydney Basin. The results of petroleum exploration have thus contributed significantly to the knowledge and understanding of sediments in the Sydney Basin.

Geological

Valuable basic geological information for petroleum exploration is contained in numerous publications and in unpublished Geological Survey of N.S.W. records, petroleum exploration companies reports and university theses. A summary of Sydney Basin geology including information on petroleum core and cuttings samples, is given in Mayne and Raine (1972) and Mayne et al., (1974). The data is also presented on 1:250 000 scale coloured geological maps produced by Geological Survey of N.S.W. A summary 1:500 000 map of the whole of the Sydney Basin was produced in 1969 (Plate 1).

Geophysical

Geophysical work commenced with an onshore aeromagnetic survey conducted by Australian Oil and Gas Corporation Ltd in 1954 (Table 4), and in later years was extended offshore for a distance of up to 48 km.

The first seismic survey, in 1957 (Table 5) was performed by the Geophysical Branch of the Bureau of Mineral Resources, supported by the N.S.W. Department of Mines. This initial survey demonstrated the usefulness of seismic work in the Sydney Basin, and a considerable amount of seismic surveying was done after 1957, both onshore and offshore. The marine surveys extended up to 48 km offshore but the results were not good, probably because the conventional shooting method employed used restricted charges in order to protect marine life. In the onshore part of the basin the terrain is generally unfavourable and large tracts are in built-up areas. To date a reasonable reconnaissance coverage has been achieved in the central and northern areas but coverage in the south is sparse.

In general the quality of seismic records was poor. Therefore, some reservations must be placed on the reliability of structure maps constructed from the seismic data.

Table 4

Sydney Basin, gravity and magnetic surveys

Name of Survey	Date	**Reference
<u>Magnetic Surveys</u>		
Sydney Basin test magnetic	1954	AOG (no report available)
Sydney Basin magnetic	1955	AOG (no report available)
West Maitland magnetic	1958	P.E. Gould (no report available)
Sydney-Nowra airborne magnetometer	1962-3	Smart (1963)
Terrigal aeromagnetic	1964	Central Coast Oil Pty Ltd (1964)
Sydney-Newcastle offshore magnetic	1966	Shell (1966b)
Aeromagnetic survey, Helensburgh area	1966	Coal Cliff Collieries Pty Ltd (1966a)
Stanwell Park offshore magnetic	1967	Ringis <u>et al.</u> (1970)
Broken Bay marine seismic and magnetic	1969	Longreach (1969)
BMR marine gravity, magnetic, seismic, and bathymetric survey	1971	BMR (no report available)

**All references in Table 4 are fully listed in Mayne et al. 1974

Table 4 (continued)

Name of Survey	Date	Reference
<u>Gravity Surveys</u>		
Sydney Basin NSW gravity	1954-6	AOG (no report available)
Sydney district gravity	1950-6	Hancock <u>et al.</u> (no report available)
Singleton area gravity	1955-63	AOG (no report available)
Gravity survey PEL 59	1961	Smart (1962d)
Helicopter gravity training survey and southern N.S.W.	1966	Lodwick & Flavelle (1968)
BMR marine gravity, magnetic, seismic, and bathymetric survey	1971	BMR (no report available)

From 1971 on no gravity surveys were conducted

Table 5
Sydney Basin, seismic surveys

Name of Survey	Date	** Reference
Central Sydney Basin seismic survey	1957	Robertson (1958)
Sydney Basin seismic survey	1961	AOG (1962a)
Newcastle-Maitland seismic survey	1962	Planet (1962)
Nowra-Coolah seismic survey	1962	Smart (1962a)
Singleton-Camden seismic survey	1962-3	AOG (1962b)
Woronora-Dural seismic survey	1962-3	AOG (1962c)
Otway and Sydney Basin experimental 'Vibroseis' seismic survey	1964	Anon (1965)
Darkes Forest seismic survey	1964	Coal Cliff Collieries (1965)
Offshore Sydney Basin marine seismic survey	1964-5	Shell (1964b)
Sydney-Newcastle seismic survey	1964-5	Shell (1964a)
Camberwell seismic survey	1965	AOG (1965a)
Richmond-Cessnock seismic survey	1965-6	Shell (1966a)
Werombi seismic survey	1965-6	Doyle <u>et al.</u> (1966)
Putty-Oakdale seismic survey	1965-6	AOG (1965d)

**All references in Table 5 are fully listed in Mayne et al. 1974

Table 5 (continued)

Name of Survey	Date	Reference
M.E.I. 25 seismic survey	1966	AOG (1966b)
Denman seismic survey	1966	AOG (1965c)
Stanwell Park seismic survey	1966	Coal Cliff Collieries (1966b)
Girvan seismic survey	1966	AOG (1966a)
Offshore Sydney seismic survey	1967	Shell (1967)
Port Jackson seismic survey	1967	Phipps & Emerson 91969)
Currumbene seismic survey	1969	Genoa (1969b)
Broken Bay marine seismic survey	1969	Longreach (1970)
Tasman-Bass Strait marine seismic and magnetic survey	1969	Magellan (1970)
BMR marine gravity, magnetic, seismic and bathymetric survey	1971	BMR (1972)
Sealion marine seismic survey	1971	Longreach (1971)

From 1971 on no seismic surveys were conducted.

Drilling

The first well drilled for petroleum in Sydney Basin was Richmond No. 1 located near Richmond. It was the first of three wells drilled in the same area between 1910 and 1916. Shows of natural gas were reported in each well, but no commercial production was obtained. From then on the drilling activity in Sydney Basin was somewhat sporadic. Figure 10 depicts the drilling activity from 1910 to 1978. Mayne et al. (1974) describes the history of petroleum exploration in Sydney Basin in great detail.

Since 1954, 60 petroleum exploration wells and several scout holes have been drilled in the Sydney Basin (Table 6, Figs. 10 and 11). All the wells have been onshore. Some of the wells began in Permian sedimentary rocks, others drilled through the Triassic sequence into Permian rocks, and some tested the Triassic section only. Several wells reached effective basement. Most wells were drilled on surface structures, but some were located to test seismically determined structures and a few of the more recent wells have been drilled where sections of clean sandstone have been predicted. The wells have provided a great deal of stratigraphic information and have given a reasonable coverage of reservoir conditions within the basin. However, commercial amounts of oil and gas were not found, and all the wells have been abandoned except Kulnura No. 1, Pogy No. 1 and Sunwell No. 1 which were suspended.

Fig.10. Petroleum drilling, Sydney Basin 1910 - 1978
(After Mayne et al. 1974, updated to 1978)

Table 6
Sydney Basin, petroleum exploration wells

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
1954-70						
Australian Oil and Gas Corporation Ltd	Kurrajong Heights No. 1	33°32'S 150°37'E	1954	1450.3 (later deepend by Exoil)	Gas trace at 610 m	Abandoned
Australian Oil and Gas Corporation Ltd	Dural (East) No. 1	33°41'S 151°03'E	1956-57	1586.9	Gas trace at 934.2 and 1073.9 m	Abandoned
Australian Oil and Gas Corporation Ltd	Dural (East) No. 2	33°40'S 151°01'E	1957-58	1971.8	20 000 m ³ /D gas at 1014.1 m	Abandoned
Australian Oil and Gas Corporation Ltd	Morisset No. 1	33°10'S 151°29'E	1957	174.2	Gas trace	Abandoned
Australian Oil and Gas Corporation Ltd	Morisset No. 2	33°10'S 151°27'E	1957	223.9		Abandoned
Australian Oil and Gas Corporation Ltd	Morisset No. 3	33°08'S 151°29'E	1957	158.3	Gas trace	Abandoned
Australian Oil and Gas Corporation Ltd	Morisset No. 4	33°09'S 151°31'E	1957	221.4	Gas trace	Abandoned
Australian Oil and Gas Corporation Ltd	Morisset No. 5	33°07'S 151°30'E	1957	83	Gas trace	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Australian Oil and Gas Corporation Ltd	Morisset No. 6	33°07'S 151°30'E	1958	92.4	Gas trace	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 1	34°05'S 150°43'E	1957	693	Dry gas at 357.8, 368.7, 413.3 m. 13 500 m ³ /D	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 2	34°05'S 150°44'E	1958	680.2	Dry gas at 328.2 and 518.2 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 3	34°09'S 150°43'E	1958	558.2	Dry gas at 278.8 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 4	34°05'S 150°42'E	1958	576.5	Dry gas at 355.9 and 368.7 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 5	34°05'S 150°46'E	1958	591.4	Dry gas at 252.8, 276.9, 372.1, 382.5, and 476.4 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 6	34°02'S 150°45'E	1959	604.2	Several gas shows below 268.4 m. 18 900 m ³ /D at 593.8 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 7	33°57'S 150°47'E	1959	520	1890 m ³ /D at 411.8 m and 2700 m ³ /D at bottom	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Australian Oil and Gas Corporation Ltd	Camden No. 8	33°53'S 150°44'E	1959	641.1	Dry gas at 531.3 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 9	33°58'S 150°48'E	1959	641.7	Dry gas at 410.5 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 10	33°56'S 150°46'E	1959	531.6	13 500 m ³ /D at 530.7 m	Abandoned
Australian Oil and Gas Corporation Ltd	Camden No. 11	33°57'S 150°45'E	1960	618.8	Dry gas at 502 and 534.7 m	Abandoned
Australian Oil and Gas Corporation Ltd	Mulgoa No. 2*	33°49'S 150°38'E	1958-59	1717.2	12 gas shows below 396.5 m yielded 1080 m ³ /D waning to 270 m ³ /D	Abandoned
Australian Oil and Gas Corporation Ltd	Baulkham Hills No. 1	33°45'S 151°01'E	1960-61	1069.9	Minor gas	Abandoned
Australian Oil and Gas Corporation Ltd	Mt Hunter	34°04'S 150°39'E	1962	1071.2	14 gas horizons yielded 1080 m ³ /D waning	Abandoned
Australian Oil and Gas Corporation Ltd	Loder No. 1*	32°38'S 151°08'E	1963	2063.9	Oil & gas shows in Branxton, Farley, & Rutherford Fms	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Australian Oil and Gas Corporation Ltd	Mt Murwin No. 1*	32°51'S 150°55'E	1963	887.6	Minor gas shows from UCM	Abandoned
Australian Oil and Gas Corporation Ltd	Mellong No. 1	33°00'S 150°42'E	1964	905.9	Minor gas shows	Abandoned
Australian Oil and Gas Corporation Ltd	Woronora No. 1*	34°12'S 150°55'E	1963-64	2314	Minor gas shows	Abandoned
Australian Oil and Gas Corporation Ltd	Kenthurst No. 1	33°40'S 150°59'E	1963	1066.6	310 m ³ /D at 436.8 m	Abandoned
Australian Oil and Gas Corporation Ltd	Fairfield No. 1	33°52'S 150°55'E	1964	854.9	Gas at 544 and 835.7 m	Abandoned
Australian Oil and Gas Corporation Ltd	Kulnura No. 1	33°13'S 151°12'E	1964	Started at 1919.4 TD at 2474.2	Gas at 2218.6 m. Outburst at 2342.4 m	Suspended
Australian Oil and Gas Corporation Ltd	Sedgefield No. 1	32°31'S 151°15'E	1964	687.5		Abandoned
Australian Oil and Gas Corporation Ltd	Cecil Park No. 1	33°52'S 150°51'E	1964-65	697.2	5400 m ³ gas p/d waning at 617.9 - 623.7 m	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Australian Oil and Gas Corporation Ltd	Cecil Park No. 2	0.8 km S of No. 1	1964	689.9	Minor gas	Abandoned
Australian Oil and Gas Corporation Ltd	Kirkham No. 1	34°02'S 150°42'E	1964	2563.8	Dry	Abandoned
Australian Oil and Gas Corporation Ltd	Badgelly No. 1	34°03'S 150°45'E	1964	660.6	Gas at 365.7 and 381.6 m	Abandoned
Australian Oil and Gas Corporation Ltd	Leehome No. 1	33°49'S 150°45'E	1965	664.6		Abandoned
Australian Oil and Gas Corporation Ltd	Belford No. 1*	32°39'S 151°17'E	1964-65	1175.5	Gas shows at 13 levels	Abandoned
Australian Oil and Gas Corporation Ltd	Camberwell No. 1*	32°32'S 151°06'E	1965	1908.1	Oil trace at about 720 m	Abandoned
Australian Oil and Gas Corporation Ltd	Martindale Nos. 1 and 1A*	32°30'S 150°37'E	1967	1182.2	Dry	Abandoned
Australian Oil and Gas Corporation Ltd	Berkshire Park No. 1	33°46'S 150°47'E	1968	1091.9	Dry	Abandoned
Australian Oil and Gas Corporation Ltd	Higher Macdonald No. 1*	33°12'S 150°55'E	1968	628.3	Dry	Abandoned
Australian Oil and Gas Corporation Ltd	Lower Portland No. 1	49 km N of Windsor	1968	890	Dry	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Sun Oil Co.	Sunwell No. 1	32°44'D 151°30'E	1953	632.6	Minor gas show	Suspended
Central Coast Oil N.L. (= Alkane Exploration Terrigal N.L.)	Terrigal Nos. 1 and 1A	33°26'S 151°26'E	1959-68	1885.5	Oil and gas shows	Abandoned
Planet Exploration Co. Ltd	East Maitland No. 1	32°46'S 151°37'E	1962	3051.2	Gas show	Abandoned
L.H. Smart Oil Exploration Co. Ltd	Greenwell Point No. 1	34°45'S 150°43'E	1962	51.9	Dry	Abandoned
L.H. Smart Oil Exploration Co. Ltd	Greenwell Point No. 2	34°45'S 150°43"E	1962	140	Dry	Abandoned
Exoil N.L.	Kurrajong Heights No. 1*	33°32'S 150°37'E	1962	Started at 1450.3, TD at 2783.3	Dry	Abandoned
L.H. Smart Oil Exploration Co. Ltd	Point Perpendicular No. 1	35°00'S 150°48'E	1962	177.5	Dry	Abandoned
Farmout Drillers N.L.	Stockyard Mt No. 1*	34°36'S 150°47'E	1962	1072.4	Gas trace	Abandoned

Table 6 (continued)

Company or Operator	Name of Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Alliance Oil Development	Cataract No. 1	34°19'S 150°53'E	1964-65	1306.6	Dry	Abandoned
A.J. Wood	Poggy No. 1	32°16'S 150°08'E	1964-67	734.1		Suspended
Planet Exploration Co. Ltd	Woodberry No. 1	32°47'S 151°41'E	1965-66	Dry	Abandoned	
Shell Development (Australia) Pty Ltd	Dural South No. 1*	33°43'S 151°01'E	1966	3060.7	Dry	Abandoned
Esso (Exploration and Production Australia Inc.)	Jerrys Plains No. 1*	32°28'S 150°56'E	1969	1596.4	Dry	Abandoned
Genoa Oil N.L.	Coonemia No. 1*	34°58'S 150°42'E	1969	797	Gas trace	Abandoned
Esso (Exploration and Production Australia	Howes Swamp No. 1*	33°07'53"S 150°41'32"E	1970	2562	Gas trace	Abandoned
Bridge Oil N.L.	Bringelly (Project NSW) No. 1	33°57'27"S 150°38'18"E	1973	704.4	Gas trace too small to measure	Abandoned

Table 6 (continued)

Company Operator	Name Well	Co-ordinates	Date Drilled	Total Depth (m)	Hydrocarbons	Status
Bridge Oil N.L.	Brinnelly No. 2	33°59'51"S 150°45'16"E	1973	760.5	Completed as a water well	Abandoned
North West Oil and Minerals Co. N.L.	Longley No. 1	33°21'S 150°17'30"E	1973	1031.1	Dry	Abandoned

* Drilling subsidised under the Petroleum Search Subsidy Act, 1959-1964.

From 1973 on no petroleum exploration wells were drilled

Fig. 11 Location of petroleum exploration wells (To 30.6.1978).
(After Mayne *et al.* 1974, updated to 1978)

CHAPTER II

METHODOLOGY

Chapter two consists of two parts. The first part describes the theoretical aspects of methodology used in this study and the second part contains examples of methods used. Full details of each of the potential reservoirs is given in Volume 2, Appendixes 1 to 7 inclusive.

PART I - THEORETICAL ASPECTS OF METHODOLOGY

Introduction

In any investigation, the methods of approach to be used and the techniques to be employed are of prime importance if the results are to be considered reliable and meaningful.

In this study time was devoted to an analysis of the suitability of techniques which could be applied to the study of a potential natural gas storage reservoir.

As a result, five main approaches were found desirable: megascopic examination, petrology, wireline log interpretation, reservoir engineering and structural analysis. Within each approach various techniques were used. A flow chart (Fig. 12) "Study Framework of a Potential Gas Storage Reservoir" has been included to show the sequence followed in this study.

STUDY FRAMEWORK OF A POTENTIAL GAS STORAGE RESERVOIR

In order to solve specific problems the approaches were grouped as follows: megascopic core and cuttings examination, petrology and wireline log interpretation were employed to determine the geometry, environment of deposition, provenance type, diagenetic history, reservoir rock type and the effective porosity and permeability of the potential reservoir.

Wireline log interpretation together with reservoir engineering and structural analysis were employed to determine the reservoir variables: gross and net pay intervals, area of closure, gross and net rock volume, spill point level and permeability/thickness in the investigated interval.

The techniques used in this study and their application to potential natural gas storage reservoirs will now be described and discussed.

Megascopic examination

This was carried out in two stages, namely, an initial literature study of relevant geological material from Sydney Basin and by a detailed study of selected arenaceous intervals which appeared to have the potential for storage of natural gas.

Forty core and one hundred and fifty cuttings samples from petroleum exploration wells were examined under low power binocular microscope. All samples were washed with water and their surfaces wetted for study. Shale and mudstone samples were washed and examined in kerosene.

The properties identified were: lithology, colour, grain roundness, grain size, grain sorting, textural variations, visible framework minerals and cements, sedimentary structures, tectonic features, fossils and estimation of visible porosity.

Petrology

Petrology was employed to obtain information on the textural properties, framework minerals and authigenic minerals including clay minerals and to assess the influence of diagenesis upon porosity and permeability in the studied potential natural gas storage reservoir.

The thin sections were cut both from cores and cuttings from seven petroleum exploration wells. Observations made in thin sections included: grain size, sorting, roundness and nature of grain contacts. Estimates were made of percentages of framework, accessory and cementing minerals, as well as the intergranular porosity.

Grain size was measured by micrometer ocular and compared with grain size scales (Fig. 13) by Ozimic (1975). Roundness was estimated visually by comparison with the roundness classes (Fig. 14) of Krumbein (1941) in: Pettijohn, 1957. Sorting was estimated by the ratio of the diameters of the largest to the smallest detrital grains present (after Pettijohn, 1957). A well sorted sandstone has up to three Udden size classes and the maximum diameter is at the most 8 times the smallest. Arenites with 4 to 6 grades, inclusive, show moderate sorting. In these the diameter of the

SCALES USED FOR MICROSCOPIC STUDIES

MODIFIED WENTWORTH SCALE		EQUIV. SCALES				SIEVE	MICROSCOPE CALIBRATIONS									
Type	Grade Name	mm	mm	micron	phi	SIZES (B.S.S.) mesh	Stereoscopic Microscope "Nikon SMZ" No. 38176 c.w. 10x eyepieces. "Zoom" Objective					Polarising Microscope "Leitz Laborlux" No. 562482 c.w. binocular head, 10x eyepieces Objective				
							0.8 x	1.0 x	2.0 x	3.0 x	4.0 x	3.5 x	10.0 x	25.0 x	50.0 x	100.0 x
GRAVEL	Cobble	64	64	μ	$\emptyset$											
	Very Coarse Pebble	32	32		-6											
	Coarse Pebble	16	16		-5											
	Medium Pebble	8	8		-4											
	Fine Pebble	4	4		-3		64	80								
	Very Fine Pebble	2	2		-2	5	32	40	80							
SAND	Very Coarse Sand	1	1		-1	8	16	20	40	60		67				
	Coarse Sand	$\frac{1}{2}$	0.5		0	16	8	10	20	30	40	33	100			
	Medium Sand	$\frac{1}{4}$	0.25		+1	30	4	5	10	15	20	17	50			
	Fine Sand	$\frac{1}{8}$	0.125		+2	60	2	2.5	5	7.5	10	8	25	62		
	Very Fine Sand	$\frac{1}{16}$	0.062		+3	120	1	1.2	2.5	3.7	5	4	12	31	62	
		$\frac{1}{32}$	0.031		+4	240 300	0.5	0.6	1.2	1.8	2.5	2	6	15	31	62
MUD (clay-silt)	Coarse Silt	$\frac{1}{64}$	0.015	32	+5				0.6	0.9	1.2	1	3	8	15	31
	Medium Silt	$\frac{1}{128}$	0.008	16	+6					0.46	0.6	0.5	1.5	4	8	15
	Fine Silt	$\frac{1}{256}$	0.004	8	+7						0.3		0.7	2	4	8
	Very Fine Silt	$\frac{1}{512}$	0.002	4	+8									1	2	4
	Coarse Clay	$\frac{1}{1024}$	0.001	2	+9									0.5	1	2
	Medium Clay			1	+10										0.5	1
	Fine Clay															

Fig. 14

Visual chart for estimating roundness and sphericity of sand grains
(After Krumbein 1941)

largest grain does not exceed that of the smallest by more than a factor of 64. All arenites with size range in excess of this have 7 or more grades and are therefore poorly sorted.

Grain contacts were classified according to the scheme proposed by Taylor (1950). This scheme groups grain contact as: tangential, long concave-convex and sutured. Grains having no contact with other grains in the plane of the thin section are termed as loose or floating grains.

Grain counts were made with the use of a "Leitz Laburlux" polarizing microscope and a mechanical stage with two knurled drums possessing click stops. Counting of each thin section was so arranged as to cover an area measuring 40 to 45 mm by 10 to 15 mm; 5 traverses were made. Spacing between the traverses was 3 mm and the horizontal point distance was 0.5 mm using the mechanical stage. A total of ten (10) thin sections were grain counted. Seven (7) from the Nowra Sandstone; one (1) from the Muree Sandstone; and two (2) from the Snapper Point Formation.

Between 108 to 332 points were counted for each thin section. The counts were converted to percentages in the usual manner.

Mineral percentages listed in the thin section descriptions (Vol. II) were visually estimated by comparison with charts (Figs. 15 and 16) proposed by Shvetsov (in:Terry and Chilingar, 1955).

Rock types were classified in accordance with the scheme (Fig. 17) devised by Folk et al. (1970).

PERCENTAGE ESTIMATE CHARTS

(After M.S. Shvetsov in R.D. Terry and G.V. Chilingar, 1955).

PERCENTAGE ESTIMATE CHARTS

(After M.S. Shvetsov in R.D. Terry and G.V.Chilingar, 1955).

Fig. 17

ARENITE CLASSIFICATION TRIANGLE

(After Folk et al. 1970)

Intergranular porosity was estimated visually. For this purpose some of the rock specimens were impregnated under vacuum and coloured with blue resin before thin sectioning. This method has been widely used for porosity study by the Institut Francais du Petrole which has reported satisfactory results (Bryan, 1968).

Wireline log interpretation

Well logging comprises measurement of various physical properties of the rocks in conjunction with a continuous measurement of depth; the two principle properties measured are resistivity and radioactivity.

Wireline logs from six Sydney Basin petroleum exploration wells were quantitatively interpreted for determination of porosity. The details of approach and interpretation are given in Appendixes 1 to 7 for each well examined.

In the current investigation the number and types of logs examined have been controlled by their availability. The following logs were studied: (i) resistivity; (ii) self potential; (iii) microlog; (iv) microcaliper; (v) caliper; (vi) gamma-ray; (vii) interval transit time; (viii) temperature. The logs were generally available at two scales, 1:500 and 1:200; the latter scale where available was chosen since it afforded greater detail. A brief description of the logs employed follows. Details of the principles, and measuring devices can be found in Wyllie (1957), Schlumberger Handbooks (1958, 1966, 1972) and White (1963).

Electrical resistivity logs

The unit of measurement is $\text{ohm-m}^2/\text{m}$, which is defined as the resistance between two faces of a cube of material, each edge measuring 1 metre. A system or device of six electrodes is used to measure this property, the electrodes being so spaced that three independent measurements are recorded simultaneously; the three different spacing values are recorded as curves which are designated: Short Normal AM = 16" (0.41 m); Long Normal AM = 64" (1.63 m); and Lateral AO = 18'8" (5.69 m).

Short Normal AM = 16" (0.41 m): A normal resistivity log is recorded with the A and M electrodes in the sonde about 16 inches (0.41 m) apart.

Long Normal AM = 64" (1.63 m): A normal resistivity log made with the A and M electrodes in the sonde (usually) 64 inches (1.63 m) apart.

The Short Normal curve value reads close to the invaded zone (the portion about a well hole into which drilling fluid has penetrated, displacing some of the formation fluid; this invasion takes place in porous permeable zones). The boundaries of beds greater than 2ft (0.61 m) in thickness will be recorded accurately on the Short Normal curve. The Long Normal curve is also influenced by the drilling mud, mud cake layer and invaded zone but is more influenced by the true resistivity (R_t) of the formation.

Lateral AO = 18'8" (5.69 m): A constant current is passed between a current electrode A on the bridle and an electrode on the surface

while the potential difference is measured across two potential electrodes, M and N, located on the sonde. The MN distance is small compared to the "spacing", the distance between the current electrode and the midpoint between the potential electrodes, typically about 18 feet 8 inches (5.69 m).

Resistivities observed in rocks are a function of the mineralised waters present which conduct electricity; they depend upon the amount of water present and its salinity. The matrix is assumed to be non-conductive. In shales and clays this water is intimately bonded to the clay plate surfaces as orientated layers, whereas in sandstone it is generally present in the pore spaces.

Resistivity logs have been used for the following purposes: (i) the location of bed boundaries; (ii) the identification of lithology; (iii) identification of coal seams; (iv) lithological and lithofacies correlation; and (v) estimation of porosity.

The effect of bed thickness on the configuration of normal and lateral curves

All the wells examined in this study have had three resistivity curves taken: short normal (16"), long normal (64") and lateral (18'8"). The shape of the resistivity curves and the value of the apparent resistivity are different according to the type of device (short normal, long normal or lateral), the spacing, the thickness of the bed and the diameter of the bore hole.

Depending on the distribution of electrodes, a device may, for instance, be good for showing the thin beds but may not give an exact representation of thick layers, whereas another device which permits the estimation of formation fluid content may not be suitable for locating formation or bed boundaries.

This combination of three curves recorded with three different devices is, however, not sufficient to give all the desired information. Theoretical considerations and field experience have shown that using one or several other spacings of the conventional type in addition to the standard one does not help much. To obtain more complex and accurate information from the electrical logging method requires the use of the new devices - Induction Logs in fresh mud and Laterologs in salty mud.

Normal resistivity curves: Having introduced the factors involved in the recording of the electrode resistivity curves in the preceding section, the effect of bed thickness upon these curves will now be discussed. Beds more resistive than the surrounding formations will be considered first. An example of this type formation would be an oil sand bounded by low resistivity siltstone and shales.

The solid lines on Figures 18, 19 and 20 show typical logs of a resistive bed recorded by the normal arrangement when the bed thickness is much less than approximately equal to, and slightly greater than the AM spacing. With reference to Figures 18, 19 and 20, the following remarks can be made: the curve is symmetrical with respect to the center plane of the bed. This is a characteristic of the normal device and will always hold true if the beds above and below the bed of interest are of equal resistivity. The curve shows a slight increase immediately above and below the bed. The peaks of

Fig. 19

Bed thickness approximately equal to
AM spacing (After C.R. Porter, 1975)

Fig. 20

Bed thickness greater than AM spacing
(After C.R. Porter, 1975)

these humps are theoretically located $1/2AM$ spacing above and below the boundaries of the bed, although in actual practice it is often difficult to use these humps to pick the bed boundaries because they are apt to be obscured by other beds or by a low mud resistivity. The curve shows a low apparent resistivity opposite these resistive beds. When the bed is very thin (Figure 18), the curve reaches a low value and remains there for some vertical distance. In this case the thin resistive streak actually appears to be a conductive bed with an apparent thickness greater than the true thickness. As the resistive bed gets thicker, and approaches the AM spacing, the low apparent resistivity opposite the bed disappears and when the bed gets slightly thicker than the electrode spacing (Figure 20), the apparent resistivity recorded by the normal device shows practically no change as it passes through the bed. A bed of this thickness, i.e., where bed thickness = AM, is referred to as a bed of "critical thickness". This characteristic of the normal electrode configuration is one of the reasons why it is often desirable to record two (2) normal curves of different AM spacings. This practice eliminates the possibility of missing any one bed with a single spacing.

The solid lines on Figures 21 and 22 show the curves to be expected when resistive beds of approximately twice the thickness of the AM spacing and very thick or "massive" beds are logged with a two electrode device. Again it should be noted that the curve is symmetrical with respect to the center line of the bed. However, the low apparent resistivity opposite the bed has disappeared and a conventional resistivity increase has taken its place. The bed appears to be thinner than its true thickness by an amount equal to the AM spacing used. Actually, the boundary of the bed occurs at a point which corresponds to approximately $2R_{sh}$. This characteristic of the

Fig.21

Bed thickness twice the AM spacing
(After C.R.Porter,1975).

Fig.22

Massive bed, more than twice the AM spacing
(After C.R.Porter, 1975).

normal curves makes it difficult to accurately pick the bed boundaries from the normal curve. It is to be emphasised that the resistivities recorded by the normal device may not be used for quantitative work unless the bed is at least twice as thick as the AM spacing of the curve, and should be four times as great.

The dotted lines on Figures 18-22 inclusive represent typical logs of conductive beds of various thicknesses. When logging conductive beds thinner than the electrode spacing AM, the slight increase in apparent resistivity above and below the beds is not present. This difference is the only feature that distinguishes a conductive from a resistive bed when the bed is thinner than the electrode spacing. When logging the thicker conductive beds (greater than the electrode spacing), the two electrode device records an apparent resistivity which is very close to R_t . This is also true for the thinner beds. However, in any case, the two electrode curve makes conductive beds appear thicker than their true thickness by an amount equal to the AM spacing. This factor is not usually serious in the case of the 16" and 18" normals, but presents a more serious problem when working with the 64" and longer normals.

It may be inferred from the figures shown that the best accuracy in the determination of the boundaries of the layers requires the shortest possible AM spacing. Figures 20 and 21 show, for example, that the difference between the "apparent" and "true" thickness of a bed is roughly equal to AM, hence, the shorter AM, the smaller will be the difference. Moreover, a resistive layer appears on a log as being resistive only when the bed is thicker than the spacing of the electrode. On the other hand, it is true that very short AM spacings are strongly influenced by the effect of the mud

column, since the diameter of the "sphere of influence" is so small that essentially only the mud column is included in its boundaries. Unless this mud column has high resistivity, the features of the diagrams will be rounded off when using these very short spacings.

Lateral curve: Because lateral curve measures the resistivity of the shell of a sphere it is much less affected by the mud and involved zones than is the normal resistivity curve.

Beds more resistive than the surrounding formation will be considered first. One example of this type of formation would be an oil bearing arenite bounded by low resistivity shales. The solid line on Figure 23 shows a typical log of a resistive bed recorded by a lateral electrode arrangement when the bed thickness is much less than the AO spacing. The thin bed is indicated by a sharp peak with an apparent resistivity much lower than R_t . A slight depression is observed above the layer, but a more striking feature is the presence of a zone of quite low resistivity below the layer, followed by a second peak. The top of the secondary peak, called a "reflection peak", is located at a distance from the bottom boundary exactly equal to the AO spacing. The zone of low apparent resistivity which separates the layer and the reflection peak is called the "blind zone".

Figure 24 shows the configuration of curve to be expected from the lateral device in a resistive bed with an AO spacing approximately twice the bed thickness. Again a slight depression is noted immediately above the bed. The curve then starts upward toward R_t , which it never reaches, and is triangular shaped with the peak at $1/2$ the MN spacing above the base of the bed. Also, there is the "blind zone" extending for a distance equal to the AO spacing below the bed and then the "reflection peak".

Fig.23

Bed thickness much less than AO spacing
(After C.R.Porter,1975).

Fig.24

Bed thickness one-third of AO spacing
(After C.R.Porter, 1975).

Figure 25 shows the curve to be anticipated from a lateral device logging a resistive bed with a thickness approximately equal to the AO spacing. The same comments apply to this case as to that represented in Figure 24, with the exception that the peak apparent resistivity will, in most cases, be higher than when the bed is thinner than the AO spacing. This case, where the bed thickness equals the AO spacing, is referred to as a bed thickness of "critical thickness", and is the most difficult case in actual practice to interpret with any degree of accuracy.

The particular features of Figures 23, 24 and 25 may be accounted for, at least qualitatively, by a very simple line of reasoning. When the current electrode A is above the bed, the current is forced upward, since this is the line of least resistance. If the M and N electrodes, which will be referred to as their center point, O, are just above the layer, the current density at O is less than it would be if the bed did not exist, all other conditions remaining the same. The apparent resistivity is less therefore, than R_{shale} . When A is above the layer and O is below the layer, O is again in a region of low current density (the MN electrodes being shielded from the current source A by the resistant bed), so that the apparent resistivity is again very low, and a blind zone is recorded until the moment A crosses the upper boundary of the layer. As A penetrates deeper into the layer, a greater part of the current flows downward, the current density at O increases, and so does the apparent resistivity. The reflection peak is reached when A is at the level of the lower boundary of the layer.

Figure 26 represents the case where the bed thickness is approximately 1.3 AO of 25' for the 19' AO spacing. It should be noted that in this case there is no noticeable blind zone. This is a characteristic of the lateral curve when the bed is thicker than the electrode spacing and results from the fact that it is no longer possible to have the bed between the current source A and the MN electrodes.

Figure 27 shows a typical lateral curve when logging a resistive zone much thicker than the AO spacing. All of the characteristics of lateral curves are again evident in this case, except that the blind zone no longer exists. One important fact is that in this case, the apparent resistivity at the peak of the curve is actually greater than the R_t of the bed.

A second example of lateral curve behaviour is in beds less sensitive than the surrounding formations. Example of this type of formation are salt water bearing arenites surrounded by comparatively tight shale beds.

The dotted line on Figure 23 shows a typical log recorded by the lateral electrode arrangement when the bed thickness is much less than the AO spacing. Immediately above the bed of interest the curve increases slightly, then, as the MN electrodes enter the conductive layer, the curve drops to a low value and gradually tapers back out to a value corresponding to the shale resistivity at a distance equal to the AO spacing below the bed. These characteristics make a conductive bed appear thicker than it actually is by an amount equal to the electrode spacing. It should be noted that the slight increase in resistivity immediately above the conductive bed is a characteristic of the lateral curve and does not mean that there is a

Fig.26
Bed thickness one third larger than AO spacing
(After C.R.Porter,1975).

Fig.27

Bed thickness much larger than AO spacing
 (C.R.Porter,1975).

resistive section at this level.

The dotted lines on Figures 24, 25, 26 and 27 show the curves to be expected from the lateral device in a conductive bed with an AO spacing approximately twice the bed thickness, equal to the bed thickness, .75 times the bed thickness and less than 1/2 the bed thickness, respectively. The significant features common to all these cases are (1) the slight increase in apparent resistivity immediately above the bed, (2) the indication of a value approximately equal to R_t in the bed itself, (3) a zone of low apparent resistivity extending from the AO spacing below the bed, effectively making the bed appear thicker by an amount equal to the AO spacing.

Summary: All the considerations discussed in the preceding sections are related to the case of a single bed being located between thick homogeneous formations. The interpretation of normal and lateral log curves is however much more complex in a series of interbedded thin beds, as in the case of Nowra Sandstone and Snapper Point Formation in Sydney Basin. For instance, in both Nowra Sandstone and Snapper Point Formation (Stockyard Mtn-1 and Kurrajong Heights-1) the thickness of the individual beds is very small and the beds are thinner than the electrode spacing on the sonde. Therefore the electrical measurements involve several beds at once and the apparent resistivity obtained in this case is an average value only, so that each separate bed was not able to be delineated.

On the other hand, where the average thickness of the beds was greater, but still smaller than the electrode spacing, each separate bed had its own response plus additional spurious peaks irrespective of whether the device was normal or lateral.

To distinguish the real significance of different features on the log curves is very difficult if not impossible. Attempts were made to refine and identify arenite beds in relation to normal and lateral curve responses. The results were however very poor. This was attributed to poor quality control of wire-line logging, almost no information on the nature of the drilling muds (its viscosity, density and resistivity), and in particular a lack of core material over the studied sequence for correlations and calibration.

For the purpose of quantitative porosity estimation it was decided on the advice of J.A.W. White (pers. comm. 1978) to use the lateral (AO 18' 8") curve values at intervals of 0.6 m (2 feet) with an understanding that porosity values so obtained are only approximate and serve as a comparative guide of porosity variation within the evaluated interval.

It has been recognised that the spot values taken at regular intervals on the resistivity curve produce spurious porosity values. As such this could have been eliminated simply by dividing the lateral resistivity log into sections to obtain a plateau value average resistivity. This value within the limits of reasonable quality control of wire-line logging would be a much closer approach to the true formation resistivity and would eliminate local peaks and valleys attributed to boundary effects on the resistivity curve. However, because of poor quality control of wire-line logging either approach would produce comparative porosity values only.

Therefore, considerable reservation must be placed on the reliability of porosity values if obtained from the resistivity curves using the porosity relationship $\phi = \sqrt{\frac{1}{F}}$ as is the case in this study.

This relationship is strictly applicable for arenites that contain no appreciable amount of shaley material rather than the shaly and thinly interbedded arenites of the studied formations.

Self potential log

The unit of measurement is expressed in millivolts and measurements are made from a base line near the centre of the log. The log records the naturally-occurring potential differences between a stationary reference electrode at the surface and a down-hole electrode which is mechanically pulled up the hole.

The electromotive forces which generate the S.P. current and cause variations on the log are considered to result mainly from two phenomena, namely electrofiltration and electro-osmosis. Electromotive forces caused by electrofiltration are considered electrokinetic in nature and are directly proportional to the pressure differences and electrical resistivity of the liquid, and are most important opposite a permeable formation. Electro-osmosis, thought to be electrochemical in origin (Schlumberger, 1972), takes place where two electrolytes come in contact with one another causing an electromotive force to be produced; in the case of a drill-hole, the drilling fluid and the salt water in the formation act as the electrolytes.

On the log a well-defined base line usually present on the right hand margin, corresponds to the "shale base line". If the formation fluid salinity is higher than that of the drilling fluid, then the current enters the formation and a negative (to the left) deflection can be observed. Thus a negative potential is produced. Although this deflection indicates porous and permeable beds, there is no direct relationship between the amplitude of the deflection and

the actual porosity or permeability.

The self potential log was used to determine the following: the position and thicknesses of permeable beds, correlation of permeable beds from one well to another and estimation of formation water resistivity and salinity.

Microlog

The unit of measurement is ohm-m²/m. A unit containing three small electrodes is used with a 1" (0.025 m) electrode spacing so designed as to investigate a small volume of formation adjacent to the hole. Two curves, a 1" x 1" (0.025 x 0.025 m) Lateral and a 2" (0.051 m) Normal curve, are recorded simultaneously.

Opposite a permeable zone the 2" (0.051 m) Normal records a higher resistivity than does the 1" x 1" (0.025 x 0.025 m) Lateral since it is less influenced by the mud cake because of its greater depth of investigation; this feature is known as positive separation. However, it is also possible to obtain positive separation where a hole is caved; this can be detected by reference to the microcaliper or caliper.

The microlog was used for the following purposes: (i) identifying permeable and porous zones within the sandstone reservoir; (ii) correlating permeable and porous zones within the reservoir facies; (iii) determining net pay thicknesses; (iv) identifying impermeable and highly resistive rocks, such as tightly cemented sandstones, siltstones and coal beds; and (v) identifying permeable and low resistivity rocks such as mudstones and shales.

Microcaliper log

This log records the hole diameter and also the thickness of the mud cake. The curve produced is a record of the distance between the faces of the two pads of the microlog sonde, and is recorded simultaneously with the microlog.

The Coal Measures display a characteristic response to the microcaliper, in that coal beds remain close to bit size whereas shales are usually caved out; furthermore, permeable and porous sandstones record less than bit size on the log because of the mud cake present.

The microcaliper log has been used in conjunction with the microlog to assist with the identification of permeable and porous zones within the sandstone facies.

Caliper log

As with the microcaliper this log records the hole diameter; it is calibrated in inches. The geometry of this sonde is different from the microcaliper in that three arms each extending over 2 cm in length are used.

The caliper log is more effective than the microcaliper when determining the cross-sectional area and volume of the hole. In addition, it is more versatile since it can be used in holes ranging from 5 cm to 75 cm in diameter, whereas the microcaliper is limited to holes between 12 cm and 50 cm. Where available this log was used to supplement the microcaliper data.

Gamma-ray log

Gamma-rays are high energy bursts of electromagnetic waves which are spontaneously emitted by certain radioactive elements; the important elements are potassium 40, uranium and thorium. Because the radioactive elements tend to concentrate in clays and shales rather than in clean formations the gamma-ray log reflects the shale content of a formation.

The units of measurement may be expressed as: counts per second (c.p.s.); microgram Radium equivalent per ton (u.g.m. Ra. eq/ton); and A.P.I. (American Petroleum Institute) units. The radioactivity is measured using Geiger Muller counters or Scintillation counters, and is recorded as a continuous line on the log.

The gamma-ray log was employed for the following purposes:

(i) assisting with identification of lithologies, especially sandstone and shale sequences; (ii) location of bed boundaries; (iii) lithological and lithofacies correlation; and (iv) calculation of shale volume.

Interval transit time log

The interval transit time log is a recording versus depth of time (Δt) required for a compressional sound wave to traverse 1 ft (0.3048 m) of the formation. Known as the interval transit time, (Δt) is the reciprocal of the velocity of the compressional sound wave. This was originally developed as an aid to seismic surveying, but additional development of down hole tools and a great deal of basic research has increased the usefulness of sonic velocity logging so that it has great utility in formation evaluation as well as seismic surveying.

The factors affecting formation velocity are:

- (1) rock type or lithology
- (2) overburden and hydrostatic pressure
- (3) formation fluid
- (4) porosity

In addition to the use of the sonic log for the determination of porosity there is also application in cement bond evaluation and fracture detection.

The interval transit time (Δt) log was employed mainly for estimation of porosity, assisting with identification of lithologies and location of bed boundaries.

Temperature log

The temperatures are measured in degrees Fahrenheit using a device containing a length of fine platinum wire; this wire quickly assumes the temperature of the fluids in the hole. The survey is generally run several hours after circulation has ceased in order for the mud to reach temperature equilibrium.

Temperature values recorded during the survey will be dependent upon the thermal conductivity of the formations penetrated and the hole size. Coal possesses a low thermal conductivity, shale is average, and sandstone has a high thermal conductivity.

A simple method has been developed by Fertl and Wichman (1977) for determining the maximum bottom hole temperatures (BHT) which are recorded during wireline logging and thus determine the static rock formation temperature.

Static formation temperature is an important working parameter for the geologist drilling and reservoir engineers. For example: After drilling to 3000 m the driller circulated six hours before starting to pull the drill pipes up. From the time the drill bit was pulled off bottom until the induction log started out of the hole, another seven hours elapsed. The maximum recording thermometer showed 104°C (220°F). Similarly, the compensated neutron - density log combination was pulled off bottom after passage of another 4½ hours. The maximum recorded temperature from this run was 107°C (225°F). The driller also decided to run the sonic log which was finally pulled off the bottom eight hours after compensated neutron - density log combination left the same point in the hole. The temperature recorded at the time was 108°C (228°F).

The basic criterion for the technique is the straight line relationship on semilogarithmic paper of maximum recorded BHT in °F versus the ratio of:

$$\frac{\Delta t}{t + \Delta t}$$

Where Δt = time after circulation stopped in hours

t = circulating time in hours.

Then, extrapolation of this straight line to a time ratio of

$$\frac{\Delta t}{t + \Delta t} = 1$$

will define time static formation temperature.

To determine the extrapolated static formation temperature the following pair of data are plotted as shown in Figure 28 and Table 7. The static bottom hole temperature at 3000 m is as shown on Figure 28, 113°C (235°F).

Fig. 28

Extrapolation of static bottom hole temperature.

Table 7

Temperature correction data

Point	Dimensionless time	Temperature °C (°F)
A $\frac{\Delta t}{t + \Delta t} = \frac{7}{6 + 7}$	0.538	104 (220)
B $\frac{\Delta t}{t + \Delta t} = \frac{7 + 4.5}{6 + 7 + 4.5}$	0.671	107 (225)
C $\frac{\Delta t}{t + \Delta t} = \frac{7 + 4.5 + 8}{6 + 7 + 4.5 + 8}$	0.765	109 (228)

Estimation of reservoir volume

The rock volume of potential reservoirs is calculated after the preparation of a structure map. The structure maps are subsurface contour maps of lines connecting points of equal elevations on the top of the mapped horizon or potential reservoir. A typical structure map prepared for this study is illustrated in Figure 29 (see Appendixes 1 to 7 inclusive for maps of all other structures).

Using a subsurface structure map alone, an area diagram (Fig. 30) may be constructed by plotting depth versus areas enclosed by contours for both top and if thickness known, the bottom of the mapped horizon. The spill point may also be located on the diagram.

When structural maps alone are used to calculate the rock volume a value for gross rock volume is obtained. To this a correction factor must be applied to obtain the net rock volume. This factor is determined by reference to wireline log interpretation, spill point

Fig. 29

Datum: Kelly Bushing 24.9m A.S.L.
Contour Interval: 50m

A B
|-----| Cross-sections

0 1 2 3 4 5 km

EAST MAITLAND STRUCTURE
STRUCTURE MAP ON TOP OF
MUREE SANDSTONE

(Modified after PLANET EXPLORATION CO. LTD, 1962, Newcastle -
Maitland Seismic Survey, BMR File 62/1596)

AREA DIAGRAM

Woronora-I Structure

level and the part of the studied interval which has adequate permeability.

Isopach maps are usually prepared as maps of net or gross rock volume. This is done where ample data is available. In this study however, only one control point was available (one well) for each individual reservoir. The principles of volume calculation are therefore straightforward.

The main concern encountered in the interpretation of net pay thickness from wireline logs, particularly in interbedded sandstone, siltstone and shale sequences, is whether each bed interpreted in the well is continuous throughout the area of the potential reservoir. Figure 31 shows a typical example of gross rock volume calculation using structure map, planimetry and pyramidal rule.

Planimetry: Planimeters are instruments for measuring the area of all shapes of plane figures. The area is obtained by tracing their perimeters. The Aristo 1137L Planimeter was used in accordance with instructions outlined in the hand manual. (Aristo-Werke Instruction for Use). By determining the number of planimetry units there are in one squared length, the area measured can be converted to squared length units by division of the two planimetry units.

Reservoir-engineering

Standard reservoir-engineering techniques were employed to estimate the potential natural gas storage capacity. Such estimates are most critical if development of a storage reservoir is to be considered.

Fig. 31

Planimetry work sheet.

APPENDIX

TABLE

PLANIMETRY RESULTS

STRUCTURE:

FORMATION:

REFERENCE STRUCTURAL MAP:

REFERENCE STRUCTURAL CROSS-SECTION:

COMMENTS:

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					

* Calibration of Instrument: Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

Volume = $\frac{\sqrt{(A_1 \times A_2)} + A_1 + A_2}{3} \times h$

The application of reservoir-engineering data to the calculation of potential natural gas storage reservoir contents was not particularly successful in this study. This was due to poor drill stem test results and incomplete data. Therefore only one pressure build-up analysis was possible (Appendix 1 - Stockyard Mountain). Absence of incremental pressure build-up hindered the full pressure build-up analysis, although the value of permeability was obtained. Dolan et al. (1957) and, Matthews and Russell (1967) describe the pressure build-up analysis in detail.

In the current study the following potential reservoir variables were estimated or calculated by reservoir-engineering methods: hydrostatic and reservoir pressure, permeability and permeability ($\times$) thickness, gas deviation factor, viscosity of reservoir water and the gas formation volume factor.

X-Ray analysis

Powder diffractometry was undertaken on selected samples from Nowra Sandstone and Snapper Point Formation arenites to identify positively various clay minerals named in the petrological descriptions.

A Phillips PW1010 Diffractometer fitted with a Phillips AW1050 goniometer, Cu radiation and Ni filter was used.

The principle of X-ray diffraction and the equipment used are described by Zussman (1967). The principles of clay analysis were adapted from the Geological Society of America Special Paper 126 (1970) by D. Carroll.

The selected samples were pulverised without fluid in an agate mortar. Approximately 1 gm of material 5 in size was pressed into a cavity mount. The samples were subjected to copper radiation with a receiving slit width of $\frac{1}{4}^{\circ}$. A scanning speed of 1° per minute and a time constant of 4 seconds. The samples were run on stainless steel discs as opposed to glass. Scans commenced at 4° (2θ) and continued through to 40° (2θ). All analyses were on untreated samples, however samples treated with glycol and heat can also be run for positive identification of chlorite.

Selected X-ray diffractograms obtained are given in Chapter IV.

PART II - METHODSResistivity determination of formation water (R_w) from
spontaneous potential (SP) logAfter Bateman, R.M. & Koenen, C.E.Method 1

The SP algorithm for the determination of formation water resistivity, R_w , conforms to the method of Gondouin, Tixier, and Simard (in: Bateman & Koenen, 1977) and published charts (Schlumberger, 1972). The basic relationship relating SP deflection to resistivity is given by equation A-1.

$$SSP = -K \log \frac{R_{mfe}}{R_{we}} \quad (A-1)$$

where: SSP = SP value in millivolts

$$K = 60 + .133 T_f$$

R_{mfe}/R_{we} = Equivalent resistivities, inversely proportional to ionic activities

T_f = Formation temperature, °F.

The determination of the equivalent mud filtrate resistivity, R_{mfe} , is given in Schlumberger (1972) and is also shown in the flow diagram (Fig. 32). Solution of equation A-1 yields the equivalent formation water resistivity, R_{we} . The published relationships (Schlumberger, 1972) for the conversion of R_{we} to the actual formation water resistivity, R_w , were curve fitted. These curve

FLOW CHART FOR DETERMINING RESISTIVITY OF FORMATION WATER
FROM THE SPONTANEOUS POTENTIAL LOG
(After Bateman, R.M., and Konen, C.E., 1977)

Adapted for Computer Programme (RWSP) by Kurylowicz, 1977

fits are shown below in Eqs. A-2 and A-3.

$$R_w @ 75^{\circ}\text{F} > .12 R_w = - .58 + 10^{(.69R_{we} - .24)} \quad (\text{A-2})$$

$$R_w @ 75^{\circ}\text{F} \leq .12 R_w = \frac{77R_{we} + 5}{146 - 337 R_{we}} \quad (\text{A-3})$$

The application of the above equations are shown in the SP flow diagram (Fig. 32). It may be observed from the flow diagram that all calculations are performed at 75°F , except the determination of the ratio R_{mfe}/R_{we} . The calculated R_w is converted to formation temperature as the final step in the program. The conversion of resistivities to temperatures other than 75°F may be accomplished by applying Eq. A-2.

Resistivity determination of formation water (R_w) from
interval transit time porosity ($\emptyset \Delta t$) and resistivity (R_t)
cross-plot

Method 2

Resistivity (R_w) of formation water can be determined satisfactorily from a sonic-resistivity cross-plot. In this method $\emptyset \Delta t$ readings are taken in the water-bearing intervals and are plotted against the equivalent resistivity readings on a grid (Fig. 33).

The grid depends on the formula used in determining the formation factor F . In well consolidated formations with strong cementation, formula $F = \frac{1}{\emptyset^2}$ (Schlumberger, 1972) is used.

RESISTIVITY VS POROSITY

FIG. 33

Dural South - 1, (2152.7-2156.7 m)

The sonic-resistivity plot works well in clean consolidated sandstone formations, but often tends to give high R_w values when relatively small amounts of shale are present.

Table 8 summarises the data used and obtained from the cross-plot on Figure 33.

Once the resistivity of formation water is known the equivalent concentration of NaCl (ppm) can be obtained from the Schlumberger chart given in Figure 34 (Schlumberger, 1972).

The estimate of the NaCl concentration is important for calculation for formation water viscosity and hydrostatic pressure of the potential reservoir.

Determination of hydrostatic pressure

Method 3

Hydrostatic pressure (and equivalent pressure gradient) is the pressure exerted at any point, caused by the weight of the liquid. The hydrostatic pressure in a subsurface natural reservoir exerted by a column of liquid is calculated as shown in the following example:

Table 8

Woronora, interval transit time porosity ($\emptyset\Delta t$) and
resistivity (R_t) cross-plot data

Depth interval m	Resistivity AO = 18'8" ohms-m ² /m	$\emptyset\Delta t$ %	Rw ohm/m	NaCl ppm
1561.1	120	11.0		
1561.7	140	8.4		
1562.4	180	8.1		
1563.0	250	7.5		
1563.6	330	6.4		
1564.2	390	9.9		<u>4000.00</u>
1564.8	400	9.2	<u>0.75</u>	
1665.4	410	7.7		
1566.0	430	8.4		
1566.6	480	8.6		
1567.2	450	7.7		
1567.8	450	8.6		
1568.5	450	9.2		
1569.1	450	9.5		
1569.7	460	6.4		
1571.5	470	6.6		
1572.7	250	6.0		

Fig. 34

Resistivity of solutions, (From Schlumberger 1972)

Example: R_m is 1.2 at 75°F (point A on chart). Follow trend of slanting lines (constant salinities) to find R_m at other temperatures; for example, at Formation Temperature (FT) = 160°F (point B) read $R_m = 0.56$. The conversion shown in this chart is approximated by the Arps formula: $R_{FT} = R_{75^\circ} \times (75^\circ + 7) / (FT \text{ (in } ^\circ\text{F)} + 7)$.

Dural South-1: Nowra Sandstone Formation reservoir

Depth (average)	7060 ft (2152 m)
NaCl concentration in reservoir water (Method 1 and 2)	3000.00 ppm @ 167°F
Density of reservoir water	1.0040
Normal pressure gradient (Schlumberger, 1972)	0.443 psi/ft (1.42 psi/m)

Pressure gradient for Nowra Sandstone Formation reservoir

Density of NaCl solution x normal pressure gradient

$$\begin{aligned}
 &1.0040 \times 0.433 \quad (1.004 \times 1.42) \\
 &= \underline{\underline{0.4347 \text{ psi/ft}}} = \underline{\underline{(1.426 \text{ psi/m})}}
 \end{aligned}$$

Hydrostatic pressure for the same reservoir

$$= \underline{\underline{3069 \text{ psi}}} \quad (\underline{\underline{3069 \text{ psi})}}$$

Estimation of formation water viscosityMethod 4

The viscosity of water is primarily a function of temperature and water salinity. Figure 35 shows this relationship.

Schlumberger

WATER VISCOSITY

© 1974 SCHLUMBERGER

Find μ_{wvf} .Given: $C_{NaCl} = 150,000$ ppm $T_{wf} = 200^\circ\text{F}$

1. Enter abscissa at $T_{wf} = 200$.
2. Go up to $C_{NaCl} = 150,000$.
3. $\mu_{wvf} = 0.43$ cp.

Fig. 35

Water viscosity determination chart, (From: Schlumberger 1974)

Determination of volume of shale

(After Poupon & Gaymard, 1970)

Method 5

Volume of Shale: since many wireline logs are substantially affected by clay in the formation, a reliable evaluation of the clay content is essential in formation evaluation from logs. This classical approach of obtaining volume of shale from the gamma-ray was employed throughout this study.

If the radioactivity level of the clay is constant, and if no other mineral in the formation is radioactive, the gamma-ray reading may be expressed as a linear function of clay content.

The formula is therefore written as:

$$\text{Volume of shale} = \frac{\text{GR} - \text{GR min}}{\text{GR max} - \text{GR min}}$$

Where GR = Gamma Ray (actual reading)

GR min = Gamma Ray reading in clean sandstone intervals

GR max = Gamma Ray reading in clay intervals

$$\text{e.g.: } V. \text{ shale} = \frac{45 - 20}{70 - 20}$$

$$= \frac{25}{50}$$

$$= 0.50$$

Volume of shale for this interval

$$= \underline{\underline{50 \text{ percent}}}$$

Formation factor and porosity

It has been established experimentally that the resistivity of a clean formation (i.e., one containing no appreciable amount of clay) is proportional to the resistivity of the brine with which it is fully saturated. The constant of proportionality is called formation resistivity factor, F . Thus, if R_o is the resistivity of a non-shaly formation sample 100% saturated with brine of resistivity R_w ,

$$F = \frac{R_o}{R_w}$$

For a given porosity the ratio R_o/R_w remains nearly constant for all values of R_w below about one ohm-m. However, experiments show that in more resistive waters, the value of F is reduced as R_w rises, and as the grain size of the sand decreases. This phenomenon is attributed to a greater proportionate influence of the surface conductance of the grains, in fresher waters.

The porosity, $\emptyset$, of a rock is the fraction of the total volume occupied by pores or voids. Formation factor is a function of porosity, and also of pore structure and pore-size distribution.

Archie (1942) proposed the formula:

$$F = a/\phi^m$$

where m is the cementation factor. The constant a is determined empirically.

Satisfactory results are usually obtained with:

$$F = \frac{.81}{\phi^2} \quad \text{in sands}$$

$$F = \frac{1}{\phi^2} \quad \text{in compacted formations}$$

Within their normal ranges of application these two formulas differ little from the so-called "Humble formula":

$$F = \frac{0.62}{\phi^{2.15}}$$

This is the relationship used in the Schlumberger charts, unless otherwise specified.

While the Humble formula is satisfactory for sucrosic rocks better results are obtained using $F = 1/\phi^2$ in chalky rocks and $F = 1/\phi^{2.2 \text{ to } 2.5}$ in compact or oolitic rocks. In some oolitic rocks, m may be as high as 3.0 (Schlumberger, 1972).

Porosity estimation from resistivity logs

When no porosity log is available, an estimate of porosity in clean, water-bearing formations may be made from resistivity log readings. If the zone under investigation is water bearing in the bottom, or if there is a nearby water-bearing formation known to have similar porosity, a porosity value can be derived from the appropriate F - ϕ relationships and one of the formulas:

$$F = R_o/R_w \quad \text{or} \quad F = R_{xo}/R_{mf}$$

Method 6

The formulae of Archie (1942) for the empirical relationship between the formation resistivity factor (F), porosity (ϕ), water saturation (S_w) and true resistivity (R_t) in clean arenite beds were used to calculate porosity from resistivity logs.

The relationship is as follows:

$$F = \frac{R_o}{R_w} = a \phi^{-m}$$

$$\frac{R_o}{R_t} = S_w^n$$

where m = porosity exponent or cementation factor, which varies between 1.5 and 3

a = proportionality constant varying from 0.6 to 1.5

R_o = resistivity of the formation when 100 percent saturated with formation water

R_w = formation water resistivity

R_t = true formation resistivity

n = saturation exponent; often $n = 2$.

"Archie's Law" assumes that $m = 2$ and $a = 1$.

The porosity ($\emptyset$) relationship is therefore:

$$\emptyset = \sqrt{\frac{1}{F}}$$

Example: $R_o = R_t = 110 \text{ ohm-m}^2/\text{m}$

$R_w = 0.83 \text{ ohm-m}^2/\text{m}$

$$F = \frac{R_t}{R_w} = \frac{110}{0.83} = 132$$

$$\emptyset = \sqrt{\frac{1}{132}}$$

$$\emptyset = 0.087$$

$\therefore \underline{\text{Porosity } (\emptyset) = 8.7 \text{ percent}}$

The Archie formula for several values of m are represented graphically on Figure 36.

Calculation of porosity ($\emptyset$) from interval transit time log (Δt)

(By M.R.T. Wyllie (Schlumberger, 1972))

Method 7

This method of calculating porosity is more accurate since it is corrected for shale content. The formula used is:

$$\emptyset \Delta t = \frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} - \left(\frac{\Delta t_{sh} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}} \right) \times V_{sh}$$

where: $\Delta t_{\log}$ = Interval transit time value read on the log

Δt_{ma} = Interval transit time of the matrix

Δt_{sh} = Interval transit time of shale

Δt_{fl} = Interval transit time of formation fluid

V_{sh} = Percent shale volume in the formation (Method 5, this Chapter)

FORMATION FACTOR VERSUS POROSITY

(After Schlumberger 1972)

Fig. 36

Example: (all values assumed)

$$\begin{aligned}
 \emptyset \Delta t &= \frac{69 - 5.12}{189 - 51.2} - \frac{67 - 51.2}{189 - 51.2} \times 0.65 \\
 &= \frac{17.8}{137.8} - \frac{15.8}{137.8} \times 0.65 \\
 &= 0.1292 - (0.1147 \times 0.65) \\
 &= 0.1292 - 0.0746 \\
 &= 0.0546
 \end{aligned}$$

Porosity ($\emptyset \Delta t$) = 5.4 percent

Rock density evaluation

Method 8

$$\text{Rock density} = \frac{\text{Weight of rock}}{\text{Volume of rock}}$$

Example for a core plug

- Dry weight = 21.66 gm
- Rock volume = 8.84 cm³
- Pore volume = 0.99 cm³
- Grain volume = 7.85 cm³

$$\begin{aligned}
 \text{Rock density} &= \frac{\text{Dry rock weight}}{\text{Rock volume}} = \frac{21.66}{8.84} \\
 &= \underline{\underline{2.45 \text{ gm}}}
 \end{aligned}$$

$$\begin{aligned}
 \text{Grain density} &= \frac{\text{Dry rock weight}}{\text{Rock volume}} = \frac{21.66}{7.85} \\
 &= \underline{\underline{2.76}}
 \end{aligned}$$

Determination of porosityMethod 9

$$\text{Porosity } (\emptyset) = \frac{\text{Pore volume of core plug}}{\text{Rock volume of core plug}} \times 100$$

Example 1

$$\frac{\text{Pore volume}}{\text{Rock volume}} = \frac{0.99}{8.85}$$

$$\text{Porosity } (\emptyset) = \underline{\underline{11\%}}$$

Determination of permeabilityMethod 10

$$\text{Basic formula (Gas or Liquid)} \quad k = \frac{Q}{T} \times \frac{L}{A} \times \frac{1}{P} \times u \times 1000$$

where k = Permeability (millidarcies)

Q = Volume flowed thr. plug (cm^3)

T = Time for this volume to flow (sec.)

L = Length of plug (cm)

A = Area of plug (cm^2)

P = Pressure differential across plug (atmos.)

I. For air or nitrogen

$$\frac{1}{P} = \frac{2P_2}{P_1^2 - P_2^2}$$

where P_1 = inlet pressure in atmospheres = Gauge pressure + atmosphere pressure

P_2 = outlet pressure in atmospheres = Atmospheric pressure

Example (Stockyard Mountain-1, Snapper Point Formation; Core No. 7)

Plug Length	= 3.52 cm	Time for flow	= 11.0 sec.
Plug area	= 6.42 cm ²	Gas Temperature	= 22°C
Quantity flowed	= 100 cm ³	Viscos. of N ₂	= 0.0176 cp
Atmospheric pressure	= 725 mm	@ 22°C	
		Gauge pressure	= 535 mm

First calculate $\frac{1}{P}$

$P_1 = 725 + 535 = 1260$ mm Convert to atmos. = $\frac{1260}{760} = 1.658$ atmos.

$P_2 = 725$ mm Convert to atmos. = $\frac{725}{760} = 0.954$ atmos.

$$\frac{1}{P} = \frac{2P_2}{P_1^2 - P_2^2} = \frac{1.908}{2.749 - 0.910} = 1.038$$

$$\therefore k = \frac{100}{11} \times \frac{3.52}{6.42} \times 1.038 \times 0.0176 \times 1000 = \underline{\underline{91.3 \text{ md}}}$$

II. For liquids

$$\frac{1}{P} = \frac{1}{\text{Gauge Pressure in atmospheres}}$$

Example (same sample as used in last example)

Plug Length	= 3.52 cm	Brine Temperature	= 20°C
Plug Area	= 6.42 cm ²	Brine Conc.	= 8 200 ppm NaCl
Quantity flowed	= 1 cm ³	Viscos. of Brine at 20°C	= 1.14 cp
Time for flow	= 32.0 sec.	Gauge Pressure	= 248 mm

First calculate $\frac{1}{P}$ Gauge Press. = $\frac{248}{760} = .326$

$$\frac{1}{P} = \frac{1}{.326}$$

$$= 3.067$$

$$\therefore k = \frac{1}{32.0} \times \frac{3.52}{6.24} \times 3.067 \times 1.14 \times 1000$$

$$= \underline{\underline{60.1 \text{ md}}}$$

Gas deviation factor (Z) and gas formation volume factor (Bg)

The gas deviation factor (Z) represents the degree to which a natural gas deviates from an ideal gas under the effects of pressure and temperature. The ideal gas law states:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

where pressure (p) is in absolute units (psia, kg/sq cm, atmospheres), volume (V) is in consistent units (cu ft, cu m), and temperature (T) is in absolute units (°R, °K). Incorporating the gas deviation factor, the relationship for natural gases becomes:

$$\frac{p_{sc} V_{sc}}{T_{sc}} = \frac{p_{wf} V_{wf}}{Z T_{wf}}$$

or, related to the reciprocal of the gas formation volume factor:

$$\frac{1}{B_g} = \frac{V_{sc}}{V_{wf}} = \frac{1}{Z} \frac{T_{sc}}{T_{wf}} \frac{p_{wf}}{p_{sc}}$$

Hence, $1/B_g$ can be determined only as accurately as Z is known.

Fig. 37 is the nomograph for determining the gas deviation factor, (Z) as a function of normalised (pseudo-reduced) pressure and temperature. This normalisation is accomplished by comparing the well-flowing pressure and temperature to the pseudo-critical pressure (p_c) and temperature (T_c); these are laboratory-derived characteristics of a given natural gas. The pseudo-reduced

pressure (p_r) is the ratio of the well-flowing pressure (p_c): $p_r = p_{wf}/p_c$. Likewise, $T_r = T_{wf}/T_c$. Absolute pressures and temperatures must be used. The pseudo-reduced pressure and temperatures are, of course, dimensionless. The gas deviation factor, (Z), is obtained from Figure 37, by entering p_r on the abscissa, going vertically to T_r , then horizontally to Z on the ordinate.

Gas deviation factor (Z) used in this study was derived from the Moomba-Sydney pipeline gas analysis (Table 9) since it is assumed if subsurface natural gas storage in Sydney Basin is taken up this type of gas would be used to fill the potential storage reservoirs.

The gas formation volume factor (B_g) is the ratio of the volume occupied by a certain weight of gas at a given temperature and pressure to the volume occupied by the same weight of gas at standard conditions Katz et al. (1959).

The gas formation volume factor (Fig. 38) may be calculated from the following formula:

$$\frac{1}{B_g} = \frac{P_r}{P_{sc}} \times \frac{T_{sc}}{T_r} \times \frac{1}{Z}$$

Where: P_{sc} = Pressure (psi) @ standard conditions

P_r = Reservoir pressure (psia)

T_{sc} = Temperature (°R) @ standard conditions

T_r = Reservoir temperature (°R)

Z = Gas deviation factor

This formula incorporates the gas deviation factor (Z).

Schlumberger

NATURAL GAS DEVIATION FACTOR

After Standing and Katz, Ref. 3.

Pseudo-Reduced Pressure, p_{pr} Find z .Given: $P_{wf} = 2,000$ psia $P_{pc} = 650$ psia $T_{wf} = 200^\circ\text{F}$ (660°R) $T_{pc} = 410^\circ\text{R}$

1. $p_{pr} = P_{wf}/P_{pc} = 2,000/650 = 3.07$.

2. $T_{pr} = T_{wf}/T_{pc} = 660/410 = 1.61$

3. Enter abscissa (top) at 3.07 (p_{pr}). Go down to T_{pr} of 1.61, between 1.6 and 1.7 lines.

4. $z = 0.828$

Fig. 37

Gas deviation factor (Z), nomograph, (From: Schlumberger 1974)

Table 9Pipeline natural gas composition

COMPONENTS	MOLECULAR WEIGHT.	MOL FRACTION
Methane	16.042	.96998
Ethane	30.068	.00000
Propane	44.094	.00001
Iso-Butane	58.120	.00000
N-Butane	58.120	.00000
Iso-Pentane	72.146	.00001
N-Pentane	72.146	.00000
Hexanes	86.172	.00000
Heptanes Plus	114.22	.00000
Hydrogen Sulphide	34.076	.00000
Carbon Dioxide	44.010	.03000
Nitrogen	28.016	.00000
	Total	1.00000

GAS FORMATION VOLUME FACTOR (Nomograph)

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Find 1/B_g.

Given: P_{wf} = 140 kg/sq cm
T_{wf} = 93°C
z = 0.828

- 1. Enter P_{wf} scale at 140 kg/sq cm. Follow lines as in small diagram.
- 2. 1/B_g = **135**

Fig. 38

Gas formation volume factor (Bg) nomograph, (From: Schlumberger 1974)

Therefore the gas formation volume factor (B_g) is the most critical variable for estimates of natural gas storage capacity in any potential reservoir. As the number of the gas formation volume factor (B_g) may be quite small, its reciprocal is commonly used ($\frac{1}{B_g}$).

Methods 11 and 11a show the calculations of both the (Z) and (B_g) factors.

Calculation of gas deviation factorMethod 11

Calculation of gas deviation factor (Z) for
Mulgoa, Nowra Sandstone potential gas storage reservoir:

Reservoir pressure	2183.3 psia
Reservoir temperature	132.0 °F
Standard conditions, pressure	14.73 psia
Standard conditions, temperature	60.00 °F
Pseudo-critical pressure	684.85 psia
Pseudo-critical temperature	350.15 °R

$$\begin{aligned}
 \therefore \text{Pseudo-reduced pressure} &= \frac{2183.3 + 14.73}{684.85} \\
 &= \underline{\underline{3.2}}
 \end{aligned}$$

$$\begin{aligned}
 \text{Pseudo-reduced temperature} &= \frac{132.0 + 460}{350.14} \\
 &= \underline{\underline{1.7}}
 \end{aligned}$$

Using nomograph Figure 37, the gas deviation factor
(Z) for Mulgoa gas storage reservoir is 0.86.

Calculation of gas formation volume factorMethod 11a

Gas formation volume factor is calculated according to the following formula:

$$B_g = \frac{P_r}{P_{sc}} \times \frac{T_{sc} (^{\circ}R)}{T_r (^{\circ}R)} \times \frac{1}{Z}$$

where P_r = Reservoir pressure (psia)

P_{sc} = Standard conditions pressure (14.73 psi)

$T_r (^{\circ}R)$ = Reservoir temperature in Rankine ($^{\circ}R$)

$T_{sc} (^{\circ}R)$ = Standard conditions temperature $60^{\circ}F + 460^{\circ}F$
($520^{\circ}R$)

Z = Gas deviation factor (Fig. 37)

Figure 38 (nomograph) shows a quick method of estimating gas formation volume factor.

Volumetric reservoir estimateMethod 12

The only feasible method of estimating the potential natural gas storage volume in a field which has no production history, is the volumetric method, according to the following formula:

$$\text{Gas "in place": } V_g = A \cdot h \cdot \emptyset \cdot (1 - sw) \cdot B_g$$

where V_g = Volume of potential natural gas stored

A = Area of reservoir

h = Net pay thickness

$\emptyset$ = Porosity (fractional %)

$(1 - sw)$ = Gas saturation in the reservoir (fractional)

B_g = Gas formation volume factor

Reservoir depletion estimateMethod 13

The time (t) in days required to deplete a particular reservoir to a particular level can be calculated according to this formula:

$$t = \frac{0.7 \times Gps}{n \times Q}$$

where Gps = Gas initially stored

 n = Number of wells

 Q = Flow rate per day per well

0.7 = Depletion to seventy percent of total
gas initially stored

Example

$$t = \frac{0.7 \times 10 \times 10^9 \text{ m}^3}{50 \times 2.5 \times 10^6 \text{ m}^3}$$

$$t = \underline{\underline{56 \text{ days}}}$$

CHAPTER IIISTRATIGRAPHY AND PETROLOGY OF SHOALHAVEN AND MAITLAND GROUPS

The third chapter of this thesis consists of four parts, which deal with detailed aspects of the stratigraphy, and petrology of four formations of the Permian Shoalhaven and Maitland Groups.

Introduction

The geology and stratigraphy of the Permo-Triassic rocks of the Sydney Basin has been discussed in some detail by Vallance and Branagan (1968), Osborne (1948), Bryan et al. (1968), Packham (1969), Menzies (1974) and Branagan et al. (1979).

An important contribution in the field of stratigraphy has also been made by Mayne et al. (1974) for its basin wide correlation (Table 3) of the Permo-Triassic rock units based on petrological and geophysical studies.

Individual formations of the Shoalhaven and Maitland Groups studied in this thesis will now be described in some detail.

PART I - SNAPPER POINT FORMATION

Two potential natural gas storage reservoirs have been delineated in the arenites of the Snapper Point Formation intersected in Stockyard Mountain-1 and Kurrajong Heights-1 wells (Appendixes I and V).

Definition and type locality

The Snapper Point Formation (Gostin and Herbert, 1973) in the south and the Greta Coal Measures (David, 1888) in the north have been correlated through deep wells on lithological, stratigraphical, palaeontological and seismic evidence. The correlation is based on comparison of lithology of the Snapper Point Formation with that of the underlying and overlying formations. Geological evidence is sparse in the area where it is postulated that the Greta Coal Measures interfinger with the marine Snapper Point Formation, but the correlation is supported by seismic evidence. Snapper Point Formation conformably overlies the Pebble Beach Formation and consists dominantly of sublitharenite (Folk et al. 1970), siltstone and conglomerate.

In the type area the Snapper Point Formation is about 170 m thick and generally consists of well bedded quartz-rich fine-grained arenite with thin layers of coarse pebbly arenite and conglomerate. Marine fossils and silty worm burrows are abundant, and concretions of calcite, pyrite, and siderite also occur. The cross-bedding and ripple marks indicate that the currents flowed northwest. The type area for the Snapper Point Formation is on the south coast (Gostin, 1968; Gostin and Herbert, 1973; Dickins et al., 1969) where it is exposed from Clear Point to Snapper Point, and from Willinga Point to Crampton Island. The name Snapper Point Formation was proposed by

Gostin (1968) for the upper sandy unit of the Conjola Formation, which has been upgraded to sub-group status within the Shoalhaven Group.

Age

Dickins et al. (1969) assigns the age of the Snapper Point Formation and its correlative (Greta Coal Measures) in the northern part of the basin as being Upper Middle Artinskian.

Subsurface lithology

In the wells used in this study the following sequences of Snapper Point Formation were encountered.

Stockyard Mountain-1 (Alcock, 1968a)

Thickness (m)

Sublitharenite, medium to coarse-grained, with minor shale beds tending to be most abundant at top and bottom. Pebbles of quartz, and sedimentary, volcanic and metamorphic rock. Quartz cement at top and bottom of sequence.

Brachiopods and bryozoa. Burrow structures. Total 185.9

Kurrajong Heights-1 (Pitt, 1968)

Thickness (m)

Sublitharenite, and litharenite, fine to coarse-grained, with carbonaceous and micaceous siltstone and mudstone beds. In places pebbles are concentrated in layers. Thick shelled brachiopods are common. Some worm tubes also occur. The cements are calcite, quartz and rare dawsonite. Total 239.2

Petrology

The results of petrological studies discussed in this section are based on core and cutting samples from two petroleum exploration wells. The Snapper Point Formation occurs in these wells over the following intervals:

Stockyard Mountain-1, 574.8 - 629.1 m, and

Kurrajong Heights-1, 1889.7 - 1965.9 m

The average arenite framework consists of quartz grains (61-69%), K-feldspar (3-4%), chert grains (2%), mica flakes (1%), calcite (3%), siderite (3%), and rock fragments: sedimentary (4-7%), metamorphic (4%), and volcanic (3%).

Accessory minerals include tourmaline, pyrite, zircon, rutile, sericite and dawsonite.

The framework is cemented by calcite and minor siderite (7%) (Stockyard Mountain-1), and by calcite, siderite (6%) and quartz (5%) (Kurrajong Heights-1). Calcareous and carbonaceous clay (5-8%) fills the interstices.

In Stockyard Mountain-1 the lack of quartz overgrowths and general lithification appears to be due to the white clay coating on the quartz grains (Plate 2). In Kurrajong Heights-1 quartz overgrowths are also present, but do not greatly affect the lithification of the arenites.

Development of siderite and pyrite suggest a change from the initial oxidising environment to one of reducing conditions and possibly indicate the development of brackish back-barrier lagoons. Other diagenetic developments are the growth of authigenic crystals of calcite and dawsonite in both reservoirs, and dolomite crystals in the

PHOTO 1; Stockyard Mountain-1, strongly silicified sublitharenite

PHOTO 2; Stockyard Mountain-1, clay coated quartz grains

Stockyard Mountain-1 reservoir. These diagenetic changes have only partially obliterated the primary porosity.

No fractures were observed, although there are numerous horizontal and sub-horizontal partings in Stockyard Mountain-1 Core No. 7.

The laboratory determined porosity on Core No. 7 in Stockyard Mountain-1 ranges from 1 to 16 percent. No cores were cut in the Kurrajong Heights-1 reservoir. Microscopic examination revealed some intergranular porosity; however percentage estimation was not carried out.

Snapper Point Formation was deposited in a marine environment, where the NaCl concentration was probably in excess of 33 000 ppm. The present NaCl concentration of less than 6 000 ppm suggests post-depositional intermixing of connate and meteoric waters, thus indicating permeability at some stage during diagenesis.

Depositional environment

The Snapper Point Formation correlative Greta Coal Measures were deposited during a marine regression - transgression from the northern part of the Sydney Basin and coal swamps which developed in the upper Hunter Valley in the Sakmarian extended into the lower Hunter Valley as the sea retreated. A marine influence during the deposition of the Snapper Point Formation is indicated by the high content of boron (Swaine, 1962). Marine fossils, principally brachiopods and pelecypods, indicate marine conditions throughout the Snapper Point Formation. The high sand/shale ratio suggests that the basin was shallow and not sheltered from open sea.

The detrital constituents and matrix in the Snapper Point Formation suggest deposition in marine waters, with reducing conditions at least during diagenesis. The sedimentary structures, carbonaceous stringers and siderite evident in the core samples provide supporting evidence for shallow, near-shore deposition. This thick arenite unit might represent deposition in a laterally migrating offshore bar complex.

Isopach and lithofacies distribution

The restored isopach map of the Snapper Point Formation and correlative Greta Coal Measures is given in Figure 39. Greta Coal Measures are up to 480 m thick in an easterly trending depression in the north that is cut off structurally by the Hunter Thrust along the northeastern margin of the basin. The Greta Coal Measures are divided from the Snapper Point Formation by a westerly trending arch in the Cessnock area.

Lithofacies distribution map (Fig. 40) indicates a high sand/shale ratio in the southern and central areas where the Snapper Point Formation is predominantly a fine to coarse grained pebbly sublitharenite. In the northern area the sand/shale ratio is also high. The grain size and sand/shale ratio decreases to the northwest where, at Muswellbrook in the upper Hunter Valley, siltstone and shale are a major component of the sequence between the coal seams. Fining or coarsening-upward sequences could not be recognized on wireline logs and the geometry of arenites within the Snapper Point Formation could not be determined because relatively isolated data points are available.

Fig.40 Lithofacies map, Greta Coal Measures and correlative Snapper Point Formation.
(After Mayne et al. 1974)

PART II - WANDRAWANDIAN SILTSTONE AND CORRELATIVE BRANXTON FORMATION

The Wandrawandian Siltstone forms the cap rock to the Snapper Point Formation potential gas storage reservoir in Kurrajong Heights-1 well (Appendix V).

Definition and type locality

The Wandrawandian Siltstone (Joplin et al., 1952) is a sequence of fine-grained litharenite and siltstone, with scattered pebbles, mainly of quartz. It is exposed around Jervis Bay and in the valleys draining the western margin of the basin. McElroy et al. (1969) states that although true siltstone is probably quite rare in the formation, the name has been applied because the rocks are relatively silty compared with those of the underlying Snapper Point Formation. David and Stonier (1890) referred to it as the Wandrawandian pebbly sandstone in the type area near Nowra. The sedimentary structures described as 'mud-swirls' consist of nearly flat irregular lensing beds of clayey siltstone, or cross-cutting wavy swirls which look like worm or reed casts.

The Branxton Formation (Engel, 1966; McKellar, 1969) in the northern part of the basin is correlated through the deep wells with the Wandrawandian Siltstone in the south. The correlation is based mainly on its stratigraphic position between the Greta Coal Measures and Snapper Point Formation below and the Mulbring and Berry Formations above.

Age

Dickins (1968) assigns the age of the Wandrawandian Siltstone and its correlative in the northern part of the basin as probable Late Artinskian and Kungurian.

Subsurface lithology

In the wells used in this study the following sequences of Wandrawandian Siltstone were encountered:

Stockyard Mountain-1 (Alcock, 1968a)

	<u>Thickness</u> (m)
Sandy mudstone, interbedded with shale and fine to medium-grained dolomitic sublitharenite, some scattered pebbles. Carbonaceous, pyritic; sandy at top. Lamination, scallop structures, churned bedding, burrow structures and marine (?) shell fragments	
Total	109.7

Kurrajong Heights-1 (Pitt, 1968)

	<u>Thickness</u> (m)
Siltstone, carbonaceous, interbedded with medium to coarse-grained slightly pebbly silty litharenite with carbonate cement. The cement is mainly siderite, but some calcite, quartz, dolomite, anhydrite, and pyrite also occurs. Worm tubes, foraminifera, and brachiopods. Cross-lamination and scallop structures.	
Total	73.2

Petrology

The results of petrological studies discussed in this section are based on core and cutting samples from two petroleum exploration wells. The Wandrawandian Siltstone occurs in these wells over the following intervals:

Stockyard Mountain-1, 295.6 - 409.7 m, and

Kurrajong Heights-1, 1676.4 - 1889.7 m

The lithology of the Wandrawandian Siltstone in Stockyard Mountain-1 and in Kurrajong Heights-1 consists of interbedded carbonaceous and micaceous sandy siltstone and litharenite. Scattered pebbles and cobbles occur throughout the sequence. In the siltstone the detrital components are mainly quartz and chert grains; feldspars are rare. Rock fragments appear to be mainly of volcanic origin, although sedimentary and metamorphic rock fragments are common. Chloritisation of both the volcanic and metamorphic rock fragments is evident. The core samples show scallop structures, laminations, and micro-crossbedding. Fossils include brachiopod fragments, and horizontal and large vertical worm tubes. Accessory minerals in both the siltstone and arenite lithologies include chlorite and pyrite. Cements are mainly siderite and calcite. A basaltic sill overlies the Wandrawandian Siltstone in Stockyard Mountain-1 and is made up of dark, olive-black porphyritic basalt. This volcanic unit may be related to the Currambene Dolerite, (Ozimic, 1971).

Diagenetic changes in this formation are associated with the formation of calcite, siderite, pyrite and chlorite.

No fractures were observed in cores from this formation. However, numerous horizontal and subhorizontal partings are present.

Laboratory determined porosity values in the Wandrawandian Siltstone range from 0 to 5 percent. The average porosity is less than 3 percent. Laboratory tests on cores from this formation detected no permeability.

Depositional environment

These two formations were deposited in a sea that transgressed over the northern part of Sydney Basin and also extended farther west. The marine fossils, including pelecypods and brachiopods, together with laminated bedding and burrow structures, indicate a quiet sublittoral marine depositional environment protected from strong tidal action. The coarser clastic material was possibly ice-rafted. The chemical and detrital constituents of the formations suggest deposition below wave-base in marine environment where bottom currents operated with varying velocities. The development of siderite and pyrite is attributed to changes in environment from oxidising to reducing conditions, at or just below the sedimentary surface, during the early burial stage.

In the northern part of the basin the general prevalence of carbonaceous material, including coal, in the Branxton Formation, together with zones of marine fossils (Fenestella Zone, Wollong Siltstone Member) indicates the proximity of the retreating coal swamps and paralic sedimentation. Interpretation of seismic sections in the area near Singleton shows that additional coal seams appear at the top of the Greta Coal Measures within rocks that pass laterally into the Branxton Formation.

Isopach and lithofacies distribution

The restored isopach map (Fig. 41) of the Wandrawandian Siltstone shows its thickest section in a northerly trending depression extending along the whole length of the Sydney Basin. The thickness of sediment in the depression increases rapidly from the centre of the basin to over 900 m in the north adjacent to the Hunter Thrust. From this depression, the rocks thin westwards.

Lithofacies distribution map (Fig. 42) indicates a general decrease in sand/shale ratio with distance in the west. "An increase in the ratio of sand to shale in the northern part of the depression possibly indicates that some of the detrital components derived from the north along the axis of the trough" (Mayne et al., 1974).

Fig. 41 Isopach map, Branxton Formation and correlative Wandrawandian Siltstone.
(After Mayne *et al.* 1974)

Fig. 42 Lithofacies Map, Branxton Formation and correlative Wandrawandian Siltstone
(After Mayne et al. 1974)

PART III - NOWRA SANDSTONE AND CORRELATIVE MUREE SANDSTONE

Seven potential natural gas storage reservoirs have been delineated in the arenites of the Nowra and Muree Sandstones (Appendixes I - VII).

Nowra SandstoneDefinition and type locality

The Nowra Sandstone (Joplin et al., 1952) is a prominent cliff-forming unit in the southern area of the Sydney Basin. There is no defined type section. Complete sections, exceeding 90 m in thickness, occur north of Burrier and north of the Shoalhaven River. According to McElroy and Rose (1962) it consists typically of quartz arenite resembling the Triassic Hawkesbury Sandstone in composition, grainsize, texture, well-defined crossbedding, mode of outcrop, topography, and vegetation. White quartz pebbles are possibly more common in the Nowra Sandstone than in the Hawkesbury Sandstone. Small fragments and large blocks of phyllitic siltstone and quartzite are also distributed throughout the formation particularly in the western part of the area.

Paix (1968) describes the following subdivisions seen in outcrop in the Nowra district:

	<u>Thickness (m)</u>
Cross-bedded quartz arenite	9
Cliff-forming quartz arenite with evidence of graded bedding	9-15
Siltstone or silty arenite	0-6
Massive quartz arenite	4.6

Ozimic (1971) subdivided the Nowra Sandstone on the basis of the gamma-ray patterns and the lithology in Wollongong Nos. 1, 2, and 2A wells, Stockyard Mountain No. 1 well, and on field observations in the Nowra district. He distinguished an upper unit of cross-bedded and thick-bedded arenite, a middle unit of interbedded arenite and shale, and a lower unit of massive bedded arenite.

Age

The fauna of the Nowra and Muree Sandstones as interpreted by Dickins et al. (1964), Dickins (1968) and Dickins et al. (1969) is assigned to early Kazanian.

Subsurface lithology

In the wells used in this study the following sequences of the Nowra Sandstone were encountered:

Stockyard Mountain-1 (Alcock, 1968a)

	<u>Thickness</u> (m)
Quartz arenite, medium-grained, silicified, calcareous, pyritic, with interbedded sandy mudstone in the middle of sequence. Quartz and chert pebbles. Brachiopods common. Poorly sorted and bedded.	
Total	39.6

Woronora-1 (Alcock, 1968b)

	<u>Thickness</u> (m)
Quartz arenite, medium-grained, silicified; pebbles of quartz, metaquartzite, and mudstone. Brachiopods.	15
Quartz arenite, fine-grained, interbedded with fine-grained silty litharenites and siltstone.	
Minor beds of shale and mudstone.	
Total	$\frac{33.5}{48.5}$

Dural South-1 (Hawkins and Ozimic, 1967)Thickness (m)

Quartz arenite, medium-grained, pebbly. Quartz grains commonly showing interlocking fabric.

Thin siltstone interbeds. Calcite, siderite and quartz cement.

Total 29.0

Kirkham-1 (Raine, 1969)Thickness (m)

Quartz arenite, fine to medium-grained, slightly pebbly, and minor siltstone. Pebbles of quartz, sandstone, siltstone and igneous rock. Calcite, siderite, quartz and dawsonite cement; pyrite.

Graded bedding (waxing and waning current types), wavy bedding, burrows.

Total 36.6

East Maitland-1 (Jensen and Bryan, 1969)Thickness (m)

Quartz arenite, fine to medium-grained, pebbly in places. Quartz grains commonly show interlocking fabric. Rare microperthite grains and fragments of fine-grained mafic volcanic rock. Quartz, siderite, calcite and dawsonite cement. Thin interbeds of siltstone and mudstone in lower half. Abundant brachiopods, bryozoans and corals at certain levels.

Total 181.7

Kurrajong Heights-1 (Pitt, 1968)Thickness (m)

Silty litharenite, fine-grained, pebbly. Siderite, calcite, and quartz cement; pyrite.

Total 9.1

Muree SandstoneDefinition and type locality

The Muree Sandstone (Engel, 1966; McKellar, 1969) is exposed in the Lochinvar Anticline and between Paterson and Raymond Terrace in the Lower Hunter Valley. The name is taken from the Muree Quarry in Raymond Terrace (Clarke, 1878). The Muree Sandstone is synonymous with the Muree Stage of David (1907) and the Muree Formation of Booker (1960).

The type section is located in Bow Wow Gorge 5.5 km southwest of Mulbring. It is described by McKellar (1969):

	<u>Thickness</u> (m)
Cliff-forming arenite, frequently conglomeratic or tillitic	39.6
Siltstone, interbedded with bench-forming units of arenite from 0.3 to 0.6 m thick	22.9
Cliff-forming arenite, frequently conglomeratic or tillitic	<u>16.8</u>
Total	79.3

The formation loses its distinctive threefold character away from the type area and is difficult to identify, so that there has been some doubt as to its correlation and distribution (Jones, 1939; Booker, 1960). Raggatt (1938) identified it also in the Loder and Belford Domes and Sedgefield Anticline in the Singleton and Muswellbrook area. Engel (1966) considers it to be largely restricted to the Lochinvar Anticline and areas immediately to the east.

Petrology

The results of petrological studies discussed in this section are based on core and cutting samples from seven petroleum exploration wells. The Nowra Sandstone occurs in these wells over the following intervals.

Stockyard Mountain-1	256.0-295.6 m
Woronora-1	1554.4-1603.2 m
Kirkham-1	1567.5-1604.1 m
Dural South-1	2151.8-2180.8 m
Mulgoa-2	1502.5-1531.3 m
Kurrajong Heights-1*	1662.9-1676.4 m
East Maitland-1	586.4-786.0 m

*In Kurrajong Heights-1 well the Nowra Sandstone potential gas storage reservoir includes 4.3 m of the lower-most Berry Formation.

The average arenite framework consists of quartz grains with quartz overgrowths (69-81%), K-feldspar (1-4%), plagioclase (1-3%), chert grains (1-5%), mica flakes (1-2%), calcite (1-6%), siderite (2-5%), and rock fragments: sedimentary (2-7%), metamorphic (2-5%), volcanic (2-7%). Accessory minerals include tourmaline, zircon, pyrite and sericite. Calcareous, carbonaceous argillaceous matrix fills the interstices. The framework is cemented by quartz (3-9%), calcite (1-6%), siderite (2-5%) and minor pyrite and dawsonite.

Diagenetic changes have resulted in the silicification of the submature arenite, the formation of quartz overgrowths and pressure welding of quartz grains. Development of pyrite and siderite suggests a change from a primary oxidising environment to one of reducing conditions. Another diagenetic feature of the Nowra and Muree Sandstones is the growth of authigenic crystals of calcite, dolomite and dawsonite, which has obliterated the primary intergranular porosity of the arenites.

The detrital constituents and the early diagenetic minerals in Nowra and Muree Sandstones suggest a nearshore marine environment with a strong continental influence. The interbedding of arenites and siltstone beds indicates changes in the energy deposition. The sequence is considered to be regressive with siderite being deposited in brackish lagoons. Biogenic reworkings and remains, evident from core material, suggest an active sea bottom life.

Fine hairline fractures occur in most sample cores from the two formations. They are mainly horizontal and occur along the bedding plain; they may be more appropriately defined as partings. Less common vertical and subvertical fractures are filled with either siderite, recrystallised calcite or carbonaceous argillaceous matrix. A prominent "pinnate" vertical fracture occurs in the East Maitland-1 reservoir (Plate 3).

Average laboratory determined porosity on cores cut in the Nowra and Muree Sandstones is 8 percent, with a maximum of 16 percent (Chapter V). Microscopic examination revealed no intergranular porosity. Extensive diagenesis accounts for the loss of most of the primary porosity.

Depositional environment

Both formations have been deposited in marine environments. However, low concentration of NaCl in the formation water suggests an active post-depositional mixing of connate and meteoric waters. The intermixing of waters implies that some permeability must have been present in these two formations at some stage during diagenesis. Table 15 summarises the formation water characteristics of the two formations.

These two units were deposited during a brief marine regression followed by transgression in the early Kazanian (Fig. 6). The depositional environment was nearshore marine, similar to that during the deposition of the Snapper Point Formation. The characteristic lithology is a pebbly sublitharenite with siltstone partings, conglomeratic in the north, coarse-grained in the south, and medium or fine-grained in the centre of the basin, indicating northerly and southerly source areas. Cross-bedding is very common in the upper part of the Nowra Sandstone. Palaeocurrent measurements indicate a dominantly southerly source (Paix, 1968; McKelvey et al., 1971).

Three units are recognised in the type section of the Muree Sandstone - two cliff-forming sandstone units separated by a unit of interbedded siltstone and sandstone. Three similar units are also distinguished in the Nowra Sandstone (Paix, 1968; Ozimic, 1971) in the Nowra-Jervis Bay area and farther north in Stockyard Mountain-1. Both regressive and transgressive units may be preserved in this area. However, the subsurface extension of the Muree Sandstone and the Nowra Sandstone in the central area is probably equivalent to the upper two units and represents only the transgressive phase (Mayne et al., 1974).

Isopach and lithofacies distribution

The restored isopach map (Fig. 43) of the Nowra Sandstone and Muree Sandstone indicates thickening eastwards.

This unit reaches a maximum of about 90 m in the southern and central areas but to the northeast in East Maitland-1 well a thickness of 180 m is attained. In the north it thins to the west and beyond Singleton it can no longer be recognised as a mappable or subsurface unit.

Fig. 43 Isopach map, Muree Sandstone and correlative Nowra Sandstone
(After Mayne et al. 1974)

Insufficient data is available to provide a lithofacies distribution map.

PART IV - BERRY FORMATION AND CORRELATIVE MULBRING SILTSTONE

The Berry Formation and correlative Mulbring Siltstone form the cap rock to all seven potential natural gas storage reservoirs delineated in the Nowra and Muree Sandstones.

Berry FormationDefinition and type locality

The Berry Formation (Card and Jaquet, 1903), has been mapped along the western margin of the Sydney Basin from Mount Talaterang in the far south to the Capertee area (McElroy and Rose, 1962). A number of nearly complete sections have been measured in the Cambewarra Range area (Rose, 1962), and the maximum estimated thickness is 143 m. The formation consists mainly of micaceous siltstone, shaly in part, with laminae of silty sandstone. Northwards from Tallong the sequence is pebbly particularly towards the base (Mayne et al., 1974).

The Berry Formation is conformable on the Nowra Sandstone in the south and on the Megalong Conglomerate on the western margin of the basin.

Mulbring SiltstoneDefinition and type locality

The Mulbring Siltstone (David, 1950), occurs in the Muswellbrook and Singleton areas, on the flanks of the Lochinvar Anticline and in the Medowie Syncline running northeast from Raymond Terrace. It is synonymous with the Mulbring or Crinoidal Stage of the Upper Marine Series and the Mulbring Sub-Group of the Maitland Group.

It has since been redefined as a formation of the Maitland Group and two members, the Glendon Siltstone Member and Dochra Siltstone Member, have been recognised between Singleton and Greta.

Age

The fauna of the Berry Formation and Mulbring Siltstone is correlated with Fauna IV of the Bowen Basin (Dickins et al., 1964; Dickins, 1968; Dickson, 1969; Dickins et al., 1969). Fauna IV is assigned a Kazanian age.

Subsurface lithology

In the wells used in this study the following sequences of Berry Formation and Mulbring Siltstone were encountered:

Stockyard Mountain-1 (Alcock, 1968a)

Thickness (m)

Shale grading into siltstone. Quartz sand and pyrite scattered throughout. Lamination, micro-cross-bedding and scallop structures. Brachiopods, bryozoa, rare foraminifera. Plant fragments near top.

Total 242.3

Woronora-1 (Alcock, 1968b)

Thickness (m)

Sandy siltstone, micaceous interbedded with quartz arenite and shale. Fragments of volcanic rock in sandstone.

73.2

Sandy siltstone with minor sandstone. Fragments of volcanic rock in sandstone.

33.5

Silty litharenite, fine-grained; abundance of volcanic rock and plagioclase fragments.

Total $\frac{15.2}{121.9}$

Kirkham-1 (Raine, 1969)Thickness (m)

Mudstone, brownish black, and slightly sandy siltstone grading down into slightly pebbly sandy siltstone to fine sandstone. Sediments carbonaceous; siderite and calcite cement; pyrite. Burrows, bioturbation, lamination, cross-bedding. Brachiopods.

Total 266.1

Dural South-1 (Hawkins and Ozimic, 1967)Thickness (m)

Siltstone, sandy, carbonaceous, with minor silty litharenites; arenaceous foraminifera (mainly Hyperammina spp.).

76.2

Sandy siltstone, massive, pyritic, carbonaceous, with claystone interbeds and rare silty quartz arenite.

Total $\frac{362.7}{438.9}$

Kurrajong Heights-1 (Pitt, 1968)Thickness (m)

Siltstone, micaceous, pyritic, carbonaceous, interlaminated with muddy very fine-grained silty litharenite. Rare quartz pebbles scattered throughout. Mainly calcite and dolomite cement; some siderite and anhydrite.

Plant fragments, worm tubes, foraminifera.

94.5

Siltstone, as above, but more arenaceous sediment.

Total $\frac{259.1}{353.6}$

Mulgoa-2 (A.O.G., 1960)

No detailed breakdown of lithology is available.

East Maitland-1 (Jensen and Bryan, 1969)Thickness (m)

Siltstone, highly carbonaceous, pyritic, grading in places into silty sandstone, overlain by thin calcareous sublitharenite.	219.5
Siltstone, carbonaceous, pyritic, sandy with mudstone and very fine-grained arenite. Calcite cement throughout. Marine fossils and burrow structures. Scallop structures (Jensen and Bryan, 1969) common at certain levels.	185.9
Siltstone, carbonaceous, micaceous, pyritic, sandy, with silty arenite and some mudstone. Brachiopods, bryozoa, and corals. Scallop structures. Distinguished from sediments above by presence of sparse small siliceous pebbles.	<u>123.1</u>
Total	528.5

Petrology

The results of petrological studies discussed in this section are based on core and cutting samples from seven petroleum exploration wells. The Berry Formation and correlative Mulbring Siltstone occurs in these wells over the following intervals:

Stockyard Mountain-1	13.7 - 256.0 m
Woronora-1	1188.7 - 1554.4 m
Kirkham-1	1286.2 - 1567.5 m
Dural South-1	1712.9 - 2151.8 m
Kurrajong Heights-1	1389.9 - 1662.9 m
Mulgoa-2	1502.6 - 1531.3 m
East Maitland-1	57.9 - 586.4 m

The formations consist of thick sequences of highly carbonaceous and pyritic siltstone, in places grading to silty and pebbly arenite, and are interbedded with thin sideritic arenite and calcareous mudstone beds. In the siltstone the detrital component consists of quartz, feldspar and fragments of sedimentary, metamorphic and volcanic rocks. The core samples show scallop structures, churned bedding, slump and scour structures and microcross bedding. Siliceous tubes, bryozoa fragments, foraminiferal casts and fragments of brachiopod are common. The dominant cementing minerals are siderite, calcite and pyrite.

Diagenetic changes in the two formations resulted in the development of siderite and pyrite, which indicate a change from the primary oxidising environment to one of reducing conditions.

Depositional environment

The chemical and detrital constituents of the Berry Formation and Mulbring Siltstone suggest a shallow nearshore environment of deposition.

No fractures were observed in the cores cut in Berry Formation and Mulbring Siltstone, but horizontal partings are common.

Laboratory and wireline log determined porosity values in the Berry Formation and Mulbring Siltstone range from 1 percent (Woronora-1) to 11 percent (Kurrajong Heights-1). The average porosity is less than 3 percent. Laboratory tests on cores from these two formations detected no measurable permeability.

The sand-shale ratio is low in the north and south and along the present coastline, and increases to the west. The main rock type is siltstone and poorly sorted fine-grained sandstone. Marine fossils

have been found in all areas except on the western margins north of the Shoalhaven River. The macrofossils include pelecypods and brachiopods. Foraminifera have been recorded in surface exposures of the Mulbring Siltstone in the northern area and in wells in the central area. The marine fossils, together with burrow and scallop structures and the fine grainsize indicate a sheltered sublittoral marine environment. The rocks were deposited in deeper quieter water during and after the marine transgression that began during the deposition of the Muree and Nowra Sandstones. This is the most widespread transgression into the Sydney Basin. Faunal evidence (Dickins, 1968) suggests that the sea was connected with the Bowen Basin at this time. The connection remained open until a regression at the end of the Kazanian brought the dominantly marine deposition to an end. In the western part of the Sydney Basin this sequence contains probably ice-rafted material, the youngest occurrence in the Sydney Basin.

Isopach and lithofacies distribution

The restored isopach map (Fig. 44) of the Mulbring Siltstone and Berry Formations indicates an increase eastwards to about 460 m in a trough called MacDonalds Depression and further east it is interpreted as thinning over the Kulnura Arch (about Cessnock) before it thickens again to 510 m west of Newcastle in East Maitland-1 well. The arch and complementary depression were probably formed by gentle warping during the deposition of the two units formations (Mayne et al., 1974).

The lithofacies map (Fig. 45) is limited to sandstone/shale assemblage, as interpreted from wireline logs and petrological studies.

Fig.44 Isopach map, Mulbring Siltstone and correlative Berry Formation
(After Mayne *et al.* 1974)

Fig.45 Lithofacies map, Mulbring Siltstone and correlative Berry Formation.
(After Mayne et al. 1974)

Summary

Examination of cores and cuttings of the Shoalhaven and Maitland Groups intersected in the seven wells used in this study, has shown a notable consistency in the mineralogy of the reservoir arenites and of the siltstones, claystones and shales of their respective cap rocks.

Quartz and carbonates are the dominant cements. These cements have effectively reduced the primary and secondary porosity of the potential reservoir rocks. The carbonate cements are a result of depositional and early diagenetic conditions, whereas the quartz cement reflects the post burial conditions.

The diagenetic effects on the arenites of the studied formations are discussed in detail in Chapter IV.

Plates 3 and 4 depict typical petrological characteristics of the potential storage reservoirs and their respective cap rocks.

The mineralogical properties of the arenites suggest a short distance of transport from the source area. The environment of deposition, based on fossil content is interpreted to be marine.

Table 10 summarises the results of petrological characteristics of the Shoalhaven and Maitland Group arenites used in this study. Table 11 and Fig. 46 depict the composition of these arenites according to the classification of Folk et al., (1970).

Photo 1 (X 250)

Photo 3 (X 250)

Photo 2 (X 100)

Photo 4 (X 100)

Diagram 1

Diagram 2

Photo 5 (X 250)

Photo 6 (X100)

Diagram 3

Photomicrographs of typical petrological characteristics of potential storage reservoirs and their respective cap rocks.

Photo 1: Woronora-1,
Berry Formation, cap rock.

Photo 2: Woronora-1
Nowra Sandstone, reservoir rock.

Diagram 1: Woronora-1,
Nowra Sandstone, reservoir rock.

Photo 3: Kurrajong Heights-1,
Snapper Point Formation, cap rock.

Photo 4: Kurrajong Heights-1
Snapper Point Formation, reservoir rock.

Diagram 2: Kurrajong Heights-1,
Snapper Point Formation, reservoir rock.

Photo 5: East Maitland-1,
Mulbring Siltstone, cap rock,

Photo 6: East Maitland-1,
Muree Sandstone, reservoir rock.

Diagram 3: East Maitland-1
Muree Sandstone, reservoir rock.

Abbreviations

Q	- quartz
Qo	- quartz overgrowth
Fe	- feldspar
Bi	- biotite
Ca	- calcite
Py	- pyrite
SRF	- sedimentary rock fragment
VRF	- volcanic rock fragment
FR	- fracture
P	- pore space

Table 10

Summary of petrological characteristics of Sydney Basin
potential natural gas storage reservoirs

Well Name	Stockyard Mountain-1	Stockyard Mountain-1	Woronora-1
FORMATION	Nowra Sandstone	Snapper Point Formation	Nowra Sandstone
DEPTH INTERVAL (m)	256.0 - 295.6	574.8 - 629.1	1554.4 - 1603.2
ROCK NAME	Sublitharenite	Sublitharenite	Sublitharenite
GRAIN-SIZE	V. fine - v. coarse	V. fine - v. coarse	Fine - v. coarse
SORTING	Poor	Poor - moderate	Poor - moderate
ANGULARITY	Angular - subangular	Angular - subangular	Subangular - subrounded
GRAIN CONTACTS	Irregular	Irregular	Irregular
CEMENT	Siliceous, calcareous	Calcareous	Siliceous, calcareous
VISIBLE POROSITY	None	5%	None
PROVENANCE	Sedimentary, metamorphic granitic, volcanic	Sedimentary, metamorphic, granitic	Sedimentary, volcanic granitic
DEPOSITIONAL ENVIRONMENT	Marine	Marine	Marine

Table 10 (continued)

Well Name	Dural South-1	Kirkham-1	East Maitland-1
FORMATION	Nowra Sandstone	Nowra Sandstone	Muree Sandstone
DEPTH INTERVAL (m)	2151.8 - 2180.8	1567.5 - 1604.1	586.4 - 786.0
ROCK NAME	Sublitharenite	Sublitharenite	Sublitharenite
GRAIN-SIZE	Fine - coarse	Fine - medium	Medium - v. coarse
SORTING	Poor	Poor - moderate	Poor - moderate
ANGULARITY	Angular - subangular	Subangular - subrounded	Angular - subangular
GRAIN CONTACTS	Irregular	Irregular	Irregular
CEMENT	Calcareous, siliceous	Siliceous, calcareous	Siliceous, calcareous
VISIBLE POROSITY	None observed	None observed	None observed
PROVENANCE	Granitic, metamorphic, sedimentary	Granitic, sedimentary, metamorphic	Granitic, sedimentary metamorphic
DEPOSITIONAL ENVIRONMENT	Marine	Marine	Marine

Table 10 (continued)

Well Name	Kurrajong Heights-1	Kurrajong Heights-1	Mulgoa-2
FORMATION	Berry Formation- Nowra Sandstone	Snapper Point Formation	Nowra Sandstone
DEPTH INTERVAL (m)	1662.9 - 1676.4	1889.7 - 1965.9	1502.5 - 1531.3
ROCK NAME	Sublitharenite	Sublitharenite	Sublitharenite
GRAIN-SIZE	V. fine - v. coarse	Fine - v. coarse	Fine - v. coarse
SORTING	Poor	Poor	Poor - moderate
ANGULARITY	Subangular	Angular to subangular	Angular - subangular
GRAIN CONTACTS	Irregular	Irregular	Irregular
CEMENT	Siliceous, calcareous	Siliceous, calcareous	Siliceous, calcareous
VISIBLE POROSITY	None	None	None
PROVENANCE	Sedimentary, volcanic, metamorphic	Sedimentary, volcanic, metamorphic	Sedimentary, metamorphic, granitic
DEPOSITIONAL ENVIRONMENT	Marine	Marine	Marine

Table 11

Summary of "Arenite Triangle Components" of Sydney Basin
potential natural gas storage reservoirs

Well Name	Status	Formation	Thin Section Depth (m)	Rock Sample Type	Arenite Triangle Components			Rock Name (Folk <u>et al.</u> , 1970)
					Quartz (Q) %	Feldspar (F) %	Rock Fragments (R) %	
STOCKYARD MOUNTAIN-1	Reservoir	Nowra Sandstone	266.7	Core	83	2	15	Sublitharenite
STOCKYARD MOUNTAIN-1	Reservoir	Snapper Point Formation	579.7	Core	79	7	14	Sublitharenite
WORONORA-1	Reservoir	Nowra Sandstone	1560.5	Core	79	3	18	Sublitharenite
			1561.7	Core	80	6	14	Sublitharenite
DURAL SOUTH-1	Reservoir	Nowra Sandstone	2185.4- 2188.4	Cuttings	85	3	12	Sublitharenite
KIRKHAM-1	Reservoir	Nowra Sandstone	1586.6	Core	85	3	!@	Sublitharenite
EAST MAITLAND-1	Reservoir	Muree Sandstone	610.2	Core	85	5	10	Sublitharenite
			690.0	Core	85	4	11	Sublitharenite

Table 11 (continued)

Well Name	Status	Formation	Thin Section Depth (m)	Rock Sample Type	Arenite Triangle Components			Rock Name (Folk, 1970)
					Quartz (Q) %	Feldspar (F) %	Rock Fragments (R) %	
KURRAJONG HEIGHTS-1	Reservoir	Berry Formation- Nowra Sandstone	1658.1	Core	87	3	10	Sublitharenite
KURRAJONG HEIGHTS-1	Reservoir	Snapper Point Formation	1950.4	Core	81	4	15	Sublitharenite
MULGOA-2	Reservoir	Nowra Sandstone	1522.0	Core	83	3	14	Sublitharenite

Fig.46 Framework mineral composition of Shoalhaven and Maitland Groups arenites.

CHAPTER IVDIAGENESIS OF SHOALHAVEN AND MAITLAND GROUPS ARENITES

This chapter consists of three parts. The first part is concerned with processes and phases of diagenesis recognised in the four studied formations of the Permian Shoalhaven and Maitland Groups. The second part deals with the factors controlling effective porosity in these units. The last part deals in detail with the origin and formation of minerals affecting primary and secondary porosity in the studied arenites of Shoalhaven and Maitland Groups.

The major objectives of this chapter are to describe the diagenetic sequence; assess the influence of diagenesis upon porosity and permeability; provide data on chemical cements and types of clay minerals filling pores; and to draw attention to the significance of diagenesis as a critical factor in the evaluation of potential gas storage reservoirs. These data would enable engineers to recommend the use of proper mud systems for a possible gas storage field development drilling and, if necessary, to design suitable fracturing for reservoir stimulation.

The constraints on availability of core material from the seven studied petroleum exploration wells resulted in examining only 25 thin sections. The available core material over the intervals of Nowra Sandstone, Muree Sandstone and Snapper Point Formation consisted of 10 cores of which the average length was less than 1.0 metre. The available core material from the overlying cap rocks was even sparser.

Aspects of diagenesis

The term 'diagenesis' is over a hundred years old. It was introduced by von Guembel in 1868 (Amstutz, G.C., and Bubenicek, J., 1967) as a designation for processes which act on the sediments after deposition. Thus, the recognition of the processes of diagenesis is not new, however the knowledge about diagenesis has been quite insufficient until the last two decades. Since then, however the insight into this particular field of lithogenesis has progressed rapidly; and the amount of literature on diagenesis has rapidly multiplied during the last decade. Significant contributions in the field of diagenesis have been made by Hedberg (1926); Weyl (1959); Fuchtbauer (1974); Galloway (1974); Fairbridge (1967); Friedman (1964); Pettijohn, Potter and Siever (1972) and Blatt, Middleton and Murray (1980).

A comprehensive selection of papers on diagenesis is given in Journal of the Geological Society, Vol. 135, Pt. I, 1978, and in the Society of Economic Palaeontologists and Mineralogists, Special Publication No. 26, 1979. The bulk of the papers are concerned with the mineral changes responsible for the observed reduction of porosity. The principal factors appear to be the precipitation of carbonate, secondary quartz, pressure solution of silica and growth of authigenic clays. These papers indicate a considerable progress towards the development of a determinative model of sandstone and clay diagenesis and are referred to in appropriate sections of this chapter.

PART I — DISCUSSION OF DIAGENESISDiagenetic sequence

The sediments of the Shoalhaven and Maitland Groups have been subjected to at least three diagenetic phases (nomenclature after Fairbridge 1967; Fig. 47) and three diastrophic events (Mayne et al., 1974) as follows:

- A - syndiagenesis,
- B - anadiagenesis,
- C - epidiagenesis,
- 1 - Hunter Bowen Orogeny,
- 2 - Upper Triassic movements, and
- 3 - Probable Tertiary epeirogenic movements.

Syndiagenesis: during the initial stage of syndiagenesis (Fig. 47) the superjacent waters exerted a dominant influence on the physiochemical conditions in the unconsolidated sediments of the Shoalhaven and Maitland Groups. Mineral grains were not in direct contact. The sediments still contained a large volume of water. Organic matter buried with the sediments provided food for bacteria and burrowing organisms. Bioturbation kept the near-surface layers of the sands and silts well oxygenated. Thus, the coarser grained sediments tended to become oxidized and cleaned of their entrapped organic matter.

Characteristic diagenetic features that were formed during this early diagenetic history of the Shoalhaven and Maitland Groups arenites have been identified in the course of petrological examination. These features (Fig. 48) are in the form of calcite, dolomite, dawsonite and siderite pore fill. The formation of this early pore fill is recognised by the loose grain packing of the arenites that are cemented by it.

Fig. 47

Nature and Development of Porosity in
Shoolhaven and Maitland Groups Arenites.
(After Ozimic, In: Kurylowicz et al. 1976)

(Plate 5, Photo 1). Associated with this diagenetic stage is also thought to be a minor amount of silica and pyrite cement. Distribution of this early diagenetic cement can be related to depositional environment and as such they are probably facies controlled. Calcite and dolomite cement probably derived from dissolution of shell fragments, limestone beds or may have precipitated from CaCO_3 saturated waters of surface or subsurface origin that were draining into the depositional area. Silica cement derived most likely from unstable silicate minerals (micas, clays etc) or even from bacterial activity which dissolves quartz and silicate minerals.

In the early burial stage of syndiagenesis (Fig. 47), the grains become more closely packed and aerobic bacteria were probably replaced by anaerobic species as reducing conditions developed. Many larger organic and inorganic molecules were broken down. Vegetable matter disintegrated and only the stable parts remained. Minerals typical of reducing conditions were formed, e.g. pyrite and siderite

Anadiagenesis: as the depth of burial increased, higher temperature and fluid pressure within the sediments of the Shoalhaven and Maitland Groups brought about the second diagenetic phase, anadiagenesis. Because this phase involves slow compaction of the sands and results in significant reduction of their intergranular porosity, it can also be termed the compaction and maturation phase of diagenesis. Geochemically this was the stage of dewatering, when connate waters from the studied sediments were progressively expelled and moved stratigraphically upwards and outwards towards the present margins of the Sydney Basin. This diagenetic phase is marked by the chemical alteration of unstable mineral grains and the mobilization of silica and aluminum which are reconstituted as authigenic clay coats and rims around detrital grains (Plate 7, Photo 1). Further

during this phase of diagenesis, there was a maximum development of silica cement (mostly as overgrowths - Plate 8, Photo 1). and lesser calcite and siderite cements. The siderite cement is regarded here as a replacement of calcite mainly on the basis of substitution of Fe^{++} for Ca^{++} in the calcite lattice. Other developments due to increasing temperature and pressure would be related to transformation of detrital clay minerals derived from the volcanic source in the northern part of the basin. For example, kaolinite and montmorillonite could have changed to sericite and illite. Montmorillonite can change into illite through a simple fixation of potassium from interstitial water or of potassium released during the decay of feldspars. Detrital illite could have been transformed into chlorite due to increased temperature.

Gradual lithification of the sands under the pressure of increasing overburden eventually produced sutured and interpenetrating quartz grains (Plate 9, Photos 1). As such, this stage is characterised by three diagenetic features namely clay coating, extensive silica pore fill in the form of quartz overgrowths and deformation of soft grains and replacement of labile constituents (Fig. 48). The clay coating that surrounds the detrital grains in the Snapper Point Formation reservoir (Stockyard Mountain-1 well) are made up of authigenic illite (Plate 7, Photo 1). These coats are attributed to formation waters that were deficient in silica content. On the other hand the extensive silica pore fill as found in the remaining Shoalhaven and Maitland Groups arenite reservoirs, is attributed to a high pressure solution activity in the adjacent rocks and complemented by a considerable vertical movement of formation waters. Other diagenetic features associated with these diagenetic stages are deformed soft minerals, (e.g. micas, Plate 13, Photo 1) and alteration and replacement of labile constituents by clays, calcite and silica.

Epidiagenesis: since the deposition of Shoalhaven and Maitland Groups sediments two major and a minor period of diastrophism have been recognised. The strongest deformation of these sediments in Sydney Basin occurred adjacent to its north-eastern margin where the Hunter-Mooki Thrust and a series of northerly trending folds with associated normal faults are developed (Figs. 5 and 8c). This folding and faulting occurred during the Upper Permian Hunter-Bowen Orogeny and resulted in the formation of numerous structures. The structures formed during this orogeny are of particular interest since most of them are of domal or anticlinal type e.g. Hunter Valley Dome Belt (Fig. 5) and are therefore suitable for accumulation and possible storage of hydrocarbons. The movements that followed in the Upper Triassic caused a more widespread deformation in particular in the central part of the basin. It is believed (Mayne et al., 1974) that the Kulnura Anticline, Dural Dome, Woronora Anticline, Nepean and Lapstone Monoclines have been formed during this movement. Most of the structures formed during the Upper Permian and Upper Triassic movements were most probably modified during the less deformative Tertiary uplift, Wellman (1979). Together, these three orogenic events contributed to the development of the epidiagenetic phase of the arenaceous members of Shoalhaven and Maitland Groups. The resulting emergence permitted deep penetration by groundwater through fractures, thus modifying the connate solutions and oxidising conditions were reintroduced into the sediments. A complete new geochemical cycle began. This new geochemical revival permitted renewed dissolution and cementation thus effectively contributing to the development and subsequent reduction of secondary porosity.

The diagenetic features (Fig. 48) attributed to the final stage of diagenetic history of the studied arenites are therefore related to the diastrophism of the Sydney Basin. The most prominent diagenetic features

identified are calcite and clay fill of fractures (Plate 10 Photo 1).

Replacement of quartz by calcite, calcite by siderite (Plate 11, Photo 1) is also considered to be epidiagenetic. Some siderite is also thought to have been formed during this phase when the sulphate activity was low and the arenites were flushed by meteoric waters.

DIAGENETIC FEATURES AND RESERVOIR PARAMETERS IN THE ARENITES OF SHOALHAVEN AND MAITLAND GROUPS

PART II — FACTORS CONTROLLING EFFECTIVE POROSITY

Introduction

The effective porosity in the arenites of Shoalhaven and Maitland Groups, at least in the seven petroleum exploration wells studied, is influenced by two factors, initial facies control and super-imposed secondary diagenetic effects.

Factors controlling porosity in arenites fall into three groups:

- (a) textural properties which govern primary porosity,
- (b) diagenetic processes which modify or destroy primary porosity, and
- (c) diagenetic processes which produce and reduce secondary porosity which is unrelated to primary porosity.

A review of these groups will be made, since the controlling factors are relevant to the understanding of the porosity modifications which have taken place in the arenites of Shoalhaven and Maitland Groups.

Factors controlling primary porosity

The inherent or primary porosity in an arenite is controlled by textural properties which in turn reflect the conditions of deposition. On the other hand the character of primary porosity is determined by the arrangements of form of the pores, the degree to which they are connected and their distribution in the sedimentary rock unit.

Studies of the pore system of the rocks has been made by numerous workers in the fields of petroleum engineering, hydrology and geology. To name just a few: Powers, 1953; Pryor, 1973; Beard and Weyl, 1973; and Scheidegger, 1974. The packing of equal sized spheres has also been studied by some of the authors named above in order to

approximate porosities found in granular material. On comparing results from such experiments with data obtained from average arenites most workers agree that variables such as particle size, particle shape, bedding, packing, the character and volume of cement and matrix, control the amount and distribution of primary porosity.

Factors controlling porosity reduction

The post-depositional history of an arenite is generally marked by a reduction in initial or primary porosity. The important processes and causes which produce porosity reduction after burial are compaction, depth of burial, cementation, and solution and redeposition. Associated with these processes, other factors must also be considered e.g. mineral composition; geometry of the arenite; depth of burial; tectonic forces; the influence of temperature; formation water circulation and chemistry; and time. There is increasing agreement among sedimentologists that post-depositional modifications in the mineralogy of arenites can be very significant and in particular the replacement of one mineral by another.

Compaction: this process is due mainly to the increasing weight of overburden. Its effect, like that of cementation, is to reduce primary porosity. The reduction of pore space by compaction in a sealed reservoir system causes an increase in reservoir pressure. Compaction of a reservoir rock is of two kinds, plastic and elastic. Plastic compaction is the squeezing of the soft accessory minerals of the matrix e.g. clays, micas, and colloids into the open pores as the pressure increases and the water is driven out (Plate 13 Photo 1). Elastic compaction mainly occurs during anadiagenesis when most of the water has been expelled.

Hedberg (1926) was of the opinion that the flattening of soft grains and the granulation of fragile grains under pressure could cause porosity reduction. Maxwell (1960) conducted experiments on the compaction and cementation of quartz sandstones under simulated deep burial conditions. His results indicate that porosity reduction is caused principally by mechanical fracturing, rotation and interpenetration of grains. He found that high temperatures and the presence of distilled and alkaline waters also facilitated compaction.

Maxwell (1964) was able to demonstrate from assembled porosity, depth and temperature data that porosity reduction in reservoir arenites takes place with depth. Where lost porosities occur, there tend to be high thermal gradients. Atwater and Miller (1965) were also able to show that void space per unit volume decreases with increasing depth of burial (Fig. 49).

Workers e.g. Rittenhouse, 1961; Dickas and Payne, 1967; Selley, 1978; and Ziegler and Spotts, 1978 who studied compaction of arenites and mudrocks agreed that the amount of compaction increases significantly with the proportion of ductile rock fragments in the detrital fraction. Fragments such as siltstone, shale, slate and phyllite deform easily at shallow depth, thus decreasing porosity and thinning the stratigraphic section. The presence of detrital clay in an arenite has the same effect as the presence of ductile fragments but increases the rate of compaction. During compaction sand grains respond by shifting into more-dense packing arrangements, hence porosity decreases.

Cementation: The most common cement in arenites is silica, but carbonates, especially calcite, dolomite and siderite also occur. Both silica and carbonate cements may form near surface and in the subsurface.

Fig. 49 Porosity vs. depth, (a) South Louisiana Tertiary sands; 17,367 samples. (From G. I. Atwater and E. E. Miller, 1965, unpub. ms.; data averaged for each 1000 ft. interval); (b) Great Valley Cretaceous and Tertiary sands; 165 reservoirs. (From D. L. Ziegler, and J. H. Spotts, 1978, *Amer. Assoc. Pet. Geol. Bull.*, **62**, 814; (c) Cis-Caucasus, U.S.S.R.; 93 samples. (From B. K. Proshlyakov, 1960, trans. by Assoc. Tech. Serv., Inc., N.J., 1965, p. 3.)

A tendency exists for younger arenites to be carbonate cemented, whereas silica as cement is more commonly found in older arenites.

Taylor (1950), Weyl (1959), Fuchtbauer (1974), Dapples (1972), Galloway (1979), and Blatt et al., (1980) recognise three processes which cause porosity reduction. These are: simple pore filling, solid flow of material, water pressure and solutions and redeposition of cements.

In an experimental study of arenite cementation, Heald and Renton (1966) found a relationship between grain size and cementation. Grain size was found to have an important effect on rates of cementation. With freely circulating cementing solutions, well sorted coarse sands became cemented faster than fine-grained sands because of the greater influx of cement into the more permeable coarse sand. However, finer grained sand samples were cemented much more rapidly than coarser sands where rate of influx of cementing solutions was the same in both cases. These relationships suggest that in natural arenites coarse-grained beds would become cemented faster than associated fine-grained beds where rapid entry of solutions occurred as, along a fault. Porosity would be greatly reduced in the coarse beds before significant porosity reduction occurred in the fine-grained beds. On the other hand, with uniform slow influx of solutions, cementation would first be completed in the fine-grained beds. This is because rate of quartz growth increases as a function of specific surface area of the quartz seeds.

Other workers who have discussed the role of both carbonate and silica cementation upon porosity reduction, include Fuchtbauer (1967), Pettijohn et al. (1972), Pittman (1979) and Blatt et al., (1980).

Solution and redeposition: this is a process in which a solid dissolves at its contact with another solid and with pore water, because increased pressure has increased its solubility. This kind of dissolution may yield sutured contacts between particles and thus weld the rock and reduce pore space. The process of pressure solution may occur during load or deformation compaction. Stylolites, which consist of the insoluble residue of material in limestones provide evidence for pressure solution. In arenites pressure solution is evident as sutured contacts between grains. This process has been confirmed as early as 1941 by Waldschmidt who found, from study of core samples, that a decrease in porosity resulted from pressure solution at points of grain contacts and from the deposition of cement. Furthermore, Sloss and Feray (1948) in their studies of oil producing arenites found that the presence of micro-stylolites between chert grains and the development of secondary quartz overgrowths affected both the porosity and permeability of the reservoir. Heald (1956) found that where stylolites occur along widely spaced seams porosity is little affected, but that such seams may reduce permeability across the bedding. Adams (1964), in a study of sandstone reservoirs, observed that pressure solution had the greatest effect in the fine-grained arenites, whilst the coarse-grained arenites were dominated by quartz overgrowths. Fuchtbauer (1967) also discussed the rôle of pressure solution and quartz overgrowth development in porosity reduction and suggested that cementation is strongly reduced if the pores are filled with hydrocarbons. Other main factor influencing the increase of quartz overgrowths with increasing depth is presumably temperature, but length of burial may also be an important additional factor. According to Fuchtbauer (1976) pressure solution in a broader sense is increased by the presence of clay or silt laminae or mica sheets between the quartz grains. There are two possible explanations

for the increased pressure solution in the presence of clay or silt laminae:

- (a) release of K^+ from the clay film produces an alkaline environment which increases solubility of silica (Thomson, 1959).
- (b) diffusion of dissolved matter is enhanced by the additional water layers within the clay films (Weyl, 1959).

In the past, most workers believed that the source of silica for quartz overgrowths in a rock is pressure solution between quartz grains in a nearby rock. According to recent thin-section studies using luminescence petrography by Siebley and Blatt (1976) it was found that pressure solution can provide only about one-third of the silica cement needed. Weyl (1959), de Boer (1977) and Robin (1978) have described the mechanism by which this one-third of silica cement may be produced. The remaining two-thirds of the cement according to Siebley and Blatt (1976) is calculated to come from vertical water circulation through the rock formation over a long period of time.

Factors controlling the development and reduction of secondary porosity

In general secondary porosity may result from or be modified by: solution; fractures, recrystallization and dolomitization, cementation and compaction.

In the arenaceous members of the Shoalhaven and Maitland Groups the development and subsequent reduction of secondary porosity is best observed in the numerous fractures that have occurred and are now calcite or clay filled (Plate 10, Photo 1). The development of secondary porosity is therefore attributed to the late diagenetic stage resulting from diastrophism in the Sydney Basin.

PART III — ORIGIN AND FORMATION OF MINERALS AFFECTINGPRIMARY AND SECONDARY POROSITYDevelopment of quartz overgrowths

Quartz overgrowths have been recognised throughout the studied arenaceous formations of the Shoalhaven and Maitland Groups with the exception of a thin unit which is characterised by clay coating on quartz grains in Stockyard Mountain-1 well. While precipitation of a minor volume of primary silica cement is also thought to have occurred during the initial stage of syndiagenesis, most of it was probably recrystallised during later phases of diagenesis. As such it would therefore be difficult to distinguish between the recrystallised cementing material and the material introduced after the sediment became lithified.

The recognition of quartz overgrowths has been greatly facilitated by the presence of discontinuous clay films, dust rings, and minor oxide rims along the detrital grains boundaries. In some fine-grained arenites the degree of secondary crystalline perfection is reduced on account of the pore size and packing. Quartz overgrowths in these rocks mutually interfere with one another along compromise boundaries to produce a mosaic of interlocking crystals (Plate 9, Photo 1). The effect of quartz cementation is to produce a hard durable arenite in which the majority of the pore spaces are filled with overgrowths. Optically continuous quartz overgrowths are controlled by the position of the crystallographic axes within the detrital grains. Three types of overgrowths were distinguished:

(a) Where unstrained quartz grains occur these produce the simplest form of overgrowth (Plate 2, Photo 1). As these grains are composed of a single unit of quartz, so the overgrowth will occur as a single unit of quartz and thus possess possibly a high degree of crystallinity.

(b) Where overgrowths occur on strained monocrystalline quartz grains, the same degree of strain in the detrital grains is transmitted into the overgrowth lattice; thus producing an equally strained continuous overgrowth.

(c) Where overgrowths occur on polycrystalline quartz grains which are mainly confined to the coarse grained arenites, they conform optically to the adjacent detrital core.

The abundance of secondary quartz as overgrowths in the arenites of the Shoalhaven and Maitland Groups is attributed to two phases of silica precipitation. During early and late anadiagenesis, suitable conditions of both low pH and temperature probably existed in these arenites for the precipitation of silica from migrating formation fluids. Thus the first phase of silica cementation is evident by large overgrowths developed in arenite fabric that displays open packing (Plate 2, Photo 1). This cementing silica could possibly have been derived from the following sources:

- silica-rich solutions derived from compacting shales and
- release of silica during alteration of feldspars to illite.

It is suggested that silica for the second phase of silica cementation in which monocrystalline quartz fill pores between overgrowths (Plate 8, Photo 1) was derived principally by pressure solution in the coarse-grained arenite and possibly by a process associated with the vertical movements of formation waters as suggested by Siebley and Blatt (1976).

Siderite, calcite, dawsonite, dolomite and pyrite

Siderite and calcite are the principal carbonate cements within the sedimentary rocks of Shoalhaven and Maitland Groups. Occurrences of dawsonite and dolomite as cements are less common.

Siderite: can be demonstrated in some occurrences to have been formed as primary precipitate during early burial stage of syndiagenesis, and as a replacement mineral of calcite and dawsonite. On the other hand some siderite could also have been formed during later stages of diagenesis and at greater depth particularly when the sulphate activity was low and when the arenite reservoirs were flushed by meteoric waters.

Siderite is found principally in the fine-grained sandstones associated with carbonaceous clay laminae, biotite and iron oxide. Possible sources of iron necessary for the precipitation of siderite have been discussed by Taylor (1949). The iron may be in the form of stabilized colloids, or as adsorbed coatings on detrital particles. Carroll (1958) has discussed the importance of clay minerals, which have large specific surfaces, as agents for the transport of adsorbed iron oxides. Some iron would be released during the decomposition of biotite.

Berner (1970) suggests that conditions necessary for the formation of primary siderite are characterised by low sulphate content, presence of carbon dioxide, neutral pH, high $\text{Fe}^{2+}/\text{Ca}^{2+}$ ratio and low Eh. Further it has been recognised by other workers (Teodorovich, 1961; Fairbridge, 1967; Blatt et al., 1980) that the formation of primary siderite is confined to a restricted marine environment (similar to that in which the Shoalhaven and Maitland Groups sediments have been deposited) in which mildly reducing conditions prevailed.

Siderite as a replacement mineral never reaches major proportions in the sedimentary rocks studied, it nevertheless acts as an important component by replacing calcite, micas and dawsonite. This process involves partial or complete replacement of either detrital calcite or mica grains or components of authigenic calcite and dawsonite (Plate 5, Photo 1).

Calcite: occurs within the arenites of Shoalhaven and Maitland Groups in three forms:

- (a) as early diagenetic precipitate,
- (b) as possible replacement of aragonite
- (c) as fragments of calcareous fossils.

The origin of early diagenetic precipitate is related to a favourable environment of deposition. According to this view, the arenite components were transported into a carbonate precipitating environment and the cement was essentially a primary precipitate while the arenite components were exposed to the saline waters. Support for this view comes from some modern sediment studies that have shown submarine lithification of carbonate and arenites, especially the report of an aragonite-cemented arenite from the Atlantic continental shelf (Allen et al., 1969). Some of this early diagenetic calcite cement may have also been derived from calcareous fossil fragments.

Some authors e.g. Galloway (1974) suggest that evidence of early formation of calcite is indicated by "loosely packed sand, the apparent random distribution of calcite-cemented arenites over the entire range of burial depths and absence of other types of cementation or grain-alteration in arenites that are thoroughly cemented by calcite". Fuchtbauer (1974) observed that cryptocrystalline calcium carbonates (mainly magnesium calcite), but also aragonite cement formed

in many modern sediments in both littoral and sub-littoral zones. The common occurrence of calcite within the studied sediments is related to the depositional environment and its distribution is most likely facies rather than depth controlled.

A common observation among the arenites of Shoalhaven and Maitland Groups is replacement of quartz, feldspar and clay particles, by calcite (Plate 11, Photo 1).

The replacement of quartz and feldspars by calcite is governed by pH, temperature and pressure. In some rocks calcium carbonate has been shown to have replaced up to 50 percent of the former quartz and feldspar grains. During such replacement, the non-replaced detrital quartz and feldspar grains become markedly corroded. Transitional stages of replacement can be traced from peripherally embayed quartz or feldspar grains to small patches of a residual grain in a calcite pseudomorph.

Clay particles too have been replaced by calcite in the sedimentary rocks of Shoalhaven and Maitland Groups. Primarily such replacement is by calcite but it may also be by dolomite and siderite. Example of such replacement (Plate 11, Photo 1) shows that at least some of the clay remains as a residue within the calcite. The mechanism of such replacement is not well understood but it appears that certain clay minerals, mainly illite and kaolinite, are flocculated by Ca-ions and occupy less interstitial space allowing the remainder to be filled by precipitated carbonate. The calcareous organic fossil remains in the studied sedimentary rocks are mainly of thick shelled brachiopods.

Dawsonite and dolomite: Dawsonite $[\text{NaAlCO}_3(\text{OH})_2]$, was detected in eight wells in the central and northern part of the Sydney Basin (Nicholas & Ozimic, 1970). It is thought to be early syndiagenetic precipitate and occurs in both the marine Shoalhaven and Maitland Groups as well as in the overlying Illawarra Coal Measures and the lower part of the Narrabeen Group. Dawsonite also occurs in veins where it is presumably of later origin. Dolomite occurs as cement in the Stockyard Mountain-1 well, Snapper Point Formation reservoir only. Dolomite replaces calcite in these arenites.

Pyrite: The common occurrence of pyrite within the sedimentary rocks of Shoalhaven and Maitland Groups reflects early diagenetic anaerobic conditions.

Clay

Even though only a limited amount of core material was available for detailed petrological examination, it was possible to establish that there are two modes of occurrence of clays within the studied sedimentary rocks; namely detrital and authigenic.

The detrital clay components occur as:

- (a) intercalated laminae,
- (b) argillaceous (shale and mudstone) fragments,
- (c) dispersed matrix, and
- (d) floccule.

In this study the first three detrital clay components have been directly related to the occurrence of shaly material within the arenites of the potential gas storage reservoirs. As such they are quantitatively evaluated and their effect on porosity and permeability is discussed in Chapter V.

The relationship between the forms of the detrital clay and shaly material is as follows:

- intercalated laminae —————> laminar shale (Plate 14, Photo 1)
- argillaceous fragments —————> structural shale (Plate 14, Photo 2)
- dispersed matrix —————> dispersed shale

The lithological representation of the shaly sand model given in Fig. 50 shows the distribution of detrital clay or shaly material forms.

The authigenic clay components in the same arenites occur as:

- clay coating on quartz grains, (Plate 7, Photo 1).
- pore fillings, (Plate 7, Photo 1).
- replacement of feldspars and mica, and
- micro-fracture fillings (Plate 10, Photo 1).

No accurate evaluation of the detrital authigenic clay ratio was possible. However the best estimate based on microscopic examination is that approximately 25 percent of total clays may be of authigenic origin.

In arenites of the Shoalhaven and Maitland Groups, petrological observation and X-ray defraction (Figs. 51 & 52) have indicated that both kaolinite and illite are common clay minerals whereas possible chlorite is less common. Illite and chlorite being chiefly confined to the fine-grained rocks and the kaolinite to the coarse-grained arenites. In the coarse-grained arenites kaolinite is present in patches often of detrital grain dimensions and consists of a micro-crystalline mosaic of low birefringent booklets set in a brown mass. Along the margins of some of the crystals high birefringent mica (?sericite) flakes occur (Plate 13, Photo 1). X-ray analysis has

Fig. 50 Lithological representation of shaly sand model (after Heslop, 1975)

confirmed the presence of kaolinite but the broad nature of some of the peaks suggests that some is poorly crystallised (Figs. 51 & 52).

Some alteration of feldspar by kaolinite is evident.

Grim (1962), Millot (1970), Shelton (1964) and Fairbridge (1967) suggest that kaolinite is deposited mainly as an authigenic mineral formed under epidiagenetic conditions, for it is normally found in sediments in which the interstitial waters are fresh. Generally, it can be stated that in the Shoalhaven and Maitland Groups kaolinite is more evident in those arenites which do not contain a large amount of carbonate cement. Although some of the kaolinite is thought to be detrital, most of it was probably formed as a result of diagenetic leaching and low pH conditions. It is assumed that such diagenetic leaching occurred during the flushing of the arenites of Shoalhaven and Maitland Groups with meteoric water.

Illite, the hydrous mica group of minerals, is thought to be either reworked from older illites or formed authigenically from less stable clays. Illite appears to be the most stable of the clays in the marine environment. During syndiagenesis it may emerge from the halmyrolysis of montmorillonite or kaolinite. Particularly K^+ is absorbed in these reactions, which are favoured by the presence of Ca^{2+} , Mg^{2+} and ferrous iron.

In the arenites of Shoalhaven and Maitland Groups illite occurs in three forms:

- (a) illitic clay rims and coats, (Plate 7, Photo 1),
- (b) scattered mica flakes, (Plate 12, Photo 1), and
- (c) illitic clay masses of feldspar dimensions.

Optically, this clay is characterised by a flaky appearance and high birefringence. In both the fine and coarse grained arenites illitic clay coats were observed around the quartz grains and along cleavage planes of potash feldspars. Alteration to clay along lithic boundaries also occurs and occasional embayments are filled with illitic clay. In the fine-grained arenites where more extensive alteration takes place, illitic clay masses of detrital grain dimensions occur, some of which possess distinctive rounded outlines. The internal properties of these masses consist of, either a mass of disoriented minute flakes of high birefringent clay, or a mass of well crystallised minute mica flakes which display preferred orientation. These masses may represent total transformation of feldspar to illite. Minor amount of chloritic clay is thought to occur along with the illite clay. This is based on petrological observation only. X-ray diffractograms show small 6° to 7° peaks which may well be chlorite (Fig. 51).

Clay coating of quartz grains: In the Snapper Point Formation (Stockyard Mountain-1) natural gas storage reservoir (Plate 2, Photo 2), the lack of silicification and presence of high porosity (12-20 percent) is attributed to the clay coating of quartz grains. In contrast, the overlying unit which serves as cap rock is strongly silicified (Plate 2, Photo 1). The occurrence of clay coats around quartz grains in this interval is interesting. The manner in which the clay coats have been formed has not been determined in this study. However, numerous workers concerned with this phenomenon have suggested various ways in which clay coating may occur. Others have demonstrated that clay coating inhibits quartz cementation.

Fig. 51

XRD - DIFFRACTOGRAM
SNAPPER POINT FORMATION
(Clay coated quartz sand)
STOCKYARD MOUNTAIN - 1

ILLITE
KAOLINITE
? MIXED LAYER

26.7 d 3.34

24.0 d 3.58 K 20 (002)

19.95 d 4.45 35(020)

17.8 d 4.99 Illite

12.4 d 7.44 Kaolinite (001)

8.95 d 9.88 Illite

5.7 d 15.5 perhaps mixed layer

Lerbekmo (1957) reported the presence in arenites of authigenic montmorillonite which formed as coatings on grains adjacent to pore spaces. He noted that the clay laths or fibres were oriented with their long dimensions normal to the surface of the detrital grains. The mechanism he attributed to this clay rim formation was that of slow precipitation on the surface of the grains from solutions in the pores.

Knight (1960) carried out an experiment in which clean dry sand was mixed with kaolinite and bentonite in water and placed on glass slides. The results showed that in the presence of bentonite a coating developed which was fairly evenly distributed on the surfaces of all the sand particles. In contrast, the particles mixed with kaolinite alone were not coated uniformly but rather the coats tended to assume the form of agglomerate concentrations at points of grain contact.

Grim (1962), reporting on the existence of montmorillonite clay coatings around quartz grains, stated that they are smooth regular coatings composed of flake-like units. The coatings are regarded as an alternation of layers of montmorillonite and rigidly held water with the water layers slightly thinner than the clay layers. It was found that Na-rich montmorillonite coatings contain sheets of water 3 molecules thick per unit of montmorillonite, whilst Ca-rich montmorillonite coatings possess sheets of water 4 molecules in thickness. Grim (1968) also considered that when clay is available in amounts of less than 4 to 6 percent, clay rims are not likely to develop. Where the clay content is so small, other factors such as adhesion of quartz and water, also play a part in the bonding action.

Many authors when discussing clay floccule formation have shown the edge to face particle configuration to be the most common and attribute it to the attraction of the positive charges on particle edges

to negatively charged particle faces (Meade, 1964). Schofield and Samson (1954) found that under conditions of excess electrolytes the edge to face attractions are partially neutralised and flocculation tends to occur in the face to face configuration. Bowles (1968) has described montmorillonite floccules from Recent marine sediments in the Gulf of Mexico which possess a mixture of EF and FF configurations. Galloway (1974) suggests that during the anadiagenesis chemical alteration of unstable grains and aphanitic volcanic debris mobilises silica and aluminum that are constituted as authigenic clay coats and rims around the detrital grains.

The most significant work on clay coating and its inhibition of quartz cementation was done by Heald and Larese (1974). The authors have demonstrated that clay coating in general interferes with the growth of secondary silica in the form of overgrowths. The authors also suggest that clay coating on quartz grains may be detrital but more commonly is formed after deposition of the arenite. Wilson and Pittman (1977) in their publication discussed effectively the origin and influence of authigenic clays and in particular clay rims on arenite reservoirs. In a selected reservoir (e.g. Stockyard Mountain-1, Snapper Point Formation) which is made up of clay coated quartz grains, the absence of silica overgrowths is not necessarily due to clay coating. Factors such as availability of silica and temperature may have been more important. The clay coats within the Snapper Point Formation reservoir in Stockyard Mountain-1 are thought to be of diagenetic illite. If it is accepted that the arenites of this reservoir represent a bar facies then the influence upon clay particle configuration by marine waters with high electrolyte content can be expected.

It is presumed that electrical charges have contributed to the adhesion of illite clay plates to one another. However, what is uncertain is the manner by which these plates have become attached to the detrital grains. To date no definite mechanism has been proposed to account for this phenomenon.

The effect of clays on arenite reservoirs

Clay is of great importance in the geology of petroleum. The presence of even a small amount of clay in an arenite is of great significance for interpretation of depositional environment and petrophysical characteristics of studied sedimentary rocks.

Two reasons largely account for the importance of clay in reservoir studies:

(a) the smallness of the individual crystal particles, many being less than two microns in diameter and some of the most active being less than half a micron.

(b) the chemical and physical instability of the clay minerals, especially of the montmorillonite group. The chemical instability is chiefly due to the presence of loosely attached exchangeable cations. The physical instability of the clay minerals is due to their lattice molecular structure which permits the entry of water between the lattices, thereby greatly changing their volume. The kaolinite, montmorillonite, illite and chlorite groups together with a number of less common species, make up the clay minerals of sediments and sedimentary rocks.

In terms of development of an arenite reservoir authigenic clays play a very important role. Authigenic clays can create problems during drilling, fracturing, and production of hydrocarbons as the result of

their ability to block pores by swelling and migrating and their ability to trap drilling fluid particulate matter. In particular, authigenic clays control petrophysical properties of a reservoir e.g. permeability and water saturation. Hydrocarbon production problems in clay-rich arenites are at least threefold:

- (a) the clay is extremely water sensitive
- (b) the clay pore linings tend to break loose and migrate during swelling; and
- (c) the atomic structure of clays causes the pore system to have a very high surface-area-to-volume ratio.

The high surface-area-to-volume ratio results in a high irreducible water saturation and high critical water saturation which can allow a well to produce water-free oil in the presence of high water saturations. Unless this fact is considered, potentially productive wells may be plugged and abandoned without proper testing because the log-derived water saturation is considered to be too high for the well to be commercial. Swelling of the clays due to the introduction of relatively fresh water into the pores will result in the sealing of the pore-throats and a resulting loss of permeability.

Studies of authigenic clays using the scanning electron microscope (Stalder, 1973; Wilson and Pittman, 1977) have found that the various species of clay minerals are characterised by different growth habits. These exotic crystal growth habits cause large decreases in rock permeability as a function not only of their volume and expandability but also in proportion to the increase in surface area produced. For example, the increase in surface area caused by the authigenic illite is much greater than the increase caused by the same volume of authigenic kaolinite and comparative decrease in permeability (Fig. 53).

Fig. 53 Effect of differing crystal habit of authigenic clay in sandstone on permeability. Porosity is unchanged, although permeability differs by nearly four orders of magnitude in extreme cases. (From P. J. Stalder, 1973, *Geol. Mijnbouw*, 54, 219. Used by permission of "Geologie en Mijnbouw.")

Summary

The progressive diagenesis of the Shoalhaven and Maitland Group arenites produced a sequence of diagenetic features that have considerably decreased the quality of the potential reservoirs mainly by the reduction of porosity and permeability. The reduction of primary and secondary porosity, as well as permeability, is therefore attributed to the following diagenetic features that have been produced during the burial and subsequent uplift:

- early pore fill (calcite, dolomite, dawsonite, siderite, silica and pyrite)
- clay coating of detrital grains (illite)
- silica pore fill (quartz overgrowths)
- late pore and fracture fill (carbonates and clay)

Other petrophysical properties that are affected by the filling of primary and secondary pore spaces with various types of cements are the bulk density and sonic wave velocity.

Legend to Plates 5 to 13 inclusive

Qtz	- quartz
Qtz-ov	- quartz overgrowth
Ca	- calcite
Si	- siderite
Bi	- biotite
Py	- pyrite
Se	- sericite
Ka	- kaolinite
C-y	- clay and clay coats
S-Rf	- sedimentary rock fragments
Fr	- fracture
Ch	- chert

PHOTO 1: Early calcite pore fill in a loosely packed (Nowra Sandstone) arenite. Note the replacement of calcite by siderite.

DIAGRAM PHOTO 1

PHOTO 1: Siderite pore fill.
Siderite is probably replacing an unstable rock fragment. (Nowra Sandstone)

DIAGRAM PHOTO 1

PHOTO 1: Clay coating of quartz grains and clay filling of pores (Snapper Point Formation).

DIAGRAM PHOTO 1

PHOTO 1: Prominent quartz overgrowths filling original pores (Snapper Point Formation).

DIAGRAM PHOTO 1

PHOTO 1: Strongly lithified arenite showing uneven quartz overgrowths and interpenetrating quartz grains. (Nowra Sandstone).

DIAGRAM PHOTO 1

PHOTO 1: Calcite filled fractures. Note replacement of calcite grain by siderite (Snapper Point Formation).

DIAGRAM PHOTO 1

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PHOTO 1: Calcite replacing quartz. Replacement of argillaceous material (clay particles) by calcite in the lower right (Nowra Sandstone).

DIAGRAM PHOTO 1

PHOTO 1: Patches of kaolinite and sericite (Nowra Sandstone).

DIAGRAM PHOTO 1

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PHOTO 1: Deformation of biotite grain due to compaction
(Snapper Point Formation)

DIAGRAM PHOTO 1

CHAPTER VPETROPHYSICAL CHARACTERISTICS OF THE SHOALHAVEN ANDMAITLAND GROUPS ARENITES

This chapter consists of three parts. The first part is concerned with evaluation of porosity, shale volume, permeability and formation water characteristics. The second part deals with detailed structural evaluation and the last part involves the determination of potential net pay storage intervals.

PART I - EVALUATION OF POROSITY, SHALE VOLUME, PERMEABILITYAND FORMATION WATER CHARACTERISTICSIntroduction

The evaluation of porosity, shale volume, permeability and formation water characteristics in the arenites of Snapper Point Formation, Nowra Sandstone and Muree Sandstone consisted of four major techniques: (a) Wireline log quantitative evaluation; (b) Drill stem test result analysis; (c) Laboratory core analysis; and (d) Thin section examination. Details of methods employed are given in Chapter II.

Porosity evaluation

Porosity is an essential element of hydrocarbon reservoir work. It is a measure of the void space expressed as a percentage of the bulk volume of rock. The total volume of connected and unconnected voids thus expressed is the absolute porosity. The effective porosity, also expressed as a percentage of the total reservoir rock volume, is an important factor in the migration, accumulation, and storage of hydrocarbons and as such is of great significance in this study.

Reservoir rocks vary widely in the size of the individual pores and in the arrangement of the pores with respect to one another. These variations are primary if they are controlled by the original depositional framework or fabric of the rock. The variations are secondary where they are the result of subsequent post-depositional factors i.e. fracturing and shattering, solution, redeposition, cementation and compaction.

The pore pattern comprises the pore size and shape, the nature of pore connections, the character of the pore walls, and the distribution and number of larger pores and their relationship to one another. The sizes of individual pores range from subcapillary and submicroscopic openings through capillary-sized openings to solution cavities of all shapes and sizes, including caverns formed in carbonate rocks. Individual pores may be tabular, rounded, or may be thin intercrystalline tabular openings which are 50-100 or more times larger in one direction than in another. The pore walls may be clean or coated with clay-mineral particles, platy accessory minerals, or rock fragments. The tortuosity of the pore pattern is the ratio of the distance between two points by way of the connected pores to the straight-line distance. Pinpoint porosity consists of minute, isolated pores visible under the binocular microscope, (Levorsen, 1958).

The pore pattern of a clastic reservoir rock is a function of several petrographic characteristics. These include grain sizes, shapes, sorting, chemical and mineral composition, matrix and cement.

In this study the porosities of the three arenite formations of the Shoalhaven and Maitland Groups in the Sydney Basin were determined in seven petroleum exploration wells by firstly, obtaining porosities from quantitative wireline log analysis; secondly, examining

all the available core analysis data; and thirdly, examination of thin sections. Tables 12 and 13 summarise the results of the porosity evaluation.

Shale volume evaluation

The presence of shale in arenite beds can affect the reading of some wireline logs thus making interpretation more complex and the results less accurate. The way shale volume affects a log reading depends on the proportion of shale, the physical properties of the shale and the way it is distributed in the formation.

Examination of core material reveals that shaly material may be distributed within the arenaceous bed in three possible ways.

a) Laminar shales interbedded with the sandy layers (Fig. 50; Plate 14, Photo 1). This type of shale, although making the permeability highly anisotropic does not markedly affect the main (horizontal) path of gas flowing to the bore hole.

b) Structural shale or shale clasts. They form part of the rock framework by replacing detrital grains of quartz, chert feldspars and also detrital shale grains (Fig. 50). In arenites where ductile rock fragments are present grain squeezing can accompany compaction. Allen (1962) in a study of Old Red Sandstone has suggested that such fragments can be broken down and intruded as plastic clay into adjacent void spaces. In this respect it is argued that structural shale could reduce effective porosity.

c) Dispersed shales fill the pore space, destroying both porosity and permeability (Fig. 50). The shales may be in the form of accumulations, adhering to or coating the sand grains, or partially fill the smaller pore channels.

Table 12

Well name and number	Interval depth (m)	Porosity evaluation, Snapper Point Formation				
		Methods				
		Wireline log evaluation		Laboratory core analysis		Thin section examination
		Range %	Mean %	Range %	Mean %	%
Stockyard Mountain-1	574.8 - 629.1	4.0 - 10.2	5.4	8.0 - 16.0	9.0	10.0
Kurrajong Heights-1	1889.7 - 1965.9	4.6 - 13.7	6.8	-	5.0	10.0

Table 13

Well name and number	Interval depth (m)	Porosity evaluation, Nowra and Muree Sandstones				
		Methods				
		Wireline log evaluation		Laboratory core analysis		Thin section examination
		Range %	Mean %	Range %	Mean %	%
Stockyard Mountain-1	256.0 - 295.6	4.6 - 10.0	9.0	2.0 - 6.0	4.0	N/O
Woronora-1	1554.4 - 1603.2	1.1 - 11.0	6.1	2.0 - 7.0	6.0	N/O
Kirkham-1	1567.5 - 1604.1	1.6 - 15.5	5.5	2.0 - 10.0	8.0	N/O
Dural South-1	2151.8 - 2180.8	1.9 - 15.1	7.7	-	-	N/O
Kurrajong Heights-1	1662.9 - 1676.4	9.4 - 21.1	12.2	-	-	N/O
Mulgoa-2	1502.6 - 1531.3	-	-	8.6 - 10.5	9.7	N/O
East Maitland-1	586.4 - 768.0	1.2 - 13.8	6.8	2.0 - 7.0	5.0	N/O

N/O = Not observed

PHOTO 1: Nowra Sandstone: Sublitharenite with lamina of shale.

PHOTO 2: Snapper Point Formation: Litharenite with structural shale.

Each accumulation contains some water adsorbed to the surface of the clays. The water forms a part of the total porosity. This type of shale therefore tends to occupy more volume and thus decreases the effective porosity.

In this study evaluations of shale volume and type were carried out in the arenaceous members of the Shoalhaven and Maitland Groups. Megascopic and microscopic examinations of core material revealed that the shale type present in the examined arenite beds is mainly laminar and structural (Plate 14, Photos 1 and 2). Some dispersed shales are however also present. A summary of results of the quantitative estimation of shale within the arenaceous members of the Shoalhaven and Maitland Groups is given in Table 14. X-ray diffraction analysis of selected core material (Table 14) showed that illite is the dominant clay.

The method employed in evaluation of shale is described in Chapter II and the results are given in Appendixes I to VII.

Formation water characteristics

The sedimentary rock environment can be regarded as a multi-phase system where the rock constitutes the solid phase and water (sometimes oil) the liquid phase. The third phase, natural gas, may also be present.

The formation fluids are active chemical and physical components of the rock-fluid system. The fluids within the pore spaces may be in equilibrium with the rock, with the adjacent fluid components and with the existing conditions of temperature and pressure.

Table 14

Shale evaluation, Shoalhaven and Maitland Groups, arenites

Well name and number	Formation	Qualitative evaluation of shale type and volume			Determination of Clays	
		Type	Volume		X-ray defraction	Microscope determination
			Range %	Mean %		
Stockyard Mountain-1	Nowra Sandstone	Laminar	-	-	Illite	Illite
Stockyard Mountain-1	Snapper Point Formation	Structural, laminar	-	-	Kaolinite, illite	Illite
Woronora-1	Nowra Sandstone	Structural, laminar	4 - 100	44.6	Kaolinite, illite	Kaolinite, illite
Kirkham-1	Nowra Sandstone	Dispersed	0 - 100	43.9	Kaolinite, illite	Kaolinite, illite
Dural South-1	Nowra Sandstone	Dispersed	0 - 100	39.2	Kaolinite, illite	Kaolinite, illite
Kurragong Heights-1	Berry - Nowra Sandstone	Dispersed	6 - 100	40.0	-	-
Mulgoa-2	Nowra Sandstone	Dispersed	-	-	-	Illite
East Maitland-1	Muree Sandstone	Dispersed	0.85	38.7	Kaolinite, illite	Kaolinite, illite

Most formation fluids in sedimentary environments are brines containing varying concentrations of soluble salts. The dominant anions may be Cl , HCO_3^- or $\text{SO}_4^{=}$, whilst with some exceptions, Na^+ is the dominant cation in chloride waters. The cation Ca^{++} is generally present in larger proportions than in seawater. The chemistry of ground and seawater is shown in Fig. 54.

In general, the deeper the formation, the more concentrated the brine becomes. The increase in salinity with depth is explained by White (1965) who says that fine-grained sediments behave as semi-permeable membranes permitting selective escape of water and concentrating dissolved components in the remaining pore fluids. Salinity of formation water is therefore a function of:

- time
- distance travelled in the rocks
- the character of the rocks through which it has travelled, and
- the initial character of the water.

In evaluation of formation waters within the arenites of the Shoalhaven and Maitland Groups wireline logs were used where available. Methods for evaluations are described in Chapter II.

The concentration of sodium chloride (NaCl) in the aquifers of Nowra and Muree Sandstones and in the Snapper Point Formation varies from 3000 to 7000 ppm (Table 15).

The sediments of the Shoalhaven and Maitland Groups were deposited in marine environment, where the NaCl solution concentration was probably in excess of 33 000 ppm. The low present NaCl concentration of less than 7000 ppm suggests active post-depositional mixing of marine, connate and meteoric waters, which, in turn, indicates

Table 15

Formation water characteristics, Shoalhaven and Maitland Groups

Well name and number	Rock unit	Interval depth (m)	Resistivity of water (ohm-m)	Temperature (°C)	Formation water concentration of NaCl (ppm)
Stockyard Mountain-1	Nowra Sandstone	256.0 - 295.6	1.10	26	4400
Stockyard Mountain-1	Snapper Point Formation	574.9 - 629.1	0.84	36	5100
Woronora-1	Nowra Sandstone	1554.4 - 1603.2	0.75	60	4000
Kirkham-1	Nowra Sandstone	1567.5 - 1604.1	0.60	55	5200
Dural South-1	Nowra Sandstone	2151.8 - 2180.8	0.83	75	3000
Kurrajong Heights-1	Nowra Sandstone	1662.9 - 1676.4	0.71	70	4200
Kurrajong Heights-1	Snapper Point Formation	1889.7 - 1965.9	0.53	68	5200
Mulgoa-2	Nowra Sandstone	1502.6 - 1531.3	0.60	56	5200
East Maitland-1	Muree Sandstone	586.4 - 768.0	0.58	40	7000

Fig. 54 Piper diagram illustrating the variation in ground water chemistry.
(after Davis and de Weist 1966)

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presence of effective porosity. Table 16 lists the chemistry of formation waters recovered from the Mulgoa-2 well. The concentration of NaCl in the recovered waters from the Berry Formation and the Wandrawandian Siltstone, as estimated by the N.S.W. Water Resources Commission (Table 16), compares favourably with the value of 5200 ppm of NaCl estimated in this study for the Nowra Sandstone formation water.

Permeability evaluation

Permeability is the property that permits the passage of a fluid through the interconnected pores of a rock - its effective porosity - without damage to or displacement of the rock particles. Permeability is, in other words, a measure of the fluid conductivity of a rock, and it is probably the most important single property of a reservoir rock. Permeability, in the geology of petroleum, is not absolute but relative; a rock is termed permeable if an appreciable quantity of fluid will pass through it in a short time (for example, an hour); it is termed impermeable if the rate of passage is negligible. It is recognised, however, that all rocks have some permeability when considered in terms of long periods of geologic time and low-viscosity gases and liquids.

The unit of measurement of the permeability of a rock has been named the Darcy after Henri Darcy, who experimented with the passage of liquids through porous media in 1856. Darcy's law states that the velocity of a homogeneous fluid in a porous medium is proportional to the pressure gradient, and inversely proportional to the fluid viscosity, or

$$q = \frac{k}{m} \times \frac{dp}{dx}$$

in which q is the linear rate of flow (assumed horizontal) in centimetres per second, k is the permeability constant in darcies, m is the

Table 16

Chemistry of waters sampled from petroleum well Mulgoa-2

Interval (m)	Geological unit	pH	Total dissolved solids	HCO ₃ ⁻	Cl ⁻	CO ₃ ⁼	SO ₄ ⁼	Co	Mg ⁺⁺	Na ⁺
All analyses in mg/l										
323 - 0	Hawkesbury Sandstone	5.3	520	260	90	n.d.	3	14	19	37
146.3 - 234	Hawkesbury Sandstone	5.3	200	50	94	n.d.	11	9	12	52
333.7 - 357.8	Narrabeen Group	7.2	480	n.d.	60	n.d.	11	100	16	57
400.8 - 426.7	Narrabeen Group	7.9	870	840	60	n.d.	10	43	60	195
780.8 - 781.8	Illawarra Coal Measures	8.1	12890	11270	503	1160	6	36	20	5390
1399 - 1299.9	Berry Formation	7.9	13950	810	8070	n.d.	48	34	23	5470
1477 - 0	Berry Formation	7.7	12680	4560	5220	n.d.	250	11	11	5190
1659.6 - 0	Wandrawandian Siltstone	8.4	11280	3420	4430	240	120	12	6	4370

(After Water Resources Commission Bore Record System - Bore No. 20309)

n.d. = not determined

fluid viscosity in centipoises, and $\frac{dp}{dx}$ is the hydraulic gradient, the difference in pressure (p) in the direction of flow (x), as one atmosphere per centimetre. This equation defines completely the viscous or laminar flow of homogeneous fluids through porous media of uniform packing and of uniform cross section. For a given value of k the rate of flow through any porous block of rock is therefore proportional to the difference in pressure across the block and to the area of the block, and inversely proportional to the viscosity of the fluid and to the length of the block.

In oil field units the linear form of Darcy's Law for flow of incompressible fluid through a rock filled with only one fluid is as follows:

$$q = 1.127 \times 10^{-3} \frac{kA(p_1 - p_2)}{B \mu L}$$

where: q = flow rate, stb/day

k = permeability, md

A = flow area, ft²

μ = viscosity, cp

L = flow length, ft

p_1, p_2 = inlet and outlet pressures, psi

B = formation volume factor, res. bbl/stb

In this study two main methods of evaluating permeability were employed:

- Wireline log (qualitative) interpretation, and
- Laboratory core analysis

Wireline log interpretation of microlog, spontaneous potential and caliper logs revealed well defined permeable zones within the Nowra and Muree Sandstones and Snapper Point Formation. However, since no reliable information is available concerning the nature of the drilling muds the qualitative permeability interpretation based on the character of the spontaneous potential log curve must be regarded as highly subjective.

Table 17 summarises the characteristics of the wireline logs used in qualitative permeability evaluation of the arenaceous formations of the Shoalhaven and Maitland Groups.

Drill stem test results provide primarily an indication of formation content. Reservoir characteristics that may also be estimated from the drill stem test (DST) analysis besides effective permeability are reservoir pressure, skin factor, radius of investigation and productivity ratio.

Of all the DST carried out in the seven studied wells only one was successful. DST No. 4 in Stockyard Mountain-1 recovered 16 m^3 of brackish water over a period of 65 minutes, in the interval 566.6 - 643.1 m (Snapper Point Formation reservoir). However, absence of incremental pressure build-up data hindered the full pressure build-up analysis and true effective permeability. By assuming the pressure difference (ΔP) value of 10 over one logarithmic cycle in the Horner Plot (Matthews and Russell, 1967) the effective permeability of 14.4 millidarcies was obtained for the DST No. 4 in Stockyard Mountain-1 (Appendix I).

Table 17

Qualitative permeability evaluation, Shoalhaven and Maitland Groups

Well name and number	Formation	Wireline logs			Qualitative permeability evaluation
		Microlog	Spontaneous potential	Caliper	
Stockyard Mountain-1	Nowra Sandstone	N/A	Moderate negative deflection	Mud cake present	Low
Stockyard Mountain-1	Snapper Point Formation	Separation strong	Moderate negative deflection	Mud cake present	Moderate
Woronora-1	Nowra Sandstone	N/A	Strong negative deflection	N/O	-
Kirkham-1	Nowra Sandstone	Separation strong	Strong negative deflection	N/O	Moderate
Dural South-1	Nowra Sandstone	Separation strong	Unreliable	N/O	Moderate
Mulgoa-2	Nowra Sandstone	No wireline logs run	-	-	-
Kurrajong Heights-1	Nowra Sandstone	Separation strong	Strong negative deflection	N/O	Moderate
Kurrajong Heights-1	Snapper Point Formation	Separation strong	Strong negative deflection	N/O	Moderate
East Maitland-1	Muree Sandstone	Separation strong	Moderate negative deflection	N/O	Moderate

N/A = Not available

N/O = Not observed

Because of previous incomplete and some unreliable petrophysical results (in Mayne et al., 1974) from the cores within the studied formations it was necessary to re-test most of the available cores.

Fresh horizontal core plugs were cut and full petrophysical analyses were carried out using dry nitrogen gas and brine. The brine used in the testing contained a concentration of 8250 ppm of sodium chloride which is slightly higher than the concentration of the formation fluids (NaCl 7000 ppm) in the studied formations. The effects on permeability values as the result of using brine of slightly higher concentration than the formation fluid would be minimal.

The results obtained in these tests are summarised in Table 18. The results show a consistent decrease in effective permeability between the air and brine. The lower permeability values obtained as a result of the use of brine (as opposed to nitrogen on core plugs) is important because if clays are present then flocculation could occur in or adjacent to pore throats thus restricting fluid flow.

Table 18

Quantitative permeability evaluation, Shoalhaven and Maitland Groups

Well name and number	Formation	Core number	Depth interval (m)	Number of samples tested	Permeability			
					Nitrogen gas		Brine	
					Range md	Mean md	Range md	Mean md
Stockyard Mountain-1	Nowra Sandstone	3	265.2 - 267.0	2	No flow	-	No flow	-
Stockyard Mountain-1	Snapper Point Fm	7	579.7 - 584.6	6	98.46 - 18.00	58.2	7.40 - 14.0	10.7
Woronora-1	Nowra Sandstone	18	1560.6 - 1563.0	4	3.09 - 1.76	2.4	1.5 - 1.0	1.3
Kirkham-1	Nowra Sandstone	17	1584.9 - 1584.7	3	23.4 - 2.41	12.9	16.0 - 1.0	8.5
Dural South-1	Nowra Sandstone	No Core	-	-	-	-	-	-
Mulgoa-2	Nowra Sandstone	10	1523.1 - 1523.2	2	4.2 - 1.0	2.6	1.0 - 0.0	1.0
Kurrajong Heights-1	Nowra Sandstone	No Core	-	-	-	-	-	-
Kurrajong Heights-1	Snapper Point Fm	24	1950.4 - 1951.6	2	4.48 - 1.50	3.0	0.1	0.1
East Maitland-1	Muree Sandstone	6	610.2 - 611.4	4	15.04 - 3.12	9.08	6.0 - 1.0	3.5

PART II - STRUCTURAL EVALUATION

Five of the structures considered in this study: Woronora, Kirkham, Mulgoa, Kurrajong Heights and East Maitland are faulted anticlines; Stockyard Mountain is an unfaulted anticline and Dural South is an irregular dome (Table 19).

The structure contour maps on top of potential storage reservoirs (Figs. 55-61) in this study are based on the relevant petroleum exploration company's pre-drilling interpretation of various Permo-Triassic structures and seismic data. Their respective structural cross-sections are shown in Appendixes I-VII. Some reservations must be placed on the reliability of the structure maps (Woronora, Kirkham, Dural South and East Maitland) that were constructed from the seismic data only. In general the quality of seismic records is poor and the volumes calculated in this study would need to be checked after high resolution seismic surveys are conducted.

The areal extent and vertical closure of the structures range from 0.22 to 45.4 sq km, and from 5 to 225 m respectively. The gross-rock volume was obtained by the following formula:

$$V = \frac{\sqrt{(A1 \times A2)} + A1 + A2 \times h}{3}$$

In which V = gross rock volume

A1 = the area enclosed by the upper contour

A2 = the area enclosed by the lower contour

h = the thickness between the contours (Fig. 62)

Table 19 summarises the characteristics of the structures studied and their evaluations.

Table 19
Summary of structural characteristics of reservoirs

Structure	Type	Vertical closure height (m)	Area (km ²)	Gross rock volume (x 10 ⁶ m ³)
Stockyard Mountain	Anticline	20.0	12.09	98.4
Woronora	Faulted anticline	47.0	1.08	27.7
Kirkham	Faulted anticline	15.0	0.22	0.9
Dural South	Dome	148.2	45.4	1850.1
Kurrajong Heights	Faulted anticline	120.0	17.5	981.1
Mulgoa	Faulted anticline	60.0	8.1	320.3
East Maitland	Faulted anticline	225.0	19.1	4803.9
Average		91.0	14.8	1154.6

Correction
Title to Figure 55 should read:
Structure Map on top of the Snapper Point
Formation Reservoir

Fig. 55

Fig. 56

Fig. 57

Fig. 58

Correction
Title to Figure 59 should read:
Structure Map on top of the Snapper Point
Formation Reservoir

Fig. 59

Fig.60

Fig. 61

PART III - DETERMINATION OF POTENTIAL NET PAY STORAGE INTERVALS

The following section provides the background information for various assumptions made in the course of determining the potential net pay storage intervals. These intervals were determined by combined results of:

lithological associations
porosity
shale volume
mud cake presence
wireline log characteristics, and
structural analysis

The potential net pay storage intervals for each prospective natural gas storage reservoir are given in Table 20.

Fig.62 PLANIMETRIC MODEL

Stockyard Mountain

Nowra Sandstone Reservoir: An initial net pay thickness (potential reservoir thickness) of 29.7 m was delineated from a given pay thickness of 39.5 m by petrological and petrophysical analyses (Fig. 63). The net pay thickness was subsequently reduced to 5.5 m due to the Stockyard Mountain structure's spill point level. No core is available in the net pay interval. The microcaliper and spontaneous potential log characteristics (mud cake and negative deflection from the shale line) suggest some permeability may be present (Fig. 63).

Snapper Point Formation Reservoir: As in the overlying Nowra Sandstone reservoir, the initially delineated net pay thickness had to be reduced from 34.1 m to 6.1 m because of the structure's spill point level. The microcaliper, spontaneous potential and microlog pattern (mud cake, negative deflection of the SP log and separations on microlog) indicate the presence of permeability in the reservoir (Fig. 64). This is supported by drill stem test No. 4 data over the interval 566.6 - 643.1 m which recovered 16 m^3 of fresh water over a period of 65 minutes.

Woronora

Nowra Sandstone Reservoir: Four net pay zones of 1.8, 9.2, 0.6 and 1.5 m were delineated within a gross pay thickness of 48.8 m. For the purpose of estimating storage capacity, only the upper three zones, totalling 11.6 m, were used (Fig. 65). The wireline log characteristics over the examined interval indicate a well defined sandstone section. The resistivity, in particular, indicates fresh water influence in the potential reservoir.

Kirkham

Nowra Sandstone Reservoir: A net pay thickness of 34.2 m (Fig. 66) based on petrological and petrophysical analyses was reduced to 5.0 m because of the structural configuration of the Kirkham structure. Two drill stem tests were carried out over the Nowra Sandstone interval. Only one was successful, and recovered 30.4 m³ of slightly gas cut mud after a 55 minute flow test.

Dural South

Nowra Sandstone Reservoir: Four net pay zones of 4.9, 2.4, 2.5 and 6.7 m were delineated in this reservoir (Fig. 67). These zones conform to combined gamma-ray and microlog resistivity patterns, indicating permeable arenite. Because of the lack of core material and drill stem test data over these intervals, the permeability value can only be speculative.

Mulgoa

Nowra Sandstone Reservoir: Because of the absence of wireline logs, a 10 m net pay zone is assumed, based on lithological evidence only.

BMR laboratory tests on core material showed the interval 1521.8 - 1524.0 to have a porosity range from 8.6 to 10.5 percent and a permeability of 5 md.

Kurrajong Heights

Berry Formation-Nowra Sandstone Reservoir: The 7.4 m thick reservoir is made up of 3.1 m of lowermost Berry Formation and 4.3 m of Nowra Sandstone. No cores are available. Microlog resistivity indicates some permeability by a continuous separation over the reservoir interval (Fig. 68).

Fig.63 Stockyard Mountain: Petrophysical characteristics of the Nowra Sandstone reservoir.

Fig. 64 Stockyard Mountain: Petrophysical characteristics of the Snapper Point Formation reservoir

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Fig. 65 Woronora: Petrophysical characteristics of the Nowra Sandstone reservoir

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Fig. 66 Kirkham: Petrophysical characteristics of the Nowra Sandstone reservoir.

Fig.67 Dural South: Petrophysical characteristics of the Nowra Sandstone reservoir

Fig. 68 Kurrajong Heights: Petrophysical characteristics of the Berry Formation – Nowra Sandstone reservoir

Fig. 69 Kurrajong Heights: Petrophysical characteristics of the Snapper Point Formation reservoir.

Fig. 70. East Maitland: Petrophysical characteristics of the Muree Sandstone reservoir.

Snapper Point Formation Reservoir: This 28.2 m thick reservoir is subdivided into five net pay zones, their thicknesses being 4.3, 11.0, 3.7, 4.9 and 4.3 m respectively (Fig. 69). Microlog resistivity shows definite separation, thus indicating some permeability.

East Maitland

Muree Sandstone Reservoir: The reservoir is subdivided into five net pay zones, their thicknesses being 15.3, 9.1, 9.2, 27.4 and 9.2 m respectively (Fig. 70). Microlog resistivity together with spontaneous log characteristics, indicate permeable intervals to be present.

Summary

The results of determination of the thicknesses of potential gross and net pay storage intervals for the Snapper Point Formation, Nowra and Muree Sandstones are summarised in Table 20.

The thicknesses of gross pay storage intervals range from 13.5 - 181.6 m, the average being 56.4 m. On the other hand the thicknesses of the net pay storage intervals range from 5.0 - 70.2 m, the average being 17.8 m.

Shoreline facies similar to Nowra Sandstone, Muree Sandstone and Snapper Point Formation commonly constitute high quality reservoirs, but from the available evidence low porosity and permeability downgrade the potential reservoirs which were the subject of this study.

Table 20

Potential gross and net pay storage intervals

Well name and number	Formation	Depth interval (m)	Potential gross storage pay (m)	Potential net storage pay (m)	Potential net to gross pay ratio
Stockyard Mountain-1	Nowra Sandstone	256.0 - 295.6	39.6	5.5	0.14
Stockyard Mountain-1	Snapper Point Formation	574.8 - 629.1	54.3	6.1	0.11
Woronora-1	Nowra Sandstone	1554.4 - 1603.2	48.8	11.6	0.24
Kirkham-1	Nowra Sandstone	1567.5 - 1604.1	36.5	5.0	0.14
Dural South-1	Nowra Sandstone	2151.8 - 2180.8	29.0	16.6	0.57
Mulgoa-2	Nowra Sandstone	1502.6 - 1531.3	28.0	10.0	0.36
Kurrajong Heights-1	Nowra Sandstone	1662.9 - 1676.4	13.5	7.4	0.55
Kurrajong Heights-1	Snapper Point Formation	1889.7 - 1965.9	76.2	28.2	0.37
East Maitland-1	Muree Sandstone	586.4 - 768.0	181.6	-70.2	0.39

CHAPTER VIEVALUATION OF DELINEATED POTENTIAL GAS STORAGE RESERVOIRS

This chapter consists of three parts. The first part is concerned with estimation of potential natural gas storage capacities of the nine delineated potential storage reservoirs. The second part evaluates the deliverability potential of these reservoirs. The third part discusses the significance of the delineated storage reservoirs.

PART I - ESTIMATION OF POTENTIAL NATURAL GAS STORAGE CAPACITIESVolumetric estimation

For this study to have an effective meaning it was necessary not only to estimate the potential storage capacities of the delineated reservoirs but also to determine the deliverability potential of the same reservoirs.

Because the delineated reservoirs had no production history the only feasible method of estimating their potential storage capacity was by the volumetric method using the following formula:

$$V_g = A \times h \times \emptyset \times (1 - S_w) \times B_g$$

in which V_g = volume of potential gas stored

A = area of reservoir

h = net storage pay

$\emptyset$ = porosity (fractional)

$(1 - S_w)$ = assumed gas saturation (fractional)

B_g = gas formation volume factor

The gas saturation ($1 - S_w$) value used in these calculations was assumed to be 80 percent. This value may be somewhat high since the irreducible liquid saturation depends on the mineralogical and textural properties of the rock and, in particular, the volume of clay present. However, since such data for the delineated reservoirs is very limited, the mean gas saturation value in numerous subsurface gas storage fields in France, U.S.A. and Rumania has been used in this study.

Because of the lack of a measured reservoir pressure in the studied reservoirs, hydrostatic pressure values were obtained for the calculations of the gas formation volume factor (B_g). The gas deviation factor (Z) was derived from a gas composition similar to the Moomba-Sydney pipeline gas (Methane 97%, Carbon Dioxide 3%), as this type of gas would be used to fill the potential storage reservoirs.

Table 21 lists the estimated variables used in determining the volume of potential gas stored in the delineated reservoirs. Details of methods employed in estimating these variables are given in Chapter II.

Table 21

Sydney Basin potential natural gas storage reservoir parameters

Potential gas storage field Reservoir parameters	Stockyard Mountain	Stockyard Mountain	Woronora	Kirkham	Dural South	Kurrajong Heights	Kurrajong Heights	Mulgoa	East Maitland
Reservoir	Nowra Sandstone	Snapper Point Formation	Nowra Sandstone	Nowra Sandstone	Nowra Sandstone	Berry Formation- Nowra Sandstone	Snapper Point Formation	Nowra Sandstone	Muree Sandstone
Depth interval (m)	256.0 - 295.6	574.8 - 629.1	1554.4 - 1603.2	1567.5 - 1604.1	2151.8 - 2180.8	1662.9 - 1676.4	1889.7 - 1965.9	1502.6 - 1531.3	586.4 - 768.0
Areal extent (km ²)	12.9	12.9	1.1	0.2	45.4	17.5	17.5	8.1	19.1
Net potential pay thickness (m)	5.5	6.1	11.6	5.0	16.5	7.4	28.2	10.0	70.2
Porosity (%)	9.0	5.4	6.1	5.5	7.7	12.2	6.8	9.7	6.8
Permeability (md)	no data	58.2	2.4	12.9	2.5	2.5	3.0	2.6	9.08
Pressure (psia)	406	841	2241	2276	3084	2389	2739	2198	1015
Temperature (°C)	26	36	60	55	75	60	68	56	40

Table **21** (continued)

Potential gas storage field Reservoir parameters	Stockyard Mountain	Stockyard Mountain	Woronora	Kirkham	Dural South	Kurrajong Heights	Kurrajong Heights	Mulgoa	East Maitland
Gas deviation factor (Z)	0.968	0.937	0.888	0.887	0.899	0.887	0.890	0.898	0.921
Gas formation volume factor (Bg)	27.42	56.78	148.67	152.37	192.86	122.30	176.16	145.89	68.46
Natural gas storage capacity (x 10 ⁶ m ³)	130	180	92	7	8878	1546	4730	922	4994

PART II - DELIVERABILITY EVALUATIONIntroduction

The estimation of the deliverability potential of the nine delineated potential natural gas storage reservoirs was carried out by a computer program for prediction of gas well deliverability by Kurylowicz & Stillwell (1978). The equations used in the program, assume a depletion drive mechanism for the Nowra Sandstone, Muree Sandstone and Snapper Point Formation potential gas storage reservoirs. However, to accommodate the pressure effects of the aquifers (unknown so far), the computer program will have to be modified to suit either water or partial depletion drive mechanisms of the potential gas storage reservoirs.

The purpose of this computer program is to calculate the flow of gas against a minimum surface pressure with a minimum of input data. Because of large storage capacity required in the computer for the running of the program it was necessary to segment the program into three sections.

The first segment which sets up a large 'COMMON' storage block calls the second segment which calculates the gas deviation factor and the viscosity from the gas composition. Then it calculates the gas potential and calls for the third segment. This third segment calculates Darcy and non-Darcy flow in the reservoir and flow in the tubing.

This program uses the latest published algorithm for obtaining the gas deviation factor. This gas deviation factor expresses the departure of real gases from the idealized behaviour of gases as predicted by Boyle's Law and by Charles' Law.

The deliverability calculations proper are based on recent mathematical developments, (Energy Resources Conservation Board, 1975) which utilise the gas-potential (or 'pseudo-pressure function') approach to preparing an array of gas potential data versus pressure.

The important constraints which govern the amount of gas a field can deliver into a pipeline are intrinsic or extrinsic. Important intrinsic constraints to be considered are:

- gas initially in place and its quality
- permeability and thickness of the reservoir
- skin factor (formation damage adjacent to well bore causing reduced permeability) and
- non-Darcy flow (or turbulence).

Five important extrinsic constraints considered in the program are:

- tubing diameter
- number of producing wells
- initial raw gas production rate
- minimum tubing head pressure (at the surface) and
- minimum (or cut-off) production rate (which is related to the economics of the field).

The gas flow rate in MMCF/D is converted to an annual flow and year end pressures are calculated from the material balance. The Darcy and non-Darcy flow are used to calculate flowing bottom-hole pressures.

The flowing tubing head pressure is calculated using the R.V. Smith-modified Weymouth equation (in Katz et al., 1959). These formulae, rearranged, are shown diagrammatically in Figure 71.

② Assume same P_{wf} as above

calculate average reservoir pressure, $\bar{P}$:

$$\bar{P} = \sqrt{P_{wf}^2 + C_4 q \bar{\mu} \bar{Z}}$$

where $C_4 = 3.28 \frac{T_r}{kh} \left[\log \frac{r_e}{r_w} - 0.326 + 0.434 S + Dq \right]$

$$G_p = G_{sc} \left(1 - \frac{Z_i}{\bar{P}_i} \frac{\bar{P}}{\bar{Z}} \right)$$

The production rate is reduced by 2% and the above calculations are redone if any one of three conditions exist:

- flowing pressure (bottom hole) is less than zero
- flowing surface pressure (tubing head) is less than zero
- flowing surface (tubing head) pressure is less than the minimum supplied in the input data.

If the wet gas flow rate, Q , is less than 0.98 of the minimum rate of production, Q is set to zero for the remaining years.

The results by years are stored in arrays for printing and plotting.

Deliverability scheme

The deliverability scheme designed for the nine delineated potential gas storage reservoirs assumes the following:

- (a) an initial annual market requirement of a volume of gas
- (b) the drilling of a number of wells for production
- (c) recovery mechanism is to be primarily by depletion drive
- (d) the volume of working gas available for production from the storage reservoir is to be 70 percent of total gas stored
- (e) the remaining 25 percent of the total gas stored is to serve as cushion gas for the life of a storage field and some of it may also eventually be recovered
- (f) each production well would produce at the maximum flow rate for the period of time necessary to deplete the reservoir of all its working gas.

Flow rate evaluation and flow rate stimulation

The computer program Kurylowicz & Stillwell (1978), was used to obtain maximum flow rates for the delineated potential storage reservoirs. The deliverability parameters and assumed variables used in the estimation of maximum flow rates for individual reservoirs are given in Appendix VIII.

The absence of useable Drill Stem Test results necessitated the use of permeability values obtained from laboratory testing of cores for the purpose of deliverability calculation. However, because of limited availability of core material over the reservoir intervals these values were extrapolated to an average permeability thus assuming the homogeneity of the reservoir rock.

The information gained from these computations revealed seven out of nine delineated potential storage reservoirs to be suitable for storage and possible retrieval of stored gas. The two unsuitable reservoirs are Nowra Sandstone at Stockyard Mountain and Kirkham. The Stockyard Mountain reservoir (256.0 - 295.6 m) is too shallow, and therefore incapable of sustaining adequate reservoir pressure for production. The Kirkham reservoir is thought to have too small a storage capacity ($7 \times 10^6 \text{ m}^3$ of natural gas).

The maximum flow rate (Q) obtained in the course of computations ranges from 0.041 to $0.256 \times 10^6 \text{ m}^3$ per day per well, and the results are summarised in Table 22. The range of the estimated flow rates (Table 22) would be reported as moderate by most reservoir engineering authorities. In the event of the development of any of the delineated potential storage reservoirs the flow rates could be improved by hydraulic fracturing, acidizing or overpressuring the individual reservoirs.

Table 22

Summary of deliverability potential

Potential gas storage field	Reservoir	Depth Interval (m)	Reservoir pressure (psia)	Permeability X thickness (kh)	Volume of potential gas stored $\times 10^6 \text{ m}^3$	Maximum flow rate $\times 10^6 \text{ m}^3/\text{D/W}$
Stockyard Mountain	Snapper Point Formation	574.8 - 629.1	841	1160	180	0.087
Woronora	Nowra Sandstone	1554.4 - 1603.2	2241	91	92	0.043
Dural South	Nowra Sandstone	2151.8 - 2180.8	3085	135	8878	0.129
Kurrajong Heights	Berry Formation- Nowra Sandstone	1662.9 - 1676.4	2389	60	1546	0.041
Kurrajong Heights	Snapper Point Formation	1889.7 - 1965.9	2739	240	4730	0.189
Mulgoa	Nowra Sandstone	1502.5 - 1531.3	2198	86	922	0.052
East Maitland	Muree Sandstone	586.4 - 786.0	1015	2070	4994	0.256

In any stimulation programme it is important to adopt stimulation techniques which suit the needs of the reservoir. Although designing and using proper mud systems and frac jobs can be expensive, the long-term benefits far outweigh the short-term cost. Satisfactory stimulation programme can only be achieved if the engineers are provided with all the information on the cements and the types of clay minerals filling the pores.

Hydraulic fracturing

Hydraulic fracture well stimulation was introduced in the early 1950's. It may be defined as the process of creating a fracture or fracture system in a porous medium by injection of fluid under pressure through the well, in order to overcome the native stresses and to cause material failure within a porous medium. It is the creation and retention of fractures in a reservoir rock. In order to obtain a fracture in reservoir rock, energy must be created by injecting fluid down a well and into the reservoir rock.

The objective of hydraulic fracturing is to increase the flow rates (well productivity) by creating a highly conductive path some distance away from the well into the reservoir rock. On creation of fractures or conductive paths, they are then retained by propping agents e.g. sand or glass beads to hold the fractures apart. The objective of propping is to maintain the desired fracture open for a much improved flow rate from the reservoir rock into the well.

Acidization

Forcing acids into a reservoir under pressure is termed acidization. The acid enters the reservoir rock along the connected voids and dissolves the soluble material as it penetrates the reservoir, thereby increasing both the permeability and porosity. Different

types of acids are used depending on the composition of the rock comprising the reservoir. In the case of the reservoirs delineated in this study acidization with hydrochloric acid would improve permeability by destroying much of the siderite and calcite occurring in the matrix of the reservoir rocks.

Overpressuring

Improvement in flow rates from low permeability reservoirs can also be obtained by overpressuring. This must however be carefully controlled so as not to fracture the cap rock. Table 23 lists the "improved" flow rates obtained by overpressuring the seven potential storage reservoirs by 10 percent (Appendix VIII). The average improvement in flow rates as a result of overpressuring the reservoirs is 14.3 percent compared to flow rates estimated using normal reservoir pressure.

Depletion estimates

An estimate of time required to deplete the delineated potential gas storage fields of all working gas (70 percent of the total stored) was made. The estimation is based on the maximum flow rates (Table 22) from 50 producing wells per storage field (Method 13, Chapter II). The estimated time of depletion for all seven reservoirs ranges from 32 to 956 days.

Table 24 and Figure 72 summarises the depletion times for all the potential gas storage reservoirs.

Table 23

Comparative flow rates, normal and overpressured reservoir conditions

Potential gas storage field	Reservoir	Flow rate estimation				
		Initial reservoir pressure (psia)	Flow rate $\times 10^6 \text{ m}^3/\text{D/W}$	Initial reservoir pressure (psia) increased by 10%	Flow rate $\times 10^6 \text{ m}^3/\text{D/W}$	% Increase in flow rate
Stockyard Mountain	Snapper Point Formation	841	0.087	925	0.103	15.5
Woronora	Nowra Sandstone	2241	0.043	2465	0.048	10.4
Dural South	Nowra Sandstone	3085	0.129	3393	0.151	14.6
Kurrajong Heights	Berry Formation-Nowra Sandstone	2389	0.041	2628	0.048	14.6
Kurrajong Heights	Snapper Point Formation	2739	0.189	3013	0.222	14.9
Mulgoa	Nowra Sandstone	2198	0.052	2417	0.061	14.7
East Maitland	Muree Sandstone	1-15	0.256	1116	0.303	15.5

Table 24

Depletion evaluation of potential gas storage reservoirs

Potential gas storage field	Reservoir	Depth Interval (m)	Maximum flow rate $\times 10^6 \text{ m}^3$	Number of wells	Production days required for 70% depletion (t)
Stockyard Mountain	Snapper Point Formation	574.8 - 629.1	0.087	50	32
Woronora	Nowra Sandstone	1554.4 - 1603.2	0.043	50	32
Dural South	Nowra Sandstone	2151.8 - 2180.8	0.129	50	956
Kurrajong Heights	Berry Formation - Nowra Sandstone	1662.9 - 1676.4	0.041	50	541
Kurrajong Heights	Snapper Point Formation	1889.7 - 1965.9	0.189	50	348
Mulgoa	Nowra Sandstone	1502.5 - 1531.3	0.052	50	258
East Maitland	Muree Sandstone	586.4 - 786.0	0.256	50	268

Fig. 72 Sydney Basin potential gas storage reservoir depletion rates.

PART III - DISPOSITION AND SIGNIFICANCE OF POTENTIAL
GAS STORAGE RESERVOIRS IN SYDNEY BASIN

Introduction

The seven potential gas storage reservoirs as delineated in this study are favourably situated to the major domestic, commercial and industrial markets as well as to the major existing and proposed gas pipelines in the region of New South Wales (Fig. 73).

Apart from their primary function for storage of natural gas for peak shaving and security of supply, these reservoirs could also be used for storing gas manufactured from coal.

Major markets

In New South Wales the major domestic, commercial and industrial markets for gas are: the Sydney Metropolitan Area, Wollongong - Port Kembla, the South Coast of N.S.W., Newcastle, the Hunter Valley and major inland provincial centres.

The domestic consumers represent a high proportion of the total existing gas users. Their consumption of natural gas can be subdivided into two groups:

- (a) cooking and water heating, and
- (b) space heating.

Group (a) would represent a relatively uniform daily load throughout the year but is confined mainly to daytime usage.

Group (b) would represent in N.S.W. the winter load with comparatively wide peaks during the coldest months from May to September.

The commercial consumers in N.S.W. are represented by their type of business e.g.: - hotels, motels, shops, public buildings, offices and factories. Their consumption falls generally into two groups:

- (a) a load reflecting their business, and
- (b) a space heating load.

Group (a) reflect the use of gas for cooking, heating and hot water in hotels, motels, and other food outlets in public buildings.

Group (b) would on the other hand represent the load for space heating for at least half of the year in hotels, motels, shops, offices, public buildings and factories.

The industrial consumers for natural gas in N.S.W. would represent a broad spectrum of industries in the three major industrial centres, of the Sydney Metropolitan Area, Wollongong - Port Kembla and Newcastle. They would have load curves with quite diverse peaks, varying on a weekly, monthly and annual basis.

The detailed daily, weekly and annual load curves for N.S.W. consumers are at present not available (pers. comm., The Australian Gas Light Company, Sydney, September 1979).

Gas pipelines

The Pipeline Authority built and completed in 1976 the 1300 km Moomba-Sydney natural gas pipeline which carries gas from the Cooper Basin gas treatment plant at Moomba in South Australia to the Sydney Metropolitan "City Gate" at Wilton, southwest of Sydney. A short gas pipeline from Wilton "City Gate" to Wollongong has also been in operation since 1978.

Figure 73 shows the N.S.W. existing and proposed gas pipelines.

Beyond the "City Gate" the N.S.W. regional gas distributor, The Australian Gas Light Company, is responsible for the construction of pipelines and for the supply of gas to the state of N.S.W.

A pipeline to carry gas from Wilton "City Gate" to Newcastle to serve the northern part of N.S.W. has been approved and construction is proceeding.

As part of an agreement between The Pipeline Authority, The Australian Gas Light Company and the Government of N.S.W., lateral gas pipelines will be constructed as soon as practicable to serve the N.S.W. provincial towns: Cowra, Orange, Bathurst, Lithgow, Cootamundra and Wagga Wagga. An agreement between the Australian Gas Light Company and the Australian Government has also been reached to build a pipeline from Yass, N.S.W. to the Australian Capital Territory.

In the event of The Australian Gas Light Company not being able to obtain any further supplies of natural gas from the Cooper Basin in the next few decades, serious consideration should be given to construction of a transcontinental gas pipeline from the North West Shelf of Western Australia via the Central Australian gas and oil fields at Palm Valley and Mereenie to Moomba in South Australia (Fig. 74).

If shortage of natural gas in N.S.W. does become a reality it would not be too late for suppliers and distributors of natural gas in N.S.W. to consider manufacturing gas from coal, which is an abundant commodity in the Sydney Basin region. Therefore, in terms of strategic market importance, the seven potential gas storage reservoirs delineated in this study are favourably situated to major N.S.W. markets, the major existing and proposed gas carrying pipelines and to areas of

Fig. 73 SYDNEY BASIN, LOCATION OF POTENTIAL SUBSURFACE GAS STORAGE RESERVOIRS.

Fig. 74. PROPOSED AUSTRALIAN TRANSCONTINENTAL GAS PIPELINE

shallow coal deposits in the northern, western and southern parts of the basin (Plate I).

In the following chapter a possible plan is outlined for the development of these potential gas storage reservoirs. Details of comparative development and maintenance costs are also included.

CHAPTER VIIDEVELOPMENT AND ECONOMICS OF SUBSURFACE GAS STORAGE

This chapter consists of two parts. The first part is concerned with the theoretical aspects of development of potential subsurface gas storage reservoirs. The second part deals with costs of development in general and a comparison of costs between the development of subsurface gas storage reservoirs in Sydney Basin and duplication of the pipeline from South Australia to New South Wales.

PART I - DEVELOPMENT OF SUBSURFACE GAS STORAGERESERVOIRS IN AQUIFERS

Before any decisions are taken for the development of subsurface gas storage reservoirs the following prerequisites should be established:

- an adequate structure, with a continuous closure on all sides is required;
- the potential reservoir rock should have a sufficient porosity for reasons of storage capacity, and an adequate permeability for reasons of deliverability;
- a considerable layer of impermeable cap rock with proved integrity for gas retention should be above the reservoir.

Development

The most important factor in development of subsurface gas storage reservoirs in aquifers is the displacement of formation water by injection of gas at pressures higher than that of the virgin pressure of the aquifer.

The gas is injected under pressure down into the aquifer bed through wells which are drilled on the crest of the structure (Fig. 75). As the injected gas flows through the interconnected voids it displaces some but not all of the water present in the reservoir rock. The injected gas first displaces zones of water that have the lowest displacement pressure; these are zones of highest permeability. The residual water occupies from 15 to 50 percent of pore space in a typical aquifer depending on the size of the voids.

The pressure of the injected gas will, by displacing much of the water from the aquifer, form what is called a "bubble" of gas. Figure 76 shows the schematic development of a gas bubble.

As the injection of gas continues the entire space around the injection well becomes filled and the bubble extends outwards until it reaches the area of further injection wells. As the bubble of gas reaches the area of other injection wells these are brought into operation and the additional gas injected into the aquifer increases the lateral growth of the gas bubble. The injection process and the growth of a uniformly saturated bubble may take months or even years depending on the permeability of the aquifer, number of injection wells and injection rates.

In order to limit the gas within a predetermined area, observation wells are drilled around the periphery of the structure (near the area of the lowest closed contour). The purpose of these wells is to determine when the gas/water contact has reached the defined perimeter of the aquifer. When this happens gas will begin to appear in the observation wells, thereby indicating that the aquifer is full and injection of gas stops.

Fig. 75 Subsurface gas storage field.

Fig. 76. Development of gas bubble in an aquifer.
(After Katz et.al. 1963)

Fig.77 . Change in gas bubble pressure during development and operation.
(After Katz et.al. 1963)

Displacement of water

When gas is injected into an aquifer most of the formation water is displaced from the pore spaces of the reservoir rock. Where does this water go? If the aquifer bed outcrops nearby or if it is in communication with other outcropping water bearing rock units some of the displaced water will be forced to the surface. In most cases however, the aquifer beds to be used for gas storage are deep below the surface and far away from the actual outcrop - therefore the water and the rock particles around the gas bubble compress and the pores expand. Normally half of the space required for the injected gas will be created by the compression of the formation water and the other half by the compression of the reservoir rock particles. The reservoir beds of the Shoalhaven and Maitland Groups possibly contain an open aquifer system. This possibility is based on identification of diagnostic diagenetic features that resulted from flushing of the reservoirs with meteoric water during diagenesis.

Once the gas bubble is established at its fullest extent the withdrawal of gas may begin. The pressure within the bubble is reduced, thus permitting the displaced water to flow back into the area of the gas bubble. The energy for the water flow is a result of expansion of previously compressed water saturating the rock around the bubble. The aquifer around the gas bubble acts like a large elastic reservoir. During the injection process the water saturated rock compresses, thus making space for more gas. Then during the withdrawal process the water saturated rock expands, thus providing the energy to drive water into the gas bubble and displace some of the gas from it (Figure 77).

Cushion gas

For gas storage in aquifers to function properly a substantial quantity of injected gas known as "cushion gas" must remain in the reservoir so as to maintain adequate gas bubble pressure and avoid water encroachment around the injection wells. While there is no general rule for the required ratio of working gas (gas available for withdrawal) to cushion gas, it is however the practice in the U.S.A. and France that about 30 percent of total gas initially injected should remain as cushion gas.

The French gas company Gaz de France (pers. comm. July 1978) developed in 1976 a method for partial replacement of conventional cushion gas by inert gas injection. Because of the quantity of gas required to serve as cushion gas this new development is of considerable economic advantage. In the case of new reservoirs, partial replacement of conventional cushion gas by inert gas can be achieved by injecting the inert gas into the central area through a bore-hole that will subsequently be used to inject natural gas. The natural gas will then drive the inert gas towards the periphery of the structure.

In reservoirs already in operation, this substitution will be effected by injecting inert gas at the periphery of the structure and recovering a corresponding volume of natural gas in the central area. The proportion of cushion gas which can be made up of inert gas will depend on the particular configuration of each reservoir. According to Gaz de France experience up to 20 percent of total cushion gas could be made up of inert gas. The use of inert gas for cushion gas will considerably reduce the cost of storage in aquifers.

PART II - THE ECONOMICS OF SUBSURFACE GAS STORAGE

There is very little information available regarding the costs of development of subsurface gas storage reservoirs and subsequent operations. However, the major costs involved would be in exploration for suitable gas storage reservoirs, development and the cost of gas to be stored.

The Herscher Gas Storage project in Illinois, U.S.A. had in the year 1960, a gas storage capacity of $1.42 \times 10^9 \text{ m}^3$ and the total investment was approximately \$US32 million, of which 22 percent of total investment was for cushion gas (Buschbach and Bond, 1967).

The capital investment in the Herscher Gas Storage project covered:

21 injection and withdrawal wells,
 13 observation wells,
 Dehydration plant (capacity $12 \times 10^6 \text{ m}^3$ of gas per day), and
 Compressor unit (capacity 10 000 hp).

In the U.S.A., Coates (1966) and Schwalm (1971) found that in general the aquifer storage costs are higher than the depleted gas field storage costs, for the following reasons:

- aquifer storage requires considerably more exploratory and development work to prove the geological requirements for subsurface gas storage
- in depleted gas field storage, a portion of the cushion gas is provided with little or no cost at the time the field is converted to storage
- the operating costs of aquifer storage fields are higher because of the larger quantities of water that must be handled during withdrawal operations.

In a major study of 181 United States subsurface gas storage fields, Coates (1966) showed that fixed charges accounted for 80 percent of total storage costs. These fixed charges included depreciation, return on investment and taxes. About 35 percent of the total investment was for cushion gas which cannot be withdrawn for practical reasons during the normal operation of the storage field. Of the total cushion gas about 60 percent is reported as non recoverable and should therefore depreciate.

Schwalm (1971) compared the costs of storing gas in depleted gas fields, aquifer reservoirs and liquid natural gas (LNG) plants. He found that the cost of storing gas in an aquifer is 13 percent higher than the cost of storage in a depleted gas field. The costs for liquid natural gas plants exceed the costs of depleted gas field storage by 100 percent and that of aquifer storage by 85 percent. Most of the investment in a LNG plant is for storage and liquification facilities. Table 25 shows a comparative cost of supplying $84.9 \times 10^6 \text{ m}^3$ ($3 \times 10^9 \text{ ft}^3$) of gas over a certain season and at $2.8 \times 10^6 \text{ m}^3/\text{Day}$ ($100 \times 10^6 \text{ ft}^3/\text{Day}$) from the three different storage facilities.

Table 25Comparative costs for different storage facilities (US \$)

	Depleted gas field storage	Aquifer storage	Liquid natural gas plant
Investment	3 690 000	4 470 000	13 300 000
Annual carrying charge	553 000	670 000	1 955 000
Annual commodity charge	750 000	750 000	750 000
Annual operating cost	150 000	240 000	300 000
Net total annual cost	1 453 000	1 660 500	3 045 000

Sydney Basin exploration development costs

In order to develop any of the Sydney Basin potential gas storage fields delineated in this study a complete exploration program would have to be carried out to prove up their potential.

The following program for exploration and development is thought to be necessary for a reliable evaluation and subsequent operation of a subsurface gas storage field.

Exploration

- 1 - Geological and geophysical appraisal of published data
- 2 - Seismic survey (close spaced line grid)
 - Evaluation and interpretation of seismic data
 - Structural interpretations based on seismic data

3 - Drilling of a key well

- coring the base of cap rock
- coring through the reservoir rock
- wireline logging and evaluation
- drill stem testing and evaluation
- well completion for further development

Development

- Appraisal of exploration data
- Drilling of injection and observation wells
- Installation of compressor unit
- Installation of dehydration plant
- Construction of pipeline from the "City Gate" to the storage structure
- Construction of pipeline to the gas distribution network
- Well stimulation

Costs

- Seismic survey	\$ 1 800 per km/line
- Drilling and evaluation (key well)	\$ 200 per metre
- Drilling and evaluation (injection wells)	\$ 100 per metre
- Drilling and evaluation (observation wells)	\$ 100 per metre
- Well stimulation	\$200 000 p/well
- Compressor units	\$200 000 p/unit
- Dehydration plants	\$1 000 000 p/unit
- Pipeline	\$ 50 000 p/km
- Gas to be stored	\$ 0.14 p/m ³

The costs of exploration and development given in the Sydney Basin are approximate and are based on 1978 estimates by BMR (Pers. comm. J.M. Henry, October 1979).

For example, the estimated costs for exploration and development of a typical potential gas storage field (Stockyard Mountain) in the Sydney Basin are given in Table 26.

Table 26Exploration and development costsStockyard Mountain gas storage field

Snapper Point Formation reservoir

Depth 600 m

- Appraisal of published geological and geophysical data	\$ 10 000
- Seismic survey	\$ 27 000
15 km/line	
- Drilling, 15 wells to 600 m	
1 initial key well	\$ 120 000
10 injection wells	\$ 600 000
4 observation wells	\$ 240 000
- Well data evaluation	\$ 10 000
- Compressor unit	\$ 200 000
- Dehydration plant	\$1 000 000
- Pipeline from Wollongong "City Gate" to the storage reservoir 30 km (@ \$50 000/km)	\$1 500 000
- Pipeline from the storage reservoir to the gas distribution area	not available

 \$3 707 000

Cost of gas (\$0.14 per m³ to be injected)

- Reservoir capacity	181.0 x 10 ⁶ m ³	
Cushion gas	54.3 x 10 ⁶ m ³	
Working gas	126.7 x 10 ⁶ m ³	
	<hr/> 181.0 x 10 ⁶ m ³	\$25 340 000
Total cost		<hr/> \$29 047 000 <hr/>

These costs agree with trends found by Coates (1966) and Schwalm (1971). Of the total cost for the Stockyard Mountain potential gas storage field, 28 percent is for cushion gas. However, operational costs for the potential gas storage fields in Sydney Basin cannot be determined.

On the other hand the cost of duplicating the 1300 km long Moomba-Sydney gas pipeline with a diameter of 86.4 cm would by far exceed the exploration, development and possible operational costs required for all seven potential gas storage fields in Sydney Basin.

The cost of construction of the 1300 km long Moomba-Sydney gas pipeline in 1976 was \$223 million (The Pipeline Authority, 1976). This cost would represent \$170 000 per km.

Summary

When considering the future problems of deliverability for the N.S.W. gas market three alternatives will be available:

- Duplication of the Moomba-Sydney gas pipeline;
- Building of liquid natural gas plants, or
- Development of gas storage in subsurface natural reservoirs.

In my opinion, it would be unrealistic and too costly to duplicate the pipeline. The second alternative may prove to be far too costly and inadequate for reasons of capacity. Therefore, the development of gas storage in natural reservoirs in Sydney Basin becomes a realistic alternative.

CHAPTER VIIILAWS AND REGULATIONS CONCERNING SUBSURFACE GAS STORAGE

This chapter comprises two parts. The first part deals with general aspects of Australia's petroleum exploration legislations. The second part names the amendments to the existing petroleum exploration legislations which appear to be required to incorporate the storage of gas in subsurface natural reservoirs. The chapter emphasizes the need for an integrated approach to solving energy problems.

PART I - PETROLEUM LEGISLATION IN AUSTRALIA

Compared with most other countries in the world, Australia is extremely well endowed with natural gas and coal resources. With a population of 14.5 million the demonstrated reserves of natural gas as at 31.12.78 are: $31 \times 10^{12} \text{ m}^3$ and that of coal $200\,000 \times 10^6$ tonnes.

Such a favourable endowment probably accounts for the fact that shortages of natural or manufactured gas have seldom aroused great public awareness in Australia until relatively recently. Today however, few issues with the exception of crude oil availability raise greater debate than issues relating to natural or manufactured gas use and development.

In Australia and its Territories, all petroleum on or below the land is and shall be deemed always to have been the property of the Crown. Ownership of freehold land does not carry with it any rights to prospect for or to produce petroleum.

A landowner, by virtue of the fact of being a landowner, is not entitled to any portion of the proceeds or profits that may be made from any petroleum, which includes natural gas, discovered on his property. A landowner may not refuse access to his property for the purposes of petroleum exploration by any company or individual authorised to carry out exploration within a title covering the area.

A landowner may claim compensation for damage to property, crops, water supplies etc., caused by petroleum exploration activities. Provision is also made for compensation or reimbursement for loss in respect of the use of land occupied.

Full control of petroleum exploration development rights and conditions of tenure of titles (permit, licence or lease) is vested in the Government or Administration of each State or Territory. No company or person is permitted to carry out any phase of petroleum exploration or development without the necessary Government authorisation.

Each of the Australian States and Territories enacted separate legislation dealing with exploration and exploitation of petroleum within the area of the State, including the State's rivers and territorial waters (Table 27). The schemes of these Acts have numerous similarities but there are certain differences in detail. Petroleum is defined under the New South Wales, Queensland and Western Australian Acts as any naturally occurring hydrocarbon or mixture of hydrocarbons, whether in a gaseous, liquid or solid state, or any naturally occurring mixture of one or more hydrocarbons together with any one or more of hydrogen sulphide, nitrogen,

Table 27List of Principal Australian Petroleum LegislationsCOMMONWEALTH

Petroleum (Submerged Lands) Act 1967

NEW SOUTH WALES

Petroleum Act 1955-1967

Petroleum (Submerged Lands) Act 1967

Pipelines Act 1967

VICTORIA

Petroleum Act 1958

Petroleum (Submerged Lands) Act 1967

Pipelines Act 1967

QUEENSLAND

Petroleum Acts 1923-1967

Petroleum (Submerged Lands) Acts 1967

SOUTH AUSTRALIA

Mining (Petroleum) Act 1940-1968

Petroleum (Submerged Lands) Act 1967

WESTERN AUSTRALIA

Petroleum Act 1967

Petroleum Pipelines Act 1969

Petroleum (Submerged Lands) Act 1967

TASMANIA

Petroleum (Submerged Lands) Act 1967

NORTHERN TERRITORY

Petroleum (Prospecting & Mining) Ordinance 1954-1968

helium or carbon dioxide. Under the South Australian and Northern Territory legislation, there is a similar definition but it is expressly stated that petroleum does not include any substance which may be extracted from coal, shale or other rock by the application of heat or by chemical process.

PART II - PROPOSED AMENDMENTS TO THE PETROLEUM LEGISLATION
OF AUSTRALIAN STATES AND TERRITORIES

Although this study refers in principle to N.S.W. only, the existing Petroleum Acts of all Australian States and Territories will have to be amended in order to incorporate the storage of gas in subsurface natural reservoirs.

I propose that the following general amendments be included in the Australian Petroleum Acts for exploration, development and operation of subsurface gas storage projects.

Exploration

- The Crown shall determine all the procedures for granting, extending, transferring, renumbering or withdrawing a permit for exploration of subsurface gas storage reservoirs.
- The Crown shall determine the criteria on which preference shall be given to applicants for an exploration permit.
- The Crown shall grant exploration permits only to applicants who can furnish proof of their technical and financial capacity to meet the required obligations as determined by the Crown for exploration of subsurface gas storage reservoirs.

- The Crown shall not grant an exploration permit unless the applicant furnishes a complete Environmental Impact statement.
- The Crown, whilst considering an application for a permit, shall invite the owners as well as users of the land, to submit their comments.
- Before granting an exploration permit for a subsurface gas storage reservoir the State's Water Resources Board shall be required to express an opinion on each application, in order that measures for protection of groundwater may be specified in the permit.
- The Crown shall not grant a permit for exploration of a subsurface gas storage reservoir in an aquifer which contains fresh water.
- The Crown shall determine the minimum requirements for exploration.
- The conditions governing exploration for subsurface gas storage reservoirs shall be specified by the Crown and shall be specific to the permit area only.
- The Crown shall obtain a deposit or bond from the successful applicant, as guarantee of compensation for damages which may occur within the permit area.
- The text of the application and the terms of the permit shall be published in at least two newspapers available in the permit area concerned.
- The Crown may withdraw or extend the permit. Its conditions may be modified.
- The holder of a permit may, with the permission of the Crown, transfer or surrender said permit.
- The holder of an exploration permit shall proceed with exploration within a specified time and according to the conditions determined by the Crown.

- On completion of exploration work the exploration permit holder should provide the Crown with a feasibility study for future development.
- The Crown shall, upon completion of a satisfactory exploration program, issue to the holder of an exploration permit, a development licence if so required.

Development and operation

- The Crown shall determine the conditions for development, operation and maintenance of the subsurface gas storage reservoir and its ancillary installations.
- The Crown shall not issue a Development Licence in respect of completion of a satisfactory exploration program, if it finds the proposed development of the subsurface gas storage reservoir to be:
 - 1 - confined to rock formations less than 200 m below the surface, or
 - 2 - damaging to the local or regional water resources, or
 - 3 - detrimental to outcropping rock formations which are considered worthy of preservation, or
 - 4 - against public interest in general.

CHAPTER IXSYNTHESIS

Chapter nine of this thesis consists of four sections, Methods, Results, Conclusions and Recommendations.

Methods

It can be demonstrated from the results presented in this thesis that methods involving megascopic, petrological, wireline log interpretations and structural analysis can be usefully employed in delineation of potential subsurface gas storage reservoirs.

Megascopic examination of cores and cuttings together with detailed petrological studies provided evidence on environment of deposition, provenance and diagenetic processes which have modified the reservoir and cap rock fabric. Wireline logs in conjunction with data on lithology and sedimentary structures provided the necessary information for identification of lithofacies, formation water characteristics, permeable zones, net pay intervals, and quantitative evaluation of porosity and shale. Reservoir-engineering and structural analysis also allowed estimation of gas deviation and gas formation volume factors, porosity, permeability, area of structures, and gross rock volumes. By intergration of the results obtained from all these techniques, it was then possible to delineate potential gas storage reservoirs with some certainty. Furthermore, the results of the five techniques allowed estimation of the natural gas

storage capacities and determination of deliverability for the delineated potential storage reservoirs.

Results

The results of this study can be summarised as follows:

1. A distinctive mineralogical framework persists for both the potential reservoirs in the Nowra Sandstone, Muree Sandstone and Snapper Point Formation, as well as for their respective cap rocks of Berry Formation, Mulbring Siltstone and Wandrawandian Siltstone.
2. The dominant lithologies of the potential reservoirs are calcite, siderite and quartz-cemented sublitharenites and thin beds of calcareous and fossiliferous siltstone.
3. The cementing minerals (quartz overgrowths, calcite, siderite and dawsonite) and clay coating of quartz grains adversely affect the properties of the potential reservoirs by obliterating the effective porosity of the sublitharenite.
4. The lithologies of the potential cap rock formation are impermeable calcareous, carbonaceous and micaceous siltstone, mudstone, claystone and shale beds interbedded with impermeable litharenites.
5. Quantitative evaluation of wireline logs of the Nowra Sandstone, Muree Sandstone and the Snapper Point Formation revealed low to moderate porosity and permeability and low salinity (<8000 ppm of NaCl) of the formation water.

6. The estimated average porosity for potential storage reservoirs in the Nowra and Muree Sandstones ranges from 5.5. to 12.2 percent (wireline log evaluation) and 4.0 to 9.7 percent (laboratory core analysis).
7. The estimated average porosity for potential storage reservoirs in the Snapper Point Formation ranges from 5.4 to 6.8 percent (wireline log evaluation) and 5.0 to 9.0 percent (laboratory core analysis). Examination of thin sections indicates porosity for this formation to be less than 10 percent.
8. The estimated average volume of shale interbedded with the arenites of Nowra and Muree Sandstone reservoirs is 43 percent and for the Snapper Point Formation reservoir 40 percent.
9. Laboratory determined permeabilities on cores from Nowra and Muree Sandstone reservoirs range from 2.4 to 9.08 md to air and 1.5 to 3.0 md to brine.
10. Laboratory determined permeabilities on cores from Snapper Point Formation range from 3.0 to 58.2 md to air and 0.1 to 44.0 md to brine.
11. The concentration of sodium chloride in the formation water of Nowra and Muree Sandstone ranges from 3000 to 7000 ppm and 5100 to 5200 ppm in the Snapper Point Formation.
12. The areal extent and vertical closure of the seven structures range from 0.22 to 45.4 km² and from 5 to 225 m respectively.

13. The natural gas storage capacity of the nine potential storage reservoirs ranges from 7 to $8878 \times 10^6 \text{ m}^3$.
14. Two of the nine delineated potential storage reservoirs are thought to be unsuitable for storage and retrieval of natural gas. The two being the Nowra Sandstone reservoirs at Stockyard Mountain-1 and Kirkham-1. The Stockyard Mountain reservoir is too shallow, and therefore incapable of sustaining adequate reservoir pressure for production and the Kirkham reservoir is thought to have too small a storage capacity.
15. Estimated deliverability potential (flow rate) for the seven potential storage reservoirs ranges from 0.041 to $0.256 \times 10^6 \text{ m}^3$ per day per well for the Nowra and Muree Sandstone and 0.087 to $0.189 \times 10^6 \text{ m}^3$ per day per well for the Snapper Point Formation.
16. Estimated deliverability potential (flow rate) based on slightly overpressured gas storage reservoirs (10 percent), shows an average increase of 14.3 percent compared to the flow rate estimated using normal reservoir pressure.
17. Estimated time required to deplete the seven potential storage reservoirs of all of their working gas using 50 producing wells per structure, ranges from 32 to 956 days.

Conclusions

1. Seven prospective subsurface reservoirs for storage of natural or manufactured gas have been outlined in the Permian water-bearing arenites of the Sydney Basin.
2. Methods involving megascopic, petrological, petrophysical and structural analysis were successfully used in delineating the potential gas storage reservoirs.
3. The prospective reservoirs have an adequate gas storage capacity to serve the future needs of the region of Sydney Basin.
4. The estimated deliverability potential of the prospective reservoirs is moderate to low but can be improved by hydraulic fracturing, acidizing or overpressuring.
5. Conclusive permeability and deliverability analysis of the Permian arenites must await the results of further drilling in the Sydney Basin.
6. The locations of the prospective gas storage reservoirs are significant both in terms of proximity to the major markets, as well as to the major gas carrying pipelines.
7. Of the three alternatives available for adequate supply of gas to the N.S.W. market, it would appear that the development of subsurface storage in natural reservoirs would be by far the most economically viable.
8. The information assembled in this study provides the basis for a more detailed re-assessment of the delineated prospective gas storage reservoirs in the event of their future development.

Recommendations

In the event of future development of subsurface storage for natural and/or manufactured gas in any of the reservoirs delineated in this study the following recommendations should be considered.

1. New seismic survey of closely spaced lines should be run to redefine the structures more accurately.
2. The new wells to be drilled should be sited some distance away from the site of the original well drilled on the structure.
3. While drilling the new wells, cores should be taken from the lower part of the cap rock and much of the target reservoir.
4. Complete suites of wireline logs should be run, drill stem testing should be carried out with a complete program to obtain pressure transient data and fluid recovery.
5. Consideration should be given to stimulation of the reservoirs by hydraulic fracturing or acidizing.
6. Consideration should be given to amend the existing Petroleum Acts of all Australian States and Territories to incorporate the storage of gas in subsurface natural reservoirs.

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PETROLOGICAL AND PETROPHYSICAL STUDY OF PERMIAN ARENITES
FOR POTENTIAL SUBSURFACE STORAGE OF
NATURAL GAS, SYDNEY BASIN, NEW SOUTH WALES, AUSTRALIA

VOLUME II

APPENDIXES

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APPENDIX I

STOCKYARD MOUNTAIN-1

ESTIMATED POTENTIAL NATURAL GAS

STORAGE CAPACITY

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SUMMARY

Stockyard Mountain potential natural gas storage field lies in the southern part of the Sydney Basin. It is located 16.8 km southwest of Port Kembla, N.S.W.

The Stockyard Mountain structure consists of a northeast-southwest trending anticline. The structure covers an area of $12.09 \times 10^6 \text{ m}^2$ and has a vertical closure of 20 m.

Two potential natural gas storage reservoirs have been delineated in the arenites of Permian age: the Nowra Sandstone and the Snapper Point Formation reservoirs in the intervals 256.6 - 261.5 and 574.8 - 629.1 m respectively.

The potential natural gas storage capacity of the Stockyard Mountain reservoirs as estimated is $311.59 \times 10^6 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of Stockyard Mountain-1 well have been examined for possible natural reservoirs which could be used for storage of natural gas.

Arenites of the Nowra Sandstone and an interval within the Snapper Point Formation appear to have the potential of becoming a natural gas storage reservoir in conjunction with suitable porous and permeable arenites.

Apart from literature study (Farmout Drillers N.L., 1963; Alcock, 1968; Mayne et al. 1974), four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well Data

Well Name, No.	: Stockyard Mountain (Farmout) No. 1
Operating Co.	: Farmout Drillers No Liability
Location	: Lat. & Long.: 34°35'42"S, 150°46'53"E 1:250 000 sheet: Wollongong, SI 56-9 General Location: about 16.8 km S.W. of Port Kembla, N.S.W.
Elevation	: Kelly Bushing (K.B.) 53.1 m A.S.L. (Kelly Bushing used as datum for determining lithological boundary depths in well.)
Total Depth	: Schlumberger: 1071.6 m Driller: 1071.6 m

Wireline Logs Available

Run	Date	Type	Interval m
1	15-08-1962	ES	30.4 - 295.3 m
2	15-08-1962	MC	295.3 - 633.6 m
3	4-09-1962	ES	633.6 - 1070.7 m
1	4.09-1962	MC	30.4 - 295.3 m
2	12-09-1962	ES	295.3 - 633.6 m
3	12-09-1962	MC	633.6 - 1070.7 m
1	15-08-1962	SP	30.4 - 295.3 m
2	4-09-1962	SP	295.3 - 633.6 m
3	12-09-1962	SP	633.6 - 1070.7 m

History and Stratigraphy

The Stockyard Mountain-1 well was drilled in 1962 by the Farmout Drillers N.L. to test the Permian strata in this part of the Sydney Basin. The well was drilled near the crest of the Stockyard Mountain structure. The structure as delineated on the map and sections (Figs. I-4 & I-5) is the result of mapping the base of the Bumbo Latite Member of the Gerringong Volcanics (Farmout Drillers N.L. 1963).

The well was spudded in the Gerringong Volcanics. It penetrated 13.7 m of this unit and 992.1 m of Permian Shoalhaven Group sediments before entering economic basement of ?Devonian age (Mayne et al. 1974).

Figure 1 shows the stratigraphic sequence encountered in Stockyard Mountain-1 well and a generalised description of lithologies, provenance and environment. "A number of porous interbeds were present between 569.0 and 627.8 m in the Permian

Shoalhaven Group sandstone, and the gas detection equipment recorded very small amounts of hydrocarbon gas present in the drilling mud while drilling below 576.0 m. A drill stem test of the interval 566.6 to 643.1 m yielded 16.0 m³ of fresh water" (Farmout Drillers N.L. 1963).

PETROLOGY AND PETROPHYSICS

Nowra Sandstone

The Nowra Sandstone extends from 256.0 - 295.6 m and is 39.6 m thick. It is made up of silicified and calcareous sublitharenite containing quartz, chert, feldspars, metamorphic, volcanic and sedimentary rock fragments together with pebbles of quartz. Table I-1 summarises the grain distribution count. Fragments of brachiopod and bryozoa fossils are common. Micas and heavy minerals are rare. Calcareous cement and argillaceous matrix have reduced the original porosity to values ranging from 4.6 to 10.0 percent (Table I-3).

The upper boundary of this interval is marked by the change from carbonaceous and calcareous mudstone beds to silicified and calcareous sublitharenite. This change is accompanied by an increase in the resistivity log curve. The spontaneous potential log curve (Fig. I-2) shows only a small negative (-) shift away from the shale line but corresponding with the build-up of mudcake over the interval. Combination of the characteristics of the two logs (spontaneous potential and the microcaliper) suggests permeability within the Nowra Sandstone in Stockyard Mountain-1 well. The resistivity (100 to 480 ohms m²/.m) (Fig. I-2) indicates moderate salinity of the formation fluids.

The lower boundary is marked by a lithological change from sublitharenite and siltstone beds to the underlying ?Currambene Dolerite (Fig. I-1).

Poor sorting, indistinct bedding and presence of broken brachiopod and bryozoa fossil fragments suggest the Nowra Sandstone was deposited in high to moderate marine energy conditions.

A dominantly sedimentary, with subordinate granitic, volcanic and metamorphic provenance is envisaged. Very fine to medium sedimentary lithic fragments are common.

Snapper Point Formation

Snapper Point Formation is 185.9 m thick in Stockyard Mountain-1 well and extends from 490.7 - 676.6 m. It consists almost entirely of quartz rich arenites and contains porous horizons, pebble beds and minor shale beds.

A 54.3 m thick porous and permeable interval (574.9 - 629.1 m (Fig. I-3)) has been investigated in detail. It is made up of pebbly sublitharenite containing numerous porous horizons and is calcite and siderite cemented. Table I-2 summarises the grain distribution count. Absence of quartz over-growths and general lithification - in contrast to the Nowra Sandstone sublitharenite, appears to have been due to the presence of calcite and kaolinite clay coatings around the quartz grains (Plate I-2, Photo 2). The uncemented sublitharenite beds have laboratory measured and wireline log estimated porosities ranging from five to six percent.

Horizontal and vertical permeabilities are 6 and 11 millidarcies respectively; (Mayne et al., 1974). Drill stem test No. 4 recovered fresh water (F.D.N.L. 1963). Recent laboratory core analysis from Snapper Point Formation revealed permeabilities of

18.0 - 98.5 md to air and 7.4 - 14.0 md to brine (Volume I, Table 18).

The upper boundary of this interval is assumed to be at 574.8 m where the first resistivity (18'8") log values are available (Fig. I-3). The spontaneous potential log over this interval shows a uniform negative (-) deflection from the shale line. The microresistivity log defining permeable intervals gives readings between 2 and 25 ohms - m^2/m . Combination of spontaneous potential, microresistivity and microcaliper logs are the basis for delineation of net pay zones (Fig. I-3).

The resistivity logs are less prominent and the 18'8" value was used in calculation of the relationship $F = \frac{R_o}{R_w}$ (Table I-4).

The lower boundary of this interval is at 629.1 m where the sublitharenite sands become more shaly and silicified. The spontaneous potential log shows a return to shale line and the microresistivity log readings increase from 15 to over 40 ohm- m^2/m and begin to fluctuate rapidly.

The abundance of rounded pebbles and general lack of fine detritus as well as presence of marine fossils suggest deposition in high-energy marine environment. Pebbles of quartz, chert, feldspars and sedimentary rock fragments imply a diverse provenance for this interval.

CAP ROCK CHARACTERISTICS

Berry Formation

The cap overlying the Nowra Sandstone potential reservoir is a sequence 242.3 m thick comprising grey shale, calcareous and mudstone. Siltstone (Plate I-1, Photo 1) increasing in the lower part of the unit. These sediments are equated to the

Permian Berry Formation (Fig. I-1). Very fine quartz and feldspar, and pyrite occur scattered throughout these lithologies. "Cores from the unit show lamination, micro-crossbedding and scallop structures", (Alcock, 1968). Fragments of marine fossils e.g. brachiopod shells, calcareous spines, bryozoa fragments and some foraminifera occur. The wireline logs show little variation throughout the unit. Core Nos 1 and 2 (92.9 and 191.1 m) respectively, consist of dark grey mudstone, silstone and calcareous mudstone. Laboratory tests on cores revealed no effective porosity and no permeability.

Snapper Point Formation Reservoir

The cap rock overlying the Snapper Point Formation potential reservoir is a sequence 79.2 m thick comprising silicified sublitharenite interbedded with shale beds.

The sublitharenite are mostly silicified with chert, cemented with potassium feldspars and pore spaces filled with deformed sedimentary rock fragments. Porosities although thought to have been moderate to high originally, (Alcock, 1968), have been severely reduced by the development of secondary silica.

Core No. 6 (494.3 - 497.4 m) is made up of silicified sublitharenite. Laboratory porosity and permeability tests on two plugs (vertical and horizontal) from Core No. 6 showed an average porosity of 8 percent but no permeability was detected. Micro-resistivity log over the lower part of this interval increases in value, fluctuates rapidly and exhibits negligible separation. The sediments of this unit are equated with the top most interval of the Snapper Point Formation (Fig. I-1).

POROSITY

Wireline log data was used in estimation of porosities for the two potential reservoirs in Stockyard Mountain-1 well. Method 6, Chapter II was used for calculation of porosities. The porosity values so obtained are only approximate. The porosity relationship $\emptyset = \sqrt{\frac{1}{F}}$ is applicable for clean sand formation rather than the shaly sands of the Stockyard Mountain reservoirs. However, this method of porosity calculation is the best approximation. The wireline log data and the summary of results for the two reservoirs are shown in Tables I-3, I-4, I-5 and I-6 respectively.

NET PAY INTERVALSNowra Sandstone

There are 29.7 m of net pay in this formation. The net to gross pay ratio (29.7/39.6) is 0.75. The 29.7 m of net pay are subdivided into three zones. Their thicknesses are 5.5, 8.6 and 15.6 m respectively (Fig. I-2, Table I-5).

The build up of mudcake as shown on the microcaliper log, and the microresistivity log pattern (Fig. I-2) were used as the base for delineating porous intervals.

Snapper Point Formation

There are 34.1 m of net pay within this formation. The net to gross pay ratio (34.1/54.3) is 0.63. The 34.1 m of net pay are subdivided into four zones. Their thicknesses being 6.1, 5.5, 3.0 and 19.5 m respectively (Fig. I-3, Table I-6). As in the Nowra Sandstone reservoir the net pay zones were delineated by a combination of microcaliper and microresistivity log characteristics.

PERMEABILITYNowra Sandstone Reservoir

No drill stem tests were carried out over this interval. Laboratory tests on Core No. 3 (265.1 - 267.0 m) revealed no permeability. Microresistivity log below the core depth interval does however indicate rapid fluctuation and some negative separation suggesting that some permeable intervals are present.

Snapper Point Formation Reservoir

Three drill stem tests were carried out over this potential reservoir.

DST-2	572.1 - 609.6 m
DST-3	576.0 - 643.1 m
DST-4	566.6 - 643.1 m

Of the three drill stem tests only No. 4 was successful and recovered 170 m (560 ft) of fresh water. DST-No. 2 recovered 0.9 m (3 ft) of drilling mud and the pressure bomb did not operate successfully. DST-No. 3 was not completed, the packer seat failed.

DST-No. 4 Test Data (F.D.N.L. 1963)

Interval Tested: 566.6 - 643.1 m

Method: Howco Hydrospring Tester
 Howco Pressure Recorder
 American Pressure Bomb
 Packer set with 30 000 lbs
 Initial shut in 15 minutes
 Valve open 65 minutes
 Final shut in 30 minutes
 Good air blow lasting throughout test
 Recovered 560' fresh water
 Initial hydrostatic pressure 820 psi
 Initial shut in pressure 700 psi
 Initial flow pressure 60 psi
 Final flow pressure 290 psi
 Final shut in pressure 700 psi
 Final hydrostatic pressure 820 psi

The production rate Q from the above given data is:

$$Q = \frac{560 \times 0.0139 \times 1440}{65}$$

$$Q = 172.4 \text{ Barrels/Day}$$

Where 560 = Feet of water recovered
 .0139 = Barrels per linear foot
 1440 = Minutes per 24 hours
 65 = Flow time in minutes

Using the rest of DST-No. 4 data, calculation of permeability (k) and permeability/thickness (k/h) is as follows:

$$kh = \frac{162.6 \times Q \times V_w \times B_w}{m}$$

Where Q = 172.4 (production rate BBl/D)

V_w = 0.57 (viscosity of formation water)

B_w = 1.014 (water formation volume factor)

m = 10 (psi/cycle) assumed value

$$kh = \frac{162.6 \times 172.4 \times 0.57 \times 1.014}{10}$$

$$= \frac{16,162.1}{10}$$

$$kh = 1620 \text{ md/ft}$$

Where h = 112 ft (34.1 m of net pay)

$$= \frac{1620}{112}$$

$$k = \underline{14.5 \text{ millidarcies}}$$

The permeability of the Snapper Point Formation reservoir is 14.5 millidarcies.

STRUCTURE

Stockyard Mountain structure is an northeast-southwest trending anticline. Stockyard Mountain-1 well was drilled on the northeastern nose of the anticline (Figs. I-4 and I-5), about 2 km north-northeast of its crest. The structure was depicted by Hopkins in 1956 (F.D.N.L. 1963) when he mapped in detail a marker horizon at the base of the Illawarra Coal Measures. Browne in 1959 (F.D.N.L. 1963) mapped independently the northern part of the Stockyard Mountain structure on the base of the Bumbo

Latite, Member of the Gerringong Volcanics, some 180 m stratigraphically lower than the Illawarra Coal Measures. "The Stockyard Mountain structure was remapped at a later date, using aneroid barometer for the purpose of selecting the site for the Stockyard Mountain-1 well" (Farmout Drillers N.L. 1963).

The structure contour maps (Figs. I-4 and I-5) on top of Nowra Sandstone and Snapper Point Formation reservoirs are based on the structure contour map of the Bumbo Latite Member as mapped by Farmout Drillers N.L. in 1962. It is assumed that the underlying strata conform with the surface expression of the Bumbo Basalt as mapped.

The spill point for the Nowra Sandstone is at 266 m BKB (Figs. I-5 and I-6) and for the Snapper Point Formation reservoir at 585 m (Figs. I-8 and I-9).

The structure has a vertical closure of 20 m (to the lowest closed contour) and covers an area of $12.09 \times \text{km}^2$.

RESERVOIRS FLUID CHARACTERISTICS

Nowra Sandstone

No drill stem testing was carried out over the Nowra Sandstone. The reservoir water resistivity (R_w) and its salinity concentration (NaCl) have been established by the Rmf/SP method (Method 1, Chapter II). Because of the absence of porosity logs it was necessary to obtain the resistivity of the reservoir water for calculation of porosity.

Snapper Point Formation

The reservoir water resistivity and its concentration of NaCl have been established by the Rmf/SP method (Method 1, Chapter II). Because of absence of porosity logs it was necessary to calculate porosity by the relationships

$$\phi = \sqrt{\frac{1}{F}} \quad (\text{Method 6, Chapter II.})$$

Drill stem test No. 4 recovered fresh water over this interval; however there are no resistivity measurements of recovered formation water.

HYDROSTATIC PRESSURE CALCULATIONNowra Sandstone reservoir

Depth	900.0 ft (274.3 m)
Resistivity of reservoir water	1.1 ohm-metre
NaCl concentration in reservoir water	4,400 ppm
Density of NaCl solution	1.0045 @ 77°F (Schlumberger 1972)
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Nowra Sandstone reservoir

$$\begin{aligned} & 1.0045 \times 0.433 \\ & = \underline{\underline{0.4349 \text{ psi/ft}}} \end{aligned}$$

Hydrostatic pressure for the Nowra Sandstone reservoir

$$\begin{aligned} & 0.4349 \times 900 \\ & = \underline{\underline{391.5 \text{ psi}}} \end{aligned}$$

Snapper Point Formation reservoir

Depth	1900.0 ft (579.1 m)
Resistivity of reservoir water	0.84 ohm-metre
NaCl concentration in reservoir water	5100 ppm
Density of NaCl solution	1.0048 @ 77°F (Schlumberger 1972)
Normal pressure gradient	0.433

Pressure gradient for Snapper Point Formation reservoir

$$1.0048 \times 0.433$$

$$= \underline{\underline{0.4350 \text{ psi/ft}}}$$

Hydrostatic pressure for Snapper Point Formation reservoir

$$0.4350 \times 1900$$

$$= \underline{\underline{826.5 \text{ psi}}}$$

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the Stockyard Mountain-1 reservoirs as estimated according to the volumetric method (Method 12, Chapter II) is $311.59 \times 10^6 \text{ m}^3$. The variables used in estimating the potential natural gas storage capacity are given in Table I-7. These parameters were derived from various analyses and calculations presented in this Appendix. Due to the structural configuration of the Stockyard Mountain reservoirs the total net pay thickness of 63.8 m of the two reservoirs has been effectively reduced to a net pay sensu stricto of only 11.6 m (Table I-7). The determining factor in the reduction of net pay thickness from 63.8 m to only 11.6 m of net pay

sensu stricto, is the position of the Stockyard Mountain structure's spill point level (Figs. I-5, I-6, I-8 and I-9). Therefore, out of seven porous and permeable zones in the two reservoirs (Figs. I-2 and I-3, Tables I-4 and I-5) as interpreted from the wireline logs, only the top zone in each reservoir qualifies for the estimation of the potential storage capacity. Table I-10 summarises the results of the potential natural gas storage capacity as estimated by the volumetric method for the Stockyard Mountain reservoirs.

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Table I-1Grain Distribution Count

WELL NAME: Stockyard Mountain-1

FORMATION: Nowra Sandstone

THIN SECTION DEPTH: 266.7 m

Rock Components	Total Count	Percent of Rock
Quartz	300	92.0
Quartz Overgrowth	5	1.5
Chert	1	0.3
Potassium Feldspar	1	0.3
Plagioclase Feldspar	0	0.00
Sedimentary Lithics	4	1.2
Metamorphic Lithics	1	0.3
Volcanic Lithics	1	0.3
Granitic Lithics	0	0.00
Calcite	7	2.0
Siderite	3	1.0
Pyrite	1	0.3
Muscovite	2	0.8
Biotite	0	0.0
Sericite	0	0.0
Tourmaline	0	0.0
Zircon	0	0.0
Garnet	0	0.0
Carbonaceous Matter	0	0.0
	326	100.0

Table I-2Grain Distribution Count

WELL NAME: Stockyard Mountain-1

FORMATION: Snapper Point

THIN SECTION DEPTH: 579.7 m

Rock Components	Total Count	Percent of Rock
Quartz	296	93.30
Quartz Overgrowth	0	0.00
Chert	3	0.90
Potassium Feldspar	3	0.90
Plagioclase Feldspar	1	0.30
Sedimentary Lithics	6	1.90
Metamorphic Lithics	0	0.00
Volcanic Lithics	0	0.00
Granitic Lithics	0	0.00
Calcite	3	0.90
Siderite	2	0.60
Pyrite	1	0.30
Muscovite	2	0.60
Biotite	0	0.00
Sericite	0	0.00
Tourmaline	0	0.30
Zircon	0	0.00
Garnet	0	0.00
Carbonaceous Matter	0	0.00
	317	100.00

Table I-3

Stockyard Mountain-1: Estimate of Porosityfor Nowra Sandstone Reservoir

Depth m	Resistivity (Ro) AO = 18'8" ohms-m ² /m	Resistivity of water (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
256.0	100	1.10	90	10.4
256.6	110		100	10.0
257.2	120		109	9.5
257.8	130		118	9.1
258.4	130		118	9.1
259.0	140		127	8.8
258.6	150		136	8.5
260.2	170		154	8.0
260.9	150		136	8.5
261.5	150		136	8.5
262.1	180		163	7.8
262.7	220		200	7.0
263.3	170		154	8.0
263.9	160		145	8.2
264.5	160		145	8.2
265.7	230		309	6.9
266.3	170		154	8.0
267.0	180		163	7.8
267.6	230		209	6.9
268.2	220		200	7.0
268.8	220		200	7.0
269.4	180		163	7.8

Depth m	Resistivity (Ro) AO = 18'8" ohms-m ² /m	Resistivity of water (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
270.0	210	1.10	190	7.2
270.6	220		200	7.0
272.2	240		218	6.7
271.8	270		245	6.3
272.4	300		272	6.0
273.1	300		272	6.0
273.7	320		290	5.8
274.3	320		290	5.8
274.9	330		300	5.7
275.5	340		309	5.6
276.1	350		318	5.6
276.7	370		336	5.4
277.3	450		409	4.9
277.9	500		454	4.6
278.5	400		363	5.2
279.1	350		318	5.6
279.8	330		300	5.7
280.4	310		281	5.9
281.0	300		272	6.0
281.6	340		309	5.6
282.2	300		272	6.0
282.8	270		245	6.3
283.4	250		227	6.6
284.0	280		254	6.2
284.6	320		290	5.8
285.2	380		345	5.3

Depth m	Resistivity (Ro) AO = 18'8" ohms-m ² /m	Resistivity of water (Rw) ohm-m	Formation Factor (F) $F = \frac{R_o}{R_w}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
285.9	370	1.10	336	5.4
286.5	420		381	5.1
287.1	430		390	5.0
287.7	450		409	4.9
288.3	480		436	4.7
288.9	440		400	5.0
289.5	350		318	5.6
290.1	270		245	6.3
290.7	260		236	6.5
291.3	250		227	6.6
291.9	240		218	6.7
292.6	250		227	6.6
293.2	280		254	6.2
293.8	250		227	6.6

Table I-4

Stockyard Mountain-1: Estimate of Porosity
for Snapper Point Formation Reservoir

Depth m	Resistivity (Ro) AO = 18'8" ohms-m ² /m	Resistivity of water ohm-m	Formation Factor (F) $F = \frac{R_o}{R_w}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
574.8	370	0.84	440	4.7
575.4	370		440	4.7
576.0	300		357	5.3
576.6	220		261	6.1
577.9	250		297	5.7
578.5	280		333	5.4
579.1	330		392	5.0
579.7	370		440	4.7
580.3	270		321	5.5
580.9	150		178	7.4
581.1	140		166	7.7
582.1	140		166	7.7
582.7	160		190	7.2
583.3	180		214	6.8
583.9	180		214	6.8
584.6	170		202	7.0
585.2	170		202	7.0
585.8	160		190	7.2
586.4	130		154	8.0
587.0	150		178	7.4
587.6	170		202	7.0
588.2	180		214	6.8
588.8	170		202	7.0

Depth m	Resistivity (Ro) AO = 18'8" ohms-m ² /m	Resistivity of water ohm-m	Formation Factor (F) $F = \frac{R_o}{R_w}$	Porosity (Ø) $\% \quad \emptyset = \sqrt{\frac{1}{F}}$
589.4	180	0.84	214	6.8
590.0	180		214	6.8
590.7	180		214	6.8
591.3	180		214	6.8
591.9	150		178	7.4
592.5	130		154	8.0
593.1	140		166	7.7
593.7	150		178	7.4
594.3	140		166	7.7
594.9	130		154	8.0
595.5	120		412	8.3
596.1	120		142	8.3
596.7	110		130	8.7
597.4	120		142	8.3
598.0	140		166	7.7
598.6	160		190	7.2
599.2	160		190	7.2
599.8	160		190	7.2
600.4	150		178	7.4
601.0	150		178	7.4
601.6	190		226	6.6
602.2	230		273	6.0
602.8	270		321	5.5
603.5	290		345	5.3
604.1	290		345	5.3

Depth m	Resistivity (Ro) AO=18'8" ohms-m ² /m	Resistivity of water ohm-m	Formation Factor (F) $F = \frac{R_o}{R_w}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
604.7	300	0.84	357	5.3
605.3	310		369	5.2
605.9	280		333	5.4
606.5	200		238	6.4
607.1	210		250	6.3
607.7	230		273	6.0
608.3	270		321	5.5
608.9	310		369	5.2
609.6	350		416	4.8
610.2	400		476	4.5
610.8	430		511	4.4
611.4	440		523	4.3
612.0	450		535	4.3
612.6	520		619	4.0
613.2	500		595	4.0
613.8	400		476	4.5
614.4	340		404	4.9
615.0	210		250	6.3
615.6	170		202	7.0
616.3	170		202	7.0
616.9	220		261	6.1
617.5	260		309	5.6
618.1	230		273	6.0
618.7	230		273	6.0
619.3	220		261	6.1

Depth m	Resistivity (RO) AO = 18'8" ohms-m ² /m	Resistivity of water ohm-m	Formation Factor (F) $F = \frac{R_o}{R_w}$	Porosity (Ø) % $\emptyset = \sqrt{\frac{1}{F}}$
619.9	200	0.84	238	6.4
620.5	170		202	7.0
621.1	130		154	8.0
621.7	110		130	8.7
622.4	130		154	8.0
623.0	170		202	7.0
623.6	250		197	5.7
624.2	280		333	5.4
624.8	270		321	5.5
625.4	210		250	6.3
626.0	150		178	7.4
626.6	100		199	9.1
627.2	80		95	10.2
627.8	90		107	9.6
628.4	110		130	8.7
629.1	150		178	7.4

Table I-5

Stockyard Mountain-1: Summary of wireline log interpretation
of the Nowra Sandstone Reservoir

Reservoir Unit and Interval m	Net Pay Depth Interval m	Net Pay Thickness (m)	Resistivity of water (Rw) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity av. (%)
Nowra Sandstone (256.0 - 295.6)	256.0 - 261.5	5.5	1.10	4400	9.0
	265.1 - 273.7	8.6	1.10	4400	6.9
	278.2 - 293.8	15.6	1.10	4400	5.8

Table I-6

Stockyard Mountain-1: Summary of wireline log interpretation
of the Snapper Point Formation Interval

Reservoir Unit and Interval m	Net Pay Depth Interval m	Net Pay Thickness (m)	Resistivity water (Rw) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity av. (%)
Snapper Point Formation Interval (574.8 - 629.1)	574.8 - 580.9	6.1	0.84	5100	5.4
	590.0 - 595.5	5.5	0.84	5100	7.4
	597.4 - 600.4	3.0	0.84	5100	7.5
	609.6 - 629.1	19.5	0.84	5100	6.3

Table I-7Stockyard Mountain-1: Summary of Reservoirs Variables

Parameters	Nowra Sandstone Reservoir	Snapper Point Formation Reservoir
Area m ² (ft ²)	12.09 x 10 ⁶ (130.09 x 10 ⁶)	12.09 x 10 ⁶ (130.09 x 10 ⁶)
Net Pay <u>sensu stricto</u> m (ft)	5.5 (18)	6.1 (20)
Porosity %	9.0	5.4
Gas Saturation %	80.0	80.0
Reservoir Pressure (psia)	406	841
Reservoir Temperature °C (°F)	26 (80)	36 (98)
Standard Condition Pressure (psi)	14.73	14.73
Standard Condition Temperature °C (°F)	15.5 (60)	15.5 (60)
Gas Deviation Factor (Z)	0.968	0.937
Gas Formation Volume Factor (Bg)	27.42	56.78

PLANIMETRY RESULTS

STRUCTURE:Stockyard Mountain.....

FORMATION:Nowra Sandstone.....

REFERENCE STRUCTURAL MAP:Figure I-4.....

REFERENCE STRUCTURAL CROSS-SECTION:Figures I-5 and I-6.....

COMMENTS: Spill point level at 266m.....

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1	246	66	710,000		
2	251	144	1,550,000	5	5,513,688
3	255	475	5,110,000	5	11,104,690
4	261	733	7,880,000	5	32,226,021
5	266	1124	12,080,000	5	49,527,594
6				20	98,373,383
7					
8					
9					
10					

* Calibration of Instrument:⁹³ Planimetry Units = 1 km².....

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$$

PLANIMETRY RESULTS

STRUCTURE: Stockyard Mountain

FORMATION: Snapper Point Formation

REFERENCE STRUCTURAL MAP: Figure I-7

REFERENCE STRUCTURAL CROSS-SECTION: ..Figures.I-8.and.I-9.....

COMMENTS: Spill point level at 574.8

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1	565	66	710,000		
2	570	144	1,550,000	5	5,513,688
3	575	475	5,110,000	5	11,104,609
4	580	733	7,880,000	5	32,226,021
5	585	1124	12,080,000	5	49,527,594
6				20	98,373,383
7					
8					
9					
10					

* Calibration of Instrument: ⁹³..... Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$$

Table I-10Stockyard Mountain-1: Potential Natural Gas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^6 \text{ m}^3$	$\times 10^6 \text{ ft}^3$
Nowra Sandstone	130.91	4622.92
Snapper Point Formation	180.68	6380.82
Total	311.59	11003.74

WELL NAME : STOCKYARD MOUNTAIN-1
ROCK UNIT : BERRY FM. DEPTH INTERVAL: 13.7 - 256.0 m
CORE DEPTH : 130.8 - 193.8 m THIN SECTION DEPTH: 191.1 m

MACROSCOPIC DESCRIPTION

Medium dark grey, poorly bedded calcareous mudstone and siltstone. Core showing micro-crossbedding and some scallop layers.

MICROSCOPIC DESCRIPTION

Very fine to very coarse silt sized particles of quartz, undifferentiated feldspars and micas are banded by calcareous and clayey matter. Traces of brachiopod shells and unidentified calcareous spines.

POROSITY .. No visible porosity was established

FRAMEWORK	%	ACCESSORIES	%
. Quartz	47	. Pyrite	tr
. Feldspar	3	. Zircon	tr
. Micas	3		
. Chlorite clay	5		
* Calcareous matter	20		
. Carbonaceous "	22		

CEMENT

* Calcareous matter (calcite and siderite)

MATRIX

ROCK CLASSIFICATION

Calcareous and carbonaceous mudstone.

WELL NAME : STOCKYARD MOUNTAIN-1ROCK UNIT : NOWRA SANDSTONEDEPTH INTERVAL: 256.0 - 295.6 mCORE DEPTH : 256.1 - 266.7 mTHIN SECTION DEPTH: 265.4 mMACROSCOPIC DESCRIPTION

Medium grey, fine to coarse grained, angular to subangular, poorly sorted,
calcareous quartz sandstone. Interbeds of siltstone. Sub-horizontal bedding.
Fragments of brachiopod shells. Pebbles of quartz are common.

MICROSCOPIC DESCRIPTION

Very fine to very coarse grained, angular to subangular, poorly sorted quartz sand
(plutonic), chert and rare feldspar grains.* Some quartz grains show regrowth.
Grain contacts distinct. Roundness moderate to low. Sedimentary rock fragments
are common comprising shale, siltstone and chloritized lithics. Some micas are
present. Trace of pyrite, tourmaline and zircon. * Some quartz grains show
regrowth. Grain contacts distinct. Roundness moderate to low. The framework
is calcite, siderite and silica overgrowths cemented. Matrix is subordinate
and of argillaceous and some calcareous matter.

POROSITY .No visible porosity was established.....

<u>FRAMEWORK</u>	<u>%</u>	<u>ACCESSORIES</u>	<u>%</u>
.Quartz.....	55..	.Pyrite.....	tr.....
.Chert.....	2..	.Tourmaline.....	tr.....
.Feldspar (plagioclase).....	2..	.Zircon.....	tr.....
.Rock fragments (sed).....	4..		
.Muscovite.....	1..		
.Biotite.....	1..		
.....			

CEMENT

..Calcite 15%; Siderite 5%....
 ..Silica overgrowths 5%.....

MATRIX

..Argillaceous....10%.....

ROCK CLASSIFICATIONCalcareous litharenite

WELL NAME : STOCKYARD MOUNTAIN-1ROCK UNIT : NOWRA SANDSTONEDEPTH INTERVAL: 256.0 - 295.6 mCORE DEPTH : 265.1 - 266.7 mTHIN SECTION DEPTH: 266.7 mMACROSCOPIC DESCRIPTION

Medium grey, fine to coarse grained, poorly sorted, calcareous sandstone with pebbles of quartz and chert. Black and grey lithics are common. Thinly bedded with stringers of siltstone. Fragments of brachiopod shells are common.

MICROSCOPIC DESCRIPTION

Very fine to very coarse grained, subangular, poorly sorted quartz, chert and potassium feldspar sand. Quartz grains show regrowth. Grain contacts are distinct and tangential. Roundness moderate to poor. Sedimentary rock fragments are common. Metamorphic and volcanic rock fragments are rare. Pebble sized quartz occurs together with abundant broken brachiopod shells. The framework is calcite, siderite cemented and secondary silica. Matrix is subordinate and comprises very coarse silt of carbonaceous, calcareous and micaceous matter.

POROSITY ...No visible porosity was established.....

<u>FRAMEWORK</u>	<u>%</u>
Quartz.....	65.....
Chert.....	1.....
Metaquartzite.....	2.....
Potassium feldspar.....	1.....
Rock fragments (Sed).....	7.....
"....." (Volc).....	2.....
Muscovite.....	1.....

<u>ACCESSORIES</u>	<u>%</u>
Pyrite.....	tr.....
Tourmaline.....	tr.....
.....	
.....	
.....	
.....	

CEMENT

.Calcite.6%; Siderite.3%.....
.Silica overgrowths.5%.....

MATRIX

..Argillaceous.....7%.....
.....

ROCK CLASSIFICATIONLitharenite

WELL NAME : STOCKYARD MOUNTAIN-1ROCK UNIT : SNAPPER POINT FM.DEPTH INTERVAL: 490.7 - 676.6 mCORE DEPTH : 579.7 - 584.6 mTHIN SECTION DEPTH: 579.7 mMACROSCOPIC DESCRIPTION

Light to brownish grey, very fine to very coarse grained, poorly sorted, subangular porous quartz rich sandstone. Pebbles of quartz and chert are common, together with black mudstone lithics. Brachiopod shells and Bryozoa fragments are common.

MICROSCOPIC DESCRIPTION

Very fine to very coarse grained poorly to moderately sorted, angular to subangular quartz sand (plutonic and strongly undulose) with chert and feldspar grains. Grain contacts are distinct. Roundness moderate. Lack of quartz overgrowths and general lithification due to presence of white clay coating on the quartz grains. Rare mica flakes. Sedimentary rock fragments comprise mudstone and micaceous siltstone. Framework is calcite and siderite cemented. Matrix is calcareous and argillaceous matter.

POROSITY Visible porosity was established but not estimated.....

<u>FRAMEWORK</u>	<u>%</u>	<u>ACCESSORIES</u>	<u>%</u>
Quartz.....	69.....	Pyrite.....	tr.....
Chert.....	5.....	Tourmaline.....	tr.....
Potassium Feldspar.....	4.....	Zircon.....	tr.....
Plagioclase.....	2.....		
Rock fragments (Sed).....	7.....		
Muscovite.....	1.....		
Biotite.....	tr.....		

CEMENT

...Calcite 4%.....
 ...Siderite 3%.....

MATRIX

Argillaceous 5%.....

ROCK CLASSIFICATION

Litharenite

(after MAYNE et al. 1974)

Well Name : STOCKYARD MOUNTAIN - 1

Datum : 53.1 m A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age	
13.7	Porphyritic basalt	Psg	SHOALHAVEN	PERMIAN	
256.0	Shale, mudstone and siltstone interbedded with sublitharenite and basaltic rock.	Psb			
295.6	Sedimentary, volcanic and lesser granitic provenance. Deposited in low to high energy marine conditions.	Psm			
490.7		Psw			
676.6	Sublitharenite silicified and porous with pebble beds and minor shale beds. Sedimentary and granitic provenance. Deposited in moderate to high energy marine conditions. Interbedded shales, siltstones and volcanics with minor limestone. Conglomerate beds at the base.	Pssp			
902.2	Sedimentary and volcanic provenance. Deposited in alternating low to high energy marine conditions.	Pspb			
1005.8- T.D. 1071.6-	Lithic sandstone, shale and siltstone. These sediments are regarded as economic basement of (?) Devonian age.	PswH			
					DEVONIAN

Intervals under investigation

STOCKYARD MOUNTAIN I
Petrophysical Characteristics of the NOWRA SANDSTONE
Interval 256.0 - 295.2m, Datum K.B.53.1m A.S.L.

Datum: K.B. 53.1 m ASL

S.O. 15-9-77

X AUS-5-431

STOCKYARD MOUNTAIN STRUCTURE
STRUCTURE MAP ON TOP OF
NOWRA SANDSTONE

(Modified after FARMOUT DRILLERS, N.L. Stockyard Mountain Well Completion Report 1963, BMR File 62/1114)

STOCKYARD MOUNTAIN STRUCTURE
SOUTHWEST - NORTHEAST STRUCTURAL CROSS-SECTION

X AUS - 5 - 432

0 1 2 km

$$\frac{V}{H} = 13.3$$

STOCKYARD MOUNTAIN STRUCTURE
NORTHWEST-SOUTHEAST STRUCTURAL CROSS-SECTION

Possible gas storage area

X AUS-5-433

STOCKYARD MOUNTAIN STRUCTURE
STRUCTURE MAP ON TOP OF
SNAPPER POINT FORMATION RESERVOIR

Modified after FARMOUT DRILLERS, N.L. Stockyard Mountain Well Completion Report 1963, BMR File 62/1114

STOCKYARD MOUNTAIN STRUCTURE
SOUTHWEST - NORTHEAST STRUCTURAL CROSS-SECTION

STOCKYARD MOUNTAIN STRUCTURE
NORTHWEST-SOUTHEAST STRUCTURAL CROSS-SECTION

Possible gas storage area

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PHOTO 1: Berry Formation.

(Thin section depth 191.1 m, crossed nicols, x 250).
Calcareous (sideritic and calcitic) and carbonaceous
mudstone, with very fine quartz sand.

PHOTO 2: Nowra Sandstone.

(Thin section depth 265.4 m, crossed nicols, x 250).
Bimodal distribution of quartz grains in a sublitharenite.
Grain boundaries distinct; note quartz overgrowths and
optical continuity.

PHOTO 1: Nowra Sandstone.

(Thin section depth 266.7 m, crossed nicols, x 100).
Moderately sorted quartz sand in a sublitharenite with
sedimentary rock fragments and potassium feldspar.
Grain boundaries less distinct due to quartz overgrowths.

PHOTO 2: Snapper Point Formation.

(Thin section depth 573.7 m, crossed nicols, x 150).
Quartz grains set in a calcareous and argillaceous matrix.
Distinct grain boundaries. White clay coating the quartz
grains. Some calcite crystals in the lower left.

APPENDIX II

WORONORA-1

ESTIMATED POTENTIAL NATURAL GAS
STORAGE CAPACITY

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- II - 1 - Woronora-1: Photomicrographs, Berry Formation and Nowra Sandstone
- 2 - Woronora-1: Photomicrographs, Nowra Sandstone

SUMMARY

Woronora potential natural gas storage field lies in the southern part of the Sydney Basin. It is located 56.3 km south of Sydney and 15 km north from Wollongong, N.S.W.

Woronora structure is a small plunging anticline. The structure covers an area of 1.08 km^2 and has a vertical closure of 47 m.

A potential natural gas storage reservoir has been delineated in the Nowra Sandstone in the interval 1554.4 - 1603.2 m. The potential storage capacity as estimated is $90.8 \times 10^6 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of the Woronora-1 well have been examined for possible natural reservoirs which could be used for storage of natural gas.

Only arenites of Nowra Sandstone appear to have the potential of becoming a natural gas storage reservoir in conjunction with suitable porous and permeable sands; suitable structure and impermeable cap rock.

Apart from literature study (A.O.G. 1963, Alcock, 1968 and Mayne et al., 1974), four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well data

Well Name, No.:	Woronora-1
Operating Co.:	Australian Oil and Gas Corporation Limited
Location:	Lat. and Long.: 34°11'40"S, 150°54'50"E. 1:250 000 sheet: Wollongong, SI/56-9, General Location: near Darkes Forest, 56.3 km south of Sydney
Elevation:	Collar Level: 357.2 m A.S.L. Collar level used as datum for determining depths in well. Ground level: 353.5 m A.S.L.
Total Depth:	Schlumberger: 2313.1 m Driller: 2313.1 m

Wireline Logs Available

Run	Date	Type	Interval m
1	2-06-1964	ITT	913.7 - 1697.7
1	2-06-1964	SP	913.7 - 1697.7
1	2-06-1964	GR	913.7 - 1697.7
1	2-06-1964	GA	913.7 - 1697.7
1	2-06-1964	ES	913.7 - 1697.7
1	2-06-1964	ML	913.7 - 1701.0
2	23-06-1964	ITT	1697.7 - 2105.2
2	23-06-1964	GR	1697.7 - 2105.2
2	23-06-1964	ML	1701.0 - 2108.3
2	23-06-1964	ES	1697.7 - 2108.3
2	23-06-1964	SP	1697.7 - 2108.3
2	23-06-1964	CA	1697.7 - 2108.3
3	5-07-1964	ITT	1701.0 - 2310.3
3	5-07-1964	GR	1701.0 - 2310.3
3	5-07-1964	SP	2077.8 - 2313.1
3	5-07-1964	CA	2077.8 - 2313.1
3	5-07-1964	ES	2077.8 - 2313.1
3	5-07-1964	ML	2077.8 - 2313.1

History and Stratigraphy

The Woronora-1 well was drilled in 1964 by the Australian Oil and Gas Corporation to test the Triassic and Permian strata of the southern Sydney Basin near the crest of the Woronora anticline. This structure was defined by seismic traverses.

The well was spudded in Triassic Hawkesbury Sandstone. It penetrated 164.5 m of this unit and 353.6 m of the Narrabeen Group beds before entering Permian sediments at 518.1 m. It then penetrated 670.6 m of Permian Illawarra Coal Measures and

1089.6 m of Permian Shoalhaven Group sediments before encountering granite at 2278.3 m (Mayne et al., 1974).

Figure (II-1) shows the stratigraphic sequence encountered in Woronora-1 well and generalised description of lithologies, provenance and environment. "Several minor gas occurrences were recorded while drilling coal and carbonaceous shale sequences, but there was little evidence of porosity within the sandstone units. No significant hydrocarbon shows were detected and the bore hole was plugged and abandoned" (A.O.G., 1964).

PETROLOGY AND PETROPHYSICS OF THE NOWRA SANDSTONE

The Nowra Sandstone in the Woronora-1 well extends from 1554.4 - 1603.2 m and is 48.8 m thick. On the basis of lithological and wireline log characteristics the Nowra Sandstone has been subdivided into an upper and a lower member.

"Upper Member"

The upper member of the Nowra Sandstone extends from 1554.4 - 1571.5 m and is 17.1 m thick. It consists of silicified sublitharenite (Plate II-1, Photo 2 and Plate II-2, Photo 1) containing quartz, chert, minor plagioclase, potash feldspar and volcanic rock fragments together with pebbles of quartz, meta-quartzite and grey mudstone. Secondary silica in the form of quartz overgrowths has reduced the initial porosity to values ranging from 1-11 percent. Core 18 (1560.5 - 1563.0 m) contains thick shelled brachiopods up to 5 cm in length. Silica, siderite and calcite form the cement, argillaceous matter with undifferentiated clay forms the matrix.

The spontaneous potential log (Fig. II-2) shows a marked negative (-) shift away from the shale line, corresponding with a very high resistivity and low gamma-ray log count. The shale volume of this unit ranges from 4 to 81 percent and the porosity from 1.4 to 11.0 percent (Fig. II-2).

The upper boundary of this interval is marked by a lithological change from silicified sublitharenite beds rich in quartz, volcanic lithics, feldspars and containing minor interbedded sandy siltstone to carbonaceous shale, siltstone and interbedded litharenite. Besides the change in composition of the arenites there is also a change in grain size from medium to coarsely grained in the upper member of the Nowra Sandstone to very fine to fine grained in the overlying Berry Formation.

The well reworked sublitharenite containing quartz and chert pebbles as well as large fragments of brachiopod shells, is thought to have been deposited in a high energy marine environment. The sublitharenite composition suggests that the sediment was derived from sedimentary, volcanic and minor granitic provenance.

"Lower Member"

The lower member of the Nowra Sandstone extends from 1571.5 to 1603.2 m and is 31.7 m thick. It consists of fine to very coarse grained silicified sublitharenite (Plate II-2), containing quartz, chert, plagioclase, potassium feldspars, volcanic, metamorphic and sedimentary rock fragments. The sublitharenite is interbedded with siltstone, mudstone and shale. Secondary silica in the form of quartz overgrowths has reduced the initial porosity to values ranging from 1.1 to 7.5 percent. Silica, calcite and

siderite form the framework cement. The matrix is made up of argillaceous matter together with undifferentiated clay.

The spontaneous potential log (Fig. II-2) falls back to the shale line but fluctuates slightly over the interval. The resistivity log also decreases, but remains at a moderately high level (100 to 300 ohms-m²/m) throughout the unit. The gamma-ray log fluctuates also, but shows an overall increase in shale volume downwards through the interval.

The upper boundary of this interval is characterised by the change in grainsize from sediments with a high content of shaly material to dominantly medium to fine grained sediments.

The lower boundary is less distinct due to gradual increase in shaly material.

The high content of shaly material of this member as well as the finer grainsize of the sublitharenite framework indicate that low energy conditions prevailed during the deposition of this unit. The sediment composition suggests that it derived from volcanic, granitic and sedimentary source rocks.

CAP ROCK CHARACTERISTICS (Berry Formation)

The cap rock overlying the potential Nowra Sandstone reservoir is a sequence 503 m thick comprising mostly siltstones and sandy siltstones with beds of fine litharenite, shale and mudstone. These sediments are equated to the Berry Formation. The immediate rocks of the Berry Formation that overlie the Nowra Sandstone between 1539.0 m and the top of the reservoir at 1554.4 m consist of siltstone with beds of litharenite, carbonaceous shale and mudstone. The litharenite is fine-grained, and contains abundant volcanic lithics and feldspars with traces of chlorite, calcite and pyrite.

Core No. 16 (1481.3 - 1482.8 m) consists of grey, calcareous carbonaceous, pyritic and sandy mudstone (Plate II-1, Photo 1). Wireline log analyses of the cap rock directly overlying the Nowra Sandstone indicate non-permeable sequence with low porosities (Fig. II-2).

POROSITY

Wireline log data was used in estimation of porosities for the Nowra Sandstone reservoir. The porosity estimation was made by the interval transit time (sonic log) log method (Method 7, Chapter II. A matrix interval transit time of 167.9 microseconds/metre was used in the acoustic velocity-porosity calculation. All the porosity values were corrected for shale volume. The porosities so determined are only approximate since only one core porosity value (5.6%, Core No. 18, 1560.5 - 1563.6 m) was available for log calibration.

PERMEABILITY

No drill stem testing was carried out in Woronora-1 well. BMR laboratory tests on Core No. 18 (1560.5 - 1563.6 m) from the Nowra Sandstone interval indicate a vertical permeability of 0.014 and a horizontal permeability of 0.431 millidarcies (Alcock, 1968). Recent tests on cores showed permeability of 3.09 - 1.76 md to air and 1.5 to 1.0 md to brine (Table 18 Volume I).

NET PAY INTERVALS

There are 13.1 m of net pay in this formation. The net to gross pay ratio (13.1/48.4) is 0.26. The 13.1 m of net pay are subdivided into four zones. Their thicknesses are 1.8, 9.2, 0.6 and 1.5 m respectively (Fig. II-2, Table II-2). Gamma-ray, spontaneous potential and resistivity logs were used for delineation of these zones.

STRUCTURE

"The Woronora Anticline was initially depicted on geological mapping of the Wianamatta-Hawkesbury and Hawkesbury-Narrabeen boundaries as a broad structure plunging gently towards the northeast (A.O.G., 1964)".

Woronora-1 well (Fig. II-3) was drilled on the southeastern flank of the anticline, about 0.15 km southeast of its crest. A fault zone limits the structure on the northwestern and southeastern side of the anticline.

The structure contour map (Fig. II-3) on top of the Nowra Sandstone is based on the seismic horizon 'B' near the base of Permian Illawarra Coal Measures as mapped by A.O.G. in 1963. The spill point of the anticline is at 1592 m (Figs. II-4 and II-5). The positions of the northwest-southeast and southwest-northeast structural cross-sections are shown in Figure II-3.

The structure has a vertical closure of 47 m (to the lowest closed contour) and covers an area of $1.08 \times 10^6 \text{ m}^2$, (Table II-5).

RESERVOIR FLUID CHARACTERISTICS

No drill stem testing was carried out in the Woronora-1 well. The resistivity of the Nowra Sandstone water (R_w) and its salinity was established by two methods.

a) the use of resistivity value of mudfiltrate (R_{mf}) and the maximum deflection value of the spontaneous potential (SP) log curve from the shale line (Method 1, Chapter II).

b) the use of interval transit time porosity ($\phi_{\Delta t}$) - resistivity (R_t) cross-plot (Method 2, Chapter II. In this well the porosity ($\phi_{\Delta t}$) taken over the interval 1561.1 to 1572.7 m (Tables II-3) are plotted against the resistivity (R_t) reading (Fig. II-5) over the same interval. Table II-4 summarises the results of the two methods.

HYDROSTATIC PRESSURE CALCULATION

Nowra Sandstone reservoir

Depth	5120 ft (1560.6 m)
Resistivity of reservoir water	0.75 ohm-metre
NaCl concentration in reservoir water	4000.00 ppm
Density of NaCl solution	1.0040 @ 77°F (Schlumberger, 1972)
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Nowra Sandstone Formation reservoir

$$1.0040 \times 0.433$$

$$= \underline{\underline{0.4347 \text{ psi/ft}}}$$

Hydrostatic pressure for the Nowra Sandstone Formation reservoir

$$0.4347 \times 5120$$

$$= \underline{\underline{2225.8 \text{ psi}}}$$

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the Woronora reservoir was estimated according to the volumetric method (Method 9, Chapter II).

The variables used in estimating the potential natural gas storage capacity are given in Table II-5. These variables were derived from various analyses and calculations presented in this Appendix.

Out of four porous and permeable zones in the Nowra Sandstone Formation (Fig. II-2) only the top three zones between 1557.5 - 1571.5 m are included in the estimation of the potential storage capacity. The lower 1.5 m porous zone between 1582.5 - 1584.0 m appears to be too isolated and therefore not included into final estimates.

Table II-7 summarises the results of the potential natural gas storage as estimated by the volumetric method for the Woronora reservoir.

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Table II-1Grain Distribution Count

WELL NAME: Woronora-1
 FORMATION: Nowra Sandstone
 THIN SECTION DEPTH: 1561.7 m

Rock Components	Total Count	Percent of Rock
Quartz	302	91.0
Quartz Overgrowth	4	1.2
Chert	14	4.2
Potassium Feldspar	2	0.6
Plagioclase Feldspar	-	0.0
Sedimentary Lithics	1	0.3
Metamorphic Lithics	-	0.0
Volcanic Lithics	1	0.3
Granitic Lithics	-	0.0
Calcite	3	0.9
Siderite	3	0.9
Pyrite	-	0.0
Muscovite	1	0.3
Biotite	-	0.0
Sericite	-	0.0
Tourmaline	1	0.3
Zircon	-	0.0
Garnet	-	0.0
Carbonaceous Matter	-	0.0
Total	332	100.0

Table II-2

Woronora-1: Estimate of Porosity for Nowra Sandstone

(Interval 1554.4 - 1603.2 m)

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\phi \Delta t$ %
1545.9	78	60	220	4.6
1546.5	78	60	220	4.6
1547.1	75	56	220	4.6
1547.7	74	55	223	5.9
1548.3	72	52	223	6.2
1548.9	73	53	226	6.8
1549.6	84	51	223	6.3
1550.2	73	53	223	6.1
1550.8	84	51	223	6.3
1551.4	75	56	220	5.0
1552.0	72	52	217	4.7
1552.6	70	49	223	6.5
1553.2	78	60	223	5.3
1553.8	75	56	213	3.5
1554.4	78	60	220	4.5
1555.0	76	57	217	4.2
1555.6	90	76	223	3.4
1556.3	94	81	217	1.4
1556.9	78	60	203	0.0
1557.5	66	44	200	2.0
1558.1	45	16	203	6.4
1558.7	48	20	203	5.5
1559.3	48	20	207	6.2
1559.9	78	60	210	2.4
1560.5	40	09	210	8.2
1561.1	36	04	220	11.0

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\sigma \Delta t$ %
1561.7	48	20	217	8.4
1562.4	45	16	213	8.1
1563.0	40	09	207	7.5
1563.6	52	25	210	6.4
1564.2	38	07	217	9.9
1564.8	43	13	217	9.2
1565.4	48	20	213	7.7
1566.0	48	20	217	8.4
1566.6	42	12	213	8.6
1567.2	52	25	213	7.1
1567.8	52	25	220	8.6
1568.5	48	20	220	9.1
1569.1	46	17	220	9.5
1569.7	56	31	213	6.4
1570.3	90	76	203	0.0
1570.9	48	20	187	1.9
1571.5	60	36	217	6.6
1572.1	100	89	217	0.0
1572.7	78	60	226	6.0
1573.3	90	76	213	1.2
1573.9	66	44	210	4.2
1574.5	72	52	200	1.1
1575.2	36	04	194	5.2
1575.8	54	28	203	4.6
1576.4	84	68	200	0.0
1577.0	54	28	197	3.1
1577.6	68	47	203	2.4
1578.2	72	52	207	2.6
1578.8	72	52	200	1.1

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\emptyset \Delta t$ %
1579.4	64	41	200	2.4
1580.0	74	55	203	1.5
1580.6	72	52	203	1.8
1581.3	66	44	203	2.7
1581.9	60	36	203	3.7
1582.5	48	20	203	5.5
1583.1	44	15	210	7.5
1583.7	55	39	207	5.2
1584.3	60	36	207	4.4
1584.9	65	43	203	2.9
1585.5	68	47	200	1.7
1586.1	60	36	203	3.7
1586.7	68	47	203	2.4
1587.3	66	44	213	4.9
1588.0	66	44	210	4.2
1588.6	68	47	190	0.0
1589.2	66	44	210	4.2
1589.8	78	60	207	1.6
1590.4	74	55	203	1.5
1591.0	60	36	194	1.5
1591.6	46	17	197	6.6
1592.2	60	36	207	4.4
1592.8	94	81	217	1.4
1593.4	90	76	203	0.0
1494.1	68	47	203	2.4
1594.7	78	60	203	0.0
1595.3	80	63	207	1.3
1595.9	82	65	203	0.0
1596.5	80	63	200	0.0
1597.1	64	41	203	3.1

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\Delta \Delta t$ %
1597.7	78	60	207	1.6
1598.3	78	60	197	0.0
1598.9	66	44	210	4.2
1599.5	108	100	223	0.0
1600.2	86	71	217	2.6
1600.8	80	63	210	2.0
1601.4	84	68	210	1.4
1602.0	84	68	207	0.0
1602.6	80	63	203	0.0
1603.2	78	60	197	1.4

Table II-3

Woronora-1: Summary of wireline log interpretation
of the Nowra Sandstone reservoir

Reservoir Unit and Interval m	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of Water (R _w) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity av. %
Nowra Sandstone	1557.5 - 1559.3	1.8	0.75	4000.00	5.1
1554.4 - 1603.2	1560.5 - 1569.7	9.2	0.75	4000.00	8.9
	1570.9 - 1571.5	0.6	0.75	4000.00	4.3
	1582.2 - 1584.0	1.5	0.75	4000.00	5.7

Table II-4

Woronora-1: Interval Transit Time Porosity ($\emptyset \Delta t$)and Resistivity (R_t) Cross-plot Data

Depth Interval m	Resistivity AO = 18'8" ohms-m ² /m	$\emptyset \Delta t$ %	Rw ohm/m	NaCl ppm
1561.1	120	11.0		
1561.7	140	8.4		
1562.4	180	8.1		
1563.0	250	7.5		
1563.6	330	6.4		
1564.2	390	9.9		<u>4000.00</u>
1564.8	400	9.2	0.75	
1565.4	410	7.7		
1566.0	430	8.4		
1566.6	480	8.6		
1567.2	450	7.7		
1567.8	450	8.6		
1568.5	450	9.1		
1569.1	450	9.5		
1569.7	460	6.4		
1571.5	470	6.6		
1572.7	250	6.0		

Table II-5Woronora-1: Summary of the Nowra SandstoneReservoir Fluid Characteristics

Depth Interval m	Method Used	Resistivity of Formation Water (Rw) ohms -metres	Concentration of NaCl (ppm)
1561.1	Rmf/SP	0.90	3300.00
1572.7	$\emptyset \Delta t / R_t$	0.75	4000.00

Table II-6Woronora-1: Summary of Reservoir Variables

Reservoir	:	Nowra Sandstone
Area $\times 10^6 \text{ m}^2$ ($\times 10^6 \text{ ft}^2$)	:	1.08 (11.63)
Net Pay Thickness m (ft)	:	11.6 (38)
Porosity %	:	6.1
Gas Saturation %	:	80.0
Reservoir Pressure (psia)	:	2240.5
Reservoir Temperature °C (°F)	:	60 (141)
Standard Condition Pressure (psi)	:	14.73
Standard Condition Temperature °C (°F)	:	15.5(60)
Gas Deviation Factor (Z)	:	0.888
Gas Formation Volume Factor (Bg)	:	248.67

PLANIMETRY RESULTS

STRUCTURE: Woronora

FORMATION: Nowra Sandstone

REFERENCE STRUCTURAL MAP: Figure II-3

REFERENCE STRUCTURAL CROSS-SECTION: Figures II-4 and II-5

COMMENTS:

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1	1545	20	26,000		
2	1555	101	263,000	10	1,238,974
3	1565	164	427,000	10	3,417,044
4	1575	252	656,000	10	5,374,186
5	1585	347	903,000	10	7,762,181
6	1592	415	1,080,000	7	9,901,808
7				47	27,694,193
8					
9					
10					

* Calibration of Instrument: 38.5 Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$$

Where: A₁ =

h =

A₂ =

Table II-8Woronora-1: Potential Natural Gas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^6 \text{ m}^3$	$\times 10^6 \text{ ft}^3$
Nowra Sandstone	90.79	3206.32

WELL NAME : Woronord-1
ROCK UNIT : Berry Fm DEPTH INTERVAL: 1188.7-1554 m
CORE DEPTH : 1364.8-1367.9 m THIN SECTION DEPTH: 1481.7

MACROSCOPIC DESCRIPTION

Dark grey to black, calcareous, carbonaceous pyritic and sandy mudstone.

MICROSCOPIC DESCRIPTION

Very fine to very coarse sized silt particles of quartz and occasional feldspar. Fragments of carbonaceous matter are common together with siderite and calcite patches. Pyrite occurs throughout. Some distorted shell fragments.

Calcite and siderite serve in parts as cement.

POROSITY No visible porosity was established.

FRAMEWORK	%	ACCESSORIES	%
Quartz	40	Pyrite	2
Chert	2	Micas	2
Feldspar	3		
Carbonaceous matter	5		
Metamorphic rock fragments	1		
Sericite			
Calcite & siderite	5		

CEMENT

Siderite	3
Calcite	2

MATRIX

Argillaceous	30
--------------	----

ROCK CLASSIFICATION

Calcareous mudstone.

WELL NAME :	WORONORA-1	
ROCK UNIT :	Nowra Sandstone	DEPTH INTERVAL: 1554.4-1603.2 m
CORE DEPTH :	1560.5-1563.0 m	THIN SECTION DEPTH: 1560.5 m

MACROSCOPIC DESCRIPTION

Massively bedded with scattered lithics of grey mudstone. Pyrite in veins together with carbonaceous siltstone. Fragments of thin and thick shelled brachiopods are common.

MICROSCOPIC DESCRIPTION

Medium to coarse grained, subangular to subrounded, poorly to moderately sorted quartz sand with occasional feldspars and chert grains. Rock fragments (volcanic and sedimentary and metamorphic) are common with rare muscovite and sericite flakes.

The framework is cemented silica, siderite and calcite. Silica being in the form of overgrowths.

Matrix is subordinate, made up mainly of argillaceous matter and some undifferentiated carbonate. Pyrite is rare.

POROSITYNo visible porosity was established.....

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	72.....	Muscovite.....	1.....
Chert.....	4.....	Sericite.....	1.....
Metaquartzite.....	3.....	Pyrite.....	tr.....
Potassium feldspar.....	1.....		
Plagioclase.....	1.....		
Volcanic lithics.....	7.....		
Sedimentary lithics.....	2.....		

CEMENT

...Silica overgrowths.....	4
...Siderite & calcite.....	2

MATRIX

...Argillaceous.....	2
.....	

ROCK CLASSIFICATION

Sublitharenite.

WELL NAME :	WORONORA-1	
ROCK UNIT :	Nowra Sandstone	DEPTH INTERVAL: 1554.4-1603.2 m
CORE DEPTH :	1560.5-1563.0 m	THIN SECTION DEPTH: 1561.7 m

MACROSCOPIC DESCRIPTION

Light grey, fine grained, pebbly, quartz rich silicified sandstone. Grey, firm mudstone lithics are common. Occasional brachiopod shells. Massively bedded.

MICROSCOPIC DESCRIPTION

Fine to very coarse grained, subangular, moderately sorted quartz rich sand with potassium and plagioclase feldspars, chert and metaquartzite fragments. Volcanic and sedimentary lithics are rare to common. Few flattened and/or elongated mudstone clasts.

The framework is cemented mainly with silica overgrowths and lesser carbonate (calcite & siderite). Matrix comprises argillaceous matter and a trace of pyrite.

POROSITYNo visible porosity was established.....

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	72.....	.Biotite.....	1.....
Chert.....	2.....	.Muscovite.....	1.....
Metaquartzite.....	4.....	.Sericite.....	
Potassium feldspar.....	2.....	.Pyrite.....	tr.....
Plagioclase.....	3.....		
Volcanic lithics.....	3.....		
Sedimentary lithics.....	4.....		

CEMENT

...Silica overgrowths.....	4..
...Calcite & siderite.....	2..

MATRIX

...Argillaceous.....	2
.....	

ROCK CLASSIFICATION

Sublitharenite

Well Name : WORONORA - 1Datum: 357.2 m A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age
164.5	Sublitharenite, and litharenite, pebbly with minor beds of grey siltstone and shale. Granitic, minor sedimentary and metamorphic provenance. Deposited in fresh water (fluvial) environment.	Rh		
518.1	Litharenite and sublitharenite with chert and sedimentary lithics. Interbedded with red-brown and grey shale beds and minor mudstone and siltstone beds. Sedimentary and lesser granitic and volcanic provenance. Deposited in fresh water (fluvial and static) oxidising conditions.		Rn	
1188.7	Carbonaceous shales, siltstones and numerous coal seams, interbedded with sublitharenite, litharenite and volcanics (tuffs). Sedimentary, volcanic and minor granitic provenance. Deposited in fresh water (static and agitated) oxidising conditions. Basal layers deposited in restricted marine.		Pi	
1554.4	Sublitharenite, litharenite and feldspathic litharenite, interbedded with carbonaceous and calcareous siltstone beds containint abundant volcanic lithics. Sedimentary granitic and volcanic provenance. Deposited in restricted near shore marine environment.	Psb		
1603.2		Psn		
1731.2		Psw		
1885.1		Pssp		
2229.6		Pspb		
2278.3		Pswh		
T.D2312.5	Granite	Granite		
<div><div></div>Interval under investigation</div>				

WORONORA - I
 Petrophysical Characteristics of the NOWRA SANDSTONE
 Interval 1554.4 - 1603.2m, Datum C.L. 357.2m A.S.L.

Fig. 11-2

WORONORA STRUCTURE STRUCTURE MAP ON TOP OF NOWRA SANDSTONE

(Modified after A.O.G. Woronora - Dural Seismic Survey, Final Report, BMR File 62/1646)

Fig. 11-5

WORONORA STRUCTURE
SOUTHWEST - NORTHEAST STRUCTURAL CROSS-SECTION

0 1km

RESISTIVITY VS POROSITY

Fig.II-6

WORONORA-1 (1561.1 - 1572.7 m B.C.L.)

PHOTO 1: Berry Formation.

(Thin section depth 1481.7 m, crossed nicols x 250)
Calcareous, carbonaceous and pyritic mudstone with very fine grained quartz sand.

PHOTO 2: Nowra Sandstone

(Thin section depth 1560.5 m, crossed nicols x 100)
Medium to coarse grained, pressure welded sublitharenite with patches volcanic rock fragments. Note quartz overgrowths.

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PHOTO 1: Nowra Sandstone.

(Thin section depth 1560.5 m, crossed nicols x 100)
Medium grained, pressure welded sublitharenite, with
sedimentary rock fragments. Note quartz overgrowths.

PHOTO 2: Nowra Sandstone.

(Thin section depth 1561.7 m, crossed nicols x 100)
Fine to very coarse grained, poorly sorted sublitharenite
with numerous rock fragments. Quartz overgrowths are notable.

APPENDIX III

KIRKHAM-1

ESTIMATED POTENTIAL NATURAL GAS

STORAGE CAPACITY

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SUMMARY

Kirkham potential natural gas storage field lies in the central part of the Sydney Basin. It is located 3.2 km north of Camden, N.S.W.

The Kirkham structure consists of a northeast-southwest trending anticline. The structure covers an area of $0.22 \times 10^6 \text{ m}^2$ and has a vertical closure of 5 m.

A potential natural gas storage reservoir has been delineated in the Nowra Sandstone in the interval 1572.2 - 1575.0 m and its potential natural gas storage capacity is estimated at about $7 \times 10^6 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of Kirkham-1 well have been examined for possible natural reservoirs which could be used for storage of natural gas.

Arenites of the Nowra Sandstone appear to have the potential of becoming a natural gas storage reservoir where suitable porous and permeable zones occur and there is a suitable structure and impermeable cap rock.

Apart from literature study (A.O.G., 1962, 1964, Raine, 1969 and Mayne et al., 1974), four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATIONWell Data

Well Name, No:	Kirkham No. 1
Operating Company:	Australian Oil and Gas Corporation Limited
Location:	Lat. & Long.: $34^{\circ}01'39''S$, $150^{\circ}42'27''E$ 1:250 000 sheet: Wollongong, S156-9 (grid ref.. 37047966). General Location: about 3.2 km north of Camden, N.S.W.
Elevation:	Ground level 82.5 m A.S.L. Kelly Bushing 86.2 m A.S.L. (Kelly Bushing used as datum for determining all depths in the well)
Total Depth:	2562.1 m (Driller) 2561.2 m (Schlumberger)
Date Drilled:	16.7.64 to 4.10.64

Formation
Testing

: D.S.T. No. 1, 641.6 - 705.9: Mis-run
D.S.T. No. 2, 1579.4 - 1587.0 m:
Abandoned

D.S.T. No. 3, 1567.8 - 1587.0 m:
Recovered 30.4 m of slightly gas
cut mud

Wireline Logs Available

Run	Date	Type	Interval
1	28-07-1964	GR	3.0 - 723.9
1	28-07-1964	ES	93.5 - 732.1
1	28-07-1964	MA/CA	93.5 - 732.1
1	28-07-1964	ITT	93.5 - 732.1
2	18-08-1964	ES	732.1 - 1654.7
2	18-08-1964	ML	732.1 - 1654.7
2	18-08-1964	ITT/GR	732.1 - 1654.7
3	31-09-1964/1-10-1964	GR	1615.4 - 2558.7
3	31-09-1964/1-10-1964	NU	320.0 - 731.5
3	31-09-1964/1-10-1964	ITT	1630.6 - 2558.7
3	31-09-1964/1-10-1964	CA	730.9 - 2558.7
3	31-09-1964/1-10-1964	ML	1630.6 - 2560.9
3	31-09-1964/1-10-1964	ES	1554.4 - 2560.9

History and Stratigraphy

The Kirkham-1 well was drilled in 1964 by the Australian Oil and Gas Corporation Limited to obtain stratigraphic information and in particular to investigate the reservoir potential of the arenaceous formations of the Permian Shoalhaven Group.

The well was drilled on the flank of a minor anticlinal structure faulted to the southwest. The structure was delineated by seismic traverses.

The well was spudded in the Triassic Wianamatta Group. It penetrated 112.7 m of this unit, 197.5 m of the Hawkesbury Sandstone and 437.6 m of Narrabeen Group beds before entering Permian Illawarra Coal Measures at 747.9 m. It then penetrated 538.2 m of Illawarra Coal Measures and 1259.7 m of Permian Shoalhaven Group sediments before encountering granite at 2545.9 m (Mayne et al., 1974).

Figure (III-1) shows the stratigraphic sequence encountered in Kirkham-1 well and a generalised description of lithologies, provenance and environment.

"Several minor gas occurrences were recorded while drilling the Narrabeen Group and the Permian coal sequences. Several sandstone sections were drill stem tested following small gas shows but results were negative. Little evidence of porosity was noted in any sandstone sections. No significant hydrocarbon shows were detected and the bore hole was subsequently plugged and abandoned", (A.O.G., 1964).

PETROLOGY AND PETROPHYSICS OF THE NOWRA SANDSTONE

The Nowra Sandstone in the Kirkham-1 well extends from 1567.5 - 1604.1 m and is 36.5 m thick. It is made up of olive grey, pebbly fine to medium grained moderately sorted sublitharenite, with minor conglomerate and carbonaceous and sideritic siltstone.

The sublitharenite contains quartz, chert, rare orthoclase and plagioclase feldspars, metamorphic and volcanic rock fragments. The framework is cemented with silica (quartz overgrowths), minor calcite, dawsonite, siderite and pyrite (Plate III-1, Photo 2). Table III-1 summarises the grain distribution count.

Core No. 17 (1584 - 1587.0 m) consists of fine to medium sublitharenite to oligomict conglomerate. Pebbles include milky quartz, black chert, quartzite sandstone, grey porphyritic acid volcanics, pyritic arkose, porphyritic microgranite and greenish grey siltstone. Other detrital components comprise metamorphic and common quartz, chert, quartz-muscovite schist, undifferentiated volcanic and sedimentary rock fragments. The core is cemented with calcite, and radial fibrous aggregates of dawsonite, (Nicholas & Ozimic, 1970). The matrix is calcareous and micaceous. Sedimentary structures in Core 17 include graded bedding, wavy bedding and burrows.

The variety of cementing minerals (calcite, siderite, silica and dawsonite) has reduced the intergranular porosity to values ranging from 1.6 to 15.5 percent (Table III-2).

The upper boundary of this interval is marked by the change in lithology from sandy siltstone to fine to medium grained sublitharenite. The change is accompanied by changes in the gamma ray, microlog resistivity and interval transit time logs. There appears to be a definite indication of permeability as indicated on the microlog resistivity curve (Fig. III-2).

CAP ROCK CHARACTERISTICS (Berry Formation)

The cap rock overlying the potential Nowra Sandstone reservoir is a sequence 281.3 m thick. In order of increasing depth it consists of brown to black mudstone and sandy siltstone grading into pebbly sandy siltstone. All the sediments are carbonaceous and contain siderite, pyrite and calcite cement. These sediments are equated to the Berry Formation.

Two cores were cut within this interval (Core Nos. 15 and 16). Core No. 15 (1408.1 - 1411.2 m) consists of olive to brownish black slightly pebbly silty litharenite grading to sandy coarse siltstone. Pebbles include quartz, black chert, argillite, microgranite, and siliceous volcanic rock. Other detrital components include quartz, plagioclase, orthoclase, muscovite, volcanic rock fragments, argillite, quartz-muscovite schist, pyritic quartz siltstone, rare glauconite, carbonaceous fragments, some brown illitic clay matrix. Cementing minerals are calcite and minor pyrite. Sedimentary structures include lamination, wavy bedding, burrows, and bioturbation.

Core 16 (1501.7 - 1503.8 m) consists of slightly pebbly very fine litharenite to sublitharenite, grading to sandy coarse siltstone (Plate III-1, Photo 1),. Detrital components are similar to Core 15, but there is a slightly greater proportion of feldspar and rock fragments. Sedimentary structures include lamination, wavy bedding, small-scale, cross-bedding, (Raine, 1969).

Laboratory tests on these two cores revealed no permeability. Porosities over the interval are generally low.

POROSITY

Wireline log data was used in estimation of porosities for the Kirkham-1 potential reservoir (Method 7, Chapter II). The wireline log data and the summary of results for the reservoir are shown in Tables III-2, and III-3.

NET PAY INTERVAL

There are 30.4 m of net pay in the Nowra Sandstone. The net to gross ratio (30.5/36.5) is 0.83. (Fig. III-2 and Table III-3).

Wireline log characteristics (spontaneous potential, gamma ray and microlog resistivity) combined with shale volume and porosity were used for delineation of the net pay interval.

PERMEABILITY

Two drill stem tests were carried out over the Nowra Sandstone interval. D.S.T. No. 2, 1579.4 - 1587.0 m was abandoned after the failure of the packer.

D.S.T. No. 3, 1567.8 - 1587.0 m recovered 30.4 m of slightly gas cut mud but no gas was detected at the surface after a 55 minute flow test. The pressure chart readings were (A.O.G., 1964):

Initial hydrostatic pressure	2700 psi
Initial flow pressure	20 psi
Final flow pressure	20 psi
Final shut-in pressure	-
Final hydrostatic pressure	2700 psi

BMR laboratory tests on Core No. 17 (1584.0 - 1587.0 m) revealed low permeability although the measured porosity ranged from 9 to 10 percent. Recent core analysis (Core 17) revealed permeability of 2.41 - 23.4 md.to air and 1.0 - 16.0 md. to brine (Volume I, Table 18),

Microlog resistivity and spontaneous potential logs indicate possible permeable intervals within the Nowra Sandstone (Volume I, Table 17).

STRUCTURE

Kirkham structure is a northeast-southwest trending minor anticline. Kirkham-1 (Fig. III-3) was drilled 0.1 km north of its crest. A fault zone limits the structure on the southwestern side of the anticline.

The structure contour map (Fig. III-3) on top of Nowra Sandstone is based on the seismic horizon 'B' near the base of Permian Coal Measures as mapped by A.O.G. in 1963.

The lowest closed contour at 1575.0 m does not coincide with the spill point of Kirkham structure which appears to be at 1600 m (Figs. III-4 and III-5).

The structure has a vertical closure of 5 m from the upper closed contour at 1570.0 m to the lowest closed contour at 1575 m and covers an area of $0.217 \times 10^6 \text{ m}^2$ (Table III-5).

RESERVOIR FLUID CHARACTERISTICS

Drill stem tests carried out over the Nowra Sandstone intervals recovered no formation water. The resistivity of the formation water and its salinity was established by the interval transit time porosity ($\emptyset \Delta t$) - resistivity (R_t) method (Method 2, Chapter II).

Interval transit time porosity (Δt) readings taken over the interval 1575.8 - 1594.1 m (Table III-4) are plotted against the resistivity (R_t) readings (Fig. III-6) over the same interval. Table III-4 also summarizes the results of this method.

HYDROSTATIC PRESSURE CALCULATION

Nowra Sandstone Reservoir

Depth (average)	5200 ft (1585 m)
Resistivity of reservoir water	0.60 ohm-metre
NaCl concentration in reservoir water	5200 ppm @ 132°F (Schlumberger, 1972)
Density of NaCl solution	1.0045 @ 77°F
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Nowra Sandstone reservoir

$$1.0045 \times 0.433$$

$$= \underline{\underline{0.4349 \text{ psi/ft}}}$$

Hydrostatic pressure for Nowra Sandstone reservoir

$$0.4349 \times 5200$$

$$= \underline{\underline{2261.5 \text{ psi}}}$$

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the Kirkham-1 reservoir as estimated, according to the volumetric method (Method 12, Chapter II) is $7.00 \times 10^6 \text{ m}^3$.

The variables used in estimating the potential natural gas storage capacity are given in Table III-6. These variables were derived from various analyses and calculations presented in this Appendix.

Table III-7 summarises the results of the potential natural gas storage capacity as estimated for the Kirkham reservoir.

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Table III-1 Grain Distribution Count

WELL NAME: KIRKHAM-1
 FORMATION: NOWRA SANDSTONE
 THIN SECTION DEPTH: 1586.6 m

<u>Rock Components</u>	<u>Total Count</u>	<u>Percent of Rock</u>
Quartz	260	94.20
Quartz Overgrowth	7	2.50
Chert	1	0.33
Potassium Feldspar	1	0.33
Plagioclase Feldspar	-	0.00
Sedimentary Lithics	1	0.33
Metamorphic Lithics	1	0.33
Volcanic Lithics	2	0.99
Granitic Lithics	-	0.00
Calcite	1	0.33
Siderite	1	0.33
Pyrite	-	0.00
Muscovite	-	0.00
Biotite	-	0.00
Dawsonite	1	0.33
Tourmaline	-	0.00
Zircon	-	0.00
Garnet	-	0.00
Carbonaceous Matter	-	0.00
	277	100.00

Table III-2Kirkham-1: Estimate of porosity for Nowra Sandstone

(Interval 1554.4 - 1615.4 m)

Depth m	Gamma-Ray API Units	Shale Volume %	Interval Transit Time microsec/m	Porosity ($\phi_{\Delta t}$) %
1554.4	87	72	239	7.6
1557.5	82	64	236	7.8
1560.5	79	60	223	5.3
1563.6	79	60	219	4.6
1566.6	69	44	213	5.0
1569.7	80	61	206	1.6
1572.7	56	24	200	4.4
1575.8	45	07	213	9.2
1578.8	45	07	219	10.7
1581.9	45	07	213	9.2
1584.9	50	15	246	15.5
1588.0	50	15	226	11.2
1591.0	45	07	236	14.3
1594.1	45	07	239	15.0
1597.1	60	30	223	8.0
1600.2	40	00	206	8.6
1603.3	60	30	193	2.2
1606.2	78	89	223	1.9
1609.3	97	87	219	1.5
1612.3	100	92	219	1.6
1615.4	105	100	229	2.2

Table III-3

Kirkham-1: Summary of Wireline log interpretation
of the Nowra Sandstone Interval

Reservoir Unit and Interval (m)	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of Water (Rw) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity av. %
Nowra Sandstone 1567.5 - 1604.1	1572.2 - 1575.0	5.0	0.60	5200.00	5.5

Table III-4

Kirkham-1: Interval Transit Time Porosity ($\emptyset$ t)
and Resistivity (Rt) Cross-Plot Data

Depth Interval (m)	Resistivity (Rt) AO = 18'8" ohms-m ² /m.	Porosity ($\emptyset \Delta t$)	Rw ohm/m	NaCl ppm
1575.8	110	9	0.60	5200.00
1578.8	83	11	0.60	5200.00
1581.9	128	9	0.60	5200.00
1584.9	48	16	0.60	5200.00
1588.0	51	11	0.60	5200.00
1591.0	47	14	0.60	5200.00
1594.1	25	15	0.60	5200.00

PLANIMETRY RESULTS

STRUCTURE: KIRKHAM
FORMATION: NOWRA SANDSTONE
REFERENCE STRUCTURAL MAP: Figure III-5
REFERENCE STRUCTURAL CROSS-SECTION: Figures III-6 and III-7
COMMENTS: Lowest closed contour does not coincide with the spill point
of the structure

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area m ²	Thickness m	Volume** m ³
1	1570	53	135,897		
2	1575	85	217,948	5	876,575
3					
4					
5					
6					
7					
8					
9					
10					

* Calibration of Instrument: 390. Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \frac{(\sqrt{A_1 \times A_2}) + A_1 + A_2}{3} \times h$$

Table III-6Kirkham-1: Summary of Reservoir Variables

Reservoir	:	Nowra Sandstone Formation
Area x 10^6m^2 (x 10^6ft^2)	:	0.217 (2.3361)
Net Pay thickness m (ft)	:	5.0 (16.4)
Porosity %	:	5.5
Gas Saturation %	:	80.0
Reservoir Pressure (psia)	:	2276.2
Reservoir Temperature °C (°F)	:	55 (132)
Standard Condition Pressure (psi)	:	14.73
Standard Condition Temperature °C (°F)	:	15.5 (60)
Gas Deviation Factor (Z)	:	0.887
Gas Formation Volume Factor (Bg)	:	152.37

Table III-7Kirkham-1: Potential Natural Gas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^6 \text{ m}^3$	$\times 10^6 \text{ ft}^3$
Nowra Sandstone Formation	7.0	247.2

WELL NAME : KIRKHAM -1
ROCK UNIT : BERRY FORMATION DEPTH INTERVAL: 1286.2-1567.5mBKB
CORE DEPTH : 1501.7-1503.8BKB THIN SECTION DEPTH: 1501.7mBKB

MACROSCOPIC DESCRIPTION

Olive black, laminated and small scale cross-bedded coarse siltstone with sand lenses and quartz pebbles

MICROSCOPIC DESCRIPTION

Very fine to very coarse silt sized particles of quartz, feldspar and undifferentiated rock fragments are bonded by sideritic and carbonaceous matter. Very fine to fine angular quartz grains occur throughout

POROSITY .No visible porosity was established.

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	15.....	Pyrite.....	1.....
Quartz (silt. sized)...	45.....		
Feldspar " ".....	4.....		
Rock fragments " ".....	10.....		
Muscovite.....	2.....		
Carbonaceous matter.....	5.....		
.....			

CEMENT

Siderite 8
.....

MATRIX

Argillaceous 10
.....

ROCK CLASSIFICATION

Carbonaceous, sideritic siltstone

THIN SECTION DESCRIPTION

WELL NAME : KIRKHAM -1

ROCK UNIT : NOWRA SANDSTONE

CORE DEPTH : 1584.0-1587.0 BKB

DEPTH INTERVAL:1567.5-1604.1m BKB

THIN SECTION DEPTH:1586.6m BKB

MACROSCOPIC DESCRIPTION

Greenish grey, fine to medium grained, poorly sorted arenite with scattered pebbles of quartz. Bedding is graded and wavy.

MICROSCOPIC DESCRIPTION

Fine to medium grained, poorly to moderately sorted subrounded to sub-angular siliceous sublitharenite with (strong) pressure welded quartz and feldspar grains. Some grains show overgrowths. Pebbles of sedimentary, metamorphic and volcanic rock fragments are common. Calcite, siderite, dawsonite and silica serve as cement. Subordinate matrix is calcareous and micaceous.

POROSITY No visible porosity was established.....

<u>FRAMEWORK</u>	<u>%</u>
Quartz.....	72
Chert.....	2
Potassium feldspar.....	1
Plagioclase.....	1
Volcanic rock fragments.....	4
Sedimentary."....."	2
Metamorphic."....."	2

<u>ACCESSORIES</u>	<u>%</u>
Pyrite.....	tr
Dawsonite.....	tr 1
Muscovite.....	tr
Tourmaline.....	tr
.....	
.....	
.....	

CEMENT

...Silica overgrowths.....9.
...Calcite, Siderite & Dawsonite 3

MATRIX

....Argillaceous...3....
.....

ROCK CLASSIFICATION

Silicious sublitharenite

Well Name : ...KIRKHAM.-1

Datum : ...86.2m.....A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age
112.7	Siltstone interbedded with sandy mudstone. Sedimentary provenance. Deposited in fluvial environment.	Rw		TRIASSIC
310.2	Sublitharenite interbedded with litharenite, siltstone and sideritic mudstone beds. Sedimentary and metamorphic provenance. Deposited in fluvial environment.		Rh	
747.9	Siltstone, mudstone and multicoloured claystone interbedded with thin beds of litharenite. Sedimentary provenance. Deposited in marginal marine environment.		Rn	
1286.2	Sublitharenites, litharenites, carbonaceous siltstone and mudstone beds interbedded with volcanic clasts lenses and coal seams. Sedimentary and volcanic provenance. Deposited in fluvial and marginal marine environment.		P1	PERMIAN
1567.5	Mudstone interbedded with carbonaceous sandy, calcareous siltstone and litharenite beds. Marine fossils are common. Sedimentary provenance. Deposited in low energy marine environment.			
1604.1	Sublitharenite siliceous and calcareous interbedded with thin beds of siltstone. Pebbles of quartz and rock fragments are common. Marine fossils are common. Diverse provenance. Deposited in high energy marine environment.	Psb		
1817.5	Siltstone, mudstone interbedded with litharenite. Marine fossils are common. Sedimentary and metamorphic provenance. Deposited in moderate to low energy marine environment.	Psn		
1078.2	Siltstone, mudstone interbedded with litharenite. Marine fossils are common. Sedimentary and metamorphic provenance. Deposited in moderate to low energy marine environment.	Psw		
2482.6	Sublitharenite and subarkose interbedded with thin siltstone beds. Pebbles of rock fragments are common. Marine fossils of brachiopods, pelecypods and foraminifera occur. Diverse provenance. Deposited in moderate to high energy marine environment.	Pssp		
2545.9	Siltstone interbedded with litharenites and pebbly sublitharenite. Carbonaceous mudstone beds occur throughout. Coal laminae occur at base. Marine fossils of brachiopods, bryozoa and foraminifera. Diverse provenance. Deposited in low to high energy marine environment.	pspb		
T.D. 2562.1	Volcanic agglomerate.			
<div>Intervals under investigation</div>				

KIRKHAM - I

Petrophysical Characteristics of the NOWRA SANDSTONE

Interval 1567.5 - 1604.1m, Datum K.B. 86.2m A.S.L.

S.O. 18-7-77

XAUS - 5 - 451

Fig.III-3

(Modified after A.O.G. Woronora - Dural Seismic Survey, Final Report, BMR File 62/1642)

RESISTIVITY VS POROSITY

KIRKHAM-1

Fig.III-6

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PHOTO 1: Berry Formation.

(Thin section depth 1501.7 m, crossed nicols x 200)
Sideritic, carbonaceous coarse siltstone with fine to very fine quartz grains.

PHOTO 2: Nowra Sandstone.

(Thin section depth 1586.6 m, crossed nicols x 200)
Fibrous dawsonite, calcite and patchy siderite in a biomodal sublitharenite.

APPENDIX IV

DURAL SOUTH-1

ESTIMATED POTENTIAL NATURAL

GAS STORAGE CAPACITY

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SUMMARY

Dural South potential natural gas storage field lies in the central part of the Sydney Basin. It is located 26 km northwest of Sydney, N.S.W.

The Dural South structure consists of a large dome. The structure covers an area of 45.4 km^2 and has a vertical closure of 148.2 m.

A potential natural gas storage reservoir has been delineated in the Nowra Sandstone in the interval 2151.8 - 2180.8 m.

The potential natural gas storage capacity of the Dural South reservoir as estimated is $8.80 \times 10^9 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of Dural South-1 well, have been examined for possible natural reservoirs which could be used for storage of natural gas.

Sandstones of the Nowra Sandstone Formation appear to have the potential of becoming a natural gas storage reservoir in conjunction with suitable porous and permeable arenites; structure and an impermeable cap rock.

Apart from literature study, (Shell, 1965, 1966; Hawkins & Ozimic, 1967; Mayne et al., 1974) four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well Data

Well Name, No.	: Dural South No. 1
Operating Company	: Shell Development (Australia) Pty Ltd
Location	: Lat. & Long.: 33°42'37"S, 151°01'02"E 1:250 000 sheet: Sydney SI 56/5 General Location: 26 miles north-west of Sydney, Central Sydney Basin, N.S.W.
Elevation	: 193.5 m Ground level, 197.8 Rotary Table. Rotary Table used as datum for determining lithological boundary depths in well.
Total Depth	: 3058.6 m (drillers depth) 3061.7 m (wireline log depth)

Drill Stem Tests

: D.S.T. Nos 1-9 were carried out within the interval 1455.1 - 3058.6 m. Only four of the tests were successfully completed.

D.S.T. No. 4, 2888.8 - 2915.7 m:
Rec. 30.4 m slightly gas cut mud

D.S.T. No. 5, 2888.8 - 2915.7 m:
Rec. 85.3 m very slightly gas cut mud

D.S.T. No. 7, 2698.6 - 2721.8 m:
Rec. 30.4 m mud

D.S.T. No. 9, 1455.1 - 1563.0 m:
Rec. 30.4 m slightly gas cut mud.

Wireline Logs Available

Run	Date	Type	Interval
1	14-07-1966	ES	157.5 - 921.4
1	14-07-1966	LL/SP	157.5 - 920.1
1	14-07-1966	ML/CA	157.5 - 921.4
1	14-07-1966	ITT/CA	157.5 - 918.9
1	14-07-1966	GR	Surface - 920.1
2	9-08-1966	ES	922.6 - 1900.4
2	9-08-1966	LL/SP	922.6 - 1899.2
2	9-08-1966	ML/CA	922.6 - 1900.4
2	9-08-1966	ITT/CA	922.6 - 1897.6
2	9-08-1966	GR	922.6 - 1897.6
2	9-08-1966	NL	922.6 - 1900.7
3	9-09-1966	ES	1900.4 - 2618.8
3	9-09-1966	ML/CA	1900.4 - 2618.8
3	9-09-1966	ITT/CA	1897.6 - 2615.7
3	9-09-1966	GR	1897.6 - 2615.7

Wireline Logs Available (Cont'd)

Run	Date	Type	Interval
4	18-09-1966	ES/SP	2179.3 - 2763.6
4	18-09-1966	ML/CA	2438.4 - 2763.3
4	18-09-1966	ITT/CA	2179.3 - 2759.9
4	18-09-1966	GR c	179.3 - 2761.4
4	18-09-1966	NL	1828.8 - 2763.3
5	5-10-1966	ES/SP	2763.6 - 3061.7
5	5-10-1966	ML/CA	2133.6 - 3062.0
5	5-10-1966	ITT/CA	2606.0 - 3059.5
5	5-10-1966	GR	2761.4 - 3061.7
5	5-10-1966	NL	2761.4 - 3061.7
5	5-10-1966	CDM	922.6 - 3057.4
6	20-10-1966	GR	2651.7 - 2956.5

History and Stratigraphy

The Dural South-1 well was drilled in 1966 by the Shell Development (Australia) Pty Ltd, to test the Permian Maitland Group sediments in the central part of the Sydney Basin. The well was drilled on the culmination of the Dural structure (Fig. IV-3). The structure was depicted by seismic survey, (Shell, 1965).

The well was spudded in the Triassic Wianamatta Group. It penetrated 36.5 m of this unit, 204.2 m of the Hawkesbury Sandstone and 591.3 m of the Narrabeen Group beds before entering Permian Illawarra Coal Measures at 832.1 m. It then penetrated 880.8 m of Upper Coal Measures and 1331.9 m of Permian Maitland Group sediments before entering volcanics at 3044.9 m, (Mayne et al., 1974).

Figure IV- shows the stratigraphic sequence encountered in Dural South-1 well and generalised description of lithologies, provenance and environment. "Three open hole formation tests were attempted of which only one was a mechanical success. However, eight of ten formation tests through casing perforations were carried out successfully. All zones tested were proved to be dry", (Shell, 1966).

PETROLOGY AND PETROPHYSICS OF THE NOWRA SANDSTONE

The Nowra Sandstone in the Dural South-1 well extends from 2151.8 - 2180.8 m and is 29.0 m thick. It is made up of siliceous and calcareous sublitharenite (Table IV-8) containing quartz (undulose and composite), rare chert and oligoclase feldspars, metamorphic and sedimentary rock fragments together with pebbles of quartz. Silica in the form of overgrowths serves as cement. Accessory minerals are muscovite, sericite and pyrite. Table IV-1 summarises the grain distribution count. Silica, calcite and siderite cements have reduced the intergranular porosity to values ranging from 1.9 to 15.1 percent (Table IV-2).

The upper boundary of this interval is marked by the change in lithology from sandy siltstone to predominantly medium grained sublitharenite. This change is accompanied by an increase in the resistivity log curve, a decrease in gamma-ray log curve (from moderate to low counts) and a definite indication of permeability as indicated on the microlog resistivity (Fig. IV-2).

The lower boundary is marked by a change in lithology from medium grained litharenite to a sandy siltstone similar to the lithology overlying the nowra Sandstone.

CAP ROCK CHARACTERISTICS (Berry Formation)

The cap rock overlying the Nowra Sandstone potential reservoir is a sequence 438.9 m thick comprising sandy siltstone, claystone and minor litharenite. These sediments are equated to the Permian Berry Formation (Fig. IV-1). Core No. 3 (2143.9 - 2146.8 m) is made up of indurated, dense sandy pyritic and calcareous siltstone grading into poorly sorted clayey silty sandstone (Table IV-9). Brown sideritic concretions are common. Thin lenses of litharenite occur throughout the core. Laboratory porosity and permeability tests on two plugs (one vertical and horizontal) from Core No. 3 showed an average porosity of 4 percent but no permeability was detected. Microlog resistivity over this interval show no significant separation. At 2144.8 m a tillitic siltstone-conglomerate band occurs. Shell (1966), describes it as: "poorly sorted, carbonaceous siltstone with large angular to subrounded pebbles. The sand and silt fraction of angular quartz is set in matrix of abundant carbonaceous clay. Large pebbles (up to 25 mm across) are mainly of quartz rich metamorphics: banded chert, quartzite and hornfels. Bedding is poorly developed and highly contorted around pebbles".

POROSITY

Wireline log data was used in estimation of porosities for the Nowra Sandstone reservoir. The porosity estimation Table (IV-3) was made by the interval transit time (sonic log) (Method 7, Chapter II. A matrix interval transit time of 167.9 microseconds/metre was used in the acoustic velocity-porosity calculation. All the porosity values were corrected for shale volume. The porosities

so determined are only approximate since no cores were available over this interval for log calibration.

The wireline log data and the summary of results for the potential reservoir are shown in Tables IV-2 and IV-3.

NET PAY INTERVALS

There are 16.5 m of net pay in the Nowra Sandstone. The net to gross pay ratio (16.5/29.0) is 0.56. The 16.5 m of net pay are subdivided into four zones. Their thicknesses are 4.9, 2.4, 2.5, and 6.7 m respectively (Fig. IV-2, Table IV-3). Gamma ray and microlog resistivity log patterns together with evaluation of shale volume and porosity were used for delineation of these zones.

PERMEABILITY

"Sands with indications of porosity and permeability were tested", (Shell, 1966). The testing did however not include the Nowra Sandstone interval, in spite of evidence of permeability on the microlog resistivity (Fig. IV-2). Absence of core material and drill stem test results over this interval, the value of permeability can only be speculative.

STRUCTURE

"The Dural Structure is only weakly expressed in the outcropping Triassic strata and no closure of importance could be mapped at this level. The seismic results indicated that the structure and structural closure becomes more pronounced with depth. The location for Dural South No. 1 was selected within the highest closed contour of seismic horizon "B". This horizon appeared to be more or less correlatable with the top of the Maitland Group (Upper Marine), the main target", (Shell, 1966).

Structure map on top of Nowra Sandstone reservoir (Fig. IV-3) is based on the structure contour map on top of the Maitland Group (horizon "B") as depicted by Shell (1965). It is assumed that the underlying strata conforms with the overlying structural expression of the Maitland Group.

The spill point for the Nowra Sandstone reservoir is inferred to be at 2300 m (Figures IV-4 and IV-5).

The structure has a vertical closure of 148.2 m to the lowest closed contour and covers an area of 45.4 km².

HYDROSTATIC PRESSURE CALCULATION

Nowra Sandstone reservoir

Depth (average)	7060 ft (2151.8 m)
Resistivity of reservoir water	0.83 ohm-metre
NaCl concentration	3000.00 ppm at 167°F
Density of NaCl solution	1.0040 @ 77°F (Schlumberger, 1972)
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Nowra Sandstone reservoir

$$1.0040 \times 0.433$$

$$= \underline{\underline{0.4347 \text{ psi/ft}}}$$

Hydrostatic pressure for Nowra Sandstone reservoir

$$0.4347 \times 7060$$

$$= \underline{\underline{3068.9 \text{ psi}}}$$

RESERVOIR FLUID CHARACTERISTICS

No drill stem testing was carried out over the Nowra Sandstone interval. The resistivity of the formation water and its salinity was established by the porosity (ϕ Δ t) - resistivity (R_t) cross-plot method (Method 2, Chapter II). Porosity (ϕ Δ t) readings taken over the interval 2152.4 to 2156.7 m (Table IV-3) are plotted against the resistivity (R_t) readings (Fig. V-6) over the same interval. Table IV-4 also summarises the results of this method.

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the Dural South-1 reservoir was estimated according to volumetric method (Method 9, Chapter II).

The variables used in estimating the potential natural gas storage capacity are given in Table IV-6. These variables were derived from various analyses and calculations presented in this Appendix.

All four porous and permeable zones totalling 16.5 m of net pay have been included into final storage capacity estimate.

Table IV-7 summarises the results of the potential natural gas storage as estimated by the volumetric method for the Dural South-1 reservoir.

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- SHELL DEVELOPMENT (AUST) PTY LTD, 1965 - Richmond-Cessnock seismic survey, final report. (Unpubl. company report. Bur. Miner. Resour. Aust. File 65/4577).
- SHELL DEVELOPMENT (AUST) PTY LTD, 1966 - Dural South No. 1 well completion report (Unpubl. company report. Bur. Miner. Resour. Aust. File. 66/4209).

Table IV-1Grain Distribution Count

WELL NAME: Dural South-1

FORMATION: Nowra Sandstone

THIN SECTION DEPTH: 2185.4 - 2188.4 m (Cuttings sample)

Rock Components	Total Count	Percent of Rock
Quartz	103	81.70
Quartz Overgrowth	3	2.40
Chert	2	1.60
Potassium Feldspar	1	0.80
Plagioclase Feldspar	-	0.00
Sedimentary Lithics	2	1.60
Metamorphic Lithics	4	3.10
Volcanic Lithics	-	0.00
Granitic Lithics	-	0.00
Calcite	7	5.60
Siderite	3	2.40
Pyrite	1	0.80
Muscovite	-	0.00
Biotite	-	0.00
Sericite	-	0.00
Tourmaline	-	0.00
Zircon	-	0.00
Garnet	-	0.00
Carbonaceous Matter	-	0.00
	126	100.00

Table IV-2

Dural South-1: Estimates of porosity and
shale volume for Nowra Sandstone

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\phi \Delta t$ %
2145.7	85	51	213	4.9
2146.4	85	51	217	5.6
2147.0	90	59	217	4.8
2147.6	83	49	213	5.1
2148.2	76	38	210	5.4
2148.8	78	41	194	1.5
2149.4	85	51	217	5.6
2150.0	83	49	207	3.6
2150.6	97	69	223	5.2
2151.2	75	37	223	84.
2151.8	55	07	220	10.7
2152.4	55	07	240	15.1
2153.1	55	07	236	14.3
2153.7	60	25	220	9.9
2154.3	50	0	220	11.4
2154.9	52	03	233	15.5
2155.5	53	04	217	10.3
2156.1	54	06	210	8.6
2156.7	78	41	220	7.3
2157.3	78	41	207	4.4
2157.9	75	37	210	5.5
2158.5	75	37	210	5.5
2159.2	75	37	213	6.3
2159.8	55	07	203	7.1
2160.4	55	07	217	10.0
2161.0	64	21	203	5.7

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\phi \Delta t$ %
2161.6	70	29	200	4.2
2162.2	80	44	213	5.6
2162.8	66	24	213	7.6
2163.4	75	37	203	4.1
2164.0	85	51	220	6.3
2164.6	62	18	207	6.7
2165.2	55	07	197	5.6
2165.9	75	37	207	4.8
2166.5	90	59	207	2.6
2167.1	90	59	213	4.1
2167.7	80	44	207	4.1
2168.3	97	69	213	3.1
2168.9	83	49	210	4.3
2169.5	85	51	210	4.1
2170.1	83	49	203	2.9
2170.7	98	71	223	5.0
2171.3	105	81	220	3.3
2172.0	113	93	220	2.1
2172.6	100	59	220	5.5
2173.2	64	21	203	5.7
2173.8	60	21	223	10.8
2174.4	60	21	210	7.1
2175.0	90	59	210	3.3
2175.6	68	26	217	8.1
2176.2	60	21	223	10.8
2176.8	65	22	220	9.2
2177.4	55	07	213	9.3
2178.1	53	04	233	13.9
2178.7	58	12	210	8.0

Depth m	Gamma Ray API units	Shale Volume %	Δt microsec/m	$\emptyset \Delta t$ %
2179.3	83	49	203	2.9
2179.9	110	88	223	3.3
2180.5	118	100	223	2.9
2181.4	100	59	217	4.8
2181.7	95	66	207	1.9
2182.3	98	71	210	2.1

Table IV-3

Dural South-1: Summary of wireline log interpretation of
the Nowra Sandstone Reservoir

Reservoir Unit and Interval m	Net Pay Depth Interval m	Net Pay Thickness m	Resistivity of water (Rw) (ohms-m)	Reservoir water Salinity (NaCl) ppm	Porosity av. %
Nowra Sandstone	2151.8 - 2156.7	4.9	0.83	3000.00	11.4
2151.8 - 2180.8	2159.9 - 2162.2	2.4	0.83	3000.00	6.5
	2164.0 - 2166.5	2.5	0.83	3000.00	5.2
	2172.6 - 2179.3	6.7	0.83	3000.00	7.8

Table IV-4

Dural South-1: Interval Transit Time Porosity ($\emptyset$ t)
and Resistivity (Rt) Cross-Plot Data

Depth Interval m	Resistivity (Rt) AO = 18'8" ohms-m ² /m	Porosity ($\emptyset \Delta t$) %	Rw ohm/m	NaCl ppm
2152.4	52	15.1		
2153.1	69	14.3		
2153.7	82	9.9	0.83	3000.00
2154.3	83	11.4		
2154.9	86	15.5		
2155.5	95	10.3		
2156.1	105	8.6		
2156.7	108	8.8		

PLANIMETRY RESULTS

STRUCTURE: Dural South

FORMATION: Nowra Sandstone

REFERENCE STRUCTURAL MAP: Figure IV-3

REFERENCE STRUCTURAL CROSS-SECTION: Figures IV-4 and IV-5

COMMENTS: Spill point at 2300 m

Unit No.	Contour Depth m	Planimetry Units*	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1	2151	18	916,666	-	-
2	2180	55	2,750,000	28.2	34,475,660
3	2210	142	7,100,000	30.0	142,687,102
4	2240	274	13,700,000	30.0	306,625,554
5	2270	503	25,150,000	30.0	574,121,927
6	2300	908	45,400,000	30.0	792,158,291
7				148.2	1,850,068,534
8					
9					
10					

* Calibration of Instrument:²⁰ Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$$

Table IV-6Dural South-1: Summary of Reservoir Variables

Reservoir	:	Nowra Sandstone
Area x 10 ⁶ m ² (x 10 ⁶ ft ²)	:	45.4 (488.7)
Net Pay Thickness m (ft)	:	16.5 (54)
Porosity %	:	7.7
Gas Saturation %	:	80
Reservoir Pressure(psia)	:	3084
Reservoir Temperature °C (°F)	:	75 (167)
Standard Condition Pressure (psi)	:	14.73
Standard Condition Temperature °C (°F)	:	15.5 (60)
Gas Deviation Factor (Z)	:	0.899
Gas Formation Volume Factor (Bg)	:	192.86

Table IV-7Dural South-1: Potential NaturalGas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^9 \text{ m}^3$	$\times 10^9 \text{ ft}^3$
Nowra Sandstone	8.80	313.52

WELL NAME : DURAL SOUTH-1

ROCK UNIT : BERRY FM

DEPTH INTERVAL: 1712.9 - 2151.8 m BRT

CORE DEPTH : 2142.7 - 2145.7 m BRT

THIN SECTION DEPTH: 2145.7 m BRT

MACROSCOPIC DESCRIPTION

Light grey and black claystone silty in part; thinly bedded with scattered subrounded quartz and chert pebbles. Dark brown (sideritic) concretions are common. Minor poorly sorted sandstone lenses.

MICROSCOPIC DESCRIPTION

Very fine to coarse sized silt particles of quartz, feldspars and chert. Rare fragments of carbonaceous matter. Metamorphic rock fragments are chloritized. The framework is banded together by argillaceous matrix and some calcite and siderite. Trace of pyrite and sericite.

POROSITY . No visible porosity was established.....

<u>FRAMEWORK</u>	%	<u>ACCESSORIES</u>	%
Quartz.....	30.....	Pyrite.....	tr.....
Chert.....	1.....		
Feldspar.....	1.....		
Carbonaceous matter...1.....			
Metamorphic rock fragments...2.....			
Sericite.....	tr.....		
.....			

CEMENT

...Calcite.....3...
...Siderite.....5...

MATRIX

...Argillaceous.....57..
.....

ROCK CLASSIFICATION

Calcareous Siltstone

WELL NAME : DURAL SOUTH-1
ROCK UNIT : NOWRA SANDSTONE DEPTH INTERVAL: 2151.8 - 2180.8 m BRT
CORE DEPTH : 2185.4 - 2188.4 m BRT THIN SECTION DEPTH: 2185.4 - 2188.4 m BRT

MACROSCOPIC DESCRIPTION

Light grey, very fine to coarse grained poorly sorted, angular quartz sandstone.
Silty and pyritic with traces of muscovite flakes.

MICROSCOPIC DESCRIPTION

Fine to coarse grained, subangular to angular, poorly sorted, undulose to composite quartz grains, rare chert and feldspar. Quartz grains are strongly interlocked and pressure welded. Silica overgrowths on quartz grains are common. Calcite appears to replace quartz and rock fragments. Sedimentary rock fragments comprise shale and pyritic siltstone. Metamorphic rock fragments are chloritized. Framework is calcite, siderite and silica cemented. Argillaceous matrix is subordinate. Pyrite patches are common.

POROSITY No visible porosity was established.....

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	69...	Pyrite.....	tr.....
Chert.....	2...		
Feldspar (Oligoclase).....	2...		
Sedimentary rock fragments.....	3...		
Metamorphic.....	"....."		
Muscovite.....	tr...		
Sericite.....	tr...		

CEMENT

MATRIX

... Calcite 8; Siderite 3.....
... Silica 3.....
... Argillaceous 5.....

ROCK CLASSIFICATION

Calcareous sublitharenite

Well Name :DURAL SOUTH - 1Datum :193.5 m A.S.L.

Lithology & Depth (m)	Description of Lithology, Provenance & Environment	Formation	Group	Age
36.5			Rw	TRIASSIC
	1 Siltstone interbedded with mudstone and thin coal lenses. Sedimentary provenance. Deposited in fluvial environment.	Rh		
240.7	2 Sublitharenite interbedded layers of pebbles and thin siltstone. Sedimentary provenance. Deposited in fluvial environment.		Rn	
	3 Sublitharenite interbedded with litharenite, siltstone, mudstone and claystone. Sedimentary provenance. Deposited in alternating fluvial marine environment.			
832.1	4 Sublitharenite interbedded with litharenite, carbonaceous siltstone, volcanogenic clasts and coal seams. Trace of marine fossils. Sedimentary and volcanic provenance. Deposited in fluvial and marginal marine.			PERMIAN
	5 Siltstone sandy carbonaceous with interbeds of claystone. Foraminifera fossils are common. Sedimentary provenance. Deposited in low energy marine environment.		P1	
	6 Sublitharenite, pebbly with thin siltstone interbeds. Diverse provenance. Deposited in high energy marine environment.			
	7 Siltstone, massive pyritic, sandy and pebbly. Fossils of brachiopods, corals and foraminifera are common. Sedimentary provenance. Deposited in low energy marine environment.			
1712.9	8 Sublitharenite, siliceous, calcareous and pebbly interbedded with calcareous siltstone. Fossils of brachiopods and foraminifera. Diverse provenance. Deposited in high energy marine environment.	Psb		
		Psn		
2151.8	9 Siltstone, mudstone and claystone interbedded with sublitharenite and bryozoal limestone. Diverse provenance. Deposited in high to low energy marine environments.	Psw		
2180.8				
2353.0	10 Tuff, very altered, contains siderite crystals, shards and devitrified glass. Volcanic provenance. Environment of deposition unknown.	Pssp		
2756.9		Pspb	SHOALHAVEN	
3044.9				
T.D. 3058.6	Interval under investigation			

DURAL SOUTH --1

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Petrophysical Characteristics of the NOWRA SANDSTONE

Interval 2151.8 - 2180.8 m

Datum: K.B. 194 m A.S.L.

Fig.IV-3

Datum: Rotary Table 194m A.S.L.
Contour Interval: 30m

A B Cross-sections

0 1 2 3 4 5 km

DURAL SOUTH STRUCTURE
STRUCTURE MAP ON TOP OF
NOWRA SANDSTONE

(Modified after SHELL DEVELOPMENT AUST. PTY LTD. Richmond - Cessnock Seismic Survey,)
Final Report 1966, BMR File 65/4577

Fig.IV - 4

RESISTIVITY VS POROSITY

FIG. IV-6

Dural South - 1, (2152.7-2156.7 m)

PHOTO 1: Berry Formation.

(Thin section depth 2145.7 m, crossed nicols x 250)
Calcareous (calcitic and sideritic) and pyritic siltstone
with very fine grained quartz sand.

PHOTO 2: Nowra Sandstone.

(Thin section from cuttings, depth 2185.4 - 2188.4 m, crossed
nicols x 250)

Medium grained quartz sand in a sublitharenite with patches
of calcite and argillaceous matrix. Grain boundaries distinct
to indistinct. Note quartz overgrowths.

APPENDIX V

KURRAJONG HEIGHTS-1

ESTIMATED POTENTIAL NATURAL GAS
STORAGE CAPACITY

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PLEASE NOTE

**PAGE 243, FIG. VII-2, IS TO BE
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SUMMARY

Kurrajong Heights potential natural gas storage field lies in the northwestern part of the Sydney Basin. It is located 67.5 km northwest of Sydney.

The Kurrajong Heights structure consists of a northeast-southwest trending structure high as part of the Lapstone Monocline and the Kurrajong Fault. The structure covers an area of 17.5 km^2 and has a vertical closure of 120 m.

Two potential natural gas storage reservoirs have been delineated in the arenites of Permian age: the Nowra Sandstone and the Snapper Point Formation reservoirs in the intervals 1662.7 - 1676.4 and 1887.7 - 1965.9 m respectively.

The potential natural gas storage capacity of the Kurrajong Heights reservoirs as estimated is $6276 \times 10^6 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of Kurrajong Heights-1 well have been examined for possible natural reservoirs which could be used for storage of natural gas.

Arenites of the lower Berry Formation and upper Nowra Sandstone and an interval within the Snapper Point Formation appear to have the potential of becoming natural gas storage reservoirs in conjunction with suitable porous and permeable arenites, structure and impermeable cap rocks.

Apart from literature study (A.O.G., 1962, Exoil, 1962, Pitt, 1968, Mayne et al., 1974), four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well Data

Well Name, No.:	Kurrajong Heights No. 1
Operating Companies:	Australian Oil and Gas Corporation Limited (1955) Exoil (N.S.W.) Pty Ltd (1962)
Location:	Lat. & Long.: 33°31'45"S, 150°37'15"E. 1:250 000 Sheet, Sydney SI56-5. General Location 67.5 km northwest of Sydney.
Evaluation:	Ground level: 567.9 m A.S.L. Kelly bushing: 572.7 m A.S.L. Kelly bushing datum used for determining all depths in well
Depth on 2/8/1955 (suspended):	1449.6 m

Total depth on 25/11/1962 2783.4 m (Driller)
 (abandoned): 2782.8 m (Schlumberger).

Wireline logs available

Run	Date	Type	Interval
1	3-08-1965	ES	219.4 - 991.5
1	3-08-1965	SP	219.4 - 991.5
1	3-08-1965	ES	195.6 - 698.6
1	3-08-1965	SP	195.6 - 698.6
1	3-08-1965	ML	659.5 - 2069.2
2	29-09-1962	ES	990.6 - 1440.3
2	29-09-1962	SP	990.6 - 1440.3
2	29-09-1962	ES	698.6 - 2069.8
2	21-11-1962	SP	698.6 - 2069.8
3	21-11-1962	ES	2069.8 - 2782.5
3	21-11-1962	CA	195.6 - 1440.5
3	21-11-1962	GR	6.0 - 2782.2
3	21-11-1962	TE	25.6 - 571.1

History and Stratigraphy

Kurrajong Heights-1 well was drilled in 1955 by the Australian Oil and Gas Corporation Limited to a depth of 1449.6 m. The well was suspended at this depth on 2 August 1955.

On 23 July 1962 the Australian Oil and Gas Corporation Limited resumed drilling Kurrajong Heights-1 for Exoil Company Pty Ltd. Drilling was completed on 29 September 1962 to total depth of 2783.4 m.

The well was drilled on a structural high between the Lapstone Monocline and the Kurrajong Fault to test the Permian strata in this part of the Sydney Basin.

The well spudded in the Triassic Hawkesbury Sandstone. It penetrated 222.5 m of this unit, 665.9 m of Narrabeen Group beds before entering Permian Illawarra Coal Measures at 888.4 m. It then penetrated 501.3 m of Illawarra Coal Measures and 1008.8 m of Permian Shoalhaven Group sediments before entering volcanics at 2398.7 m of Permo-Carboniferous age (Mayne, et al., 1974).

Figure V-1 shows the stratigraphic sequence encountered in Kurrajong Heights-1 well and generalised description of lithologies, provenance and environment. "Porosities in the Triassic sequence range from good to poor but measured permeabilities are generally low. Porosities in the Permian sequences are mostly slight to poor and measured permeabilities are negligible; an exception may be the coarse grained protoquartzite near the middle of the Permian marine sequence. Visual estimates of porosity in the protoquartzite range to about 10% despite the presence of some cement; estimates or determinations of permeabilities were unattainable because of lack of core, and non-definitive wireline logs" (Pitt, 1968).

PETROLOGY AND PETROPHYSICS

Nowra Sandstone Reservoir

The Nowra Sandstone reservoir includes 4.3 m of the lower Berry Formation, extends from 1662.9 - 1676.4 m and is 13.5 m thick. It is made up of very fine to very coarse silica and carbonate cemented sublitharenite containing abundant quartz, minor chert and potassium feldspar. Sedimentary, metamorphic and volcanic rock fragments are common. The latter two types show strong alteration. Table V-1 shows the grain distribution count.

Accessory minerals comprise pyrite, zircon, tourmaline and muscovite. Carbonaceous matter is rare. Traces of arenaceous foraminifera together with fragments of calcareous shells also occur. Siliceous and calcareous cement have reduced the intergranular porosity to values ranging from 9.4 to 14.2 percent (Table V-3).

The sublitharenite is interbedded with thin beds of carbonaceous siltstone and minor laminated sandy mudstone.

The upper boundary of the Nowra Sandstone reservoir is a level of textural discontinuity and to a lesser extent a change in composition. Below the boundary the arenites become more sandy although still subordinate to argillaceous lithologies. This change is accompanied by an increase in resistivity, decrease in gamma-ray counts and an indication of permeability as shown on the microlog resistivity and spontaneous potential log.

The lower boundary is marked by an increase in shale content and a return to similar lithologies and wireline log characteristics noted above the reservoir.

Poor sorting, poor bedding and the presence of broken marine fossil shells suggests that this interval was deposited below wave-base in a marine environment where bottom currents operated with varying velocities.

A dominantly sedimentary, with subordinate volcanic and metamorphic provenance is envisaged.

Snapper Point Formation Reservoir

Snapper Point Formation is 239.2 m thick in Kurrajong Heights-1 well and extends from 1889.7 - 2129.0 m. It consists almost entirely of quartz rich arenites and contains porous horizons, pebble beds and minor carbonaceous and calcareous siltstone and shale beds.

A porous and permeable interval 1889.7 - 1965.9 m (Fig. V-3) 76.2 m thick has been investigated in detail. It is made up of pebbly sublitharenite containing numerous porous horizons and is calcite, siderite and dawsonite cemented. Quartz overgrowths are rare. Kaolinite coated quartz grains are common. The framework of the sublitharenite (Core No. 24, 1950.4 - 1951.6 m) is made up of subangular to subrounded undulose quartz, minor chert and feldspars. Sedimentary and volcanic rock fragments are common (Plate V-2, Photo 1). Siderite, calcite and silica occur as cement. Patches of pyrite occur together with argillaceous matrix (Plate V-2, Photo 2). Table V-2 summarises the grain distribution count. Siderite cement and argillaceous matrix have reduced the intergranular porosity which now ranges from 4.7 to 13.7 percent (Table V-4).

In places, pebbles of quartz, chert and metaquartzite are concentrated in layers but they are also scattered throughout the interval. Core No. 24 shows some quite massive textural layering. Fossils found are large thick shelled brachiopod fragments, horizontal and vertical worm tubes and carbonized plant fragments.

The upper boundary of this unit is delineated on the basis of the distinct lithologies present, namely the massive unit of coarse grained sublitharenite. Compositionally, the unit is marked by an abundance of quartz. The change in distinct lithologies is also accompanied by the change in the pattern of wireline log. There is a distinct decrease in gamma-ray count; an increase in resistivity as well as some change on the microlog resistivity and spontaneous potential log.

CAP ROCK CHARACTERISTICS

Berry Formation

The cap rock overlying the Nowra Sandstone potential reservoir is a sequence 273.1 m thick comprising interlaminated micaceous, carbonaceous and siltstone, mudstone and very fine grained litharenite beds (Plate V-1, Photo 1). Cores Nos. 17 and 18 (1419.1 - 1421.8 m and 1448.1 - 1449.6 m) reveal laminated bedding, micro cross-bedding and, in places, a bedding surface fissility. Fossils present include plant fragments, worm tubes, foraminifera and brachiopod spines and fragments. Significant accessory minerals comprise pyrite, chlorite, calcite and siderite. The latter is mainly in the form of cement.

The wireline logs show little variation throughout the unit. Laboratory tests on the two cores show moderate porosity and no permeability. These sediments are equated to the Permian Berry Formation (Fig. V-1).

Snapper Point Formation

The cap rock overlying the Snapper Point Formation potential reservoir is a sequence 40 m thick comprising thinly interbedded fine to coarse grained litharenite, carbonaceous and micaceous siltstone with pebbles of quartz. Cores Nos. 22 and 23 (1780.3 - 1781.5 m and 1865.3 - 1866.9 m) show bedding ranging from thin to laminated, with some lithological mixing, scallop structures and micro cross-bedding. Fossils found include brachiopod fragments, horizontal and vertical worm-tubes. Important accessory minerals include chlorite and pyrite grains, and cements are mainly siderite and calcite.

Laboratory tests on core samples indicate low porosity and no permeability.

The sediments of this unit are equated with the top most interval of the Snapper Point Formation (Fig. V-1).

POROSITY

Wireline log data was used in estimation of porosities for the two potential reservoirs in Kurrajong Heights-1 well. Method 6, Chapter II, was used for calculation of porosities. The porosity ($\emptyset$) values so obtained are only approximate. The relationship $\emptyset = \sqrt{\frac{1}{F}}$ is applicable for clean sand formation rather than shaly sands of the Kurrajong Heights reservoirs. The wireline log data and summary of results for the two reservoirs are shown in Tables V-3, V-4, V-5, V-6 and V-7.

NET PAY INTERVALSBerry Formation - Nowra Sandstone Reservoir

There are 7.4 m of net pay in this interval (Fig. V-2). The net to gross pay ratio (7.4/13.5) is 0.54. Table V-3 summarises the wireline log interpretation. Combination of wireline log patterns, shale volume and porosity values were used as the base for delineation of the net pay interval.

Snapper Point Formation Reservoir

There are 28.2 m of net pay within this formation (Fig. V-3). The net to gross pay ratio (28.2/76.2) is 0.37. The 28.2 m of net pay are subdivided into five zones. Their thickness being 4.3, 11.0, 3.7, 4.9 and 4.3 m respectively (Fig. V-3, Table V-6).

As in the Berry Formation - Nowra Sandstone reservoir the net pay zones were delineated by a combination of wireline log patterns, shale volume and porosity values.

PERMEABILITY

No drill-stem tests were carried out over the two delineated potential reservoirs. BMR laboratory tests on cores in the Snapper Point Formation reservoir revealed no effective permeability (Pitt, 1968). Microlog resistivity does however indicate permeability by a continuous positive separation over the reservoir intervals.

Recent core analysis revealed permeability of 1.5 - 4.48 md. to air and less than 1.0 md. to brine (Volume I, Table 18).

STRUCTURE

Kurrajong Heights-1 well is located in the structurally high area between the Lapstone Monocline and the Kurrajong Fault. The structure contour map (Fig. V-4) on top of Nowra Sandstone is based on the structure map of the Hawkesbury Sandstone as mapped by A.O.G. in 1962 (A.O.G., 1962a).

The well was drilled within the highest closed contour. The spill point for the Nowra Sandstone reservoir is at 1670 m (Fig. V-4) and for the Snapper Point Formation reservoir at 1970 m (Fig. V-5).

The structure has a vertical closure of 60 m and covers an area of $17.5 \times 10^6 \text{ m}^2$.

RESERVOIR FLUID CHARACTERISTICS

Nowra Sandstone and Snapper Point Formation

The reservoir water resistivity (R_w) and its salinity concentration (NaCl) for the two formations have been established by the R_{mf}/SP method (Method 1, Chapter II). Because of the absence of porosity logs it was necessary to obtain the resistivity of the reservoir water for calculations of porosity and hydrostatic pressures. Tables V-5 and V-6 summarise the reservoir water characteristics.

HYDROSTATIC PRESSURE CALCULATIONBerry Formation - Nowra Sandstone Reservoir

Depth (average)	: 5460 ft (1664.2 m)
Resistivity of reservoir water	: 0.71 ohm-metre
NaCl concentration in reservoir water	: 4200 ppm
Density of NaCl solution	: 1.0044 @ 77°F (Schlumberger 1972)
Normal pressure gradient	: 0.433 psi/ft

Pressure gradient for Berry Formation - Nowra Sandstone reservoir

$$1.0044 \times 0.433$$

$$= \underline{0.4349 \text{ psi/ft}}$$

Hydrostatic pressure for the base Berry Formation - Nowra Sandstone reservoir

$$0.4349 \times 5460$$

$$= \underline{2374.5 \text{ psi}}$$

Snapper Point Formation Reservoir

Depth (average)	: 6260 ft (1908.0 m)
Resistivity of reservoir water	: 0.53 ohm-metre
NaCl concentration in reservoir water	: 5200 ppm
Density of NaCl solution	: 1.0049 @ 77°F (Schlumberger 1972)
Normal pressure gradient	: 0.433

Pressure gradient for Snapper Point Formation reservoir

$$1.0049 \times 0.433$$

$$= \underline{0.4351 \text{ psi/ft}}$$

Hydrostatic pressure for Snapper Point Formation reservoir

$$0.4351 \times 6260$$

$$= \underline{2723.9 \text{ psi}}$$

POTENTIAL NATURAL GAS STORAGE CAPACITY

The variables used in estimating the potential natural gas storage capacity are given in Table V-7. These variables were derived from various analyses and calculations presented in this Appendix.

The potential natural gas storage capacity of the combined Kurrajong Heights-1 reservoirs estimated according to the volumetric method (Method 9, Chapter II) is $6276 \times 10^6 \text{ m}^3$.

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Table V-1Grain Distribution Count

WELL NAME: Kurrajong Heights-1
 FORMATION: Nowra Sandstone
 THIN SECTION DEPTH: 1658.1 m (Cuttings sample)

Rock Components	Total Count	Percent of Rock
Quartz	87	80.55
Quartz Overgrowth	6	5.55
Chert	1	0.32
Potassium Feldspar	2	2.77
Plagioclase Feldspar	0	0.00
Sedimentary Lithics	4	3.70
Metamorphic Lithics	1	0.32
Volcanic Lithics	0	0.00
Granitic Lithics	0	0.00
Calcite	3	2.77
Siderite	4	3.70
Pyrite	0	0.00
Muscovite	0	0.00
Biotite	0	0.00
Sericite	0	0.00
Tourmaline	0	0.00
Zircon	0	0.00
Garnet	0	0.00
Carbonaceous Matter	1	0.32
	108	100.00

Table V-2Grain Distribution Count

WELL NAME: Kurrajong Heights-1
 FORMATION: Snapper Point Formation
 THIN SECTION DEPTH: 1950.4 m

Rock Components	Total Count	Percent of Rock
Quartz	306	93.56
Quartz Overgrowth	4	1.22
Chert	2	0.62
Potassium Feldspar	2	0.62
Plagioclase Feldspar	0	0.00
Sedimentary Lithics	3	0.91
Metamorphic Lithics	2	0.00
Volcanic Lithics	1	0.30
Granitic Lithics	0	0.00
Calcite	2	0.62
Siderite	2	0.62
Pyrite	0	0.00
Muscovite	0	0.00
Biotite	0	0.00
Sericite	0	0.00
Tourmaline	0	0.00
Zircon	0	0.00
Garnet	0	0.00
Carbonaceous Matter	3	0.91
	327	100.00

Table V-3

Kurrajong Heights-1: Estimate of Porosity forBerry Formation - Nowra Sandstone

(Interval 1645.9 - 1691.6 m)

Depth m	Gamma- Ray API Units	Shale Volume %	Resis- tivity AO=18'8" ohms-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1645.9	45	70	30	0.71	42	15.3
1646.5	48	80	30		42	15.3
1647.1	50	87	21		40	15.6
1647.7	49	83	28		39	15.9
1648.3	47	77	27		38	16.2
1648.9	45	70	27		38	16.2
1649.5	45	70	26		36	16.5
1650.1	45	70	27		38	16.2
1650.7	51	90	26		36	16.5
1651.5	53	96	25		35	16.8
1652.0	48	80	23		32	17.5
1652.6	45	70	23		32	17.5
1653.2	50	87	23		32	17.5
1653.8	49	83	22		30	17.9
1654.4	41	58	23		32	17.5
1655.0	37	45	25		35	16.8
1655.6	41	58	26		36	16.5
1656.2	48	80	25		35	16.8
1656.8	40	54	25		35	16.8
1657.5	37	45	30		42	15.3
1658.1	42	61	32		45	14.8

Depth m	Gamma- Ray API Units	Shale Volume %	Resis- tivity AO=18'8" ohms-m ² /m {Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1658.7	43	64	31	0.71	43	15.1
1659.3	54	1.00	28		39	15.9
1659.9	50	87	26		36	16.5
1660.5	42	61	27		38	16.2
1661.1	42	61	27		38	16.2
1661.7	35	38	28		39	15.9
1662.3	35	38	31		43	15.1
1662.9	33	32	35		49	14.2
1663.5	25	06	40		56	13.3
1664.2	25	06	44		61	12.7
1664.8	30	22	43		60	12.8
1665.4	30	22	45		63	12.5
1666.0	25	06	58		67	21.1
1666.0	23	00	60		84	10.8
1667.2	26	09	65		91	10.4
1667.8	26	09	65		91	10.4
1668.4	25	06	65		01	10.4
1669.0	25	06	70		98	10.0
1669.6	30	33	75		105	9.7
1670.3	30	33	75		105	9.7
1670.9	38	48	75		105	9.7
1671.5	38	48	70		88	10.0
1672.1	42	61	80		112	9.4
1672.7	40	54	75		105	9.7
1673.3	32	29	70		98	10.0

Depth m	Gamma Ray API Units	Shale Volume %	Resis- tivity AO=18'8" ohms-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\phi = \sqrt{\frac{1}{F}}$
1673.9	33	32	60	0.71	84	10.8
1674.5	35	38	65		91	10.4
1675.1	40	54	70		98	10.0
1675.7	36	41	60		84	10.8
1676.4	40	54	48		67	12.1
1677.0	39	51	45		63	12.5
1677.6	38	48	46		64	12.4
1678.2	38	48	40		56	13.3
1678.8	38	48	40		56	13.3
1679.4	39	51	35		49	14.2
1680.0	38	48	32		45	14.8
1680.6	40	54	38		53	13.6
1681.2	46	74	37		52	13.8
1681.8	40	54	34		47	14.4
1682.4	41	58	34		47	14.4
1683.1	42	61	30		42	15.3
1683.7	40	54	26		36	16.5
1684.3	42	61	24		33	17.1
1684.9	45	70	25		35	16.8
1685.5	44	67	26		36	16.5
1686.1	42	61	32		45	14.8
1686.7	39	51	36		50	14.0
1687.3	43	64	37		52	13.8
1687.9	42	61	40		56	13.3

Depth m	Gamma Ray API Units	Shale Volume %	Resis- tivity AO=18'8" ohms-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1688.5	43	64	42	0.71	59	13.0
1689.2	42	61	43		60	12.8
1689.8	46	74	44		61	12.7
1690.4	42	61	42		59	13.0
1691.1	43	64	41		57	13.1
1691.6	45	70	41		57	13.1

Table V-4

Kurrajong Heights-1: Estimate of Porosityfor Snapper Point Formation

(Interval 1874.5 - 1981.2 m)

Depth m	Gamma Ray API	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\phi = \sqrt{\frac{1}{F}}$
1874.5	92	68	50	0.527	94	10.2
1875.1	92	68	51		108	9.6
1875.7	90	66	57		108	9.6
1876.3	92	68	57		108	9.6
1876.9	90	66	60		113	9.3
1877.5	88	64	65		123	9.0
1878.1	100	77	70		132	8.6
1878.7	106	84	75		142	8.3
1879.3	108	86	65		123	9.0
1880.0	110	88	60		113	9.3
1880.6	102	80	55		104	9.7
1881.2	86	62	47		89	10.5
1881.8	92	68	49		92	10.3
1882.4	100	77	60		113	9.3
1883.0	98	75	60		113	9.3
1883.6	84	60	46		87	10.7
1884.2	78	53	44		83	10.9
1884.8	84	60	47		89	10.5
1885.4	78	53	57		108	9.6
1886.1	90	66	60		113	9.3
1886.7	116	95	75		142	8.3

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1887.3	102	80	70	0.527	132	8.6
1887.9	84	60	45		85	10.8
1888.5	80	55	42		79	11.2
1889.1	70	44	43		81	11.2
1889.7	64	37	43		81	11.2
1890.3	64	37	45		15	10.8
1890.9	78	53	50		94	10.2
1891.5	70	44	60		113	9.3
1892.1	58	31	50		94	10.2
1892.8	58	31	46		87	10.7
1893.4	56	28	48		91	10.4
1894.0	52	24	60		113	9.3
1894.6	50	22	70		132	8.6
1895.2	58	31	90		170	7.6
1895.8	56	28	110		208	6.9
1896.4	70	44	105		199	7.0
1897.0	62	35	110		208	6.9
1897.6	62	35	100		189	7.2
1898.2	60	33	90		170	7.6
1898.9	70	44	90		170	7.6
1899.5	62	35	100		189	7.2
1900.1	58	31	115		218	6.7
1900.7	74	48	140		265	6.1
1901.3	70	44	170		322	5.5

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\phi = \sqrt{\frac{1}{F}}$
1901.9	46	17	140	0.527	265	6.1
1902.5	60	33	100		189	7.2
1903.1	60	33	100		189	7.2
1903.7	40	11	100		189	7.2
1904.3	30	00	100		189	7.2
1905.0	40	11	100		203	6.9
1905.6	50	22	115		218	6.7
1906.2	46	17	120		227	6.6
1906.8	46	17	115		218	6.7
1907.4	60	33	115		218	6.7
1908.0	80	55	120		227	6.6
1908.6	52	24	130		246	6.3
1909.2	36	06	125		237	6.4
1909.8	40	11	140		265	6.1
1910.4	52	24	170		322	5.5
1911.0	50	22	180		341	5.4
1911.7	52	24	160		303	5.7
1912.3	62	35	140		265	6.1
1912.9	84	60	120		227	6.6
1913.5	70	44	130		246	6.3
1914.1	106	84	140		265	6.1
1914.7	100	77	140		246	6.3
1915.3	92	68	90		170	7.6
1915.9	98	75	80		151	8.1
1916.5	102	80	70		132	8.6

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1917.1	102	80	65	0.527	123	9.0
1917.8	108	86	50		94	10.2
1918.4	110	88	44		83	10.9
1919.0	110	88	42		79	11.2
1919.6	110	88	39		74	11.6
1920.2	120	100	40		75	11.4
1920.8	118	97	35		66	12.2
1921.4	66	40	28		53	13.7
1922.0	42	13	30		56	13.2
1922.6	48	20	35		66	12.2
1923.2	80	55	40		75	11.4
1923.8	82	57	45		85	10.8
1924.5	68	42	47		89	10.5
1925.1	70	44	49		82	10.3
1925.7	40	11	60		113	9.3
1926.3	50	22	65		123	9.0
1926.9	80	55	85		161	7.8
1927.5	80	55	110		208	6.9
1928.1	60	33	115		218	6.7
1928.7	60	33	110		208	6.9
1929.3	60	33	120		227	6.6
1929.9	70	44	130		246	6.3
1930.6	72	46	140		265	6.1
1931.2	66	40	130		246	6.3
1931.8	60	33	135		256	6.2
1932.4	78	54	150		284	5.9

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1933.0	78	53	170	0.527	322	5.5
1933.6	90	66	150		284	5.9
1934.2	98	75	150		294	5.9
1934.8	82	57	130		246	6.3
1935.4	52	24	120		227	6.6
1936.0	42	13	120		227	6.6
1936.6	60	33	120		227	6.6
1937.3	74	48	125		237	6.4
1937.9	60	33	130		246	6.3
1938.5	50	22	125		237	6.4
1939.1	64	37	130		246	6.3
1939.7	90	66	150		284	5.9
1940.3	60	33	170		322	5.5
1940.9	66	40	150		284	5.9
1941.5	84	60	180		341	5.4
1942.1	62	35	195		370	5.1
1942.7	50	22	185		351	5.3
1943.4	64	37	185		351	5.3
1944.0	70	44	205		388	5.0
1944.6	60	33	240		455	4.5
1945.2	50	22	230		436	4.7
1945.8	52	24	230		436	4.7
1946.4	36	06	200		379	5.1
1947.0	36	06	150		284	5.9

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=28'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1947.6	34	04	120	0.527	227	6.6
1948.2	34	04	90		170	7.6
1948.8	40	11	80		151	8.1
1949.5	60	33	80		151	8.1
1950.1	64	37	75		142	8.3
1950.7	68	42	75		142	8.3
1951.3	80	55	75		142	8.3
1951.9	80	55	70		132	8.6
1952.5	62	35	60		113	9.3
1953.1	64	37	60		113	9.3
1953.7	62	35	70		132	8.6
1954.3	56	28	80		151	8.1
1954.9	60	33	90		176	7.6
1955.5	80	55	105		199	7.0
1956.2	92	68	115		218	6.7
1956.8	90	66	115		218	6.7
1957.5	62	35	105		199	7.0
1958.0	58	31	105		199	7.0
1958.6	70	44	110		208	6.9
1959.2	80	55	120		227	6.6
1959.8	60	33	120		227	6.6
1960.4	60	33	120		227	6.6
1961.0	58	31	135		256	6.2
1961.6	52	24	150		234	5.9
1962.3	54	26	165		313	5.6

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1962.9	52	24	175	0.527	332	5.4
1963.5	58	31	200		379	5.1
1964.1	60	33	230		436	4.8
1969.7	86	62	230		436	4.8
1965.3	78	53	235		445	4.7
1965.9	74	48	200		379	5.1
1966.5	70	44	200		379	5.1
1967.1	74	48	200		379	5.1
1967.7	98	75	200		379	5.1
1968.3	80	55	195		370	5.1
1969.0	90	66	150		284	5.9
1969.6	80	55	130		246	6.3
1970.2	62	35	120		227	6.6
1970.8	60	33	110		208	6.9
1971.4	64	37	110		208	6.9
1972.0	70	44	120		227	6.6
1972.6	80	55	135		256	6.2
1973.2	76	51	155		294	5.8
1973.8	80	55	160		303	5.7
1974.4	64	37	150		284	5.9
1975.1	70	44	165		313	5.6
1975.7	68	42	180		341	5.4
1976.3	62	42	180		341	5.4
1976.9	70	44	200		379	5.1
1977.5	90	66	230		436	4.7

Depth m	Gamma Ray API Unit	Shale Volume %	Resis- tivity AO=18'8" ohm-m ² /m (Ro)	Resis- tivity (Rw) ohm-m	Formation Factor (F) $F = \frac{Ro}{Rw}$	Porosity % $\emptyset = \sqrt{\frac{1}{F}}$
1978.1	100	77	240	0.527	455	4.6
1978.7	64	37	220		417	4.8
1979.3	80	55	175		332	5.4
1979.9	102	80	200		379	5.1
1980.5	102	80	190		360	5.2
1981.2	80	55	150		284	5.9

Table V-5

Kurrajong Heights-1: Summary of wireline log interpretation
of the Berry Formation-Nowra Sandstone Reservoir

Reservoir Unit and Interval (m)	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of water (Rw) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity av. (%)
Berry Formation- Nowra Sandstone (1662.9 - 1676.4)	1662.9 - 1670.3	7.4	0.71	4200	12.2

Table V-6

Kurrajong Heights-1: Summary of wireline log interpretation
of the Snapper Point Formation Reservoir

Reservoir Unit and Interval (m)	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of Water (Rw) (ohms-m)	Resistivity Water Salinity (NaCl) (ppm)	Porosity av. (%)
Snapper Point Formation (1889.7 - 1965.9)	1892.1 - 1896.4	4.3	0.53	5200	9.4
	1901.3 - 1912.3	11.0	0.53	5200	6.4
	1935.4 - 1939.1	3.7	0.53	5200	6.4
	1944.6 - 1949.5	4.9	0.53	5200	6.1
	1959.8 - 1964.1	4.3	0.53	5200	5.7

Table V-7

Kurrajong Heights-1: Summary of Reservoirs Variables

Variables	Base of Berry Formation - Nowra Sandstone Reservoir	Snapper Point Formation Reservoir
Area m ² (ft ²)	17.5 x 10 ⁶ (188.4 x 10 ⁶)	17.5 x 10 ⁶ (188.4 x 10 ⁶)
Net pay m (ft)	7.4 (24)	28.2 (93)
Porosity %	12.2	.8
Gas Saturation % (assumed)	80.0	80.0
Reservoir Pressure (psia)	2389.23	2738.63
Reservoir Temperature °C (°F)	60 (140)	68 (155)
Standard Condition Pressure (psi)	14.73	14.73
Standard Condition Temperature °C (°F)	15.5 (60)	15.5 (60)
Gas Deviation Factor (Z)	0.887	0.890
Gas Formation Volume Factor (Bg)	122.8	176.16

PLANIMETRY RESULTS

STRUCTURE: Kurrajong Heights-1
FORMATION: Berry Formation-Nowra Sandstone
REFERENCE STRUCTURAL MAP: Figure V-4
REFERENCE STRUCTURAL CROSS-SECTION: Figure V-6
COMMENTS: Spill point at 1790 m (assumed)

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area _{m²}	Thickness m	Volume** m ³
1	1670	10	2.5 x 10 ⁶		
2	1700	18	4.5 x 10 ⁶	30	103.5 x 10 ⁶
3	1730	28	7.0 x 10 ⁶	30	171.1 x 10 ⁶
4	1760	46	11.5 x 10 ⁶	30	274.6 x 10 ⁶
5	1970	70	17.5 x 10 ⁶	30	431.9 x 10 ⁶
6				120	981.1 x 10 ⁶
7					
8					
9					
10					

* Calibration of Instrument: 4 Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

Volume = $\left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$

PLANIMETRY RESULTS

STRUCTURE: Kurrajong Heights-1
FORMATION: Snapper Point Formation
REFERENCE STRUCTURAL MAP: Figure V-5
REFERENCE STRUCTURAL CROSS-SECTION: Figure V-6
COMMENTS: Spill point at 1970m(assumed)

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area ₂ m ²	Thickness m	Volume** m ³
1	1850	10	2.5 x 10 ⁶		
2	1880	18	4.5 x 10 ⁶	30	103.5 x 10 ⁶
3	1910	28	7.0 x 10 ⁶	30	171.1 x 10 ⁶
4	1940	46	11.5 x 10 ⁶	30	274.6 x 10 ⁶
5	1970	70	17.5 x 10 ⁶	30	431.9 x 10 ⁶
6				120	981.1 x 10 ⁶
7					
8					
9					
10					

* Calibration of Instrument: Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

$$\text{Volume} = \left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$$

Table V-10Kurrajong Heights-1: Potential Natural Gas StorageCapacity

Reservoir	Total Gas Stored	
	$\times 10^6 \text{ m}^3$	$\times 10^6 \text{ ft}^3$
Berry Formation- Nowra Sandstone	1 546	54 596
Snapper Point Formation	4 730	167 038
Total	6 276	221 635

Thin Section Description

THIN SECTION DESCRIPTION

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WELL NAME : KURRAJONG HEIGHTS-1

ROCK UNIT : BERRY FORMATION

DEPTH INTERVAL: 1389.8-1667.2 m B.K.

CORE DEPTH : 1626.7-1629.1 m B.K.B.

THIN SECTION DEPTH: 1627.6 m B.K.B.

MACROSCOPIC DESCRIPTION

Light grey, poorly to moderately sorted, very fine to coarse grained, carbonaceous and siltic silty sandstone. Laminated bedding and scallop structures throughout. Rare fine pebbles.

MICROSCOPIC DESCRIPTION

Very fine to medium, angular to subangular poorly to moderately sorted quartz grains with chert, feldspar and rock fragments. Metamorphic and volcanic rock fragments are strongly altered. Framework is siltic cemented. The matrix is mainly of sericite clay and calcareous and carbonaceous argillate. Traces of arenaceous foraminifera. Trace of dolomite rhombs occurs in association with volcanic rock fragments. Pyrite occurs throughout the rock.

POROSITY No visible porosity was established.....

<u>FRAMEWORK</u>	<u>%</u>
Quartz.....	40
Chert.....	2
Feldspar Undiff.....	6
Sedimentary Rock Fragments.....	10
Metamorphic.....	3
Volcanic.....	6

<u>ACCESSORIES</u>	<u>%</u>
? Dolomite.....	tr
Pyrite.....	tr
Muscovite.....	tr
Sericite.....	2
Carbonaceous Matter.....	1
Tourmaline.....	tr
Zircon.....	tr

CEMENT

Siderite.....	20
---------------	----

MATRIX

Sericite clay.....	8
Argillaceous.....	2

ROCK CLASSIFICATION

Litharenite

WELL NAME : KURRAJONG HEIGHTS-1

ROCK UNIT : NOWRA SANDSTONE

CORE DEPTH : CUTTINGS SAMPLE

DEPTH INTERVAL: 1662.9-1676.4 m B.K.B.

THIN SECTION DEPTH: 1658.1 m B.K.B.

MACROSCOPIC DESCRIPTION

Light grey to brown, poorly sorted, very fine to coarse grained sandstone with pebbles of quartz. Trace of mica and pyrite.

MICROSCOPIC DESCRIPTION

Very fine to very coarse, subangular, poorly sorted, undulose to composite quartz grains, rare chert and feldspar. Quartz grains show strong pressure welding. Grain contacts are indistinct to distinct. Rock fragments of sedimentary, volcanic and metamorphic source are common. The latter two types are strongly altered. Framework is silico and carbonate cemented. The matrix is subordinate and made up of micaceous matter. Few arenaceous foraminifera together with fragments of calcareous shells also occur. Pyrite patches are common.

POROSITY ..No visible porosity was established.

<u>FRAMEWORK</u>	%
Quartz	70
Chert	2
Potassium Feldspar	2
Sedimentary Rock Fragments	4
Volcanic "	2
Metamorphic "	2

<u>ACCESSORIES</u>	%
Pyrite	tr
Zircon	tr
Tourmaline	tr
Carbonaceous Matter	1
Muscovite	tr

CEMENT

Silica	8
Calcite & Siderite	4

MATRIX

Argillaceous	5
--------------------	---

ROCK CLASSIFICATION

Sublitharenite

WELL NAME : KURRAJONG HEIGHTS-1

ROCK UNIT :WANDRAWANDIAN SILTSTONE

DEPTH INTERVAL: 1676.4-1889.7 m B.K.B.

CORE DEPTH : 1865.3-1866.9 m B.K.B.

THIN SECTION DEPTH: 1866.0 m B.K.B.

MACROSCOPIC DESCRIPTION

Dark grey, micaceous, sideritic sandy, slightly pebbly siltstone. Fragments of brachiopods and carbonaceous matter occur throughout the core sample. Disturbed finely laminated bedding.

MICROSCOPIC DESCRIPTION

Sideritic, sandy coarse sized siltstone with rounded to subangular quartz grains. Feldspars are undifferentiated. Metamorphic and volcanic rock fragments are strongly altered, mainly chloritized. Sedimentary rock fragments are of carbonaceous mudstone pellets. Calcareous fossil fragments are common.

POROSITY ...No visible porosity was established.....

<u>FRAMEWORK</u>	<u>%</u>
Quartz.(silt.sized).....	20.....
Quartz.(sand.sized).....	15.....
Feldspar.(silt-sized)....	4.....
Volcanic rock fragments	10.....
Sedimentary."....."	3.....
Metamorphic."....."	5.....

<u>ACCESSORIES</u>	<u>%</u>
Pyrite.....	tr.....
Sericite.....	tr.....
Muscovite.....	tr.....
Zircon.....	tr.....
Tourmaline.....	tr.....

<u>CEMENT</u>	
Siderite.....	15.....
Calcite.....	3.....

<u>MATRIX</u>	
Argillaceous.....	25.....

ROCK CLASSIFICATION

Sideritic sandy siltstone.

WELL NAME : KURRAJONG HEIGHTS-1

ROCK UNIT : SNAPPER POINT FM.

CORE DEPTH : 1950.4-1951.6 m B.K.B.

DEPTH INTERVAL: 1889.7-2129.0 m B.K.

THIN SECTION DEPTH: 1950.4 m B.K.B.

MACROSCOPIC DESCRIPTION

Pale grey, calcareous, poorly sorted, silty in parts quartz rich arenite.

Large calcareous fossils fragments occur throughout. Massive crude bedding.

MICROSCOPIC DESCRIPTION

Fine to very coarse grained, angular to subangular, poorly sorted, quartz sand with occasional feldspars and chert grains. Rock fragments (sedimentary volcanic and metamorphic) are common. Strong pressure welding is evident from some quartz fragments, together with quartz overgrowths. The framework is calcite, siderite and silica cemented. Matrix is of chloritic silt and clay. Fossil fragments appear to be thick shelled brachiopods. Dawsonite occurs in fibrous patches.

POROSITY ..No visible porosity was established.....

<u>FRAMEWORK</u>	%
Quartz.....	61.....
Chert.....	2.....
Potassium Feldspar.....	3.....
Volcanic Rock fragments.....	3.....
Metamorphic " ".....	4.....
Sedimentary " ".....	4.....
Carbonaceous matter.....	3.....

<u>ACCESSORIES</u>	%
Pyrite.....	tr.....
Dawsonite.....	1.....
Muscovite.....	tr.....
Zircon.....	tr.....
Tourmaline.....	tr.....
Rutile.....	tr.....

CEMENT

..Calcite...3.....
 ..Siderite 3, ..Silica 5.....

MATRIX

..Argillaceous...8.....

ROCK CLASSIFICATION

Calcareous sublitharenite.

(after MAYNE et al. 1974)

Well Name : KURRAJONG HEIGHTS-1

Datum : 572.7m.....A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age
222.5	Sublitharenite, interbedded with mudstone, claystone multicoloured siltstone. Sedimentary provenance, deposition in fluvial environment.	Rh		
888.4	Sublitharenite and litharenite interbedded with multicoloured claystone and siltstone beds. Massively bedded, cross-stratification throughout. Sedimentary provenance. Fluvial environment of deposition. Traces of glauconite suggest some marine influence.		Rn	
1389.8	Sublitharenite and subarkose, sideritic and clayey interbedded with calcareous and carbonaceous mudstone and sandy siltstone. Coal seams occur near the base of the interval. Sedimentary provenance. Deposition in fluvial environments.			
1667.2	Siltstone, sideritic micaceous, pyritic and carbonaceous interbedded with mudstone and fine grained litharenites. Fossil fragments of plants, foraminifera and brachiopods are common. Diverse provenance. Deposited in marine environments.		PI	
1667.2	Sublitharenite, siderite, calcite and silica cemented. Fossil fragment of foraminifera and broken shells occur. Diverse provenance. Deposited in marine environment.	Psb		
1889.7	Carbonaceous and calcareous siltstone and mudstone beds interbedded with fine grained litharenite. Occasional pebble beds. Fossil fragment of foraminifera, and brachiopods occurs. Dominantly sedimentary provenance. Deposition in low energy marine environments.	Psn Psw	SHOALHAVEN	
2363.7	Sublitharenite, silica, siderite and dawsonite cemented, interbedded with minor shale and siltstone beds. Pebbles of quartz and sedimentary, volcanic and metamorphic rocks. Brachiopod and Bryozoa fragments are common. Diverse provenance. Deposition in marine environment.	Pssp		
2398.7		Psw Pdal		
T.D.2783.4				

TRIASSIC

PERMIAN

Interval under investigation

KURRAJONG HEIGHTS-I

Petrophysical Characteristics of the BERRY FORMATION & NOWRA SANDSTONE

Interval 1662.9 - 1676.4m Datum K.B. 572.7m A.S.L.

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Fig.V -2

Petrophysical Characteristics of the Permeable Interval 1889.7-1965.9 m
within the SNAPPER POINT FORMATION

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Fig.V -3

Datum K.B. 572.7m A.S.L.

KURRAJONG HEIGHTS-I

STRUCTURE MAP ON TOP OF NOWRA SANDSTONE

Datum: Kelly Bushing 572.7 A.S.L.

Contour Interval: 30m

A B
|-----| Cross-Sections

(Modified after A.O.G. Sydney Basin Seismic Survey
final report 1962a BMR File 62/1546)

KURRAJONG HEIGHTS-I

STRUCTURE MAP ON TOP OF SNAPPER POINT FORMATION

Datum: Kelly Bushing 572.7 A.S.L.

Contour Interval: 30m

A B
Cross-Sections

0 4 8 12 16 20km

(Modified after A.O.G. Sydney Basin Seismic Survey
final report 1962a BMR File 62/1546)

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PHOTO 1: Berry Formation.

(Thin section depth 1627.6 m, crossed nicols x 100)
Siderite cemented silty, fine grained litharenite.

PHOTO 2: Nowra Sandstone

(Thin section depth 1658.1 m, crossed nicols x 100)
Bimodal quartz grains in sublitharenite. Large quartz fragments show outline of original grain boundaries. Volcanic and sedimentary rock fragments in the lower left and right corner.

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PHOTO 1: Wandrawandian Siltstone

(Thin section depth 1865.3 m, crossed nicols x 150).
Sideritic sandy siltstone with abundant volcanic and
metamorphic rock fragments.

PHOTO 2: Snapper Point Formation.

(Thin section depth 1950.4 m, crossed nicols x 150)
Fine to very coarse grained, pressure welded sublitharenite
with patches of volcanic and sedimentary rock fragments.
Note the large quartz fragments showing outline of the
original grains.

APPENDIX VI

MULGOA-2

ESTIMATED POTENTIAL NATURAL

GAS STORAGE CAPACITY

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- VI - 1 - Mulgoa-2: Photomicrograph Nowra Sandstone

SUMMARY

Mulgoa potential natural gas storage field lies in the western part of the Sydney Basin. It is located 56 km west of Sydney, N.S.W.

The Mulgoa structure is a north-south trending faulted anticline. The structure covers an area of 8.1 km^2 and has a vertical closure of 60 m to the spill point level.

A potential natural gas storage reservoir has been delineated in the Nowra Sandstone in the interval 1502.6 - 1531.3 m.

The potential natural gas storage capacity of Mulgoa reservoir as estimated is $0.92 \times 10^9 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of Mulgoa-2 well, have been examined for possible natural reservoirs which could be used for storage of natural gas. Mulgoa-1 well drilled in 1935 was abandoned in the Illawarra Coal Measures.

Arenites of the Nowra Sandstone appear to have the potential of becoming a natural gas storage reservoir in other wells studied. Since wireline logs are not available nor is there sufficient core material available for detailed study, it is assumed that the characteristics of the Nowra Sandstone intersected in Mulgoa-2 well are much the same as in other wells.

Apart from literature study, (A.O.G. 1960, Mayne et al., 1974) four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well Data

Well Name, No.:	Mulgoa-2
Operating Co.:	Australian Oil and Gas Corporation Limited
Location:	Lat. & Long.: 33°43'S, 150°38'E General Location: 56 km west of Sydney, NSW.
Elevations:	Floor Level: 152.7 m A.S.L. (datum for well) Ground Level: 151.4 m A.S.L.
Total Depth:	1716.0 m

Wireline Logs Available

None.

History and Stratigraphy

The Mulgoa-2 well was drilled in 1958/59 by the Australian Oil and Gas Corporation Limited to test the Permian marine sediments at the western margin of Sydney Basin.

The well was spudded in Triassic Wianamatta Group. It penetrated 21.3 m of this unit, 237.7 m of Hawkesbury Sandstone and 502.3 m of Narrabeen Group before entering Permian sediments at 761.3 m. It then penetrated 412.1 m of Permian Illawarra Coal Measures and 542.5 m of Permian Shoalhaven Group sediments.

Figure VI-1 shows the stratigraphic sequence encountered in Mulgoa-2 well and generalised description of lithologies, provenance and environment.

In Mulgoa-2: "Many natural gas horizons were encountered throughout the Triassic and Permian beds but none proved to be commercial" (A.O.G., 1960). Traces of natural gas were also encountered in the Nowra Sandstone interval.

PETROLOGY AND PETROPHYSICS OF THE NOWRA SANDSTONE

The Nowra Sandstone in Mulgoa-2 well extends from 1502.6 - 1531.3 m and is 28.7 m thick. It is made up of siliceous, partly calcareous sub-litharenite containing quartz, minor chert, potassium feldspar, metamorphic and sedimentary rock fragments together with pebbles of quartz (Table VI-1). Accessory minerals are muscovite, sericite and trace of pyrite. Calcite and siderite are common (Plate VI, Photo 1 and 2). The dominant cement is siliceous in the form of quartz overgrowths.

The upper boundary of the Nowra Sandstone (based on drill cuttings) is marked by a change in lithology from a fine grained sandy siltstone to medium and coarse grained quartz rich sub-litharenite in part conglomeratic. The lower boundary (based on drill cuttings) is marked by change in lithology from the medium and coarse grained conglomeratic arenite to medium grained sandy siltstone.

The high amount of quartz, poor sorting and irregular bedding (Core interval 1522.0 - 1524.0 m) suggests that this unit was deposited in agitated water. Detrital components point to a granitic source with some metamorphic and sedimentary rock influence.

CAP ROCK CHARACTERISTICS (Berry Formation)

The cap rock overlying the Nowra Sandstone potential reservoir is a sequence 502.5 m thick comprising sandy siltstone. The siltstone beds are carbonaceous and calcareous. A few very thin limestone beds occur (A.O.G., 1960). "Below 1232.9 m a marked increase in the amount of mica in the sediment has been noted. This falls into line with observed lithology of other deep wells in the basin where marked increases in mica content of the sediments have occurred a short interval above foraminiferal strata" (A.O.G., 1960).

No core and drill cuttings are available from this interval, hence no petrological examination could be carried out.

POROSITY AND PERMEABILITY

As no wireline logging or systematic core analyses were carried out it is difficult to make any estimate of porosity and permeability of the sediments intersected in this well.

Microscopic examinations of small amounts of core material available (Table VI-1) showed poor porosity. Core interval 1521.8 - 1524.0 m recovered only 1.4 m of core. Table VI-1 summarises the core recovery in the Nowra Sandstone interval and the BMR laboratory core analyses results. The average porosity as measured by BMR is 9.7 percent and the permeability of 5 millidarcies. Recent core analysis (Volume I, Table 18) revealed permeability of 1.0 to 4.2 md to air and 1.0 md to brine.

NET PAY INTERVAL

Because of absence of wireline logs and core material no definite net pay zones were able to be established in Mulgoa-2 well. However core material from the interval 1522.0 - 1524 m (Table VI-2) indicates porosities ranging from 8.6 to 10.5 percent and one segment of core revealed measured permeability of 5 millidarcies. It is therefore taken in this study that this interval will be regarded as the net pay zone of 10.00 m in the Nowra Sandstone.

STRUCTURE

Mulgoa-2 well was drilled on a small anticline which is part of the regional Lapstone Monocline. The structure as shown in Figure VI-2 is based on surface mapping of the Wianamatta Group (A.O.G., 1960). The spill point for the Nowra Sandstone is at 1500 m (Figs. VI-3 and VI-4). The structure has a vertical closure of 60 m (to the lowest closed contour) and covers an area of 8.1 km².

RESERVOIR FLUID CHARACTERISTICS

The resistivity of the formation water and its salinity for the Nowra Sandstone was unable to be estimated because of poor drill stem test recoveries and lack of wireline logs. The NaCl concentration was therefore assumed to be the same as in the Nowra Sandstone in Kurrajong Heights-1 well i.e. 5200 ppm (Appendix V).

HYDROSTATIC PRESSURE CALCULATIONNowra Sandstone

Depth (average)	5020 ft (1530.0 m)
Resistivity of reservoir water	0.6 ohm-m
NaCl concentration	5200 ppm
Density of NaCl solution	1.0044 @ 77°F (Schlumberger 1972)
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Nowra Sandstone reservoir

$$1.0044 \times 0.433$$

$$= \underline{\underline{0.4349 \text{ psi/ft}}}$$

Hydrostatic pressure for the Nowra Sandstone reservoir

$$0.4349 \times 5020$$

$$= \underline{\underline{2182 \text{ psi}}}$$

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the Mulgoa-2 reservoir was estimated according to volumetric method (Method 9, Chapter II).

The variables used in estimating the potential natural gas storage capacity are given in Table VI-5. These variables were derived from various analyses and calculations presented in this Appendix.

Table VI-6 summarises the results of the potential natural gas storage as estimated by the volumetric method for the Mulgoa-2 reservoir.

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- MAYNE, S.J., NICHOLAS, E., BIGG-WITHER, A.L., RASIDI, J.S., and RAINE, M.J., 1974 - Geology of the Sydney Basin - A Review. Bur. Miner. Resour. Aust. Bull. 149.

Table VI-1Grain Distribution Count

WELL NAME: Mulgoa-2
 FORMATION: Nowra Sandstone
 THIN SECTION DEPTH: 1523.6 m

Rock Components	Total Count	Percent of Rock
Quartz	260	88.1
Quartz Overgrowth	5	1.8
Chert	1	0.4
Potassium Feldspar	1	0.4
Plagioclase Feldspar	0	0.0
Sedimentary Lithics	5	1.8
Metamorphic Lithics	1	0.4
Volcanic Lithics	1	0.4
Granitic Lithics	0	0.0
Calcite	5	1.8
Siderite	3	0.9
Pyrite	1	0.4
Muscovite	2	0.7
Biotite	0	0.0
Sericite	0	0.0
Tourmaline	0	0.0
Zircon	0	0.0
Garnet	0	0.0
Carbonaceous Matter	0	0.0
Argillaceous Matrix	10	2.9
	295	100.0

Table VI-2Mulgoa-2: Measured Porosity and Permeability of theNowra Sandstone, Core Interval 1522.0 - 1524.0 m

(BMR Core Analysis)

Core Intervals (m)	Recovery (m)	Porosity %	Permeability	
			Horizontal (md)	Vertical (md)
1522.0 - 1522.4	0.4	9.4	N/D	N/D
1522.5 - 1522.8	0.3	10.5	N/D	N/D
1523.9 - 1523.4	0.4	8.6	N/D	N/D
1523.6 - 1523.7	0.1	9.8	5	0
1523.8 - 1524.0	0.2	10.3	N/D	N/D

N/D = Not determined

Table VI-3

Mulgoa-2: Summary of net pay interval interpretation of the Nowra Sandstone

Reservoir Unit and Interval (m)	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of water (R _w) (ohms-m)	Reservoir Water Salinity (NaCl) (ppm)	Porosity (%)
Nowra Sandstone 1502.6 - 1531.3	1518.0 - 1528.0	10	0.6	5200	9.7

PLANIMETRY RESULTS

STRUCTURE: Mulgoa-2
FORMATION: Nowra Sandstone
REFERENCE STRUCTURAL MAP: Figure 3
REFERENCE STRUCTURAL CROSS-SECTION: Figures 4 and 5
COMMENTS: Spill point (assumed) at 1500 m

Unit No.	Contour Depth m	Planimetry* Units	Planimetered Area _{m²}	Thickness m	Volume** m ³
1	1440	48	2.7 x 10 ⁶		
2	1470	88	5.4 x 10 ⁶	30	119.2 x 10 ⁶
3	1500	145	8.1 x 10 ⁶	30	201.1 x 10 ⁶
4				60	320.3
5					
6					
7					
8					
9					
10					

* Calibration of Instrument: 18. Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

Volume = $\left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$

Table VI-5Mulgoa-2: Summary of Reservoir Variables

Reservoir	Nowra Sandstone
Area m ² (ft ²)	8.1 x 10 ⁶ (3.1 x 10 ⁶)
Net Pay m (ft)	10 (33)
Porosity %	9.7
Gas Saturation % (assumed)	80.0
Reservoir Pressure (psia)	2197.7
Reservoir Temperature °C (°F)	55.5 (132)
Standard Condition Pressure (psi)	14.73
Standard Condition Temperature °C (°F)	15.5 (60)
Gas Deviation Factor (Z)	0.898
Gas Formation Volume Factor (B _g)	145.89

Table VI-6Mulgoa-2: Potential Natural Gas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^9 \text{ m}^3$	$\times 10^9 \text{ ft}^3$
Nowra Sandstone	0.92	32.6

WELL NAME : Mulgoa-2
ROCK UNIT : Nowra Sandstone DEPTH INTERVAL: 1502.6-1531.5 m B.F.L.
CORE DEPTH : 1522.0-1524.0 m B.F.L. THIN SECTION DEPTH: 1523.8-1524.0 m B.F.L.

MACROSCOPIC DESCRIPTION

Light grey, moderately sorted quartz arenite with coarse grains and occasional pebbles of quartz. Traces of calcareous shell fragments.

MICROSCOPIC DESCRIPTION

Medium to very coarse grained moderately sorted quartz rich arenite with chert and feldspar grains. Sedimentary and metamorphic rock fragments are common. The framework is silica, siderite and minor calcite cemented. Matrix is subordinate, commonly sideritic.

POROSITY ..No visible porosity was established.....

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	65	Muscovite.....	tr
Chert.....	3	Chert.....	2
Feldspar.....	2	Siderite.....	2
Sedimentary Rock.....		Calcite.....	tr
Fragments.....	5	Pyrite.....	tr
Metamorphic Rock.....			
Fragments.....	3		

CEMENT

...Silica..4.....
...Siderite 6 Calcite 2....

MATRIX

...Argillaceous.....5
.....

ROCK CLASSIFICATION

Sublitharenite

Well Name : MULGOA - 2Datum : 152.7 m A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age
21.3	A - Siltstone and mudstone. Sedimentary provenance. Fluvial environment.		Ru	TRIASSIC
259.0	1 Sublitharenite, conglomeratic in parts, interbedded with thin beds of mudstone and shale. Sedimentary provenance. Deposition in fluvial environment.	Rh		
	2 Litharenites, conglomeratic towards the base, interbedded with siltstone and multicoloured claystone. Sedimentary provenance. Deposition in fluvial and low energy marine environment.		Rn	
761.3	3 Siltstone, litharenite beds with coal seams. Sedimentary provenance. Deposition in fluvial environment.		P1	PERMIAN
1173.4	4 Siltstone, shale beds, carbonaceous and sandy. Thin beds of limestone and lenses of coal occur. Marine fossils are common. Diverse provenance. Deposition in low energy marine environments.	Psb		
1502.6	5 Sublitharenite, siliceous, conglomeratic interbedded with thin siltstone beds. Marine fossils are common. Diverse provenance. Deposition in high energy marine environment.	Psn		
1531.3	6 Siltstone and mudstone beds, interbedded with litharenite. Some pebble layers occur. Trace of marine fossils. Sedimentary and volcanic provenance. Deposition in low energy marine environment.	Psw		
1716.0

Interval under investigation

MULGOA STRUCTURE

STRUCTURE MAP ON TOP OF NOWRA SANDSTONE

(Modified after A.O.G. , Mulgoa -2 , Well Completion
Report 1962 , BMR File 62/1024)

Fig. VI -3

MULGOA STRUCTURE
WEST - EAST STRUCTURAL CROSS - SECTION

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PHOTO 1: Nowra Sandstone.

(Thin section depth 1523.8 - 1524.0 m, crossed nicols x 100)
Bimodal sublitharenite, with metamorphic quartz showing
irregular grain contacts.

PHOTO 2: Nowra Sandstone.

(Thin section depth 1523.8 - 1524.0 m, crossed nicols x 100)
Siderite cement filling primary pores. Note large chert
fragment in the upper right side. Calcite crystal in the
lower right corner.

APPENDIX VII

EAST MAITLAND-1

ESTIMATED POTENTIAL NATURAL

GAS STORAGE CAPACITY

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SUMMARY

East Maitland potential natural gas storage field lies in the northern part of the Sydney Basin. It is located 1.6 km east of East Maitland township, N.S.W.

The East Maitland structure is a gentle northeast-southwest faulted anticline. The structure covers an area of $19.1 \times 10^6 \text{ m}^2$ and has a vertical closure of 225 m to the spill point level.

A potential natural gas storage reservoir has been delineated in the Muree Sandstone in the interval 586.4 to 768.0 m.

The potential natural gas storage capacity of East Maitland reservoir as estimated is $4.98 \times 10^9 \text{ m}^3$.

INTRODUCTION

Sediments penetrated by the drilling of East Maitland-1 well, have been examined for possible natural reservoirs which could be used for storage of natural gas.

Arenites of the Muree Sandstone appear to have the potential of becoming a natural gas storage reservoir in conjunction with suitable porous and permeable arenites, structure and an impermeable cap rock.

Apart from literature study, (Planet Oil Co. Pty Ltd 1962, 1963; Jensen & Bryan 1969, Mayne et al., 1974) four main approaches were made to analyse the suitability for potential natural gas storage reservoirs - petrology, petrophysics, structural analysis and reservoir engineering.

GENERAL INFORMATION

Well Data

Well Name, No.:	East Maitland No. 1
Operating Company:	Planet Oil Company Pty Ltd
Location:	Lat. & Long.: 32°45'47"S, 151°37'05"E. 1:250 000 sheet: Newcastle, SI/56/2. General location: 1.6 km east of East Maitland, NSW
Date drilled:	22 October 1962 - 2 May 1963
Elevation:	Kelly Bushing (K.B.): 9.3 m A.S.L. (Datum for all depths in well) Ground: 4.6 m A.S.L.
Total depth:	Schlumberger: 3045.8 m Driller: 3049.2 m

Wireline Logs Available

Run	Date	Type	Interval m
1	28-10-1962	ES	30.4 - 201.1
2	2-12-1962	ES	201.1 - 906.1
3	6-01-1963	ES	906.1 - 1517.9
4	6-01-1963	ES	1517.5 - 1995.8
5	2-03-1963	ES	1998.8 - 2353.9
6	9-04-1963	ES	2353.5 - 3045.5
1	2-12-1962	MCL	197.5 - 894.5
2	6-01-1963	MCL	895.1 - 1516.9
3	6-02-1963	MCL	1516.9 - 1995.2
4	3-03-1963	MCL	1995.2 - 2253.9
5	9-04-1963	MCL	2353.9 - 2828.5
6	28-04-1963	MCL	2828.5 - 3045.5
1	29-04-1963	GR	30.4 - 3044.0
1	28-10-1962	ITT	20.7 - 200.5
2	2-12-1962	ITT	200.5 - 894.2
3	6-02-1963	ITT	894.5 - 1734.3
4	28-04-1963	ITT	1734.3 - 3044.6

History and Stratigraphy

The East Maitland-1 well was drilled in 1962/63 by the Planet Oil Company Pty Ltd to test the marine sediment of Permian age in the northern part of the Sydney Basin.

The well spudded near the base of Permian Tomago Coal Measures which continued to 57.9 m. Underlying the coal measures, the Maitland Group (Upper Marine) extended to 1417 m. This in turn was underlain by the Greta Coal Measures to 1460.9 m and then the Dalwood Group, continued to Total Depth (3045.8 m). However, below 1898.5 m tuffs and minor basaltic flows were encountered.

Figure VII-1 shows the stratigraphic sequence encountered in East Maitland-1 and generalised description of lithologies, provenance and environment. No significant hydrocarbon shows were detected (Planet, 1963).

PETROLOGY AND PETROPHYSICS OF THE MUREE SANDSTONE

The Muree Sandstone in the East Maitland-1 well extends from 586.4 to 768.0 m and is 181.6 m thick. It is made up of medium to coarse grained, poorly to moderately sorted, angular to subangular siliceous and calcareous sublitharenite. The framework of sublitharenite consists of quartz, chert, weathered potassium feldspars, sedimentary, metamorphic and basic volcanic rock fragments together with quartz and chert pebbles. Accessory minerals are muscovite, pyrite and rare tourmaline. Table VII-1 summarises the grain distribution.

Quartz grains commonly show strong interlocking fabrics. A vertical pinnate fracture is noted in Core No. 6 (Plate VII-2, Photos 1 and 2).

The framework is silica, calcite, siderite and dawsonite cemented. Matrix is made up of argillaceous matter and minor colourless clay.

Cementing minerals and pressure welding of quartz grains have reduced the intergranular porosity to values ranging from 1.0 to 13.8 percent (Table VII-2).

The sublitharenite is interbedded with thin beds of carbonaceous, calcareous, sandy and pebbly mudstone and siltstone. Marine fossil fragments are common throughout the unit.

The upper boundary of this interval is placed at 586.4 m, below which there is a noted decrease in shale content as seen on the gamma ray log and a definite indication of permeability as indicated on the microlog resistivity (Fig. VII-2). The change is also marked in lithology from sandy siltstone to medium grained, clean sublitharenite.

The lower boundary is marked by a change from sublitharenite to siltstone and litharenite beds of the underlying unit. This change is noted on the spontaneous potential gamma ray and interval transit time logs and in particular the increase in shale volume at 768.0 m.

Marine fossil fragments, abundance of quartz and poor sorting suggest that this unit was deposited in high energy marine conditions. Detrital components point to a sedimentary, metamorphic and minor volcanic provenance.

CAP ROCK CHARACTERISTICS (Branxton Formation)

The cap rock overlying the potential Muree Sandstone reservoir is a very uniform sequence 528.5 m thick comprising siltstone, sandy siltstone and in places fine sandstone (Plate VII-I, Photo 1).

The sediments of this interval are pyritic, carbonaceous and micaceous; brachiopod, bryozoan and coral fragments are found within the interval. Scallop structures were also seen in Core No. 5 from the lower part of the interval at 458.0 - 561.1 m. Laboratory tests on the plugs taken from the core showed low porosity and no permeability was detected.

POROSITY (Muree Sandstone)

Wireline log data was used in estimation of porosities for the Muree Sandstone reservoir. The porosity estimation was made by the interval transit time (sonic log) log method (Method 7, Chapter II).

A matrix interval transit time of 167.9 microseconds/metre was used in the acoustic velocity-porosity calculations. All the porosity values were corrected for shale volume. The porosities so determined are only approximate since only two core porosity values (6.0% Core No. 6, 610.5 - 612.0 m and 3.5% Core No. 7, 690.0 - 691.8 m) were available for log calibration.

Wireline log data and the summary of results for the potential reservoir are shown in Tables VII-2 and VII-3.

NET PAY INTERVALS

There are 70.2 m of net pay in this formation. The net to gross pay ratio (70.2/181.6) is 0.38.

The 70.2 m of net pay are subdivided into five zones. Their thicknesses are 15.3, 9.1, 9.2, 24.7 and 9.2 m respectively. (Fig. VII-2, Table VII-3). Gamma-ray and microlog resistivity patterns together with evaluation of shale volume and porosity were used for delineation of these zones.

PERMEABILITY

No drill stem testing was carried out over this interval in East Maitland-1 well.

Recent laboratory tests on Core No. 6, 610.2 - 611.4 m from Muree Sandstone indicate permeability of 3.12 to 15.04 to air and 1.0 to 6.0 md to brine (Volume I, Table 18).

Microlog resistivity and spontaneous potential logs show moderately permeable intervals within the Muree Sandstone (Fig. VII-2).

STRUCTURE

East Maitland-1 well was drilled on the highest closed contour on a gentle northeast-southwest folded anticline. The northeastern side of the anticline is faulted by a high angle fault (Figs. VII-4 and VII-5).

Structure map on top of Muree Sandstone (Fig. VII-3) is based on the Reflection Seismic Control Map of horizon "A" of the Newcastle Area as depicted by Planet Exploration Company Pty Ltd, 1962. It is assumed that the overlying Muree Sandstone Member horizon conforms with the underlying structural expression of the mapped horizon 'A'. The spill point for the Muree Sandstone Member is inferred to be at 810 m (Figs. VII-4 and VII-5).

RESERVOIR FLUID CHARACTERISTICS

No drill stem testing was carried out over the Muree Sandstone interval. The resistivity of the formation water and its salinity was established by the porosity (ϕ Δt) - resistivity (Rt) cross-plot method (Method 2, Chapter II). Porosity (Rt) reading taken over the interval 588.2 to 624.8 m (Table VII-4) are plotted against the resistivity (Rt) readings (Fig. VII-6) over the same interval. Table VII-3 also summarises the results of this method.

POTENTIAL NATURAL GAS STORAGE CAPACITY

The potential natural gas storage capacity of the East Maitland-1 reservoir was estimated according to volumetric method (Method 9, Chapter II).

The variables used in estimating the potential natural gas storage capacity are given in Table VII-6. These variables were derived from various analyses and calculations presented in this Appendix.

All five porous zones totalling 70.2 m of net pay have been included into final storage capacity estimate. Table VII-7 summarises the results of the potential natural gas storage as estimated by the volumetric method for the East Maitland-1 reservoir.

HYDROSTATIC PRESSURE CALCULATIONMuree Sandstone

Depth (average)	2330 ft (710.1 m)
Resistivity of reservoir water	0.58 ohm-metre
NaCl concentration in reservoir water	7000 ppm @ 95°F
Density of NaCl solution	1.006 @ 70° (Schlumberger 1972)
Normal pressure gradient	0.433 psi/ft

Pressure gradient for Muree Sandstone reservoir

$$1.006 \times 0.433$$

$$= \underline{\underline{0.4355 \text{ psi/ft}}}$$

Hydrostatic pressure for Muree Sandstone reservoir

$$0.4335 \times 2330$$

$$= \underline{\underline{1014.7 \text{ psi}}}$$

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Table VII-1Grain Distribution Count

WELL NAME: East Maitland-1

FORMATION: Muree Sandstone

THIN SECTION DEPTH: 610.2 m

Rock Components	Total Count	Percent of Rock
Quartz	160	80.40
Quartz Overgrowth	2	1.00
Chert	1	0.50
Potassium Feldspar	2	1.00
Plagioclase Feldspar	1	0.50
Sedimentary Lithics	1	0.50
Metamorphic Lithics	2	1.00
Volcanic Lithics	1	0.50
Granitic Lithics	0	0.00
Calcite	3	1.55
Siderite	2	1.00
Pyrite	1	0.50
Muscovite	0	0.00
Biotite	0	0.00
Dawsonite	2	1.00
Tourmaline	0	0.00
Zircon	0	0.00
Garnet	0	0.00
Carbonaceous Matter	1	0.50
Argillaceous Matrix	20	10.05
	199	100.00

Table VII-2

East Maitland-1: Estimate of porosity forMuree Sandstone

(Interval 548.6 - 822.9 m)

Depth m	Gamma-ray API units	Shale Volume %	Interval Transit Time micro/sec/m (Δt)	Porosity ($\emptyset$) (Δt)
548.6	34	85	236.2	4.7
551.6	36	95	229.6	2.0
554.7	35	90	232.9	3.3
557.7	30	65	219.8	3.4
560.8	35	90	223.1	1.2
563.8	32	75	223.1	2.9
566.9	34	85	219.8	1.0
569.9	30	65	223.1	4.1
573.0	31	70	232.9	5.7
576.0	34	85	219.8	1.0
579.1	33	80	236.2	5.3
582.1	32	75	232.9	5.1
585.2	30	65	223.1	4.1
588.2	24	35	219.8	7.0
591.3	23	30	229.6	9.8
594.3	25	40	229.6	8.6
597.4	20	15	239.5	13.8
600.4	21	20	219.8	8.8
603.5	23	30	209.9	5.4
606.5	30	65	206.7	1.0
609.6	27	50	196.8	0.0
612.6	30	65	223.1	4.1

Depth m	Gamma-ray API units	Shale Volume %	Interval Transit Time micro/sec/m (Δt)	Porosity (ϕ) (Δt)
615.6	25	40	209.9	4.2
618.7	22	25	209.9	6.0
621.7	23	30	214.2	6.2
624.8	24	35	203.4	3.4
627.8	22	25	213	6.8
630.9	23	30	200	3.3
633.9	24	35	197	1.9
637.0	24	35	297	1.9
640.0	19	10	190	3.5
643.1	22	25	197	3.1
646.1	25	40	203	3.5
649.2	25	40	208.7	3.7
652.2	30	65	243	8.5
655.3	20	15	194	3.6
658.3	27	50	223	5.9
661.4	21	20	200	4.5
664.4	26	45	297	2.9
667.5	25	40	213	3.0
670.5	24	35	203	3.4
673.6	25	40	217	5.7
676.6	25	40	203	2.8
679.7	27	50	223	5.9
682.7	25	40	207	3.5
685.8	20	15	207	6.5
688.8	24	35	200	2.7
691.8	25	40	210	4.2

Depth m	Gamma-ray API units	Shale Volume %	Interval Transit Time micro/sec/m (Δt)	Porosity (ϕ) (Δt)
694.9	24	35	217	6.3
697.9	30	65	213	2.0
701.0	17	0	210	8.3
704.0	18	5	213	9.2
707.1	18	5	210	8.4
710.1	27	50	213	3.8
713.2	25	40	207.7	3.5
716.2	25	40	213.2	5.0
219.3	30	65	230	5.6
722.3	24	35	213	5.8
725.4	30	65	243	8.5
728.4	30	65	230	5.6
731.5	30	65	213	2.0
734.5	25	40	219	6.4
737.6	30	65	223	4.1
740.6	18	5	219	10.6
743.7	25	40	229	8.6
746.7	25	40	229	8.6
749.8	25	40	209	4.0
752.8	34	85	216	0.0
755.9	21	20	200.1	4.5
758.9	24	35	206.7	4.1
762.	27	50	213.2	3.8
765.0	19	10	206.7	7.1
768.0	25	40	203.4	2.8

Depth m	Gamma-ray API units	Shale Volume %	Interval Transit Time micro/sec/m (Δt)	Porosity ($\emptyset$) (Δt)
771.1	33	80	223.1	2.3
774.1	30	65	219.8	3.4
777.2	33	80	213.2	0.0
780.2	27	50	213.2	3.8
783.2	34	85	216.5	0.0
786.3	30	65	213.2	2.0
789.4	23	30	216.5	6.9
972.4	26	45	213.2	4.4
795.5	27	50	213.2	3.8
798.5	22	25	216.5	7.5
801.6	30	65	229.6	5.6
804.6	30	65	232.9	6.3
807.7	30	65	229.6	5.6
810.7	31	70	239.5	7.2
813.8	32	75	239.5	6.6
816.8	28	55	236.2	8.3
819.9	30	65	226.3	4.9
822.9	27	50	226.3	6.4

Table VII-3

East Maitland-1: Summary of wireline log interpretation
of the Muree Sandstone Reservoir

Reservoir Unit and Interval (m)	Net Pay Depth Interval (m)	Net Pay Thickness (m)	Resistivity of Water (Rw) (ohms-m)	Reservoir Water Salinity (NaCl) ppm	Porosity av. %
Muree Sandstone (586.4 - 768.0)	588.2 - 603.5	15.3	0.58	7000.00	8.9
	618.7 - 627.8	9.1	0.58	7000.00	5.3
	652.2 - 661.4	9.2	0.58	7000.00	5.6
	701.0 - 728.4	27.4	0.58	7000.00	6.3
	740.6 - 749.8	9.2	0.58	7000.00	7.9

Table VII-4

East Maitland-1: Interval Transit Time Porosity ($\emptyset\Delta t$)
and Resistivity (Rt) Cross-Plot Data

Depth Interval (m)	Resistivity (Rt) AO=18'8" ohms-m ² /m	Porosity ($\emptyset\Delta t$) %	Rw ohm/m	NaCl ppm
588.2	140	7.0		
591.3	130	9.8		
594.3	140	8.6	0.58	7000.00
597.4	110	13.8		
600.4	120	8.8		
618.7	190	6.0		
621.7	190	6.2		
624.8	180	3.4		

PLANIMETRY RESULTS

STRUCTURE: East Maitland-1
FORMATION: Muree Sandstone
REFERENCE STRUCTURAL MAP: Figure VII-3
REFERENCE STRUCTURAL CROSS-SECTION: Figures VII-4 and VII-5
COMMENTS: Spill point level at 810 m

Unit No.	Contour Depth m	Planimetry Units*	Planimetered Area ₂ m ²	Thickness m	Volume ^{**} m ³
1	585	37	1,190,000.00		
2	635	76	2,451,000.00	50	89,147,199.00
3	685	195	6,290,000.00	50	211,123,700.00
4	735	325	10,484,000.00	50	414,910,221.00
5	785	490	15,806,000.00	50	652,714,061.00
6	810	593	19,129,000.00	25	436,027,499.00
7				225	4,803,922,680.00
8					
9					
10					

* Calibration of Instrument: 31 Planimetry Units = 1 km²

** Calculation of volume by Pyramidal Rule:

Volume = $\left(\frac{\sqrt{A_1 \times A_2} + A_1 + A_2}{3} \right) \times h$

Table VII-6East Maitland-1: Summary of Reservoir Variables

Reservoir	Muree Sandstone
Area km ² (sq. mile)	19.1 (7.4)
Net Pay Thickness m (ft)	70.2 (230)
Porosity %	6.8
Gas Saturation	80
Reservoir Pressure (psia)	1015
Reservoir Temperature °C (°F)	40 (104)
Standard Condition Pressure (psi)	14.73
Standard Condition Temperature °C (°F)	15.5 (60)
Gas Deviation Factor (Z)	0.921
Gas Formation Volume Factor (Bg)	68.46

Table VII-7East Maitland-1: Potential Natural Gas Storage Capacity

Reservoir	Total Gas Stored	
	$\times 10^9 \text{ m}^3$	$\times 10^9 \text{ ft}^3$
Muree Sandstone	4.98	176.2

WELL NAME : EAST MAITLAND-1
ROCK UNIT : BRANXTON FORMATION
CORE DEPTH : 558.0 - 561.1 m B.K.B.
DEPTH INTERVAL: 454.1 - 598.6 m B.K.B.
THIN SECTION DEPTH: 560.3 m B.K.B.

MACROSCOPIC DESCRIPTION

Dark grey, poorly sorted, pyritic, micaceous and sandy siltstone. Thinly bedded with truncated scallop structures.

MICROSCOPIC DESCRIPTION

Very fine to coarse grained silt sized particles of quartz, feldspar set in a massive calcareous, argillaceous carbonaceous and pyritic matter. Quartz grains up to 1 mm across occur throughout. Feldspars appear to be fresh and of plagioclase clay.

POROSITY

FRAMEWORK	%	ACCESSORIES	%
.Quartz.(sand.sized).....	10.	..Pyrite.....	1.....
.Feldspar.(...".....)	2.	..Carbonaceous matter...	5.....
.Quartz.(silt.sized).....	30.	..Tourmaline.....	tr.....
.Feldspar....."	5.		
.Metamorphic rock fragments..	5.		
.Calcite.....	3.		
.Muscovite.....	1.		

CEMENT

....Calcite.....5..
....Siderite.....5..

MATRIX

..Greenish clay.....30..
.....

ROCK CLASSIFICATION

Calcareous Siltstone

WELL NAME : EAST HAITLAND-1
ROCK UNIT : MUREE SANDSTONE DEPTH INTERVAL: 586.4 - 786.0 m B.K.
CORE DEPTH : 610.2 - 613.2 m B.K.B. THIN SECTION DEPTH: 610.2 m B.K.B.

MACROSCOPIC DESCRIPTION

Light grey, moderately to well sorted, subangular, medium to coarse grained quartz rich arenite with calcite cement. Trace of calcareous shell fragments.

MICROSCOPIC DESCRIPTION

Medium to coarse grained moderately sorted quartz with occasional chert and feldspar grains. Rock fragment of various origins are common, together micas and carbonate minerals including dawsonite. The framework is silica (quartz overgrowths); calcite and siderite cemented. Matrix is subordinate and comprises silt sized carbonaceous and calcareous matter.

POROSITY ..No visible porosity was established.....

FRAMEWORK	%	ACCESSORIES	%
Quartz.....	66....	Pyrite.....	tr.....
Chert.....	1....	Muscovite.....	tr.....
Potassium Feldspar.....	2....	Calcite.....	3.....
Plagioclase.....	1....	Biotite.....	1.....
Volcanic Rock fragments.....	2....	Siderite.....	2.....
Metamorphic "....."	3....	Dawsonite.....	1.....
Sedimentary "....."	2....		

CEMENT

....Silica.....5.
....Calcite & Siderite.....6

MATRIX

....Argillaceous.....5.
.....

ROCK CLASSIFICATION

Calcareous sublitharenite.

WELL NAME : EAST MAITLAND-1
ROCK UNIT : MURREE SANDSTONE DEPTH INTERVAL: 586.4-768.0 m B.K.B.
CORE DEPTH : 690.0 - 692.5 m B.K.B. THIN SECTION DEPTH: 690.0 m B.K.B.

MACROSCOPIC DESCRIPTION

Light grey moderately sorted, medium grained calcareous arenite. Patches of dark carbonaceous matter is common. Traces of calcareous fossil shell fragments.

MICROSCOPIC DESCRIPTION

Medium to very coarse grained, poorly sorted, angular to subangular quartz with minor chert and feldspar grains. Volcanic and metamorphic rock fragments are strongly altered. The framework is silica and calcite cemented. Matrix is mainly of carbonaceous and micaceous matter.

A fracture (as shown in Plate 2 Photos 1 and 2) occurs in core No. 7.

POROSITY No visible porosity was established.

FRAMEWORK	%	ACCESSORIES	%
Quartz	70	Pyrite	tr
Chert	3	Calcite	tr
Potassium Feldspar	2	Siderite	tr
Plagioclase	1	Muscovite	tr
Volcanic Rock Fragments	2	Dawsonite	tr
Metamorphic "	4		
Sedimentary "	3		

CEMENT

Silica	4
Calcite	6

MATRIX

Argillaceous	5

ROCK CLASSIFICATION

Calcareous Sublitharenite

Well Name : EAST MAITLAND - 1

Datum : 9.3 m A.S.L.

Lithology & Depth (m)	Description of Lithology , Provenance & Environment	Formation	Group	Age
57.9	1 Sublitharenite interbedded with siltstone and coal lenses. Sedimentary provenance. Deposition in fluvial environment.		PG	PERMIAN
586.4	2 Siltstones, carbonaceous, sideritic, pyritic and calcareous. Interbedded with thin beds of calcareous sublitharenites, mudstone and thin coal beds. Marine fossils are common. Sedimentary provenance. Deposition in low to moderate marine environment with minor fluvial influence.	Pmm		
768.0	3 Sublitharenite, pebbly in places interbedded with thin interbeds of siltstone and mudstone. Abundant marine fossils. Diverse provenance. Deposition in high energy marine environment.	Pmms		
1395.9	4 Litharenite beds, calcareous, carbonaceous and pyritic interbedded with siltstone and mudstone beds. Marine fossils of Bryozoa, brachiopods and foraminifera.	Pmb	MAITLAND	
1461.8	5 Litharenite with petromict conglomerate beds, enveloping a 4.3 m thick coal seam.		Pgc	
1886.7	6 Siltstone interbedded with litharenite beds. Sequence pyritic throughout and very carbonaceous at base. Rare brachiopod fragments. Sedimentary and volcanic provenance. Deposition in low energy marine environment.	Pdfr		
T.D. 3049.2	7 Pyroclastic rocks, very altered, including lapilli tuff interbedded with litharenite, siltstone and mudstone beds. Marine fossils are common. Volcanic and sedimentary provenance. Deposited in marine environment.	Pdal	COOMONDALWOOD	
<div>Interval under investigation</div>				

Fig.VII - 2

Datum: Kelly Bushing 24.9m A.S.L.

Contour Interval: 50m

A B Cross-sections

0 1 2 3 4 5 km

EAST MAITLAND STRUCTURE STRUCTURE MAP ON TOP OF MUREE SANDSTONE

(Modified after PLANET EXPLORATION CO. LTD, 1962, Newcastle -
Maitland Seismic Survey, BMR File 62/1596)

S.O. 5-12-77

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EAST MAITLAND STRUCTURE
WEST-EAST STRUCTURAL CROSS SECTION

RESISTIVITY VS POROSITY

Fig. VII-6

EAST MAITLAND-1

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PHOTO 1: Branxton Formation.

(Thin section depth 560.3 m, crossed nicols x 100)
Very coarse quartz in a sideritic and carbonaceous siltstone.

PHOTO 2: Muree Sandstone

(Thin section depth 610.2 m, crossed nicols x 100)
Medium grained, strongly silica cemented quartz rich sublitharenite. Rock fragments are common. Note biotite grain in the left top corner.

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TOP OF THE CORE

PHOTO 1: Muree Sandstone.

(Thin section depth 690.0 m, crossed nicols x 100)
Medium grained calcareous sublitharenite. Note the east-west "pinnate" fracture.

TOP OF THE CORE

PHOTO 2: Muree Sandstone

(Thin section depth 690.0 m, crossed nicols x 250)
Enlarged photo of the east-west "pinnate" fracture.

APPENDIX VIII

DELIVERABILITY ESTIMATES

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STOCKYARD MOUNTAIN-1

DELIVERABILITY POTENTIAL

Computer Input Data - Snapper Point Formation Reservoir

Computer Output Data - Snapper Point Formation Reservoir
(Normal Reservoir Pressure)

Computer Output Data - Snapper Point Formation Reservoir
(Reservoir Overpressured by 10%)

TITLE																						
1	STOCKYARD MOUNTAIN SPFR																					
	RUN				DATE				LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1										
2	0	0	0	1	0	8	—	0	5	—	7	9	43	0	0	0						
	C1				C2		C3		IC4		NC4		IC5		NC5		C6	C7+	H ₂ S	CO ₂	N ₂	
3	0.96999				0.00		0.00001		0.00				0.0001		0.00		0.00		0.00	0.00	0.03	0.00
	PRESS				TEMP		(PVT DATA)															
4	841				93																	
	PA1 (KPMAX)																					
4A																						
	C3P (KPMAX)																					
4B																						
	C5P (KPMAX)																					
4C																						
Notes:																						

	VOL	POR	SATW	AVETH								
5	6357	0.05	0.20	20								
	NYRMAX	NW	MAR									
6	16	20	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	1160	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	2.5	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	1900	2.972	0.014	1.0	80	-1						
Notes :												

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	6357	(MMSCF)
POROSITY	.0500	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	20.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	93	(DEGREES F)
INITIAL RESERVOIR PRESSURE	841	(PSIA)

WELL DATA

WELL RADIUS	5410	(FT)
PERMEABILITY*THICKNESS	1160.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	1900	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	80	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	4.0000	(MMSCF/D/Well)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/Well)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = ##### CUBIC FEET / BARREL

0001 22-05-79

PAGE 3

STOCKYARD MTN SPR

RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
841.0	93.0	.908	.0124	.001298	2.635 (.042)	.0183
400.0	93.0	.954	.0117	.002617	1.192 (.019)	.0083

0001 22-05-79

STOCKYARD MTN SPR

PAGE 4

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			PRESSURES (PSIA)		
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	TOP	BOT	RES
1	3.08	1.12	.01	.01	1.12	.000	.000	90.5	140.0	703.5
2	2.32	.85	.01	.00	1.97	.000	.000	69.2	106.3	597.0
3	1.71	.62	.00	.00	2.59	.000	.000	71.5	94.2	516.6
4	1.26	.46	.00	.00	3.06	.000	.000	67.7	82.3	456.3
5	.93	.34	.00	.00	3.40	.000	.000	62.2	71.9	411.3
6	.78	.28	.00	.00	3.68	.000	.000	63.5	71.0	373.4
7	.69	.25	.00	.00	3.93	.000	.000	65.3	71.8	339.7
8	.62	.23	.00	.00	4.16	.000	.000	61.0	66.7	308.9
9	.55	.20	.00	.00	4.36	.000	.000	61.9	67.0	281.5
10	.49	.18	.00	.00	4.54	.000	.000	62.5	67.0	257.0
11	.43	.16	.00	.00	4.70	.000	.000	62.8	66.9	235.3
12	.38	.14	.00	.00	4.84	.000	.000	63.0	66.7	215.9
13	.35	.13	.00	.00	4.97	.000	.000	60.0	63.5	198.3
14	.31	.11	.00	.00	5.08	.000	.000	60.0	63.2	182.6
15	.27	.10	.00	.00	5.17	.000	.000	62.3	65.3	169.0
16	.24	.09	.00	.00	5.26	.000	.000	60.1	62.9	156.6

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	6357	(MMSCF)
POROSITY	.0500	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	20.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	93	(DEGREES F)
INITIAL RESERVOIR PRESSURE	925	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	1180.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	1900	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	80	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	4.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	0.0001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	0.0001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	0.0000
NITROGEN	28.016	482.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000
AVERAGE MOLECULAR WEIGHT OF GAS =	16.83	GAS GRAVITY = 583		
SALES GAS	=	1.0000	MMSCF/MMSCF RAW GAS	
DRY-BASIS HEATING VALUE	=	982.	BTU/CUBIC FOOT VAPOR AT 14.696 PSIA, (.36575E+08 JOULE/CUBIC METRE)	
LPG	=	.01	BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)	
CONDENSATE	=	.01	BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)	
GAS/CONDENSATE (OR OIL) RATIO	=	\$\$\$	CUBIC FEET / BARREL	

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STOCKYARD MTN SPR

RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIAK-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
925.0	93.0	.899	.0126	.001187	2.924 (.047)	.0203
500.0	93.0	.943	.0118	.002116	1.508 (.024)	.0105
100.0	93.0	.988	.0113	.010118	.288 (.005)	.0020

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STOCKYARD HTN SPR

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION				CUMULATIVE PRODUCTION				PRESSURES (PSIA)		
		SALES GAS BCF	LPG MBBL	COND MBBL		SALES GAS BCF	LPG MBBL	COND MBBL	FRAC PROD	TOP	BOT	RES
1	3.62	1.32	.01	.01		1.32	.000	.000	.2076	83.2	149.5	747.8
2	2.56	.94	.01	.00		2.26	.000	.000	.3549	72.7	114.9	617.7
3	1.78	.65	.00	.00		2.91	.000	.000	.4572	67.9	92.7	525.0
4	1.37	.50	.00	.00		3.41	.000	.000	.5359	78.2	93.5	452.6
5	1.14	.42	.00	.00		3.82	.000	.000	.6016	66.6	79.2	391.5
6	.93	.34	.00	.00		4.17	.000	.000	.6552	90.4	99.0	340.8
7	.78	.28	.00	.00		4.45	.000	.000	.6999	75.9	83.1	298.1
8	.65	.24	.00	.00		4.69	.000	.000	.7372	61.8	67.9	262.2
9	.53	.19	.00	.00		4.88	.000	.000	.7676	69.3	74.2	232.6
10	.43	.16	.00	.00		5.04	.000	.000	.7925	74.2	78.5	208.3
11	.36	.13	.00	.00		5.17	.000	.000	.8133	64.1	67.7	187.9
12	.30	.11	.00	.00		5.28	.000	.000	.8302	66.4	69.7	171.1
13	.24	.09	.00	.00		5.37	.000	.000	.8441	67.9	71.0	157.4
14	.20	.07	.00	.00		5.44	.000	.000	.8556	61.5	64.2	146.0
15	0.00	0.00	0.00	0.00		5.44	.000	.000	.8556	140.4	146.0	146.0
16	0.00	0.00	0.00	0.00		5.44	.000	.000	.8556	140.4	146.0	146.0

WORONORA-1DELIVERABILITY POTENTIAL

Computer Input Data - Nowra Sandstone Reservoir

Computer Output Data - Nowra Sandstone Reservoir (Normal
Reservoir Pressure)

Computer Output Data - Nowra Sandstone Reservoir (Reservoir
Overpressured by 10%)

TITLE																	
WORONORA NSR																	
RUN		DATE						LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1						
0	0	0	2	0	5	—	0	8	—	7	9	43	0	0	0		
C1		C2		C3		IC4		NC4	IC5	NC5	C6	C7+	H ₂ S	CO ₂	N ₂		
0.96999		0.0		0.00001		0.0		0.0	0.00001	0.0	0.0	0.0	0.0	0.03	0.0		
PRESS		TEMP															
2241		141		(PVT DATA)													
PAI (KPMAX)																	
C3P (KPMAX)																	
C5P (KPMAX)																	
Notes:																	

	VOL	POR	SATW	AVETH								
5	3249	0.06	0.20	38.0								
	NYRMAX	NW	MAR									
6	16	5	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	91	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	1.0	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	5120	2.972	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	3249	(MMSCF)
POROSITY	.0600	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	38.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	141	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2241	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	91.9000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5120	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	80	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	5.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = ##### CUBIC FEET / BARREL

WORONORA NSR

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
2241.0	141.0	.877	.0160	.000455	6.685 (.107)	.0464
1800.0	141.0	.885	.0150	.000588	5.324 (.085)	.0370
1400.0	141.0	.900	.0141	.000767	4.071 (.065)	.0283
1000.0	141.0	.922	.0134	.001069	2.838 (.045)	.0197
600.0	141.0	.950	.0127	.001747	1.653 (.026)	.0115
200.0	141.0	.982	.0121	.005087	.533 (.009)	.0037

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION				CUMULATIVE PRODUCTION				PRESSURES (PSIA)		
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	FRAC PROD	TOP	BOT	RES	
1	1.52	55	00	00	55	000	000	1706	208.1	246.3	1872.2	
2	1.14	42	00	00	97	000	000	2991	112.1	140.6	1597.9	
3	.86	31	00	00	1.29	000	000	3960	105.4	126.8	1389.5	
4	.68	25	00	00	1.53	000	000	4720	190.9	214.5	1226.8	
5	.54	20	00	00	1.73	000	000	5328	167.8	188.0	1094.2	
6	.43	16	00	00	1.89	000	000	5816	147.4	164.8	986.6	
7	.37	13	00	00	2.02	000	000	6230	128.2	143.2	895.1	
8	.31	11	00	00	2.14	000	000	6583	104.6	116.9	816.1	
9	.27	10	00	00	2.24	000	000	6883	79.2	88.8	748.2	
10	.22	08	00	00	2.32	000	000	7133	106.5	118.3	691.1	
11	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.1	691.0	691.0	
12	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.2	691.1	691.1	
13	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.2	691.1	691.1	
14	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.2	691.1	691.1	
15	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.2	691.1	691.1	
16	0.00	0.00	0.00	0.00	2.32	000	000	7133	623.2	691.1	691.1	

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	3249.	(MMSCF)
POROSITY	.0600	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	38.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	141.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2465.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	91.9000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5120.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	80.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	5.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE),

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
2465.0	141.0	.877	.0166	.000403	7.355 (.118)	.0511
2000.0	141.0	.880	.0154	.000522	5.946 (.095)	.0413
1600.0	141.0	.891	.0145	.000668	4.697 (.075)	.0326
1200.0	141.0	.910	.0137	.000895	3.450 (.055)	.0240
800.0	141.0	.935	.0131	.001325	2.238 (.036)	.0155
400.0	141.0	.966	.0124	.002584	1.084 (.017)	.0075

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(PSIA)

WONORA NSR

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION				CUMULATIVE PRODUCTION				PRESSURES (PSIA)		
		SALES GAS BCF	LPG MMBBL	COND MMBBL		SALES GAS BCF	LPG MMBBL	COND MMBBL		TOP	BOT	RES
1	1.71	.63	.00	.00		.63	.000	.000		162.9	205.7	1997.7
2	1.22	.44	.00	.00		1.07	.000	.000		230.1	263.9	1676.8
3	.92	.33	.00	.00		1.40	.000	.000		137.3	160.8	1435.3
4	.69	.25	.00	.00		1.66	.000	.000		139.4	159.1	1251.2
5	.55	.20	.00	.00		1.86	.000	.000		76.6	90.5	1103.1
6	.44	.16	.00	.00		2.02	.000	.000		87.9	100.4	983.1
7	.35	.13	.00	.00		2.15	.000	.000		89.8	101.3	885.5
8	.28	.10	.00	.00		2.25	.000	.000		87.0	97.5	806.5
9	.25	.09	.00	.00		2.34	.000	.000		73.3	82.2	737.8
10	.21	.08	.00	.00		2.42	.000	.000		69.6	77.8	677.6
11	0.00	0.00	0.00	0.00		2.42	.000	.000		611.0	677.4	677.4
12	0.00	0.00	0.00	0.00		2.42	.000	.000		611.1	677.6	677.6
13	0.00	0.00	0.00	0.00		2.42	.000	.000		611.1	677.6	677.6
14	0.00	0.00	0.00	0.00		2.42	.000	.000		611.1	677.6	677.6
15	0.00	0.00	0.00	0.00		2.42	.000	.000		611.1	677.6	677.6
16	0.00	0.00	0.00	0.00		2.42	.000	.000		611.1	677.6	677.6

DURAL SOUTH-1DELIVERABILITY POTENTIAL

Computer Input Data - Nowra Sandstone Reservoir

Computer Output Data - Nowra Sandstone Reservoir (Normal
Reservoir Pressure)

Computer Output Data - Nowra Sandstone Reservoir (Reservoir
Overpressured by 10%)

TITLE															
DURAL SOUTH NSR															
RUN				DATE				LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1				
0 0 0 1				0 8 — 0 5 — 7 9				43	0	0	0				
C1		C2		C3		IC4		NC4	IC5	NC5	C6	C7+	H ₂ S	CO ₂	N ₂
0.96999		0.00		0.00001		0.00		0.0	0.00001	0.0	0.0	0.0	0.0	0.03	0.0
PRESS		TEMP		(PVT DATA)											
3085		167													
PA1 (KPMAX)															
4A															
C3P (KPMAX)															
4B															
C5P (KPMAX)															
4C															
Notes:															

	VOL	POR	SATW	AVETH								
5	313524	0.08	0.20	54								
	NYRMAX	NW	MAR									
6	16	10	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	135	10	0								
	Q	QMIN	THPMIN	QOVER								
8	10	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	7150	2.972	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	313525.	(MMSCF)
POROSITY	.0800	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	54.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	167.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	3085.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	135.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	7150.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	10.0000	(MMSCF/D/WELL)
NUMBER-OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR, OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
3085.0	167.0	.910	.0182	.000296	8.504 (.136)	.0591
2600.0	167.0	.900	.0169	.000374	7.243 (.116)	.0503
2200.0	167.0	.899	.0160	.000461	6.138 (.098)	.0426
1800.0	167.0	.804	.0151	.000580	4.993 (.080)	.0347
1400.0	167.0	.916	.0143	.000755	3.833 (.061)	.0266
1000.0	167.0	.934	.0137	.001056	2.685 (.043)	.0186
600.0	167.0	.957	.0131	.001734	1.572 (.025)	.0109
200.0	167.0	.985	.0125	.005075	.509 (.008)	.0035

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			FRAC PROD	PRESSURES (PSIA)		
		SALES GAS BCF	LPG MBBL	COND MBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL		TOP	BOT	RES
1	4.55	1.66	.01	.01	1.66	.000	.000	.0053	258.8	439.0	3067.5
2	4.55	1.66	.01	.01	3.32	.000	.000	.0106	91.6	342.3	3050.1
3	4.48	1.63	.01	.01	4.95	.000	.000	.0158	274.1	446.3	3032.9
4	4.46	1.63	.01	.01	6.57	.000	.000	.0210	129.5	351.6	3015.9
5	4.37	1.59	.01	.01	8.17	.000	.000	.0261	288.6	453.7	2999.1
6	4.37	1.59	.01	.01	9.76	.000	.000	.0311	158.4	361.0	2982.4
7	4.28	1.56	.01	.01	11.32	.000	.000	.0361	302.5	461.2	2965.9
8	4.28	1.56	.01	.01	12.89	.000	.000	.0411	182.9	370.5	2949.6
9	4.19	1.53	.01	.01	14.42	.000	.000	.0460	315.8	468.8	2933.5
10	4.19	1.53	.01	.01	15.95	.000	.000	.0509	204.6	380.0	2917.5
11	4.11	1.50	.01	.01	17.45	.000	.000	.0557	328.7	476.4	2901.8
12	4.11	1.50	.01	.01	18.95	.000	.000	.0604	224.2	389.6	2886.1
13	4.03	1.47	.01	.01	20.42	.000	.000	.0651	341.1	484.2	2870.7
14	4.03	1.47	.01	.01	21.89	.000	.000	.0698	242.4	399.2	2855.4
15	4.03	1.47	.01	.01	23.36	.000	.000	.0745	108.3	314.0	2840.1
16	3.95	1.44	.01	.01	24.80	.000	.000	.0791	256.9	406.9	2825.0

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE (MMSCF) 313525
POROSITY (FRACTION) .0800
WATER SATURATION (FRACTION) .2000
AVERAGE THICKNESS OF RESERVOIR (FT) 54.0000
INITIAL RESERVOIR TEMPERATURE (DEGREES F) 167
INITIAL RESERVOIR PRESSURE (PSIA) 3393

WELL DATA

WELL RADIUS (FT) .5410
PERMEABILITY*THICKNESS (MDS-FT) 135.0000
SKIN FACTOR 10.00
TURBULENCE FACTOR 0.0000
TUBING ELEVATION (TRUE VERTICAL DEPTH) (FT) 7150
TUBING DIAMETER (IN) 2.9720
FRICTION FACTOR .0140
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR 1.0000
TEMPERATURE OF GAS AT SURFACE IN TUBING (DEGREES F) 100

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE (MMSCF/D/Well) 10.0000
NUMBER OF PRODUCING WELLS 1
PEAK PRODUCTION RATE / PRODUCTION RATE (RATIO) 1.1000
MINIMUM TUBING HEAD PRESSURE (PSIA) 60
MINIMUM (OR CUT-OFF) PRODUCTION RATE (MMSCF/D/Well) 2000

DEFINITIONS

SALES GAS - METHANE, ETHANE; AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88

GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

 DRY-BASIS HEATING VALUE = 982 BTU/CUBIC FOOT VAPOR AT 14.696 PSIA.
 (.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR, OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
3393.0	167.0	.920	.0191	.000258	9.252 (.148)	.0642
2900.0	167.0	.905	.0177	.000323	8.035 (.129)	.0558
2500.0	167.0	.899	.0167	.000393	6.972 (.112)	.0484
2100.0	167.0	.900	.0157	.000487	5.854 (.094)	.0407
1700.0	167.0	.907	.0149	.000617	4.703 (.075)	.0327
1300.0	167.0	.920	.0142	.000814	3.544 (.057)	.0246
900.0	167.0	.939	.0136	.001170	2.403 (.038)	.0167
500.0	167.0	.964	.0129	.002069	1.301 (.021)	.0090
100.0	167.0	.992	.0125	.010076	.253 (.004)	.0018

DURAL SOUTH NSR

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			FRAC PROD	PRESSURES (PSIA)		
		SALES GAS BCF	LPG MBBL	COND MBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL		TOP	BOT	RES
1	5.35	1.95	.01	.02	1.95	.000	.000	.0062	307.9	518.6	3369.3
2	5.24	1.91	.01	.02	3.86	.000	.000	.0123	324.0	576.0	3346.2
3	5.24	1.91	.01	.02	5.78	.000	.000	.0184	286.7	496.8	3323.3
4	5.13	1.87	.01	.02	7.65	.000	.000	.0244	364.3	554.1	3300.4
5	5.13	1.87	.01	.02	9.52	.000	.000	.0304	229.7	450.8	3278.0
6	5.03	1.84	.01	.01	11.36	.000	.000	.0362	345.4	533.2	3255.7
7	5.03	1.84	.01	.01	13.20	.000	.000	.0421	165.9	406.7	3233.8
8	4.93	1.80	.01	.01	15.00	.000	.000	.0478	327.1	513.0	3212.0
9	4.93	1.80	.01	.01	16.80	.000	.000	.0536	77.3	364.4	3190.6
10	4.83	1.76	.01	.01	18.56	.000	.000	.0592	299.4	485.5	3169.2
11	4.74	1.73	.01	.01	20.29	.000	.000	.0647	376.0	546.4	3148.6
12	4.74	1.73	.01	.01	22.02	.000	.000	.0702	257.3	447.8	3128.1
13	4.64	1.69	.01	.01	23.71	.000	.000	.0756	360.6	528.3	3107.7
14	4.64	1.69	.01	.01	25.40	.000	.000	.0810	211.5	410.2	3087.7
15	4.55	1.66	.01	.01	27.06	.000	.000	.0863	345.7	511.1	3067.8
16	4.55	1.66	.01	.01	28.72	.000	.000	.0916	161.7	374.0	3048.2

KURRAJONG HEIGHTS-1DELIVERABILITY POTENTIAL

Computer Input Data - Berry Formation - Nowra Sandstone
Reservoir

Computer Output Data - Berry Formation - Nowra Sandstone
Reservoir (Normal Reservoir Pressure)

Computer Output Data - Berry Formation - Nowra Sandstone
Reservoir (Reservoir overpressured by 10%)

TITLE																					
KURRAJONG HEIGHTS - BNSR																					
RUN				DATE				LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1										
0	0	0	1	0	8	—	0	5	—	7	9	43	0	0	0						
C1				C2		C3		IC4		NC4		IC5		NC5		C6	C7+	H ₂ S	CO ₂	N ₂	
0.96999				0.0		0.00001		0.00		0.0		0.00001		0.0		0.0		0.0	0.0	0.03	0.0
PRESS				TEMP																	
2389				140		(PVT DATA)															
PAI (KPMAX)																					
4A																					
C3P (KPMAX)																					
4B																					
C5P (KPMAX)																					
4C																					
Notes:																					

	VOL	POR	SATW	AVETH								
5	54596	0.12	0.20	24								
	NYRMAX	NW	MAR									
6	16	10	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	60	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	10	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	5460	2.972	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	54596.	(MMSCF)
POROSITY	.1200	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	24.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	140.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2389.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	60.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5460.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	3.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000

GAS GRAVITY = .583

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = ##### CUBIC FEET / BARREL

KURRAJONG HEIGHTS BNSR

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIAK-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
2389.0	140.0	.876	.0164	.000420	7.150 (.115)	.0496
1900.0	140.0	.881	.0152	.000554	5.651 (.091)	.0392
1500.0	140.0	.895	.0143	.000715	4.395 (.070)	.0305
1100.0	140.0	.915	.0136	.000975	3.150 (.050)	.0219
700.0	140.0	.942	.0128	.001507	1.947 (.031)	.0135
300.0	140.0	.974	.0122	.003420	.807 (.013)	.0056

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			PRESSURES (PSIA)			
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	FRAC PROD	TOP	BOT	RES
1	1.45	53	00	00	53	000	000	0097	89.2	132.6	2366.5
2	1.42	52	00	00	1.05	000	000	0192	163.6	201.1	2344.5
3	1.39	51	00	00	1.56	000	000	0285	229.0	268.0	2322.9
4	1.36	50	00	00	2.05	000	000	0376	269.1	310.2	2301.7
5	1.34	49	00	00	2.54	000	000	0466	287.5	329.6	2280.9
6	1.34	49	00	00	3.03	000	000	0555	106.5	143.5	2260.2
7	1.31	48	00	00	3.51	000	000	0643	170.9	205.8	2239.8
8	1.28	47	00	00	3.98	000	000	0728	229.8	266.9	2219.8
9	1.26	46	00	00	4.44	000	000	0813	268.7	308.1	2200.2
10	1.23	45	00	00	4.89	000	000	0895	285.4	325.8	2181.0
11	1.23	45	00	00	5.34	000	000	0977	117.2	150.2	2161.8
12	1.21	44	00	00	5.78	000	000	1058	174.4	207.0	2142.9
13	1.18	43	00	00	6.21	000	000	1137	227.6	262.8	2124.4
14	1.16	42	00	00	6.63	000	000	1215	267.4	305.3	2106.3
15	1.14	42	00	00	7.05	000	000	1291	282.6	321.5	2088.6
16	1.14	42	00	00	7.46	000	000	1367	123.6	153.7	2070.8

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	54536.	(MMSCF)
POROSITY	.1200	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	24.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	140.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2628.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	60.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5460.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	3.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000

GAS GRAVITY = .583

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = ##### CUBIC FEET / BARREL

KURRAJONG HEIGHTS BNSR

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
2628.0	140.0	.877	.0171	.000370	7.851 (.126)	.0545
2200.0	140.0	.876	.0159	.000465	6.579 (.105)	.0457
1800.0	140.0	.884	.0149	.000588	5.338 (.086)	.0371
1400.0	140.0	.899	.0141	.000767	4.081 (.065)	.0283
1000.0	140.0	.921	.0134	.001069	2.844 (.046)	.0198
600.0	140.0	.950	.0127	.001748	1.656 (.027)	.0115
200.0	140.0	.982	.0121	.005088	.534 (.009)	.0037

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KURRAJONG HEIGHTS BNSR

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PRESSURES (PSIA)

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			PRESSURES (PSIA)		
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	TOP	BOT	RES
1	1.70	.62	.00	.01	.62	.000	.000	228.1	273.6	2597.9
2	1.67	.61	.00	.01	1.23	.000	.000	231.3	276.1	2568.4
3	1.64	.60	.00	.00	1.83	.000	.000	234.4	278.6	2539.5
4	1.60	.59	.00	.00	2.41	.000	.000	237.4	281.0	2511.2
5	1.57	.57	.00	.00	2.99	.000	.000	240.3	283.4	2483.5
6	1.54	.56	.00	.00	3.55	.000	.000	243.1	285.7	2456.3
7	1.51	.55	.00	.00	4.10	.000	.000	245.9	288.1	2429.6
8	1.48	.54	.00	.00	4.64	.000	.000	248.6	290.4	2403.5
9	1.45	.53	.00	.00	5.17	.000	.000	251.3	292.6	2377.9
10	1.42	.52	.00	.00	5.69	.000	.000	253.9	294.8	2352.9
11	1.39	.51	.00	.00	6.20	.000	.000	256.4	297.0	2328.3
12	1.36	.50	.00	.00	6.69	.000	.000	258.8	299.2	2304.2
13	1.36	.50	.00	.00	7.19	.000	.000	73.8	116.8	2280.2
14	1.34	.49	.00	.00	7.68	.000	.000	85.7	125.3	2256.6
15	1.31	.48	.00	.00	8.16	.000	.000	96.6	133.6	2233.5
16	1.28	.47	.00	.00	8.63	.000	.000	106.7	141.9	2210.8

KURRAJONG HEIGHTS-1DELIVERABILITY POTENTIAL

Computer Input Data - Snapper Point Formation Reservoir

Computer Output Data - Snapper Point Formation Reservoir
(Normal Reservoir pressure)

Computer Output Data - Snapper Point Formation Reservoir
(Reservoir overpressured by 10%)

TITLE																				
1	KURRAJONG HEIGHTS SPFR																			
	RUN				DATE				LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1								
2	0	0	0	1	0	8	—	0	5	—	7	9	43	0	0	0				
	C1		C2		C3		IC4		NC4		IC5		NC5		C6		C7+	H ₂ S	CO ₂	N ₂
3	0.96999		0.0		0.00001		0.0		0.0		0.00001		0.0		0.0		0.0	0.0	0.03	0.0
	PRESS		TEMP		(PVT DATA)															
4	2739		15.5																	
	PA1 (KPMAX)																			
4A																				
	C3P (KPMAX)																			
4B																				
	C5P (KPMAX)																			
4C																				
Notes:																				

	VOL	POR	SATW	AVETH								
5	167039	0.07	0.20	80								
	NYRMAX	NW	MAR									
6	16	10	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	240	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	5	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	6260	2.979	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	167039	(MMSCF)
POROSITY	.0700	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	80.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	155	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2739	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	240.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	6260	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	10.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982 BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$ CUBIC FEET / BARREL

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
2739.0	155.0	.892	.0173	.000349	7.849 (.126)	.0545
2300.0	155.0	.889	.0162	.000438	6.615 (.106)	.0453
1900.0	155.0	.893	.0152	.000549	5.438 (.087)	.0378
1500.0	155.0	.905	.0144	.000708	4.238 (.068)	.0294
1100.0	155.0	.923	.0137	.000967	3.047 (.049)	.0212
700.0	155.0	.947	.0131	.001499	1.889 (.030)	.0131
300.0	155.0	.976	.0125	.003412	.786 (.013)	.0055

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PRESSURES (PSIA)

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			FRAC PROD	PRESSURES (PSIA)		
		SALES GAS BCF	LPG MBBL	COND MBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL		TOP	BOT	RES
1	6.68	2.44	.02	.02	2.44	.000	.000	.0146	264.9	530.9	2698.1
2	6.54	2.39	.02	.02	4.82	.000	.000	.0289	206.4	489.8	2658.1
3	6.41	2.34	.02	.02	7.16	.000	.000	.0429	134.0	449.7	2618.9
4	6.16	2.25	.01	.02	9.41	.000	.000	.0564	305.8	531.3	2581.3
5	6.03	2.20	.01	.02	11.62	.000	.000	.0695	260.7	493.8	2544.5
6	5.91	2.16	.01	.02	13.77	.000	.000	.0825	212.1	457.0	2508.4
7	5.80	2.12	.01	.02	15.89	.000	.000	.0951	156.2	421.1	2473.1
8	5.68	2.07	.01	.01	17.96	.000	.000	.1075	77.5	386.0	2438.5
9	5.45	1.99	.01	.01	19.95	.000	.000	.1195	253.6	458.7	2405.3
10	5.35	1.95	.01	.01	21.90	.000	.000	.1311	212.5	425.8	2372.7
11	5.24	1.91	.01	.01	23.82	.000	.000	.1426	167.2	393.7	2340.8
12	5.13	1.87	.01	.01	25.69	.000	.000	.1538	112.2	362.2	2309.6
13	5.03	1.84	.01	.01	27.53	.000	.000	.1648	78.4	344.6	2280.0
14	4.83	1.76	.01	.01	29.29	.000	.000	.1754	253.9	427.6	2251.9
15	4.74	1.73	.01	.01	31.02	.000	.000	.1857	245.5	416.6	2224.4
16	4.64	1.69	.01	.01	32.71	.000	.000	.1958	237.1	405.8	2197.4

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	167039.	(MMSCF)
POROSITY	.0700	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	80.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	155.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	3013.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	240.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	6260.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	10.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE),

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIAK-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
3013.0	155.0	.898	.0181	.000306	8.578 (.137)	.0596
2600.0	155.0	.890	.0170	.000374	7.466 (.120)	.0518
2200.0	155.0	.889	.0159	.000463	6.324 (.101)	.0439
1800.0	155.0	.896	.0150	.000583	5.139 (.082)	.0357
1400.0	155.0	.909	.0142	.000760	3.939 (.063)	.0274
1000.0	155.0	.929	.0136	.001061	2.753 (.044)	.0191
600.0	155.0	.954	.0129	.001739	1.608 (.026)	.0112
200.0	155.0	.984	.0123	.005080	.520 (.008)	.0036

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PRESSURES (PSIA)

CUMULATIVE PRODUCTION

ANNUAL PRODUCTION

RATE

YR

PER
WELL
RAW GAS
MMCFD

WELL RAW GAS MMCFD	SALES		LPG MMBBL	COND		SALES GAS BCF	LPG MMBBL	COND MMBBL	FRAC PROD	TOP	BOT	RES
	GAS	BCF		MMBBL	MMBBL							
1	7.85	2.86	.02	.02	.02	2.86	.000	.000	.0171	302.7	618.1	2958.0
2	7.69	2.81	.02	.02	.02	5.67	.000	.000	.0340	109.8	523.3	2904.1
3	7.39	2.70	.02	.02	.02	8.37	.000	.000	.0501	305.3	594.7	2852.6
4	7.24	2.64	.02	.02	.02	11.01	.000	.000	.0659	93.3	490.3	2802.1
5	6.95	2.54	.02	.02	.02	13.55	.000	.000	.0811	285.2	558.6	2753.8
6	6.81	2.49	.02	.02	.02	16.03	.000	.000	.0960	86.9	461.3	2706.5
7	6.54	2.39	.02	.02	.02	18.42	.000	.000	.1103	269.5	526.6	2661.2
8	6.41	2.34	.02	.02	.02	20.76	.000	.000	.1243	89.1	436.0	2616.9
9	6.16	2.25	.01	.01	.01	23.01	.000	.000	.1377	284.3	516.2	2575.6
10	6.03	2.20	.01	.01	.01	25.21	.000	.000	.1509	205.9	460.3	2535.9
11	5.91	2.16	.01	.01	.01	27.37	.000	.000	.1639	95.2	405.7	2497.1
12	5.68	2.07	.01	.01	.01	29.44	.000	.000	.1763	282.6	490.7	2459.8
13	5.57	2.03	.01	.01	.01	31.47	.000	.000	.1884	214.8	439.3	2423.3
14	5.45	1.99	.01	.01	.01	33.46	.000	.000	.2003	129.9	389.0	2387.4
15	5.24	1.91	.01	.01	.01	35.38	.000	.000	.2118	280.6	467.5	2353.1
16	5.13	1.87	.01	.01	.01	37.25	.000	.000	.2230	221.4	420.2	2319.4

MULGOA-2DELIVERABILITY POTENTIAL

Computer Input Data - Nowra Sandstone Reservoir

Computer Output Data - Nowra Sandstone Reservoir (Normal
Reservoir Pressure)

Computer Output Data - Nowra Sandstone Reservoir (Reservoir
Overpressured by 10%)

TITLE																															
MULGOA-2 NSR																															
RUN				DATE				LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9	IPL 0 or 1																				
0	0	0	1	0	8	-	0	5	-	7	9	43	0	0	0																
C1				C2		C3		IC4		NC4		IC5		NC5		C6	C7+	H ₂ S	CO ₂	N ₂											
0.96999				0.0		0.00001		0.0		0.0		0.00001		0.0		0.0	0.0	0.0	0.03	0.0											
PRESS				TEMP		(PVT DATA)																									
2198				132																											
PAI (KPMAX)																															
C3P (KPMAX)																															
C5P (KPMAX)																															
Notes:																															

	VOL	POR	SATW	AVETH								
5	32560	0.10	0.20	33								
	NYRMAX	NW	MAR									
6	16	10	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	86	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	5	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	5020	2.972	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	32560.	(MMSCF)
POROSITY	.1000	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	33.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	132.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2198.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	86.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5020.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	5.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 18.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
2198.0	132.0	.869	.0159	.000468	6.719 (.108)	.0467
1700.0	132.0	.880	.0147	.000630	5.130 (.082)	.0356
1300.0	132.0	.899	.0138	.000831	3.843 (.062)	.0267
900.0	132.0	.924	.0131	.001189	2.587 (.041)	.0180
500.0	132.0	.955	.0123	.002088	1.390 (.022)	.0097
100.0	132.0	.991	.0119	.010093	.268 (.004)	.0019

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PRESSURES (PSIA)

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			FRAC PROD	PRESSURES (PSIA)		
		SALES GAS BCF	LPG MMBL	COND MMBL	SALES GAS BCF	LPG MMBL	COND MMBL		TOP	BOT	RES
1	1.82	.66	.00	.01	.66	.000	.000	.0204	102.0	154.1	2155.5
2	1.75	.64	.00	.01	1.30	.000	.000	.0400	159.7	202.9	2114.6
3	1.68	.61	.00	.00	1.92	.000	.000	.0588	208.3	249.2	2075.3
4	1.65	.60	.00	.00	2.52	.000	.000	.0773	116.7	160.0	2036.7
5	1.58	.58	.00	.00	3.09	.000	.000	.0950	164.3	202.8	1999.5
6	1.55	.57	.00	.00	3.66	.000	.000	.1124	69.4	118.0	1963.0
7	1.49	.54	.00	.00	4.20	.000	.000	.1291	119.8	157.6	1927.9
8	1.43	.52	.00	.00	4.72	.000	.000	.1451	160.5	195.1	1894.1
9	1.40	.51	.00	.00	5.23	.000	.000	.1608	77.1	117.5	1860.9
10	1.34	.49	.00	.00	5.73	.000	.000	.1758	118.8	152.3	1829.0
11	1.29	.47	.00	.00	6.20	.000	.000	.1903	154.0	185.3	1798.3
12	1.27	.46	.00	.00	6.66	.000	.000	.2045	79.6	114.3	1768.2
13	1.22	.44	.00	.00	7.10	.000	.000	.2181	115.1	145.0	1739.2
14	1.17	.43	.00	.00	7.53	.000	.000	.2312	145.7	174.2	1711.3
15	1.14	.42	.00	.00	7.95	.000	.000	.2441	101.0	129.5	1684.6
16	1.12	.41	.00	.00	8.36	.000	.000	.2566	64.9	96.7	1658.8

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	32560	(MMSCF)
POROSITY	.1000	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	33.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	132	(DEGREES F)
INITIAL RESERVOIR PRESSURE	2417	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	86.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	5020	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	5.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96938
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000

GAS GRAVITY = 583

16.88

AVERAGE MOLECULAR WEIGHT OF GAS =

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$ CUBIC FEET / BARREL

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU. FT.) ((GM/CC))	GAS GRADIENT (PSI/FT)
2417.0	132.0	.868	.0165	.000414	7.396 (.118)	.0514
2000.0	132.0	.872	.0153	.000524	6.093 (.098)	.0423
1600.0	132.0	.884	.0145	.000672	4.807 (.077)	.0334
1200.0	132.0	.904	.0136	.000900	3.524 (.056)	.0245
800.0	132.0	.932	.0129	.001331	2.281 (.037)	.0158
400.0	132.0	.964	.0122	.002589	1.102 (.018)	.0077

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PRESSURES (PSIA)

MULGOA NSR

YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			PRESSURES (PSIA)			RES
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	TOP	BOT		
1	2.14	78	01	01	78	000	000	167.3	222.0	2360.4	
2	2.06	75	00	01	1.53	000	000	155.0	208.1	2306.0	
3	1.97	72	00	01	2.25	000	000	142.5	194.2	2253.7	
4	1.90	69	00	01	2.94	000	000	129.9	180.3	2203.4	
5	1.82	66	00	00	3.61	000	000	117.0	166.5	2155.0	
6	1.75	64	00	00	4.25	000	000	103.9	152.9	2108.6	
7	1.68	61	00	00	4.86	000	000	90.5	139.3	2063.9	
8	1.61	59	00	00	5.45	000	000	76.6	126.0	2020.9	
9	1.55	57	00	00	6.01	000	000	105.1	146.5	1980.6	
10	1.49	54	00	00	6.56	000	000	162.6	198.7	1942.6	
11	1.43	52	00	00	7.08	000	000	212.3	248.1	1906.1	
12	1.40	51	00	00	7.59	000	000	86.2	124.9	1870.2	
13	1.34	49	00	00	8.08	000	000	137.3	170.1	1835.7	
14	1.29	47	00	00	8.55	000	000	180.9	212.8	1802.4	
15	1.27	46	00	00	9.01	000	000	61.0	99.6	1769.7	
16	1.22	44	00	00	9.46	000	000	108.5	138.7	1738.3	

EAST MAITLAND-1DELIVERABILITY POTENTIAL

Computer Input Data - Muree Sandstone Reservoir

Computer Output Data - Muree Sandstone Reservoir (Normal
Reservoir Pressure)

Computer Output Data - Muree Sandstone Reservoir (Reservoir
Overpressured by 10%)

	TITLE																												
1	EAST MAITLAND MSR																												
	RUN				DATE						LUN 3 or 6	ICODE 0 or 1	KPMAX 0 to 9					IPL 0 or 1											
2	0	0	0	1	0	8	-	0	5	-	7	9	43	0	0	0													
	C1				C2		C3		IC4		NC4	IC5	NC5	C6	C7+	H ₂ S	CO ₂	N ₂											
3	0.96999				0.0		0.00001		0.0		0.0	0.00001	0.00	0.0	0.0	0.0	0.03	0.0											
	PRESS				TEMP		(PVT DATA)																						
4	1015				104																								
	PAI (KPMAX)																												
4A																													
	C3P (KPMAX)																												
4B																													
	C5P (KPMAX)																												
4C																													
Notes:																													

	VOL	POR	SATW	AVETH								
5	176362	0.07	0.20	230								
	NYRMAX	NW	MAR									
6	16	10	0									
	QMAR →											
6A												
	QMAR →											
6B												
	QMAR →											
6C												
	RW	KH	S	DTURB								
7	0.541	2070	10	0.0								
	Q	QMIN	THPMIN	QOVER								
8	5	0.2	60	1.1								
	TBGEL	TBGDIA	FR	FAC	TEMTOP	IEND						
9	2330	2.972	0.014	1.0	100	-1						
Notes :												

DELIVERABILITY PARAMETERS

RESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	176362.	(MMSCF)
POROSITY	.0700	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	230.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	104.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	1015.	(PSIA)

WELL DATA

WELL RADIUS	5410	(FT)
PERMEABILITY*THICKNESS	2070.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	2330.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	20.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
LPG - PROPANE AND BUTANES
CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
		AVERAGE	AVERAGE	TOTAL
		685.09	349.34	1.00000

GAS GRAVITY = .583

16.88

AVERAGE MOLECULAR WEIGHT OF GAS =

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA,
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = \$\$\$\$\$\$ CUBIC FEET / BARREL

EAST MAITLAND MSR

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
1015.0	104.0	.899	.0129	.001078	3.148 (.050)	.0219
600.0	104.0	.937	.0121	.001772	1.785 (.029)	.0124
200.0	104.0	.978	.0116	.005110	.570 (.009)	.0040

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			PRESSURES (PSIA)			
		SALES GAS BCF	LPG MMBBL	COND MMBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL	FRAC PROD	TOP	BOT	RES
1	8.91	3.25	02	03	3.25	000	000	0184	148.3	371.8	998.0
2	8.74	3.19	02	03	6.44	000	000	0365	131.6	358.9	981.3
3	8.56	3.12	02	02	9.57	000	000	0542	113.8	346.2	964.8
4	8.39	3.06	02	02	12.63	000	000	0716	93.7	333.6	948.7
5	8.22	3.00	02	02	15.63	000	000	0886	69.3	321.2	932.8
6	7.90	2.88	02	02	18.51	000	000	1050	127.5	328.0	917.5
7	7.74	2.82	02	02	21.34	000	000	1210	111.3	316.1	902.4
8	7.58	2.77	02	02	24.10	000	000	1367	93.4	304.4	887.6
9	7.43	2.71	02	02	26.82	000	000	1521	72.5	292.8	873.1
10	7.14	2.61	02	02	29.42	000	000	1668	120.0	298.6	859.1
11	6.99	2.55	02	02	31.98	000	000	1813	105.0	287.6	845.3
12	6.86	2.50	02	02	34.48	000	000	1955	88.7	276.7	831.8
13	6.72	2.45	02	01	36.93	000	000	2094	69.8	265.9	818.5
14	6.45	2.35	02	01	39.28	000	000	2228	110.4	270.9	805.7
15	6.32	2.31	02	01	41.59	000	000	2358	96.4	260.6	793.1
16	6.20	2.26	01	01	43.85	000	000	2487	81.1	250.5	780.8

DELIVERABILITY PARAMETERSRESERVOIR DATA

VOLUME OF GAS INITIALLY IN PLACE	176362.	(MMSCF)
POROSITY	.0700	(FRACTION)
WATER SATURATION	.2000	(FRACTION)
AVERAGE THICKNESS OF RESERVOIR	230.0000	(FT)
INITIAL RESERVOIR TEMPERATURE	104.	(DEGREES F)
INITIAL RESERVOIR PRESSURE	1116.	(PSIA)

WELL DATA

WELL RADIUS	.5410	(FT)
PERMEABILITY*THICKNESS	2070.0000	(MDS-FT)
SKIN FACTOR	10.00	
TURBULENCE FACTOR	0.0000	(D/MMSCF)
TUBING ELEVATION (TRUE VERTICAL DEPTH)	2330.	(FT)
TUBING DIAMETER	2.9720	(IN)
FRICTION FACTOR	.0140	
ACTUAL LENGTH / TRUE VERTICAL DEPTH FACTOR	1.0000	
TEMPERATURE OF GAS AT SURFACE IN TUBING	100.	(DEGREES F)

ASSUMED REQUIREMENTS

INITIAL RAW GAS PRODUCTION RATE	20.0000	(MMSCF/D/WELL)
NUMBER OF PRODUCING WELLS	1	
PEAK PRODUCTION RATE / PRODUCTION RATE	1.1000	(RATIO)
MINIMUM TUBING HEAD PRESSURE	60.	(PSIA)
MINIMUM (OR CUT-OFF) PRODUCTION RATE	.2000	(MMSCF/D/WELL)

DEFINITIONS

SALES GAS - METHANE, ETHANE, AND UP TO 3% CARBON DIOXIDE
 LPG - PROPANE AND BUTANES
 CONDENSATE - PENTANES PLUS

COMPONENTS	MOLECULAR WEIGHT	CRITICAL PRESSURE (PSIA)	CRITICAL TEMPERATURE (R)	MOL FRACTION
METHANE	16.042	673.1	343.2	.96998
ETHANE	30.068	708.3	549.8	0.0000
PROPANE	44.094	617.4	665.9	.00001
ISO-BUTANE	58.120	529.1	734.6	0.0000
N-BUTANE	58.120	550.7	765.3	0.0000
ISO-PENTANE	72.146	483.0	829.7	.00001
N-PENTANE	72.146	489.5	845.6	0.0000
HEXANES	86.172	439.7	914.2	0.0000
HEPTANES PLUS	114.22	362.1	1024.9	0.0000
HYDROGEN SULPHIDE	34.076	1306.0	672.4	0.0000
CARBON DIOXIDE	44.010	1073.0	547.7	.03000
NITROGEN	28.016	492.0	226.9	0.0000
	AVERAGE	685.09	AVERAGE 349.34	TOTAL 1.00000

AVERAGE MOLECULAR WEIGHT OF GAS = 16.88 GAS GRAVITY = .583

SALES GAS = 1.0000 MMSCF/MMSCF RAW GAS

DRY-BASIS HEATING VALUE = 982. BTU/CUBIC FOOT VAPOR AT 14.696 PSIA.
(.36575E+08 JOULE/CUBIC METRE)

LPG = .01 BARRELS/MMSCF RAW GAS, (.04 CUBIC METRES/MM CUBIC METRES)

CONDENSATE = .01 BARRELS/MMSCF RAW GAS, (.05 CUBIC METRES/MM CUBIC METRES)

GAS/CONDENSATE (OR OIL) RATIO = ##### CUBIC FEET / BARREL

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RESERVOIR PRESSURE (PSIA)	RESERVOIR TEMPERATURE (F)	GAS DEVIATION FACTOR (Z)	VISCOSITY AT RESERVOIR CONDITIONS (CP)	COMPRESS- IBILITY (PSIA*-1)	GAS DENSITY (LB/CU.FT.) (GM/CC)	GAS GRADIENT (PSI/FT)
1116.0	104.0	.891	.0131	.000985	3.493 (.056)	.0243
700.0	104.0	.927	.0122	.001532	2.105 (.034)	.0146
300.0	104.0	.968	.0117	.003442	.864 (.014)	.0060

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YR	RATE PER WELL RAW GAS MMCFD	ANNUAL PRODUCTION			CUMULATIVE PRODUCTION			FRAC PROD	PRESSURES (PSIA)		
		SALES GAS BCF	LPG MBBL	COND MBBL	SALES GAS BCF	LPG MMBBL	COND MMBBL		TOP	BOT	RES
1	10.69	3.90	.03	.03	3.90	.000	.000	.0221	125.8	426.5	1093.7
2	10.48	3.82	.03	.03	7.73	.000	.000	.0438	78.6	406.9	1071.7
3	10.06	3.67	.02	.03	11.40	.000	.000	.0646	135.3	407.1	1050.6
4	9.86	3.60	.02	.03	15.00	.000	.000	.0850	97.3	388.3	1029.7
5	9.47	3.46	.02	.03	18.46	.000	.000	.1046	140.9	388.2	1009.7
6	9.28	3.39	.02	.02	21.84	.000	.000	.1239	108.3	370.3	989.9
7	9.10	3.32	.02	.02	25.16	.000	.000	.1427	63.9	352.6	970.5
8	8.74	3.19	.02	.02	28.35	.000	.000	.1608	112.9	352.1	951.8
9	8.56	3.12	.02	.02	31.48	.000	.000	.1785	75.9	335.2	933.3
10	8.22	3.00	.02	.02	34.48	.000	.000	.1955	114.9	334.5	915.6
11	8.06	2.94	.02	.02	37.42	.000	.000	.2122	82.7	318.4	898.1
12	7.74	2.82	.02	.02	40.24	.000	.000	.2282	115.1	317.6	881.3
13	7.58	2.77	.02	.02	43.01	.000	.000	.2439	86.4	302.2	864.7
14	7.28	2.66	.02	.01	45.67	.000	.000	.2590	114.0	301.2	848.8
15	6.99	2.55	.02	.01	48.22	.000	.000	.2734	134.1	300.2	833.4
16	6.72	2.45	.02	.01	50.67	.000	.000	.2873	146.0	297.0	818.7