DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1973/170

EVAPORITES IN AUSTRALIA

PART I

A Review of Sedimentary Basin and Modern Continental deposits with brief comparative notes on overseas occurrences

by

A.T. Wells

PART II

A Short Report on Evaporite Deposits of Australia

by

G. Richter-Bernburg

Record 1973/170

EVAPORITES IN AUSTRALIA

PART I

A Review of Sedimentary Basin and Modern Continental deposits with brief comparative notes on overseas occurrences

by

A.T. Wells

PART II

A Short Report on Evaporite Deposits of Australia

by

G. Richter-Bernburg

CONTENTS

APPENDICES

Page

TABLES

PLATES

FIGURES

TABLES

FIGURES

PART I

SUMMARY

Major evaporite basins have been discovered in Australia over the past decade chiefly as a result of the large increase in the number of wells drilled in the search for petroleum. The main basins so far known are the Adavale, Amadeus, Canning, Officer and offshore Bonaparte Gulf Basins. In the Adavale, Canning, and offshore Bonaparte Gulf Basins the evaporites are obscured beneath several thousand metres of sediments. However, in the Officer and Amadeus Basins the less soluble evaporites of the basin sequence are partly exposed either in the cores of eroded folds, along fault trends, or in diapiric structures. Two diapirs have been drilled in the Bonaparte Gulf and proved to be salt domes. The evaporites are Precambrian, Cambrian, possibly Silurian, and Devonian in age. Over 600 m of evaporites have been penetrated in the Canning Basin in one hole drilled into a diapiric structure, and a similar thickness of bedded evaporite was penetrated in a petroleum exploration well. Potash has been discovered only in the Adavale Basin but the thickness of the beds is less than 25 cm. Native sulphur has only been found in modern surface deposits of playa lakes.

Further exploration of these evaporite deposits, with location of economic minerals in mind, can proceed logically from an investigation by mapping and shallow drilling of a selected number of the surface occurrences to detailed geophysical investigations of some near-surface deposits. The drilling will primarily be used to establish the mineralogy of the evapaporites. Further drilling targets no doubt will present themselves as a result of both petroleum company geophysical investigations and the detailed surveys. Besides drilling and geophysical surveys, lithofacies studies and the elucidation of the palaeogeographic history of a basin are the major objectives in determining the distribution and framework of an evaporite deposit. Lithofacies studies of well sections and formations in outcrop can be used to delineate areas for further investigation.

None of the modern playa lake evaporite deposits appear to hold any potential for producing economic minerals apart from halite. Any commercial production of other minerals would be a by-product of halite harvesting.

The world resources of sulphur are very large and ample to supply any foreseeable future demand. Resources of potassium compounds are sufficient for several thousand years. If an economic method of recovering potassium from sea water is found supply will be virtually infinite.

One of the biggest problems is translating large surplus production capacity in a few countries into shipments to the countries in need. The economics of successfully working these large deposits varies considerably and could be important, for example when considering the cost of transport of the Canadian deposits, which lie far inland and will therefore be at a disadvantage, compared with deposits near tidal water, such as the recently discovered Ethiopian potash. Long range plans should incorporate exploration programs for potash and sulphur in areas that will at least compete with established producers.

The framework of an exploration program is determined primarily by the following

1. Locating shallow deposits of high grade
2. Locations within reach of transport and labour
3. The country in which they are found should have both a stable economy and political climate
4. Favourable transport facilities.

It appears that some need exists in Australia for continuing exploration for elemental sulphur deposits and potassium minerals, but not just in times of shortages, when new deposits generally are developed too late to even out the imbalance.

INTRODUCTION

This report reviews the available information on Australian evaporite occurrences and presents new data on these deposits gathered mainly during discussions with geologists of State Geological Surveys and Mines Departments and exploration companies. Their offices were visited in company with Dr G. Richter-Bernburg, Director of the Federal West German Geological Survey, who was employed by the Bureau as a consultant specialist from 21 April to 24 May 1971. His recommendations and personal views are presented in Part II of this Record.

The report presents a general review of Australian evaporite occurrences and in addition some notes on the pertinent features of a few evaporite deposits in foreign countries. Recommendations for a program of exploration and research into evaporite occurrences, with emphasis on the location of economic deposits of potash and sulphur, are also outlined.

Thin surface accumulations of salt (chiefly halite) in playa lakes have been known since the early exploration of Australia. However, it is only in the last decade that substantial amounts of subsurface evaporites have been located, mostly in the course of drilling for petroleum. Even where there are surface occurrences of bedded evaporites, exposed in some sedimentary basins by erosion of the sedimentary sequence, these have been discovered only as a result of recent regional geological mapping.

Although evaporites can be important in some structures as cap rocks for hydrocarbon accumulations, there was little incentive for the oil exploration companies to continuously core the evaporite sequences. In most well sections there are only one or two cores in any evaporite sequence and in some wells no cores were attempted in what were undoubtedly thick evaporites. As a result, some of the more important details of depositional history are missing. It is, however, unlikely that significant beds of potassium-rich minerals have been overlooked as they would undoubtedly be recorded on the gamma ray logs.

Thirty petroleum exploration wells have intersected small or large evaporite beds. The known number of wells that have been purposely drilled to test or explore for evaporite deposits includes five drilled by the Bureau of Mineral Resources and five by exploration companies.

DISTRIBUTION OF EVAPORITES IN AUSTRALIA

In past geological time large tracts of what is now continental Australia were subjected to marine inundations. However, during long periods of time these areas were not open sea, but large restricted basins, either narrowly connected to the open sea, or separated from it by a shallow shelf or bar. Evaporation of large quantities of sea water from these basins resulted in the formation of thick deposits of evaporites. This classic theory is generally called the Ochsenius bar theory of saline deposition. (Ochsenius, 1877, 1888), and quantitative data in its support were recently presented by Whelan (1972).

Subsurface evaporites are widespread in Australia, in sedimentary rocks. Thick deposits were formed, chiefly in the late Precambrian, Cambrian, Silurian, and Devonian, and are preserved in the Canning, Amadeus, Adavale, Officer, Carnarvon, Arckaringa, and offshore Bonaparte Gulf Basins. The largest deposits, volumetrically, in Australia are distributed between 18° and 28° south. The thickest known evaporites occur within this zone and known evaporites outside it are relatively poorly developed. There does not appear to be any significance in this distribution, as the deposits are of several ages; their present distribution may be partly controlled by the structural evolution of individual basins.

Presently-forming evaporite deposits of significant extent and thickness are unknown in Australia, though surface evaporites in modern playa lake deposits are common in areas of low rainfall, subdued topography, and internal drainage, such as are found in many parts of Western and South Australia, and the Northern Territory.

SEDIMENTARY BASIN OCCURRENCES

The pertinent statistics of the major evaporite deposits in Australia are summarized in Table I.

Petroleum exploration wells containing evaporites are listed, by company, in Table II and their location shown in Plate VI.

The sequences in wells that intersected evaporites are illustrated graphically in Plates I to III, and details of the evaporite intervals are given in Table III.

Canning Basin

Evaporites of possible Siluro-Devonian age have been intersected in eight petroleum exploration wells, although in only four does the salt attain a thickness of several hundred metres. There are no surface exposures of evaporites.

TABLE I. THE MAJOR EVAPORITE DEPOSITS OF AUSTRALIA

BASIN	FORMATION	PROBABLE AGE OF EVAPORITES	MAXIMUM GROSS HALITE THICKNESS (m)	WELL IN WHICH THICKNESS MEASURED	INFERRED AREA OF EVAPORITES ($km^2 \times 10^3$)	POTASH OCCURRENCES
Canning (WA)	Carribuddy Fm.	Siluro-Devonian	740	McLarty No. 1	207	not known
Amadeus (NT)	Bitter Springs Fm.	Late Precambrian	215	Mt Liebig No. 1	83	not known
Amadeus (NT)	Chandler Lst.	Early Cambrian	225	Mt Charlotte No. 1	41	not known
Adavale (Qld)	Etonvale Fm.	Middle Devonian	550	Bury No. 1	8	Thin beds in two well sections (less than 15 cm)
			900	Estimated from seismic results		
Carnarvon (WA)	Dirk Hartog Fm.	Late Silurian	37	Yaringa No. 1 (distributed in eight beds)	1.3	not known
Officer (WA)	Browne Beds ?	Late Precambrian, possibly also early Palaeozoic	15+	Warri No. 20	3.1	not known
				Presence of salt domes suggests halite beds at least several hundred metres thick.		
Bonaparte Gulf (WA) (offshore part)	Ningbing Lst. ?	Famennian ?	185	Pelican Island No. 1	26	not known

7

TABLE II - EXPLORATION WELLS CONTAINING EVAPORITES

Company and Well Name and No.	Basin
West Australian Petroleum Pty Ltd	
Kidson No. 1	Canning (Kidson sub-basin)
Sahara No. 1	" (" ")
Willara No. 1	"
Frome Rocks No. 1	Canning (Jurgurra Terrace)
Parda No. 1	Canning
Pendock I.D. No. 1	Carnarvon
Munda No. 1	Canning
Exoil N.L.	
Alice No. 1	Amadeus
Ooraminna No. 1	"
Erldunda No. 1	"
Phillips Australian Oil Company	
Stafford No. 1	Adavale
Bonnie No. 1	"
Bury No. 1	"
Hartogen Explorations Pty Ltd	
Alva No. 1	Adavale
Hunt Oil Co.	
Browne No. 1	Officer
Browne No. 2	"
Hunt-Placid Oil Co.	
Yowalga No. 2	Officer
Continental Oil Company of Australia	
Birksgate No. 1	Officer

A.G.O./A.O.G.	
Aquarius No. 1	Capricorn embayment
S.A. Department of Mines	
Cootanoorina No. 1	Arckaringa
Australian Aquitaine Petroleum Ltd	
Wilson Cliffs No. 1	Canning (Kidson Sub-basin)
Total Exploration	
McLarty No. 1	Canning (Broome Platform)
Amoseas	
Boree No. 1	Adavale
Amerada Petroleum	
McDills No. 1	Pedirka
Transoil N.L.	
Mt Charlote No. 1	Amadeus
Magellan Petroleum (Australia) Ltd	
Hamelin Pool No. 1	Carnarvon
Hamelin Pool No. 2	"
Orange No. 1	Amadeus
B.O.C. of Aust. Ltd	
Rob Roy No. 1	Browse
Continental Sun	
Yaringa No. 1	Carnarvon
Arco Aust. Ltd	
Pelican Is No. 1	Bonaparte Gulf - offshore
Sandpiper No. 1	" " - "

Bureau of Mineral Resources

B.M.R. Madley No. 1	Officer
B.M.R. Warri No. 20	"
B.M.R. Alice No. 3	Amadeus
B.M.R. Mount Liebig No. 1	"
B.M.R. Lake Amadeus No. 3, 3A, 3B	"

The evaporites occur within the Carribuddy Formation, which underlies an area of 210 000 km^2 in the Canning Basin, although evaporites are not present throughout this area. This area does not take into account the salt penetrated in the Frome Rocks salt dome, which is considered to be most probably of a different age to the Carribuddy Formation, or at least from a different facies, and hence of unknown extent (see Richter-Bernburg, this record p.). Most geologists, however, consider that it is probably derived from the Carribuddy Formation.

The Carribuddy Formation is thickest in the centre of the Kidson Sub-basin (Fig. 1) south of the Fitzroy Trough; isopachs on the formation, and a cross-section of the Kidson Sub-basin, using well sections for control, are shown in Plates 4 and 5.

The pre-Permian sequence in the Kidson Sub-basin has been discussed by Koop (1966) and more recently by Creevey (1971) and the sequence (slightly modified from their work) is -

TOP - Mellinjerie Limestone - Frasnian to ?Givetian (prob. basal Frasnian)

Tandalgoo Red Beds - Gedinnian

Carribuddy Fm (Unit A, " B, " C, " D, " E) Age not certain (Siluro-Devonian?)

Nita Formation - Llanvirnian to Llandeilian

Goldwyer Formation - Llanvirnian to ?Llandeilian

Thangoo Limestone - Arenigian

BASE - Nambeet Formation - Tremadocian? to Arenigian

The generalized sequences of five informal units in the Carribuddy Formation in the Kidson No. 1 well and their thicknesses are:

TOP	- Unit A	- shale, some sandstone and dolomite	370 m	)
	" B	- halite	520 m	)
	" C	- shale, grey and grey-green	460 m	) 1710 m
	" D	- halite, shale and red dolomite	150 m	)
BASE	- " E	- shale	210 m	)

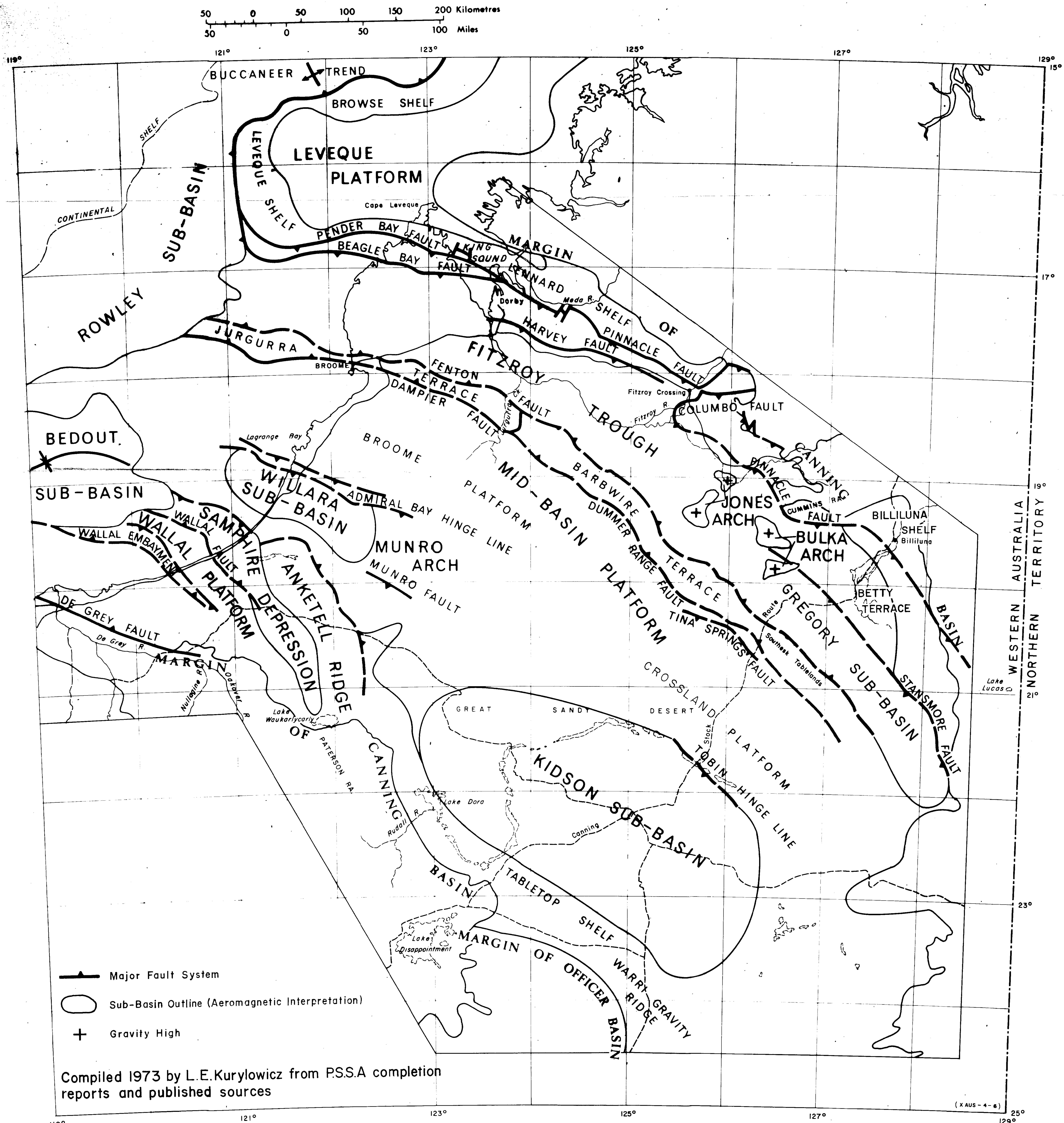
The evaporites are more common in units B and D of the formation but thickest in unit B; they consist predominantly of halite with minor anhydrite. Minor anhydrite and halite occur in units A and C, which are composed mostly of shale, with subordinate mudstone, limestone, and dolomite.

The thickest sequence of evaporites was penetrated in McLarty No. 1 well (740 m); other major evaporite sequences were intersected in Frome Rocks No. 1 (530 m), Kidson No. 1 (530 m) and Willara No. 1 (204 m +). Evaporite sections penetrated in Parda No. 1 and Wilson Cliffs No. 1 were poorly developed and only the top of the Carribuddy Formation was penetrated in Sahara No. 1. The bottom hole core 1 060.70 - 1 066.80 m, in Munda No. 1 well contains halite, but no other details were available at the time of writing. Sections of the Carribuddy Formation have been penetrated in other wells, e.g. Kemp Field No. 1 and Matches Springs No. 1, but lack any noticeable thicknesses of salt.

There are no published reports available describing any internal evidence for the age of the Carribuddy Formation. McTavish (pers. comm.) states that palynomorphs, conodonts, ostracods, foraminifera, and fish scales have been recorded and discussed in reports by WAPET and TOTAL, and he favours a Devonian age. More specifically McTavish indicated that there were possible ? Lower Devonian fish scales in the upper part of the Carribuddy Formation penetrated in the Kemp Field No. 1 well, (about 60 m from the top of the Formation).

In the Kidson No. 1 well a Devonian age has been suggested for cores 17 and 18 (3742.1 - 3744.5 m; 3864.3 - 3867.4 m; and in Willara No. 1 palynology indicates a Devonian age for samples from a core at about 1750 m. For some time the oldest known formation overlying the Carribuddy Formation was the Mellinjerie Limestone of Upper to possibly Middle Devonian age. Similarly the youngest known formation below was the Lower Ordovician (Llanvirnian - ?Llandeilian) Goldwyer Formation.

FIG 1-TECTONIC MAP OF CANNING BASIN



Compiled 1973 by L.E.Kurylowicz from P.S.S.A completion reports and published sources

To accompany Record 1973/170

AUS 1/221A

TABLE III - DETAILS OF EVAPORITE INTERVALS IN PETROLEUM AND MINERAL EXPLORATION WELLS

(Abridged from well completion reports)

All measurements in metres unless stated otherwise

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
WA	Canning (Kidson Sub-basin)	Wapet	Kidson No. 1 22°37'00"S 125°00'22"E	Mellingerie Limestone (1570.6-1837.0) Unit 1	M.-U.? Devonian	1570.6-1667.2	Dolomite with some micro-crystalline anhydrite; sandstone and dolomitic siltstone.	Carribuddy Fm. No. 9, Rec. 3.0, 2608.5-2611.5 Anhydritic sandy dolomite. No. 10, Rec. 3.0, 2768.8-2771.9 Anhydritic dolomite and anhydrite veins. No. 11, Rec. 1.8, 2929.4-2932.5 Anhydritic dolomite. No. 12, Nil rec. No. 13, Rec. 4.6, 3095.2-3102.9 55% Halite, 35% Qtz. No. 14, Rec. 0.4, 3276.6-3282.7 Halite and Qtz. No. 15, Rec. 2.1, 3543.0-3546.0 Anhydritic calc. claystone. No. 16, Nil rec. No. 17, Rec. 2.4, 3742.0-3744.5, limestone. No. 18, Rec. 3.0, 3864.3-3867.3, 50% clay, 23% Qtz., 22% halite and halite-bearing limestone. No. 19, Rec. 3.0, 4031.3-4034.3, 60% dolomite, 10% clay, 15% Qtz., 5% halite. No. 20, Rec. 1.2 4191.6-4193.7, siltstone.	9.1 intervals to 975.4, and 3.0 intervals to T.D.
				Unit 2		1667.2-1837.0	Dolomite, dolomitic siltstone, some anhydrite.		
			(TD 4431.4)	Carribuddy Formation (2570.0-4279.3)	Siluro- Devonian?				
				Unit A		2570.0-2941.3	Dolomite, siltstone, sandstone.		
				Unit B		2941.3-3467.7	Dominantly halite; coarse anhydrite in claystone.		
				Unit C		3467.7-3905.0	Claystone, with some microcrystalline anhydrite in sandstone; some halite in sandy limestone.		
				Unit D		3905.0-4071.2	Claystone, with dolomite and interbedded halite.		
				Unit E		4071.2-4279.3	Claystone and dolomite with rare thin beds and veins of halite and anhydrite.		
WA	Canning (Kidson Sub-basin)	Wapet	Sahara No. 1 21°04'40"S 123°23'30"E	Tandalgoo Red Beds (1127.8-1726.6) Unit B	L. Devonian	1199.3-1359.4	Red sandstone with minor siltstone; minor anhydrite below 1341.1.	NIL	Available
				Unit D		1417.3-1726.6	Red sandstone, with ?anhydrite or ?kaolin.	No. 9, 1552.0-1555.6 Rec. 2.4	Available
			(TD 2120.1)	Carribuddy Formation (1726.7-2120.2) Spotted Shale, Unit A	Siluro- Devonian?	1726.6-2033.0	Shale, with rare anhydrite and halite patches.	No. 12, 1999.7-2003.1 Rec. 3.0	Available according to well completion report, but none shown 1798.3-1889.7 on % lithology log.

TABLE III - Page 2.

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
				Evaporite, Unit B		2033.0-2120.1 (T.D.)	Shale and claystone, with salt and anhydrite as nodules and crystals, and rare crystalline veins up to 2.5 cm	No. 13, 2118.6-2120.1 Rec. 12.7 cm	Available
WA	Canning	Wapet	Willara No. 1 19°10'48" S 122°04'14"E (TD 3903.2)	Carribuddy Formation (1255.1-1873.9)	Siluro-Devonian?				
				Unit A		1873.9-1458.5	24.4 claystone, underlain by rock salt and anhydrite.		
				Unit B		1458.5-1736.4	Claystone, siltstone and sandstone; rock salt and anhydrite throughout interval.		
				Unit C		1736.4-1873.9	Dolomite with anhydrite to 1786.1; limestone below.		
WA	Canning (Fitzroy Trough)	Wapet	Frome Rocks No. 1 18°11'48"S 133°38'42" E (TD 1220.1)		Pre-Mesozoic	687.6-1220.1	532.4 of halite with scattered small fragments of dolomite & occasionally anhydrite, & several beds of dolomite breccia, & some claystone. Analysis of core No. 5 755.9-758.9 showed that the water-soluble part of the specimen consists essentially of halite with a little gypsum. Thin sections of cores Nos 5,6, and 8 contain about 5% of anhydrite.	No. 5, 755.9-758.9; Rec. 2.7 No. 6, 835.1-838.2; Rec. 3.0 No. 7, 894.8-897.9; Rec. 3.0 No. 8, 957.6-960.7; Rec. 2.7 No. 9, 1021.0-1024.1; Rec. 2.4 No.10, 1085.0-1088.1; Rec. 3.0 No.11, 1149.0-1152.1; Rec. 3.0 No.12, 1211.5-1214.6; Rec. 2.4	Available
WA	Canning (Fitzroy Trough)	Wapet	Grant Range No.1 18°01'00"S 124°00'30"E (TD 3936.4)	Anderson Formation (1856.2-3936.5)	Upper Carboniferous	2950.4-3102.8	Interbedded limestone, shale and anhydrite.		
WA	Canning	Wapet	Parda No. 1 18°56'08"S 122°00'34"E (TD 1906.8)	Carribuddy Formation (980.2-1183.8)	Siluro-Devonian?				
						980.2-1152.1	Red-brown claystone, with anhydrite in fine-medium crystalline nodules and also as powder disseminated through the claystone.	Sidewall cores 20 (2)-7(2)	Available
						1152.1-1183.8	Green and grey-green claystone, moderately to very anhydritic, and limestone with anhydrite crystals.	Sidewall cores 5(2)-1(2)	Available

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
				Goldwyer Formation (1183.8-1495.3) (tentative identification)	Ordovician	1183.8-1269.4	Limestone, anhydrite, dolomitic and pyritic.	No. 1, 1184.7- 1188.1; Rec. 3.4	
WA	Canning (Willara Sub-basin)	Wapet	Munda No. 1 19°28'27" S 122°17'32"E (TD 1066.8)	Carribuddy Formation (800.4-1066.8+)	Siluro-Devonian?	Unit A, 800.4-1012.5		No. 1, 1060.7-1066.8 Sidewall core at 1036.3, Rec. 2.5 cm of red-brown and grey claystone with white salt stringers.	9.1 intervals
						Unit B, 1012.5-1066.8	Unit B 1012.5-1021.9, halite common in claystone. 1021.9-1066.8, halite, massive rock salt, brown, pink and colourless, transparent to translucent, coarsely crystalline. Band and fragments of claystone similar to 961.9-1012.5 with minor siltstone and shale.		
WA	Canning (Kidson Sub-basin)	Australian Aquitaine	Wilson Cliffs No. 1	Mellinjerie Limestone (966.8-1094.2)	M.-U. Devonian	1009.1-1094.2 (Member 2)	Dolomite with anhydrite in thin beds, vein fillings or kernal of oolites.	No. 2, 1010.7-1016.8 No. 8, 1814.7-1819.3, Rec; 4.2 No. 9, 1992.4-1996.8, Rec; 4.6 No. 10, 2211.6-2214.9, Rec, 3.3 No. 11, 2434.1-2437.1, Rec, 3.0	
				Carribuddy Formation (1778.5-2532.8)	Siluro-Devonian?	2029.3-2368.2 (Unit C)	Grey calcareous shale, anhydrite nodules & veins in parts, trace gypsum throughout.		
						2368.2-2496.3 (Unit D)	Mostly halite, traces anhydrite, some shale and sandstone		
				Goldwyer Formation (2532.8-2847.4)	M. Ordovician (Llanvirnian-Llandeilian)	2532.9-2847.4	Shale and limestone, traces anhydrite in shale.	No. 12, 2568.5-2572.2; Rec, 3.7 No13, 2679.1-2683.7; Rec. 4.6 No. 14, 2780.9-2784.0; Rec. 3.0	
WA	Canning (Broome Platform)	Total Exploration	McLarty No. 1 19°23'45" S 123°39'30" E (TD 2590.8)	Carribuddy Formation (452.0-1687.3)	Siluro-Devonian?	452.0-675.4 (Unit A)	Dolomite with interbeds of shale, and shale and siltstone. Halite and anhydrite intercalations towards base.	No. 5, 463.2-466.3; Rec. 2.4 No. 6, 577.5-580.6; Rec. 1.9	
						675.4-1414.8 (Unit B)	Halite, minor mudstone and traces of anhydrite.	No. 7, 735.7-738.8; Rec. 1.7 No. 8, 738.8-744.9; Rec. Nil No. 9, 1288.3-1291.4; Rec. 2.7 No. 10, 1495.9-1499.0; Rec. 2.9	
						1414.8-1511.5 (Unit C)	Mudstone with some halite inclusions.		

35

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
						1511.5-1577.9 (Unit D)	Halite and mudstone interbedded at top, overlying mudstone with halite and anhydrite inclusions.		
						1577.9-1687.3 (Unit E)	Mudstone, anhydrite and anhydritic dolomite in upper part (1577.9-1630.6) and limestone minor shale and anhydrite (1630.6-1687.3)	No.11, 1663.9-1666.3; Rec. 2.8	
N.T.	Amadeus	Exoil	Alice No. 1 23°54'47"S 133°58'00"E (TD 2291.4)	Giles Creek Dolomite (1568.8-2017.1)	Middle Cambrian	1568.8-2017.1	Shale and minor dolomite in the upper part, dolomite and minor shale in the lower. Abundant "felty" anhydrite occurs throughout, in beds, lenses and patches.	No.17, 1574.2-1577.0; Rec. 2.7 No.18, 1660.8-1662.9; Rec. 2.1 No.19, 1744.3-1745.8; Rec. 1.5 No.20, 1847.6-1848.9; Rec. 1.2 No.21, 1858.0-1859.5; Rec. 1.0 No.22, 1864.1-1865.0; Rec. 0.1 No.23, 1865.0-1870.8; Rec. 4.9 No. 24, 1963.8-1964.7; Rec. 0.8	
				Chandler Limestone (2017.1-2176.3)	Lower Cambrian	2017.1-2176.3	Halite, mudstone, dolomitic clay, shale. "Felty" primary anhydrite is common.		
							Halite, 2064.7-2088.4 " 2094.5-2129.0 " 2148.4-2181.7	No.25, 2059.8-2061.6; Rec. 1.6 No. 26, 2095.8-2102.5; Rec. 2.8	
N.T.	Amadeus	Exoil	Ooraminna No. 1 24°00'06" S 134°09'50" E (TD 1858.3)	Bitter Springs Formation (1299.9-1858.3)	Adelaidean				
				Loves Creek Member		1299.9-1609.3	Limestone and claystone with three dolerite bands; anhydrite occurs in veins and cavities in limestone below 1338.0.	No.15, 1351.1-1351.7; Rec. 0.46 No.17, 1505.4-1506.9; Rec. 1.0 No. 18, 1591.9-1594.1; Rec. 1.8 No.19, 1690.4-1690.7; Rec. 0.1 No.20, 1792.5-1793.1; Rec. 0.5 No.21, 1854.7-1857.7; Rec. 2.1 (Estimated)	Available Available
				Gillen Member		1609.3-1858.3+	1609.3-1804.4 Dolomitic limestone, with coarse crystalline anhydrite and rare gypsum in patches and veins;		

E

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
							below 1804.4, claystone, with very coarse anhydrite crystals mixed with transparent halite.		
N.T.	Amadeus	Exoil	Erldunda No. 1 25°18'36"S 133°11'48"E (TD 1665.1)	Bitter Springs Formation (1310.6–1665.1)	Adelaidean				
				Loves Creek Member		1310.6–1447.8	Dolomite with lenses and crystals of anhydrite and gypsum; sandstone and siltstone.	NIL	
				Gillen Member		1447.8–1665.1	Dolomite, anhydrite and minor gypsum, in beds, to 1618.4, 1618.4 - TD, coarsely crystalline halite.	No.10, 1460.3–1463.7; Rec. 2.7 No.12, 1661.1–1665.1; Rec. 0.03	Available
N.T.	Amadeus	Transoil	Mt Charlotte No.1 24°53'41"S 133°59'11"E (TD 2116.2)	Chandler Limestone (710.7–936.3)	Lower Cambrian	710.936.3	Coarsely crystalline halite generally pure but some interstitial clay; interbeds of calc. siltstone, 852.8–883.9.	No. 8, 795.2–801.3; Rec. 1.2 No. 9, 885.4–891.5; Rec. 1.8	Available except for interval 1469.1–1481.3
				Bitter Springs Formation (1423.4–2116.2)	Adelaidean				
				Loves Creek Member		1423.4–1554.4	Dolomite, with interbedded shale, siltstone, and sandstone. Anhydrite and gypsum, of secondary origin, are present as intrusive layers, in patches and as intergranular crystals.	No.16, 1531.6–1539.2; Rec. 7.8	
				Gillen Member		1554.4–2116.2 (TD)	Rhythmically laminated dolomite and anhydrite with halite, shale, siltstone and sandstone. Halite at 1862.9–1903.4, and streaks at 1924.8, 1938.5, 1961.3, 1999.4, 2036.0, 2048.2 and 2060.4.	No.17, 1565.7–1568.8; Rec. 3.3 No.18, 1613.0–1619.4; Rec. 3.7 No.19, 1650.7–1654.7; Rec. 4.0 No.21, 1772.4–1776.0; Rec. 3.7 No.22, 1869.9–1873.9; Rec. 3.7 No.23, 1944.9–1947.3; Rec. 2.0 No.24, 2043.0–2046.4; Rec. 3.5 No.25, 2055.8–2060.1; Rec. 4.4 No.26, 2114.3–2116.2; Rec. 1.5	

21

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
N.T.	Amadeus	Magellan	Orange No. 1 24°02'34"S 133°46'32"E (TD 2641.3)	Chandler Limestone (2274.4-2502.4)	Lower Cambrian	2314.6-2502.4	Believed to be mainly halite, with interbedded impure carbonate, anhydrite and shale in the intervals 2336.2-2352.4, and 2401.8-2420.1; and thin shale and mudstone 2453.6-2502.4.	Nil Recovery	Very small volume returns, no cuttings 2322.5-2325.6 2328.6-2331.7 2398.7-2405.7
QLD.	Adavale	Phillips	Stafford No. 1 15°17'33"S 145°26'03"E (TD 3141.2)	Etonvale Formation (1996.4-2749.6) Boree Salt Member	Middle Devonian	2672.4-2749.6	Interpreted as predominantly rock salt with thin random sandstone and shale interbeds; some anhydrite.	No.15, 2709.9-2713.0; Rec. 1.2	Available
QLD.	Adavale	Phillips	Bonnie No. 1 25°00'43"S 145°22'01"E (TD 2744.7)	Etonvale Formation (1825.8-2326.2) Boree Salt Member	Middle Devonian	2225.6-2326.2	Salt assumed on drilling rate and Core No. 3 rock salt with rare clayey shale laminae.	No. 3, 2241.4-2244.5; Rec. 2.7	Available
QLD.	Adavale	Phillips	Bury No. 1 25°02'40"S 145°36'20"E (TD 2744.4)	Etonvale Formation (1402.1-2358.6) Boree Salt Member	Middle Devonian	1774.5-2358.6 1774.5-1798.3 1798.3-1805.0 1805.0-2358.6	 Anhydrite. Shale and limestone. Rock salt with traces of anhydrite and rare laminae and interbeds of shale.	No. 8, 1809.9-1812.9; Rec. 2.3 No. 9, 1969.0-1972.0; Rec. 2.9 No.10, 2123.8-2127.0; Rec. 3.7 No.11, 2279.2-2282.3; Rec. 2.8	Available
QLD.	Adavale	Amoseas	Boree No. 1 24°45'32"S 145°34'36"E (TD 2676.4)	Etonvale Formation (1358.5-2426.5) Boree Salt Member	Middle Devonian	1919.6-1954.6	White, finely crystalline gypsum, with dolomitic siltstone and shale. Traces of anhydrite.		

22

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
						1954.6–2426.5	Rock salt, with thin beds of shale and siltstone, rare gypsum.	No.18, 1957.7–1960.7 Rec. 2.5 Analysis: 98.5% NaCl No.19, 2125.0–2131.4; Rec. 6.2 Analysis: 95.8% NaCl, 2.14% $CaSO_4$ No.20, 2280.8–2286.9; Rec. 6.0 Analysis: 78.7% NaCl 8.9% $CaSO_4$ 2.0% $CaCO_3$ 2.1% $MgCO_3$	Available
QLD	Adavale	Hartogen Explorations Pty Ltd	Alva No. 1 25°11'47"S 145°23'02"E (TD 3596.9)	Etonvale Formation (2626.8–3297.3) Boree Salt Member	Middle Devonian		Halite (200.2 net) with a few thin tough interbeds.	Nil	9.1 intervals 0 to 1261.9 and 3.1 from 1264.9 to T.D. Colourless to pale brown, massive and very finely crystalline halite with minor shale.
						3097.1–3285.8	Halite with a few thin shale beds.		
						3285.8–3297.3	Anhydrite.		
WA	Officer	Hunt	Browne No. 1 25°51'15"S 125°48'58"E (TD 386.7)	Browne Beds (132.6–386.8)	Proterozoic	132.6–386.8	Interbedded calcareous shale, dolomitic limestone, anhydrite, gypsum and halite.	No. 2, 213.4–216.4 ; Rec. 1.0 No. 3, 257.6–260.6 ; Rec. 2.7. No. 4, 354.5– ? Rec. 0.1 No. 5, 354.5–357.3; Rec. 2.3	?
WA	Officer	Hunt	Browne No. 2 25°56'00"S 125°57'45"E (TD 292.6)	Browne Beds (262.1–292.6)	Proterozoic	262.1–292.6	Evaporites occur in thin beds or as secondary fracture fillings. May be equivalent to Babbagoola Beds.	No. 2, 259.1–262.1; Rec. 1.9 No. 3, 288.3–291.4; Rec. 0.4	0–228.6
WA	Officer	Hunt-Placid	Yowalga No. 2 26°10'12"S 125°58'00"E (TD 989.3)	Babbagoola Beds (845.9–989.4)	Proterozoic				
				Unit A (845.9–887.0)			851.3 Dolomitic to anhydritic sandstone (10% anhydrite).	No. 5, 851.0–854.0; Rec. 1.9	Available
				Unit B (887.0–893.0)			893.0 Silicified dolomite anhydrite.	No. 7, 891.8–894.8; Rec. 1.9	
				Unit C (893.0–989.4)			893.3 Anhydrite (70%)	No. 7, 891.8–894.8; Rec. 1.9	

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
WA	Officer	Continental	Birksgate No. 1 27°56'20"S 129°48'10"E (TD 1878.2)	Unit "B" (662.3–952.5)	Proterozoic	777.2–798.5	Shale and limestone with up to 10% anhydrite.	Nil	Available
WA	Carnarvon	Wapet	Pendock I.D. No. 1 23°17'02"S 113°20'10"E (TD 2500.9)	Dirk Hartog Formation (1849.5–2500.9)	Upper Silurian	1901.9–1905.0 1929.3 2127.2 2136.6–2139.6	Anhydrite " " "	Nil	Available 3.0 intervals
WA	Carnarvon	Continental Sun	Yaringa No. 1 26°03'58"S 114°21'35"E (TD 2288.4)	Dirk Hartog Formation (855.3–1526.4)	Upper Silurian	1204.5–1271.1 1342.6–1345.6	33.2 of halite in 7 beds. 3.0 bed of halite. Total of 36.2 of halite in 8 beds.	No.15, 1235.9–1239.0; Rec. 2.6	3.0 intervals to TD
WA	Carnarvon	Magellan Petroleum	Hamelin Pool No.1 26°01'31"S 114°12'17"E (TD 1595.6)	Dirk Hartog Formation (852.2–1558.4)	Upper Silurian	1130.8–1131.4 1164.9–1165.5 1236.8–1243.5 1245.1–1247.5 1274.6–1277.7 1283.8–1288.6 1388.6–1391.7	Total of 22.9 halite in seven beds.	No. 1, 1103.0–1104.5 No. 2, 1240.5–1244.8 No. 3, 1244.8–1262.1 No. 4, 1275.8–1282.2 (100% recovery in all cores)	3.0 intervals to TD
WA	Carnarvon	Magellan Petroleum	Hamelin Pool No.2	Dirk Hartog Formation (791.3–1219.2)	Upper Silurian	1138.7–1139.6 1174.1–1167.9 1174.1–1176.7	Total of 5.2 halite in three beds.	No. 1, 1141.4–1150.6 No. 2, 1150.6–1168.9 No. 3, 1168.9–1187.1 No. 4, 1187.1–1205.4 (100% recovery in all cores)	3.0 intervals to TD.
WA	Bonaparte Gulf (offshore)	ARCO Aust. Ltd.	Pelican Island No. 1 14°46'19"S 128°46'27"E (TD 1981.2)	Interbedded with or older than the Bonaparte Beds. (1791.3–1981.2)	M.-U. Devonian?	1791.3–1981.2	Halite.	Sidewall Cores; 1889.7, Rec. 3.1 cm halite, light grey translucent to transparent, fractured; 1965.9, Rec. 1.9 cm halite as above.	3.0 intervals.
WA	Bonaparte Gulf (offshore)	ARCO Aust. Ltd.	Sandpiper No.1 13°18'53"S 127°58'35"E (TD 1891.6)	(Equivalent of Ningbing Limestone onshore) (944.0–1891.6)	Upper Devonian to L. Carboniferous cap rock, Famennian? halite.	944.0– 1752.9 1752.9–1891.6	Cap rock. Halite. Transition zone from 1752.9–1793.7.	Sidewall cores of halite at 1789.1, 1798.3, 1801.3, 1813.5, 1815.3, 1821.1, 1828.8, 1840.9, 1848.3, 1854.4, 1859.2, 1868.4, 1874.5, 1882.1 and 1885.1.	No cuttings of halite recovered.
QLD	Capricorn Embayment (offshore)	AGO/AOG	Aquarius No. 1 22°37'13"S 152°39'02"E (TD 2650.2)	Unnamed Unit (1245.1–1702.3)	Lower Tertiary	1453.8–1478.2	Interbedded shale and anhydrite.	Sidewall core 20 1411.2 Rec. 40%; anhydrite and sandstone. Core 19, 1444.7, Rec. 80%;anhydrite. Core 15, 1530.0, Rec. 100%;anhydrite and sandstone.	Available 3.0 intervals.
				Unnamed Unit (1702.3–2642.6)	Pre-Tertiary? Mesozoic	2079.0	0.1 anhydrite	-	

STATE	BASIN	COMPANY	WELL NAME & NO. CO-ORDINATES (Lat. & Long.)	FORMATION and thickness	AGE	INTERVAL	BRIEF DESCRIPTION	CORE	CUTTINGS
WA	Browse Basin (offshore)	B.O.C. of Aust. Ltd.	Rob Roy No. 1 13°58'15.6"S 124°11'57.1"E (TD 2286.0)	Unnamed Unit 1572.4-2255.5	Lower Permian (Sakmarian)	1572.4-2187.2	Interbedded sandstone and claystone with minor siltstone and occasional veins of anhydrite.	No. 2, 1888.2-1897.4; Rec. 9.1 1895.8-1897.4 Fine to medium sandstone with siltstone laminae and patches and veins of anhydrite up to 15 cm wide.	
SA	Arckaringa Basin	S.Aust. Dept. of Mines	Cootanoorina No. 1 28°00'30"S 135°20'00"E (TD 948.2)	Unit 3 (891.5-948.2)	Devonian	891.5-948.2	Dolomite, dolomitic shale, anhydrite.	No. 10.	
				Unit 1 (516.7-777.2)	L. Permian	634.0-667.5	Anhydritic siltstone.		
SA	Arckaringa Basin	Occidental Minerals (Oxy min)	Boorthanna No.1 28°56'04"S 135°45'18"E (TD 1225.6)	-	-		Evaporite expected in Devonian but Permian rests on Precambrian metavolcanics		
NT	Pedirka	Amerada	McDills No. 1 25°43'50"S 135°47'25"E (TD 3240.9)	Todd River Dolomite (2750.5-3205.0)	Lower Cambrian	2750.5-3205.0	Dolomite and limestone with anhydrite filling fractures, particularly in Core No. 31.	No.29, 2851.0-2854.1; Rec. 2.7 No.30, 2935.8-2938.8; Rec. 3.0 No.31, 3065.6-3068.7; Rec. 2.7	

The Tandalgoo Red Beds that commonly overlie the Carribuddy Formation contain probable aeolian sands, and rare fossils have recently been described. Agnathid and acanthian fish scales (Gross, 1971) from the Tandalgoo Red Beds in the Wilson Cliffs No. 1 well over the interval 1353.0 - 1345.5 m; have Early Devonian affinities. The specimens appear to be abraded and could have been reworked. This would imply that the lower part of the Tandalgoo Red Beds or the Carribuddy Formation could be Early Devonian. However, opinions on the age of the beds differ widely and some workers favour a Silurian age. Hence the evaporite sequence is Early Devonian or older, and younger than Lower Ordovician (Llandeilian).

If the Carribuddy Formation is older than Lower Devonian, it could be correlated with the Dirk Hartog Formation of the Carnarvon Basin, a view favoured by some oil company geologists. Others favour the correlation of the Tandalgoo Red Beds with the Dirk Hartog Formation (Playford & Cope, 1971); though the correlation does not appear to be valid both from the evidence of the fish scales and the recent discovery of Devonian spores in the Upper Tandalgoo Red Beds (K.J. Creevey, pers. comm.).

Other interbasin correlations do not solve the problem of the age of the Carribuddy Formation, and in any case could not be expected to give anything more than an indication of age. Similarities of the Tandalgoo Red Beds with the Mereenie Sandstone of the Amadeus Basin suggest that the evaporites may be Ordovician in age, because there is ample evidence of evaporitic conditions in the pre-Mereenie Larapinta Group.

The evidence of widespread Devonian evaporites in Australia could also be used as an argument for the age of the Carribuddy Formation. K.J. Creevey (pers. comm.) states that K/Ar ages on clays of Wilson Cliffs cores 2-10 gave a Lower Devonian age. No more details are available on this determination, but cores 8 and 9 are from Unit A of the Carribuddy Formation, and core 10 is from Unit C. Cores 3 to 7 are from the Tandalgoo Red Beds, and Core 2 is from the Mellinjerie Limestone.

The Carribuddy Formation is unconformably overlain, after considerable erosion, by Lower Permian sediments in the Parda No. 1, Willara No. 1, and McLarty No. 1 wells. The thickness of the overlying Permian rocks and the distribution of the salt as shown by seismic surveys suggests the presence of solution features, and solution of the salt is considered to be an intra or pre-Permian event. Permian sediments appear to thicken off the residuals. In this way salt solution structures may form anomalous zones that give indication of closures (Fig. 2). For example Willara No. 1 is not on a structure but may be situated on a salt remnant. Similar features have been described in the North Sea by Lohmann (1972), in southwestern Ontario by Grieve (1955) and in the English Zechstein by D.B. Smith (1972a). In addition the thickness of the Carribuddy Formation is commonly modified by salt solution in the region of fracture zones. For example, in the Munro area the Carribuddy is dissolved over an old fracture system in the underlying Goldwyer Formation. The Munro core hole was programmed to drill in an area of reduced Permian section, near thicker Permian deposited in the depression formed by solution in the underlying salt.

There are no marked lateral variations within the evaporite sequence, although it seems evident that some facies changes to a carbonate sequence are present. Some of these changes may have been largely obliterated by the removal of parts of the sequence below the Permian unconformity. In early interpretations the distinct increase in carbonate (dolomite) content was assigned to the lower part of the Carribuddy Formation and was called the Nita 'Facies'. A Devonian date has been obtained from sediments immediately above the Nita 'Facies' and there is an unconfirmed report of a Devonian? microflora just below the salt in the Willara No. 1 well (Core 5, 1741.6 - 1743.5 m) (McTavish, unpubl. report for WAPET); but this may not necessarily mean that the formation in other wells is Devonian. More recent interpretations (McTavish, pers. comm.) place the dated material from Core 5 in the Carribuddy Formation, which has its base at 1759.6 m. The Nita 'Facies' has been renamed the Nita Formation and is dated now as Llanvirnian to Llandeilian on the evidence of conodont faunas found in several wells. The microfloral content indicates a similar age and a single pelecypod genus supports a late Lower or early Late Ordovician age. It is not now considered to be part of the Carribuddy Formation.

The beds in the Kidson Sub-basin (Plate V) are only gently folded, and probably because of this there has been no halokinesis (Trusheim, 1957 - literally, 'salt movement') in the salt members. The structures have probably been formed by compaction and the tectonic disturbance is slight. However, interpretation of recent seismic surveys (Angove & Douglass, 1972) in the Kidson Sub-Basin has suggested that diapirism has probably caused turn-over at shallow levels. On some lines the seismic cross-section has been likened to those across salt domes in the North Sea. The extent of piercement is uncertain but appears to be limited to deeper levels. In the section above the pierce-

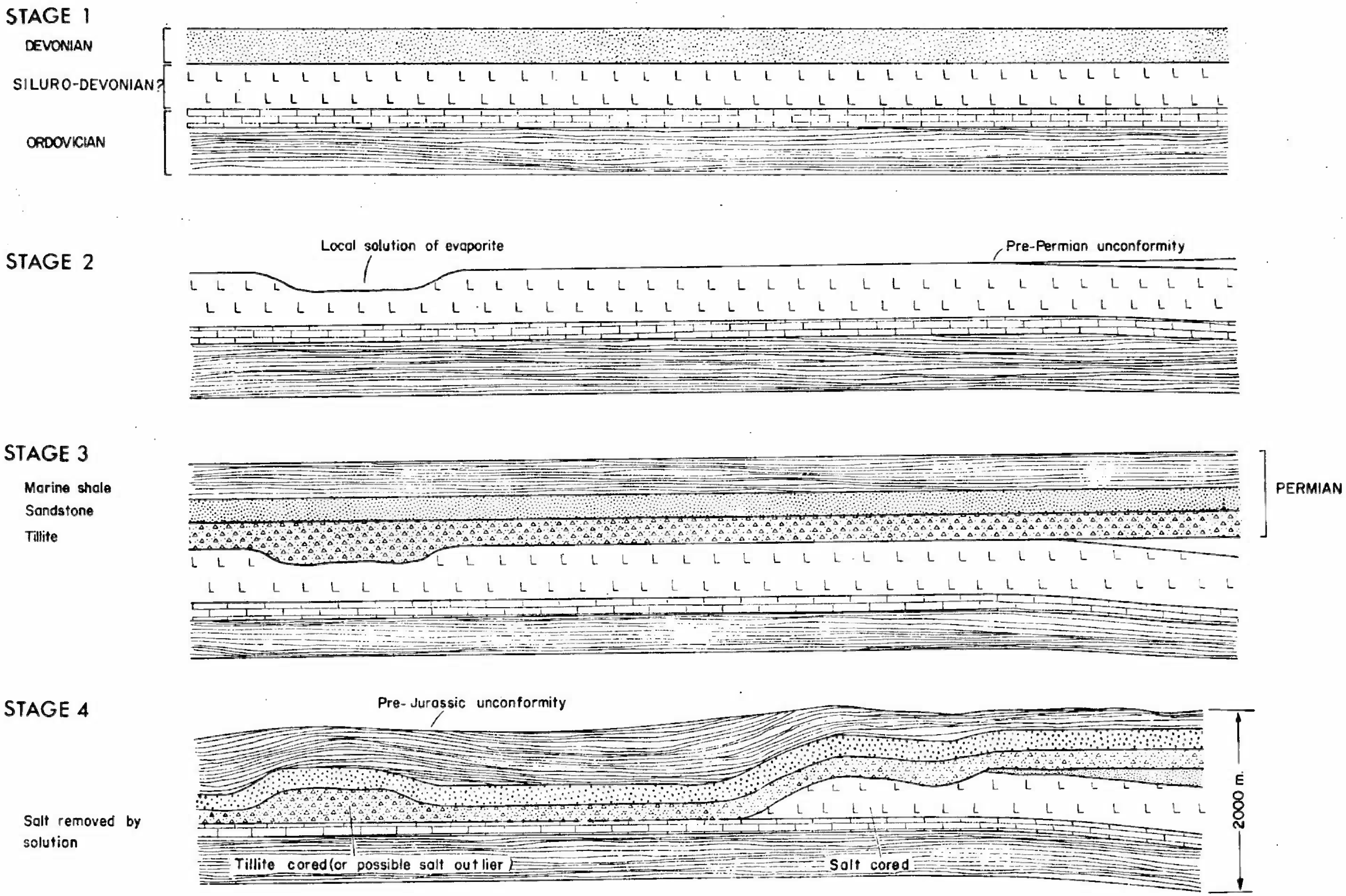


FIG 2 SEQUENCE OF SALT SOLUTION AND SEDIMENTATION, CANNING BASIN
(From Munda No1 Well Completion Report)

To accompany Record 1973/170

E 51/A/24

ment zone there appears to be arching of the sediments suggesting upward displacement. The preponderance of multi-cycle events deep in the section is consistent with diapirism.

A salt dome or wall is postulated in the Proterozoic rocks. Movements are apparent during the intervals P-G and B-O and quiescent period over the G-B or Carribuddy Formation. (P = late Precambrian, G = top Goldwyer, B = top Carribuddy, D = base Permian unconformity) the structural style fits well with salt tectonics, with broad deformation on the P level, narrower on R and G and the final phase by a near surface fault.

In the Fitzroy Trough (Fig. 1) where the sediments are more strongly folded and faulted at least one salt dome (Frome Rocks) has been discovered. In early interpretations the salt was shown intruded along the Fenton Fault and probably originating in beds in the deeper parts of the Fitzroy Trough. Later workers consider that this picture is probably not correct and there is no clear evidence for intrusion along the fault line.

In Frome Rocks No. 1 well about 460 m of dolomite is underlain by halite. The dolomite is thought to be a cap rock on the salt, but is composition is unusual, as cap rocks mostly consist of limestone and anhydrite or gypsum. Wapet geologists consider that the Frome Rocks dome may have resulted from tectonic movements because other wells drilled on similar anomalies failed to intersect salt. As mentioned earlier the origin of the salt in the Frome Rocks No. 1 well is not certain. The Matches Springs well was expected to intersect a thick sequence of marine shales and dolomites of the Carribuddy Formation, but only 180 - 200 m was penetrated. Either faulting or thinning of the units must be invoked to explain the reduced section, but if the formation is thinning then it appears unlikely that the Carribuddy is the source of the Frome Rocks salt, and another supply must be sought.

Several domes were indicated by seismic and gravity surveys, eg. at Logue and Doran. Gravity maxima over the crests of the domes suggest that they are probably not caused by salt intrusion. A core hole drilled on the Doran Structure to 760 m intersected Upper Famennian shales*.

* The Logue No. 1 well was completed at the time of writing. It reached a total depth of 2699.7 m and terminated in Famennian siltstone and shale.

Besides the unequivocal evidence from the Frome Rocks No. 1 well for the presence of evaporites in the Fitzroy Trough there are other indications of thick salt beds in the Trough and its continuation into the northeast part of the Canning Basin. On the northern side of the Fitzroy Trough the Blackstone No. 1 well penetrated red siltstone with evaporites, of Givetian age, overlying an Ordovician sequence. The presence of evaporites was indicated by the marked increase in salinity of the drilling fluid. In the Blackstone No. 1 well completion report it is stated that the 'Blackstone Formation' (sic; amended to Poulton Formation) contained traces of salt. It is likely that this red bed sequence contains crystalline halite. Although no halite was seen in cuttings or cores, since this part of the well was drilled using aerated water as the drilling fluid, the salinity of the water rose from 6800 ppm NaCl at 1852 m to 48 000 ppm NaCl at 2226 m. Such an increase in salinity while penetrating an essentially tight formation can only be attributed to solution of rock salt. This siltstone of Givetian age, with evidence of evaporites in the succession, has been named the Poulton Formation and indicates environmental similarities with the Kidson Sub-basin. In fact if the Carribuddy Formation is indeed Devonian in age then the Poulton Formation could be correlated with either the Tandalgoo Red Beds or perhaps the Carribuddy Formation.

Minor evaporites have been noted in the Devonian reef complex at the northern margin of the Fitzroy Trough in the Copley Valley (Playford & Lowry, 1966).

The Fitzroy Trough and the Broome Platform continue essentially uninterrupted into the northeast Canning Basin. The equivalent of the Broome Platform, the Helena Platform, appears to extend to the southeast and eventually terminates near marginal Precambrian outcrops on the Webb Sheet area. In the southeast extension of the Fitzroy Trough, the Gregory Sub-basin, the sediments are up to 9000 m thick. There is a major unconformity in the sequence, and Permian rocks rest unconformably on the eroded Carboniferous sediments. In Lake Betty No. 1 and Point Moody No. 1 wells the Permian Grant Formation overlies Carboniferous sequences about 900 m, and 466 m thick respectively. The Point Moody well was still in Lower Carboniferous at total depth, so an appreciably thicker Carboniferous section may be present in this area. Gravity and magnetotelluric surveys (Australian Aquitaine Petroleum, 1968b) in this area suggest the presence of salt.

The Broome Platform was a strongly positive feature in the early Palaeozoic and in the east was, at times, probably emergent; refraction studies show that the formations thin and pinch out towards it. Magnetotelluric surveys (A.A.P., 1968b) also show pinched out sediments in the south, against the ridge. The platform may have been the northern margin of the Kidson Sub-basin, but the northern margin of the Canning Basin at this time was probably in approximately the same position as mapped today. In the area close to the Amadeus Basin the sediments do not appear to be pinched out, but salt is not apparent. Some onlap of formations is apparent in this area.

The Kidson Sub-basin and Fitzroy Trough were apparently connected until Carboniferous time, but Carboniferous sediments were deposited only in the Fitzroy Trough. In earlier Palaeozoic times, during the period of salt deposition, the Broome Platform may not have been sufficiently pronounced, to completely sever connections between the two basins and channelways probably existed across the swell. From the middle Devonian to Permian the source of sediments lay partly in the Broome Platform.

McTavish (pers. comm.) comments that 'on the Broome Platform Ordovician carbonates equivalent in age to basinal pelites, the absence of thick sections of Nambeet Formation, and reduced thicknesses of some Ordovician sections suggest that this part of the 'Broome Swell' (sic; Broome Platform) may have acted as a partial barrier between the Kidson Sub-basin and the Fitzroy Depression (sic; Fitzroy Trough) especially during the Lower Ordovician'.

Geophysical evidence suggests a similar palaeogeographic situation in the area of the Crossland Platform during the Ordovician. Nevertheless, a connection between the Kidson Sub-basin and Fitzroy Depression may have been present in the central part of the 'Broome Swell' (sic.)'

Glover (1973) analysed the halite-bearing cores from the Carribuddy formation and concluded that the low bromine content was in accord with the absence of potassium salts. The halite is colourless to red-brown, the latter perhaps caused by ferric hydrate precipitation, a precursor of haematite, from percolating oxygenated water, which dissolved and reprecipitated the halite. The bromine content is generally greater in the red-brown than in the colourless halite suggesting that the colourless variety was not dissolved. In addition Glover concludes that the diagenetic sequence in the halite of the formation is halite; dolomite and anhydrite; quartz; and hematite pigment. Colour patterns in the halite veins indicate that the minerals have not moved significantly since pre-Middle Devonian times. Most of the pigment in the red-beds with the halite has probably formed in place by diagenesis, but some could have been transported to the basin.

Conclusions

From the known distribution of the Carribuddy Formation in the Kidson Sub-basin it appears that the evaporites were confined within the present basin outline and the extent and thickness of the deposits suggest that they most probably originated by seasonal evaporation of sea water in a large restricted shallow sea. A bar could have existed between the basin and the sea to the northwest. The evaporites thin from the centre of the basin not only towards the postulated position of the barrier but also towards the margins of the basin, although some of the thinning is obviously due to salt solution.

No potentially economic minerals are known in the evaporite deposits and it is unlikely that the halite could be exploited, as the top of the shallowest deposits occurs at a depth of about 700 m, at Frome Rocks. If the Kidson Sub-basin was a more or less symmetrical basin with the bittern salts concentrated in the residual brines, it would seem logical to expect the more soluble salts of the evaporite sequence to be preserved in or near the geographical centre of the basin. The geography of the mid-Palaeozoic basin may have been such that slight irregularities of the basin floor would allow concentration of the more soluble salts in small ponds situated in depressions, or in smaller satellite basins, separated from the open sea by the main evaporite basin, in a similar manner to that proposed by Goldsmith (1966 and 1969). If these beds were of sufficient thickness and lateral extent they could possibly be located and outlined by seismic surveys.

Notes on Well Sequences (Plate III)

Kidson No. 1 - Anhydrite is more common in Kidson No. 1 than in the evaporite sequences of other wells except Wilson Cliffs No. 1. It contains the thickest Carribuddy Formation. Unit B is proporionately thicker compared to other well sections, but the ratios of thicknesses of the other units are about the same. A sketch of core No. 19 is shown in Figure 3.

Wilson Cliffs No. 1 - Unit B of the Carribuddy Formation is missing, probably because of the structurally high position. It contains the thinnest salt and shale (128 m) of Unit D. The Tandalgoo Red Beds are Lower Devonian.

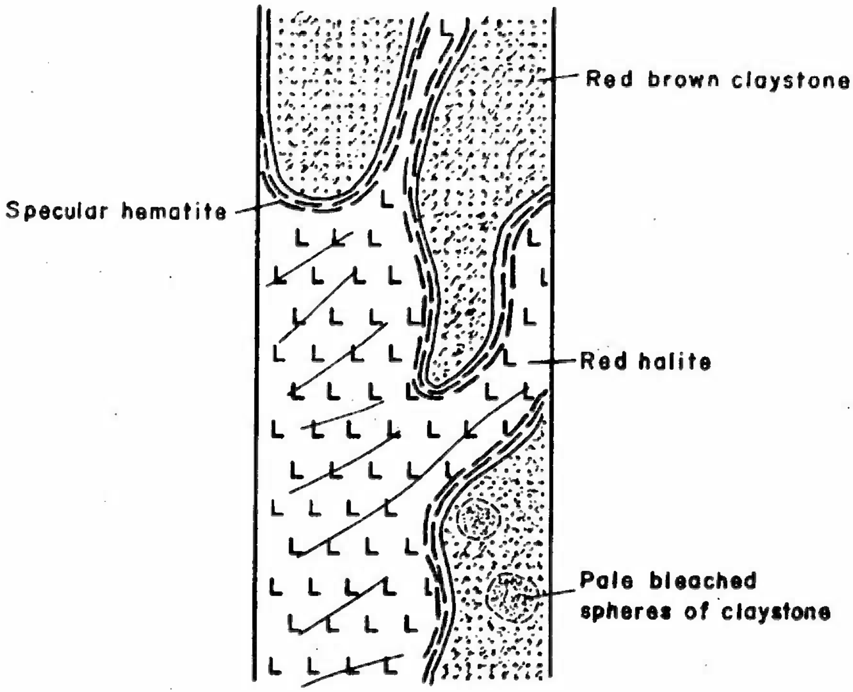


Fig. 3 SKETCH OF PART OF CORE No. 19, KIDSON No. 1 WELL, SHOWING SECONDARY RED SALT ENCASING HEMATITE-SHEATHED FRAGMENTS OF RED-BROWN CLAYSTONE

To accompany Record 1973/170 M(s)239

Sahara No. 1 - The sequence in the Mellinjerie Limestone is more truly marine than in most other well sections, and indicative of a less restricted environment. Some geologists consider that the Mellinjerie Limestone is a true reef limestone in Kemp Field No. 1 well, as also is the Upper Devonian in Matches Springs No. 1 well. McTavish (pers. comm.) considers that the 'Mellinjerie Limestone of Kemp Field No. 1, 563-831 m, is regarded as composed of a transgressive marine unit overlain by platform and forebank carbonate. No 'true reef' limestone is present according to our interpretation'.

McLarty No. 1 - Contains the thickest known salt sequence and is comparatively uncontaminated with detrital material. The Ordovician conodont fauna high in the Carribuddy Formation is reworked.

Kemp Field No. 1 - A ?Lower Devonian fish scale was found about 60 m from the top of the Carribuddy Formation.

Tappers Inlet No. 1 - The base of the Pillara Formation is Givetian in age. The age of the Poulton Formation is unknown.

Barbwire No. 1 - The Tandalgoo Red Beds are late Devonian in age, which is similar to that of the Pillara Formation.

Frome Rocks No. 1 - Dolomite fragments from Core No. 5 (775.9-759.0 m) yielded fish plates and a single fragment of a conodont (Glenister, 1962). The meagre fossil and petrological evidence is inconclusive but suggests that the carbonate rocks penetrated in the well may be both Ordovician and either Late Devonian or early Carboniferous in age.

Willara No. 1 - An alternative interpretation (cf Plate III) suggests that unit A is missing and the salt, which contains a large proportion of detrital material, is probably part of Unit D. A chert bed is present at the base of the Permian and locally may be environmentally significant. Palynology suggests a Devonian age for core from about 1750 m.

AMADEUS BASIN

The Amadeus Basin is one of the two sedimentary basins in Australia (the Officer Basin is the other) in which the interbedded evaporites are partly exposed. The evaporite outcrops consist mostly of earthy weathered gypsum which generally occurs together with outcrops of dolomite and shale of the Late Precambrian Bitter Springs Formation. The unweathered form of the gypsum is distinct from that in outcrops of modern gypsum deposits of playa lakes and soil profiles, in that it is crystalline, compact, and generally either strongly brecciated or tightly folded, and contains, in many places, erratic blocks of dolomite. The folding of the gypsum is easily discernible as there are usually thin dark contorted laminae threaded through it. Figure 4 shows the location of the BMR drill sites and the position of known evaporite occurrences in the Bitter Springs Formation.

Exploratory wells drilled for petroleum in the Amadeus Basin penetrated the Bitter Springs Formation in several structures, and thick salt sequences were intersected in the formation in the Ooraminna No. 1, Mt Charlotte No. 1, and Erldunda No. 1 wells (Figs 4, 8). In addition a younger evaporitic sequence in the Lower Cambrian Chandler Limestone was penetrated in Alice No. 1, Orange No. 1, and Mt Charlotte No. 1 (Figs 4, 7). The Bitter Springs Formation is thought to underlie the whole basin, whereas the Chandler Limestone is restricted to the northeastern part (Fig. 5), and passes, westwards, into an arenitic facies in which there are no evaporite beds. No discernible major facies changes have so far been described in the Bitter Springs Formation.

Gypsum of the Bitter Springs Formation crops out chiefly in a zone trending east-southeast from Johnstone Hill in the northwest and terminating a few kilometres north of Curtin Springs. The only exceptions are an occurrence near the Gardiner Fault in the Gardiner Range and at the Ringwood Dome and Santa Teresa Mission in the eastern part of the basin (Fig. 6). The last mentioned deposit has been discovered only recently (by Wells) and was not described in the original mapping of the basin. In the Johnstone Hill-Curtin Springs zone the gypsum crops out in the cores of eroded anticlines, in isolated outcrops which show no relation to the country rocks, and in structures that have been described as diapiric in origin. Three of these surface gypsum deposits, two of them outside the main zone, have been drilled by BMR - at the Ringwood Dome, Alice Springs BMR No. 3 (Stewart, 1969); in the Gardiner Range, Mount Liebig BMR No. 1; and an outcrop north of Curtin Springs, Lake Amadeus BMR Nos 3, 3A, and 3B (Wells & Kennewell, 1972). The Ringwood and Curtin Springs holes produced somewhat similar sequences of strongly folded and in part brecciated gypsum, anhydrite, mixed evaporite rocks, and dolomite. The proportion of anhydrite increases with depth and first appears at about 100 m in each hole. The mixed evaporite rocks consist of anhydrite, gypsum, dolom-

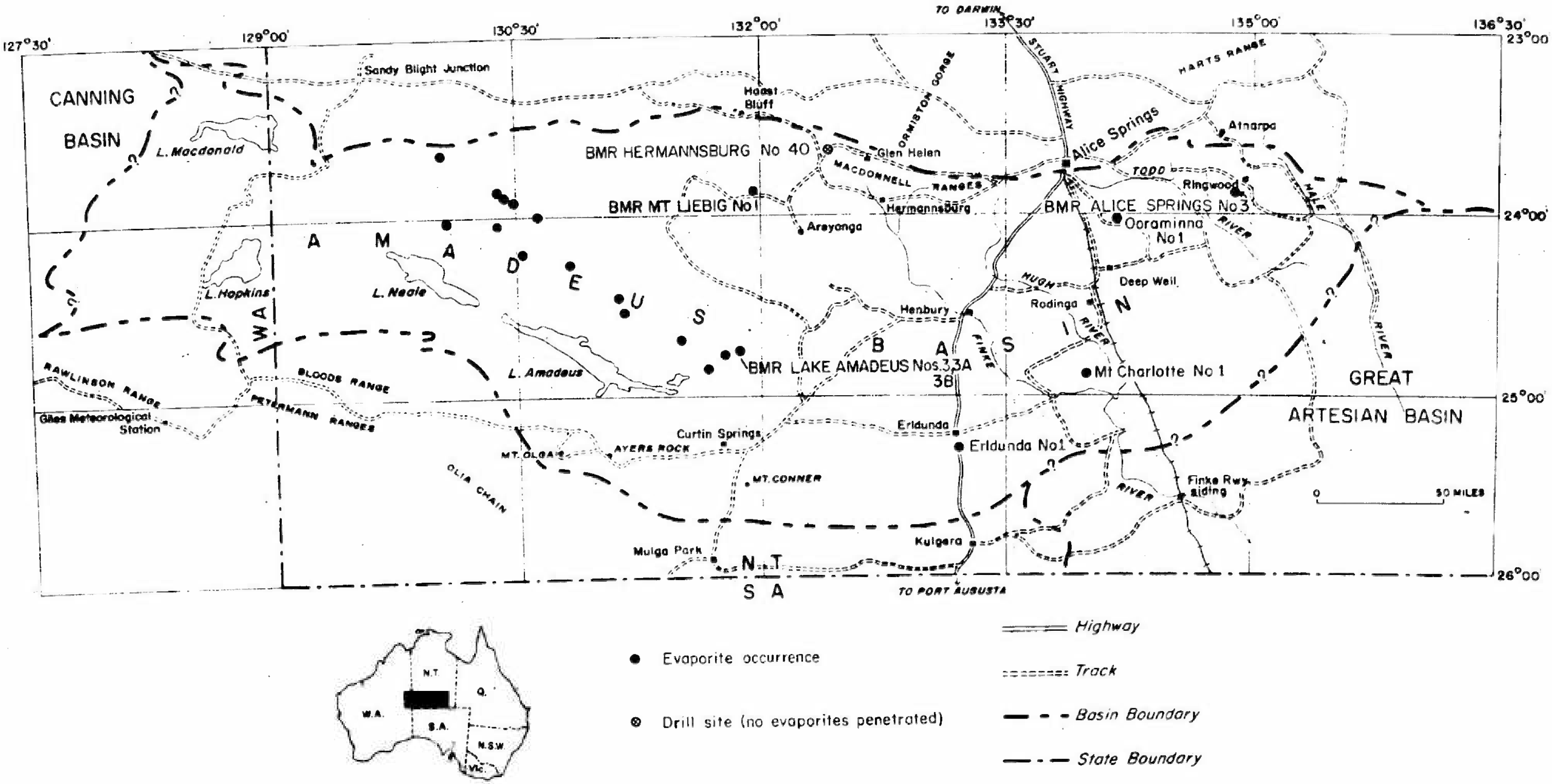
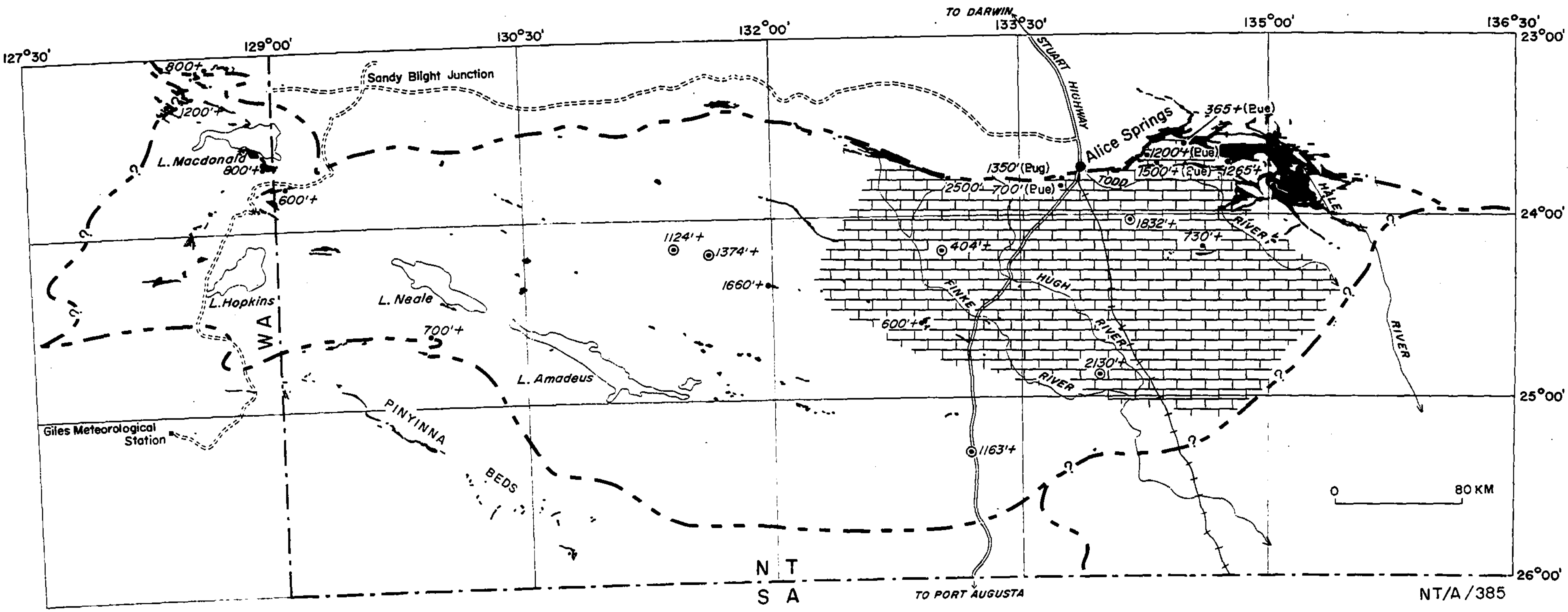


Fig. 4. Amadeus Basin, showing locations of BMR drill sites and positions of known evaporite occurrences in Bitter Springs Formation and Chandler Limestone

To Accompany Record 1973/170

NT/A 422



To accompany Record 1973/170

Outcrop of Bitter Springs Formation

• 730'+ Section locality – outcrop } showing thickness

⊙ 1163'+ Section locality – well section } showing thickness

(Pue) Loves Creek Member

(Pug) Gillen Member

Probable extent of the Chandler Limestone

Outline of Amadeus Basin

FIG. 5 – DISTRIBUTION OF THE BITTER SPRINGS FORMATION AND CHANDLER LIMESTONE IN THE AMADEUS BASIN

37

Qa	*Alluvium*	Pzm	*Mereenie Sandstone*	Єk	*Giles Creek Dolomite*
T	*Tertiary limestone*	Єs	*Shannon Formation*	Єa	*Arumbera Sandstone*

Fig 6 Sketch map showing gypsum occurrence at Santa Teresa Mission

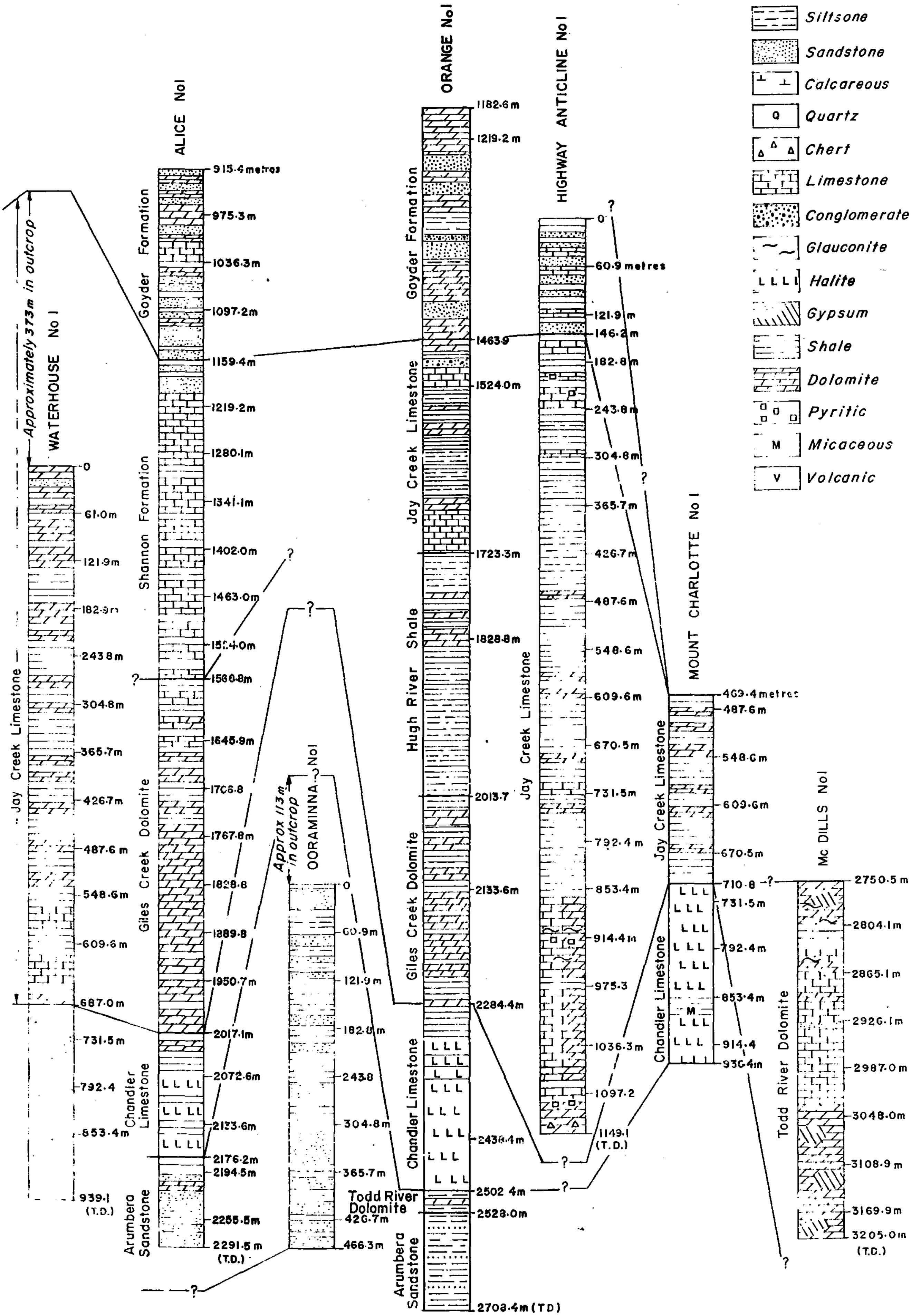


FIG 7 - GRAPHIC LOGS OF PETROLEUM EXPLORATION WELLS SHOWING HALITE IN THE LOWER CAMBRIAN CHANDLER LIMESTONE

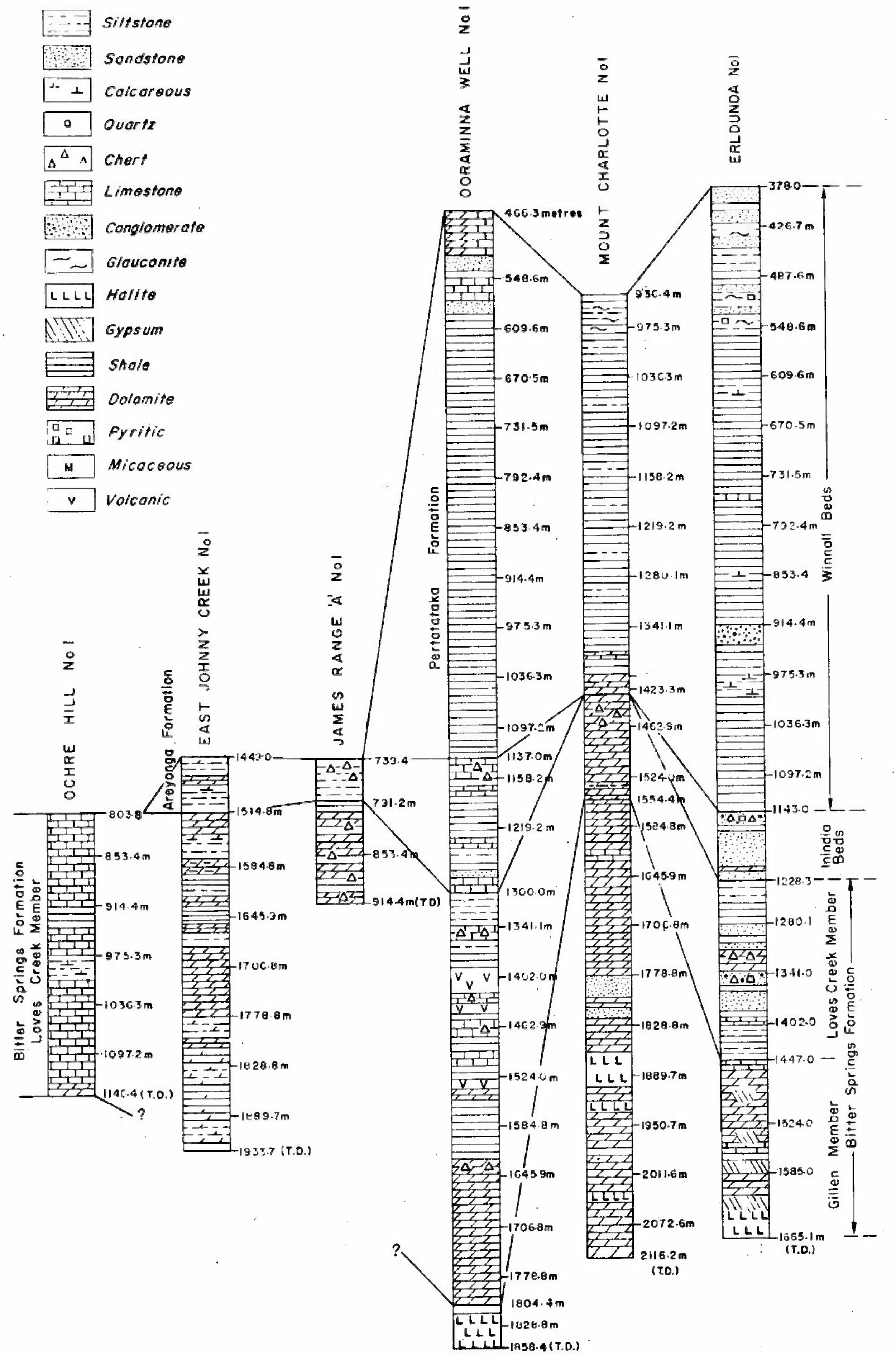


FIG 8 - GRAPHIC LOGS OF PETROLEUM EXPLORATION WELLS SHOWING HALITE IN THE LATE PRECAMBRIAN BITTER SPRINGS FORMATION ite, and euhedral quartz in various proportions. The hole drilled into the Gardiner Range occurrence penetrated 100 m of brecciated mixed evaporite rocks and 210 m of pink and red halite which contained minor impurities. The red coloration of the salt, probably caused by ferric iron content, may be indicative of a shallow water environment. The rocks of the top 100 m are very similar to those encountered in subrosion (subsurface leaching of saline rocks) zones in German salt domes (Richter-Bernburg, 1972b). The salt in the lower part of the drill hole has a brecciated appearance, but no features of strong tectonic transport are impressed on it. A brecciated appearance can be caused by erosion of salt, owing to the influx of undersaturated salt water into a basin; the beds of anhydrite would remain and a breccia be formed by their collapse and recementation. The evaporites of the Bitter Springs Formation in the Gardiner Fault zone were probably emplaced during thrusting in the course of the late Palaeozoic Alice Springs Orogeny. It is commonly found in the Amadeus Basin that decollement folding is the typical tectonic style and that it is facilitated by the evaporite sequences in both the Bitter Springs Formation and the Chandler Limestone.

The distribution of the gypsum outcrops mainly in the Johnstone Hill-Curtin Springs zone has not so far been satisfactorily explained, but it obviously has a structural control. The wells that have intersected evaporites lie outside this zone in the central and eastern part of the basin. This distribution of evaporites may indicate that the centre of the evaporite basin lies within the eastern part of the Amadeus Basin, with a halite zone surrounded by a gypsum 'halo'. The residual 'bitter' liquors with the most soluble salts would be expected in the palaeotopographic lows near the centre of this basin. Magellan had a number of mineral exploration claims over several evaporite occurrences, chiefly the Bitter Springs formation in the Amadeus Basin, but have subsequently relinquished the leases.

Newmont investigated the evaporites of the Bitter Springs Formation, and drilled one hole at the eastern end of Lake Amadeus. This site was picked after a consideration of firstly the geophysical anomalies and secondly the structural framework of the basin. Cross-sections were constructed across the basin using magnetic profiles to give the basin configuration. An anomaly was found between the known thickness of sediments and the postulated depth of the basement. The anomaly was explained by the presence of low density halite in the sequence and it was considered that Lake Amadeus was in a position where increased thickness of evaporites would be expected. The late Precambrian/early

Cambrian Petermann Ranges Orogeny which occurred in the southwest was primarily responsible for the formation of the southern margin of the Amadeus Basin and considerable northerly transport of sediments took place in front of the Petermann Ranges Nappe, formed during the orogeny. In the northeast a similar structural evolution took place in the Devonian and Carboniferous during the Alice Springs Orogeny. The northern margin of the basin was formed, and sedimentary blocks were thrust south in front of the nappes, such as the Arltunga Nappe Complex, Blatherskite Nappe, and Ormiston Gorge Nappe. Hence, the Lake Amadeus salt lake chain was postulated to be in a position over a salt anticlinorium. In the hole drilled about 60 m of Cainozoic clays and silt overlie about 60 m of limestone, dolomite, and some sandstone of the Bitter Springs Formation. The sandstone could possibly be equated with a similar sandstone in the formation at the Parana Hill Anticline. The postulated salt anticlinorium in the Lake Amadeus region could probably be best outlined by detailed gravity surveys, which would distinguish salt from anhydrite/gypsum intercalations.

Apart from the thick evaporite beds in the late Precambrian Bitter Springs Formation and Lower Cambrian Chandler Limestone, there are indications of evaporitic environments in many of the younger formations in the Amadeus Basin. Halite pseudomorphs, probably of similar age to the Chandler Limestone, have been recorded in the northeast, from the youngest beds of the Arumbera Sandstone. Evidence of evaporitic conditions was also found in sandstone beds of the lower part of the Cambrian Goyder Formation in the western part of the Walker Creek Anticline, at many localities in siltstone of the Ordovician Stokes Siltstone, and the Upper Ordovician Carmichael Sandstone of the Larapinta Group, and in the Upper Devonian Parke Siltstone of the Pertnjara Group. The Devonian? Horseshoe Bend Shale of the Finke Group in the southeast contains halite pseudomorphs and is commonly gypsiferous.

Notes on Amadeus Basin Cores*

Mount Charlotte No. 1

The 'paper' shales found in cores 18 and 19 are similar to those found at the base of the German salt sequence. Dark anhydritic material and pink salt occurs in core 22. The anhydrite occurs in large brecciated fragments and has probably been broken by tectonic movements. No bituminous material is apparent, although it could be expected.

* Portions of all cores obtained from subsidized drilling operations are available for inspection at the BMR Core and Cuttings Laboratory, Fyshwick, A.C.T.

Core 23 consists of tough dolomitic rock and ?anhydrite with gypsiferous claystone at 1946.1 m. In Core 24 anhydrite occurs at 2044.3 m.

Core 25 contains finely crystalline anhydrite at 2057.7 m. It is similar to mantling anhydrite around German salt domes, but in this case it is a primary precipitate. The salt at 2060.1 m is dark grey in the core but is colourless when broken into small pieces. It contains anhydrite fragments and appears to be distinct from other salt in the well.

Core 26 contains dark clay and marly material in normal grey marly limestone. It is similar to the calcareous rocks that occur beneath the Zechstein salt.

ADAVALE BASIN

The Adavale Basin is entirely concealed (Fig. 9) beneath the practically flat-lying sediments of the Eromanga Basin sequence. Its lower Palaeozoic stratigraphy is as follows (after Galloway, 1970):

Lower Permian				Siltstone, shale
MAJOR UNCONFORMITY				
Upper Devonian to Lower Carboniferous		Buckabie Formation	0-2 100 m	Sandstone, siltstone, shale
Middle Devonian	Adavale Group	Etonvale Formation	0- 240 m	D1 Shale - siltstone Member
			0- 500 m	D2 Sandstone member
			0- 40 m	D3 Cooladdi Dolomite Member
				Boree Salt Member
		Log Creek Formation	0- 600 m	D4 Gilmore Sandstone Member
			0- 450 m	Shale member
			0- 600 m	Bury Limestone Member
		Gumbardo Formation	0- 750 m	Volcanic rocks, tuffs and sediments
MAJOR UNCONFORMITY				
Ordovician to Silurian				Igneous and metamorphic rocks

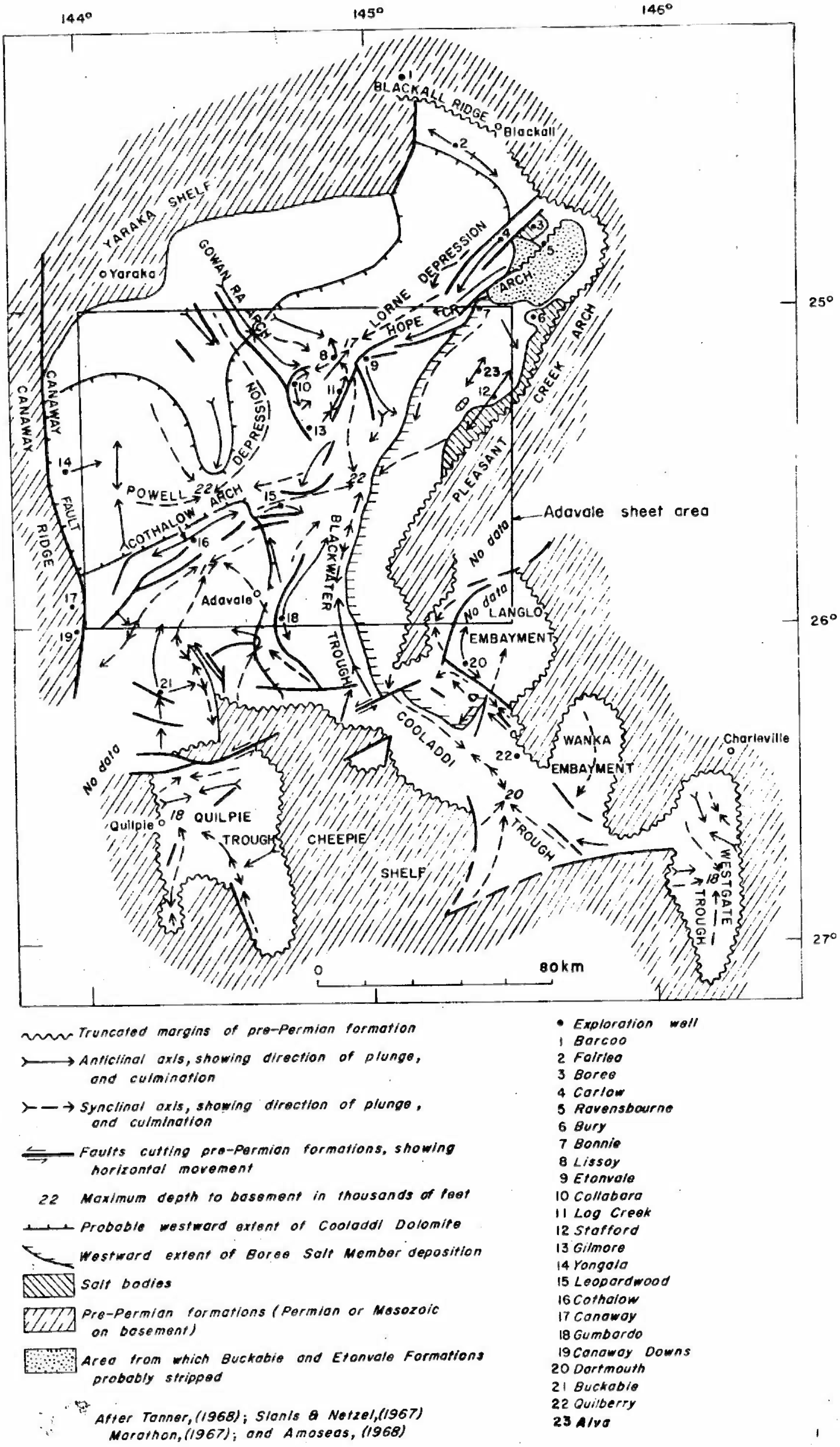


FIG 9 - STRUCTURE MAP OF THE ADAVALE BASIN SHOWING DISTRIBUTION OF THE BOREE SALT MEMBER (after Galloway, 1970)

The top and bottom of the Devono-Carboniferous sequence are marked by major unconformities, and a weaker unconformity occurs between the Log Creek and Etonvale Formations. The clastic sediments in the Middle Devonian formations appear to be derived from the west. A transition is evident, from lutites and arenites in the west to evaporitic rocks in the east.

Five petroleum exploration wells have penetrated rock salt along the eastern margin of the Adavale Basin. The salt occurs in the Boree Salt Member of the Etonvale Formation and was intersected in Boree No. 1, Bonnie No. 1, Bury No. 1, Stafford No. 1, and Alva No. 1 wells. The extent of the Boree Salt Member has been outlined by seismic work. The greatest thickness of salt is thought to occur in an elongate northeast-trending body between the Warrego Fault (Pleasant Creek Arch) and Stafford No. 1 well to the west. The salt occurs below 2673.1 m in this well, where it is about 77 m thick; however, it thickens eastward to about 600 m and occurs at shallower depth, with its top at about 1500 m below the surface, in the vicinity of the Warrego Fault (Galloway, 1970).

The very marked thickening of the salt along the Warrego Fault may be partly due to diapirism. Phillips Australian Petroleum estimate from seismic surveys that the salt may thicken up to 900 m close to the fault and the top of the salt may be only 900 m deep in places (Fig. 10). The salt has not been drilled in the thickened zone. A probable salt diapir was detected by the Lake Dartmouth Seismic survey in 1965 (Tallis & Fjelstul, 1966), about 100 km south of the Stafford No. 1 well. The seismic work also showed a that the unconformity at the base of the Permian has a very uneven surface, which has been interpreted as hogbacks of Devonian sediments protruding into the Permian sequence (Fig. 11); any evaporites present in the sequence would be expected in the intervening areas.

Evidence for stratigraphic thickening of the salt has been given by other authors. Keevers (pers. comm.) considers that-

'the thickening of the salt eastwards is largely due to rapid sedimentary thickening of the D3 salt horizon. The Adavale Basin was almost certainly an intracratonic basin separated from the Cooper Basin to the west during D3 times and barred to the east. Normal marine sedimentation probably occurred eastwards in the orogenic zone of the Tasman Geosyncline. The eastern part of the basin would have been the deepest where the thickest salt was deposited. In the middle to upper part of the salt section the potash salts were deposited. This would have been in the deepest part of the basin particularly since the classical evaporite sequence from carbonates through anhydrite - rock salt to potash bearing rock occurs.

'The D3 salt horizon can be divided into a number of units based largely on the resistivity, sonic velocity, density and gamma ray down hole logs. There is a strong correlation between these sedimentary units in each of the oil wells Bonnie No. 1, Boree No. 1 and Bury No. 1, although the thickness of the salt increases from 100.6 m in Bonnie No. 1 to 506 m in Boree No. 1 and 597 m in Bury No. 1.

'This suggests that there has been little disturbance of the sedimentary pile in the D3 member as far east as Bury No. 1 which is only 3-5 km west of the fault.'

Interpretation of seismic records by Hartogen suggests that thrusting rather than diapirism caused the thickening. Thrust faults are present in the sediments on the west side along the Pleasant Creek Arch. They are particularly clearly defined in the Bury Limestone. A salt pillow is evident on the seismic cross section, 10 km southwest of Stafford No. 1. The salt here is 640 m thick and only about 30 m deeper than at Stafford. At the western edge of the salt member the thickness of the interval from the base of the Permian to the top of the salt is 1500 m. The Devonian sequence pinches out towards the west, but the older beds (Log Creek Formation?) thin much more rapidly than those in the younger sequence (Etonvale Formation?) (Fig. 12). In the area of salt deposition the Bury Limestone appears to thin rapidly towards the centre of the salt basin. Seismic reflections in the centre of the basin indicate, at the base of the salt section, the presence of a lenticular body which may possibly be anhydrite (Fig. 12). The electric logs in Bonnie No. 1, Boree No. 1, and Bury No. 1 wells clearly indicate the presence of anhydrite.

Salt solution has been used to explain the existence of several unusual structures, somewhat similar to those described in the Canning Basin. Salt removal at different periods could produce several types of structures (Fig. 13). For example, in the Adavale Basin salt solution could have occurred in the east, towards the fault line, in D2 time and in the west during the late Devonian. In some places it is difficult to decide if the structure has been caused by removal of salt or if two different formations interfinger. Hartogen considers that the sequence in Leopardwood No. 1 well is indicative that salt was originally present. On the seismic cross-section there is an anomaly, east of Leopardwood No. 1 and west of the main salt

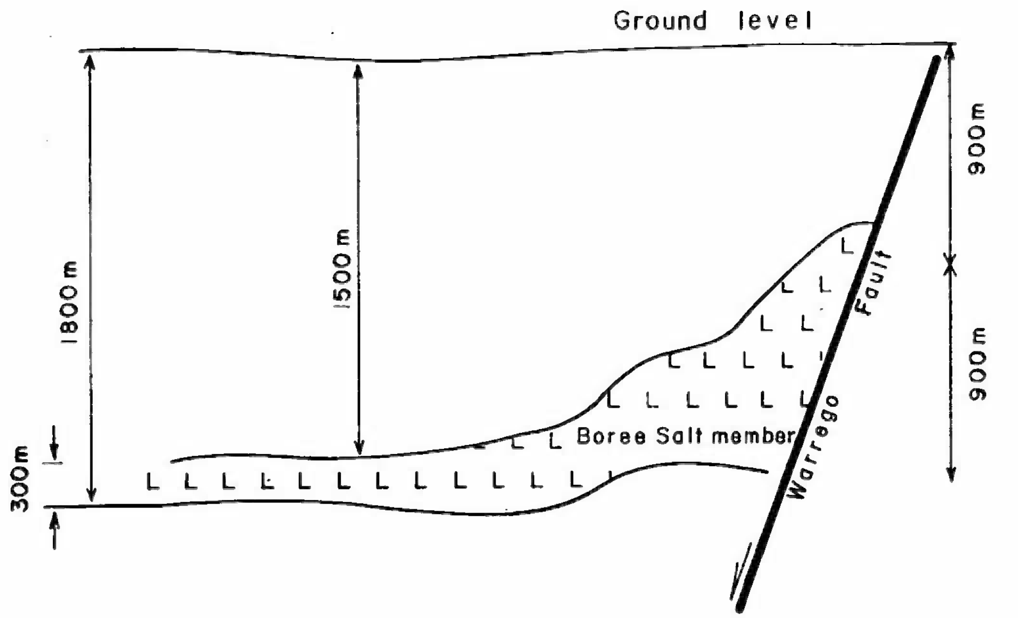


FIG 10-CROSS SECTION OF BOREE SALT MEMBER SHOWING DIAPIRIC? THICKENING NEXT TO PLEASANT CREEK ARCH, ADAVALE BASIN

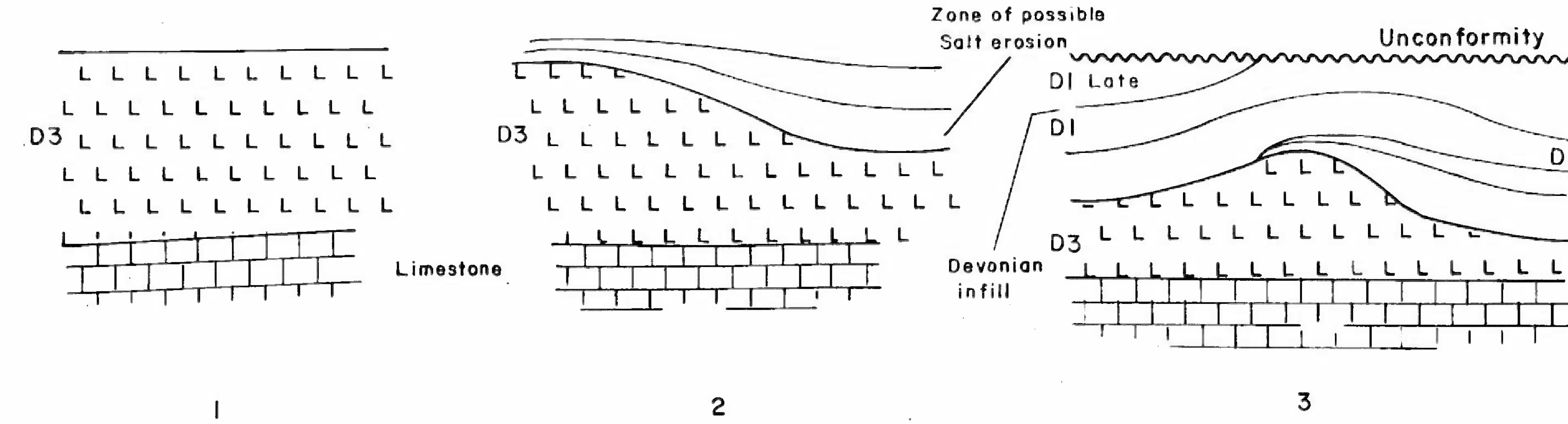


FIG 13-INTERPRETED STAGES IN STRUCTURAL DEVELOPMENT BY SOLUTION OF D3 SALT MEMBER

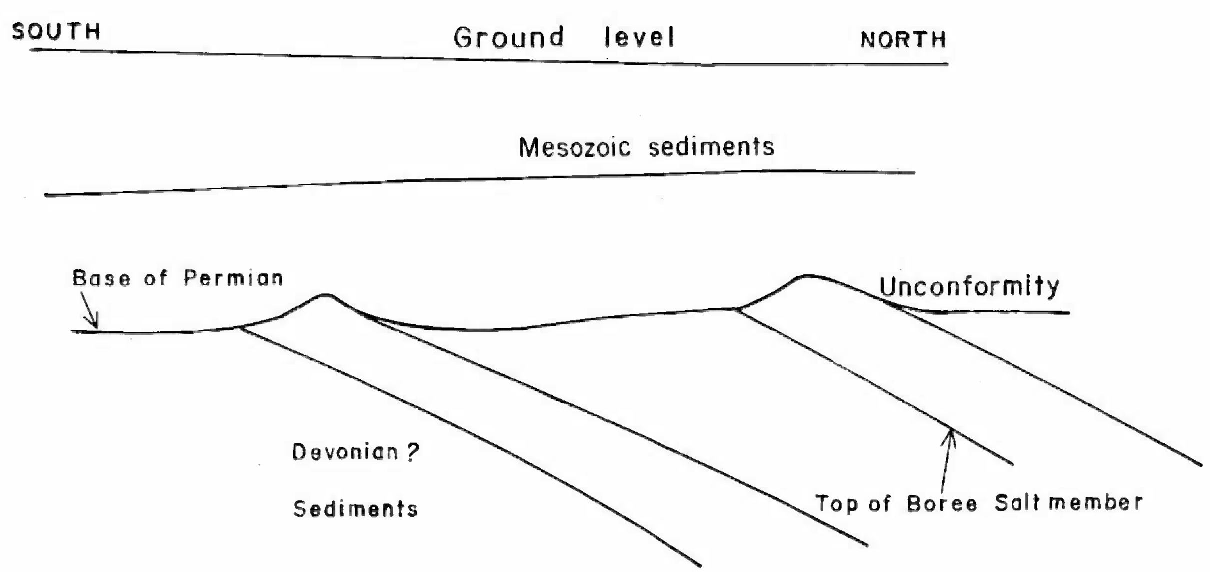


FIG 11-INTERPRETATIONS OF SEISMIC RECORDS, ADAVALE BASIN. PERMIAN SEQUENCE UNCONFORMABLY OVERLYING HOGBACKS FORMED IN THE LOWER DEVONIAN? SEDIMENTS

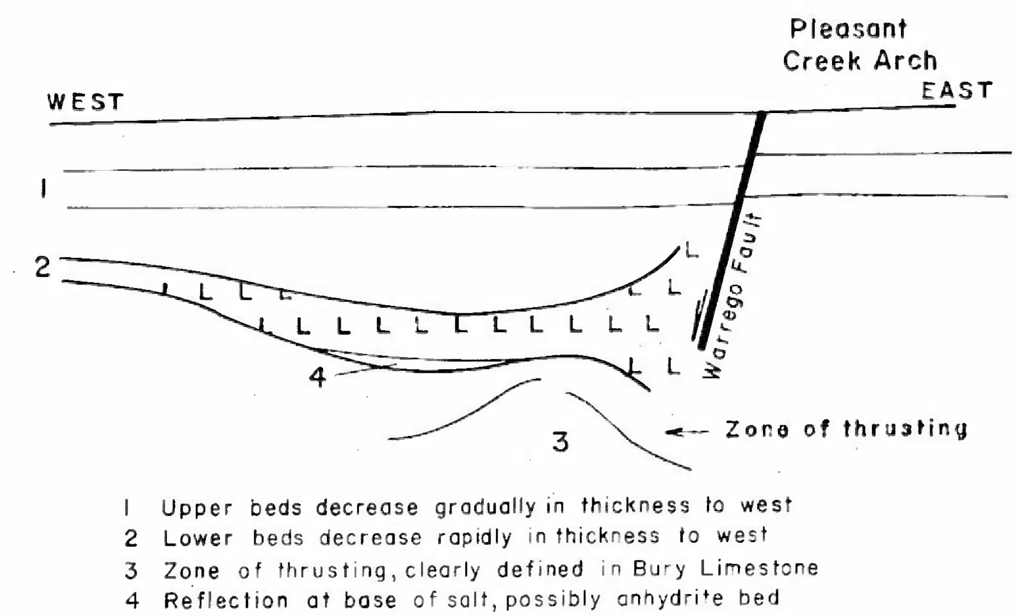


FIG 12-SEISMIC CROSS SECTION IN AREA OF PLEASANT CREEK ARCH, ADAVALE BASIN

a ab reduce to ac c b

GA/5495

FIG 14-SYLVINITE IN CORE No 3 (7362'3") BONNIE No 1 WELL, ADAVALE BASIN, QUEENSLAND (K-Sylvite; Na-Halite) zero line, which is almost certainly a salt outlier and, therefore, indicative of solution between that point and the zero line. Clastic rocks predominate in the well section and the only evaporite minerals are traces of anhydrite and accessory dolomite. Keevers (pers. comm.) considers that this paucity of evaporite minerals, the reduced thickness of the D3 horizon (39.6 m), and its position in the basin all point to the unlikelihood that part of the section ever contained more than trace amounts of salt.

The Adavale Basin contains the only evaporite sequence that includes interbeds of potassium minerals. Sylvite occurs in Bonnie No. 1, Bury No. 1, and Boree No. 1 wells. Coarse sylvite and halite occur in a bed 10 cm thick in core No. 3 at 2243.9 m in Bonnie No. 1 well (Fig. 14). Core No. 19 in Boree No. 1 contains a 2.5 cm bed and irregular pods of sylvite at 2125.7 m, and about 15 cm of interbedded sylvite and halite at 2129.3 m. Sylvite occurs in the Bury No. 1 well in Core No. 8 at 1809.9 - 1812.2 m and in Core 9 at 1969.0 - 1971.8 m. Keevers (1968), of Mines Exploration Pty Ltd, suggested that in Bury No. 1 well there was evidence of two evaporite cycles, with the second cycle only partly developed or alternatively partly removed by erosion or re-solution.

The presence of potash in the Adavale Basin and the classical evaporite succession from dolomite through anhydrite to salt make it, for the time being, one of the most prospective basins in Australia; the most prospective area is adjacent to the Pleasant Creek Arch.

Notes on Well Sequences

Fairlea No. 1 - D3 Member (Boree Salt Member) is missing.

Carlow No. 1 - The D3 Member (Boree Salt Member) is a different facies to that present in most other well sections. Bottomed in Lower Devonian tuff.

Ravensbourne No. 1 - Unnamed Permian rocks encountered. The D4 Member (Lower Devonian) is unnamed.

Bury No. 1 & Bonnie No. 1 - The dip in the cores is generally fairly uniform at about 30-40° but in some parts is considerably steeper. In places the salt cores show grain boundaries as distinct from cleavage boundaries. The grain boundaries are visible on the broken surface and show rounded surfaces whereas cleavage planes are flat and regular. The mineral koenenite (an oxychloride of aluminium and magnesium) is present in Core No. 9 of Bury No. 1 well; it is formed by the interaction of halite, pyrite, and some clay. It is red owing to included hematite.

CARNARVON BASIN

Thin evaporite deposits of Silurian age have recently been discovered in the Gascoyne Basin (Fig. 15) of the Carnarvon Basin. The Shark Bay area is one of the few sedimentary regions in Australia that have been drilled specifically to evaluate evaporite deposits. The presence of evaporites in Silurian rocks penetrated in bores has been mentioned by Condon (1965). Silurian rocks do not crop out; they were first recorded in the Dirk Hartog No. 17B bore and the name Dirk Hartog 'Limestone' (amended to Dirk Hartog Formation by Henderson & Shannon, 1966 in the Yaringa No. 1 well completion report) was proposed for the sequence of dolomite, minor limestone, siltstone, and anhydrite. The age was determined as Ludlovian from conodonts in the limestone.

Only Tertiary rocks crop out close to Shark Bay but cross-sections by Condon (1965) suggest the presence of over 6000 m of sedimentary section consisting primarily of Ordovician Tumblagooda Sandstone overlying Precambrian granulitic rocks and overlain by Dirk Hartog Formation, possible Devonian rocks, Lower Permian, and thin Cretaceous and Tertiary.

Geary (1970) describes Pendock No. 1 well, an offshore well which reached a total depth of 2501 m and bottomed in the Upper Silurian Dirk Hartog Formation. Anhydrite occurs mainly in the upper cryptocrystalline dolomite.

Yaringa No. 1 well (TD 2288.4 m), drilled by Continental and Sun, discovered 36.3 m of salt in eight beds in the Dirk Hartog Formation. Until Yaringa No. 1 was drilled there was no evidence of halite in the Dirk Hartog Formation. Exploration of the Dirk Hartog Formation for potash deposits was undertaken on a farmout arrangement to Magellan Petroleum (N.T.) Pty Ltd from Continental Oil Co. of Australia Ltd and Australian Sun Oil Co. Ltd. Two exploratory holes were drilled - Hamelin Pool No. 1 (TD 1595.3 m) and No. 2 (TD 1219.2 m) on temporary reserves 4186 H and 4187 H. The location of these wells is shown in Figure 16. In Hamelin Pool No. 1 seven beds, totalling 22.9 m of salt, were recognized, and in Hamelin Pool No. 2 5.2 m of salt is distributed over three beds of varying thickness. The thinning of salt beds in Hamelin Pool No. 2 suggests that the well site is near the southeast edge of the saline deposits. In Hamelin Pool No. 1 the upper salt beds are not present, either because of erosion or non-deposition, but the remaining beds are about the same thickness. Pendery (1970a) suggests that the evaporites may thicken to the

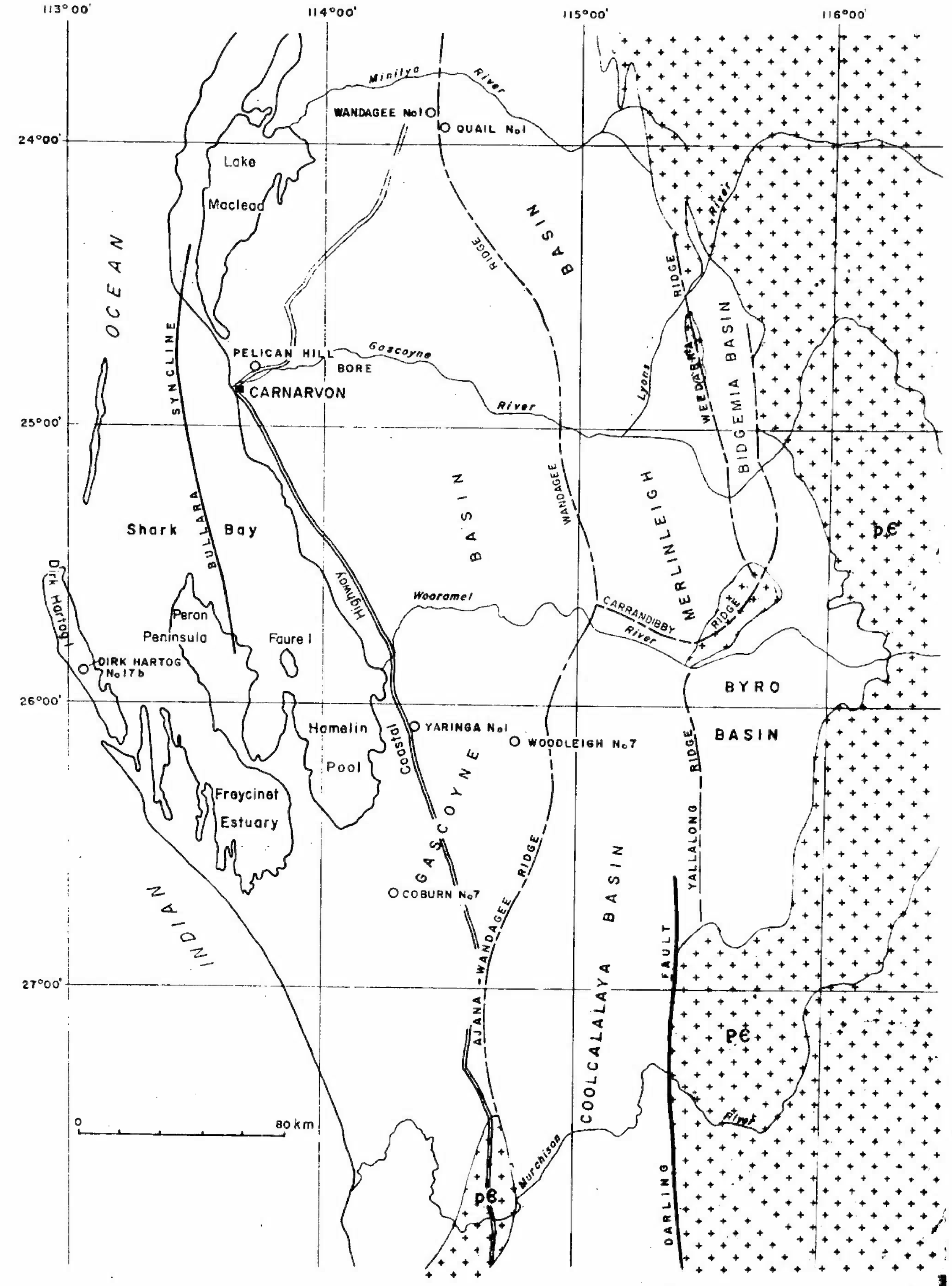


FIG 15 - STRUCTURE MAP OF THE CARNARVON BASIN (after Condon, 1968)

Record 1973/170

W/A 247

northwest or north from the Yaringa location. However, the evaporite sequence is apparently undetectable by geophysical methods and may be relatively thin throughout the area. The correlation of the salt beds between the wells is shown in Figure 17.

Analyses of the Dirk Hartog evaporites show that salt bed 2, present only in Yaringa No. 1, is the most prospective for possible bittern salt deposition in that bromine values are high (Appendix 6) and the bed is relatively thick. Salt beds 3 and 4 may also be of interest as they also have high bromine values and would appear to be more persistent laterally.

The significance of bromine content of evaporite deposits is discussed on p.

In some parts of the Carnarvon Basin, local doming of formations may be related to diapirism (Sturmfels, 1952). Domes occur in Permian sediments near Hill Springs on the west side of the Kennedy Range, and small circular structures are present near the Lyndon River. However, it has been pointed out that the derivation of thick evaporites would be most unusual from the thick glacial Permian rocks of the Lyons Group, which underlies the area, and the source may lie in the older Palaeozoic sequence. The Artinskian rocks may neither have had a thick interbedded evaporite sequence nor have been buried sufficiently deep to allow piercement structures to develop. Noakes (1972) states that salt domes inland from Shark Bay, W.A., were explored for potash, but with no encouraging results.

Other geologists consider that the domal structures are essentially tectonic features associated with major zones of faulting and are unlikely to have a diapiric origin. The circular features near the Lyndon River are thought to be synclinal drags by some workers. Evaporite gypsum occurs in outcrops of the Artinskian Bulgadoo Shale and Wandagee Formation, and brine occurs in bores drilled in the Wangagee Formation on the Lyons River station. Condon (1967, 1968) mentions the occurrence of evaporite material in the Quinnanie Shale, the Madeline Formation, and in the Bulgadoo Shale all of which are Artinskian.

Notes on the Dirk Hartog Formation and its position in the stratigraphic sequence

The Yaringa Salt Member of the Dirk Hartog Formation is known mainly from the Gascoyne Basin and is upper Silurian (middle upper Ludlovian). The age has been determined by G. Philips (1969), using conodonts found in a limestone of the formation.

The Dirk Hartog Formation (Dirk Hartog 'Limestone' of McWhae et al., 1958; amended to Dirk Hartog Formation by Henderson & Shannon, 1966) is 671.2 m thick (855.3 - 1526.4 m) in Yaringa No. 1 well and in the type section in Dirk Hartog 17B well where the formation was first described it is 739.1 m thick (665.4 - 1404.5 m). The top of the formation is an erosion surface farther north in the Carnarvon-Minilya area, where it is unconformably overlain by Devonian rocks. However, salt is not known in the Pendock, Quail and Wandagee wells (Fig. 16), which penetrate the formation in the north, but anhydrite is common and has been reported also in the Dirk Hartog well. The Wandagee and Quail sequences in the Dirk Hartog Formation are somewhat similar, though the Quail well is outside the Gascoyne area in the adjacent Merlinleigh Basin; the two basins were not separated (by faulting) until the Upper Jurassic.

The Tumblagooda Sandstone occurs beneath the Dirk Hartog Formation in the Dirk Hartog Well. It is a fluvial deposit shed primarily from the Darling Fault area, although it is known in Wandagee No. 1, considerably farther north of the Darling Fault area. It contains high salt brines, is up to 3000 m thick in outcrop, mostly red, and grades upwards into the Dirk Hartog Formation, which suggests that the Tumblagooda Sandstone also may be Silurian. The sandstone in the Quail and Wandagee sections beneath the Dirk Hartog Formation are lithologically similar to the Tumblagooda Sandstone.

The Middle to Upper Devonian Point Maud Formation shows a reefoid development in Pendock No. 1 well. In addition to the Silurian evaporites, minor Devonian evaporites are present in the Gneudna Formation in Yaringa No. 1, and these may have important palaeogeographic implications.

It has been suggested by some geologists that very thick evaporites could be present in the Rough Range area and may be situated on the basinal side of a reef, but no evidence in support of this claim has been cited.

The structure between the Dirk Hartog 17B well and the Yaringa well is shown in Figure 18, and the sequences penetrated in Yaringa No. 1 and Hamelin Pool Nos 1 and 2 wells is shown in the table below, which has been taken from the Hamelin Pool No. 2 well completion report.

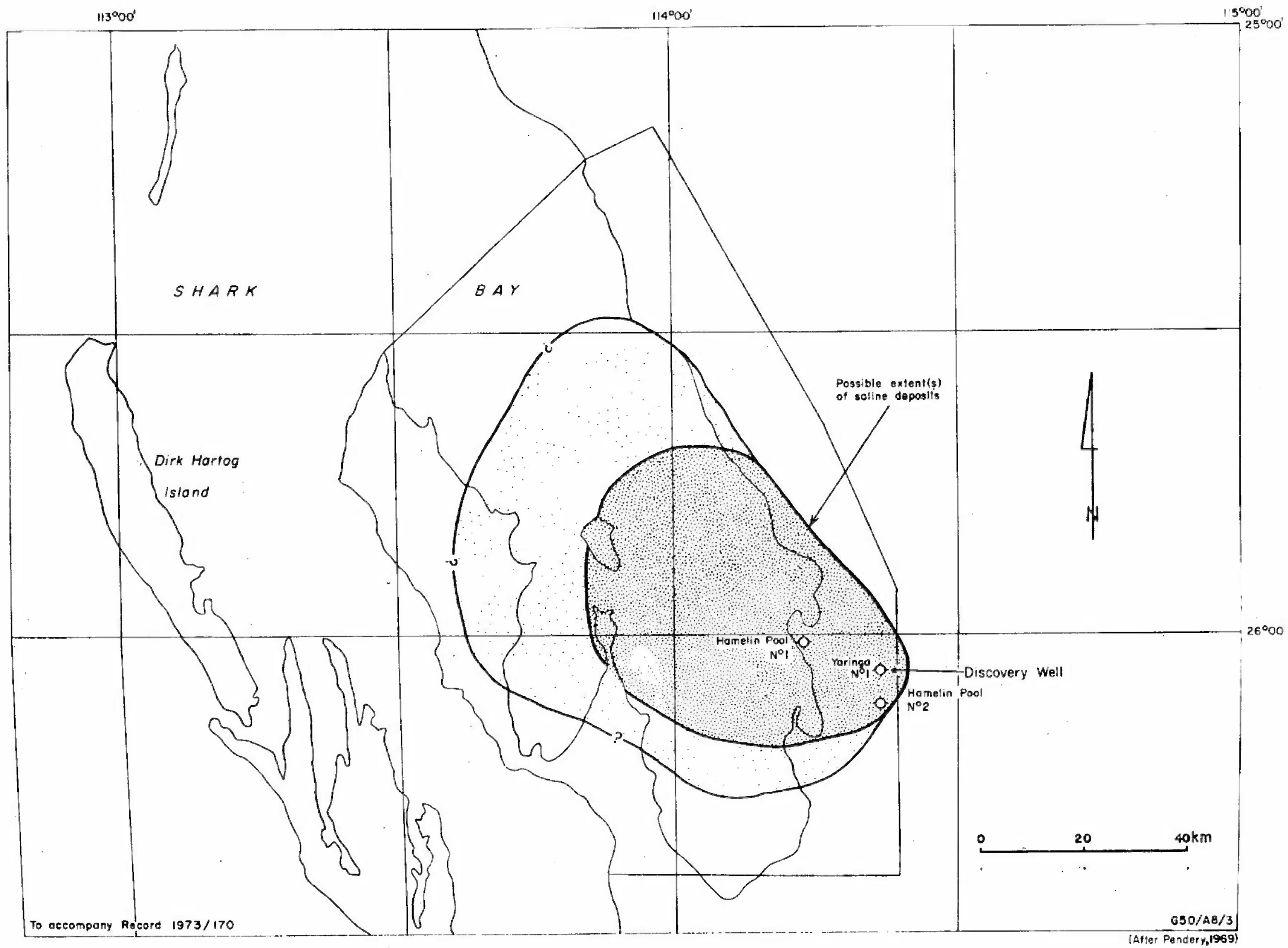
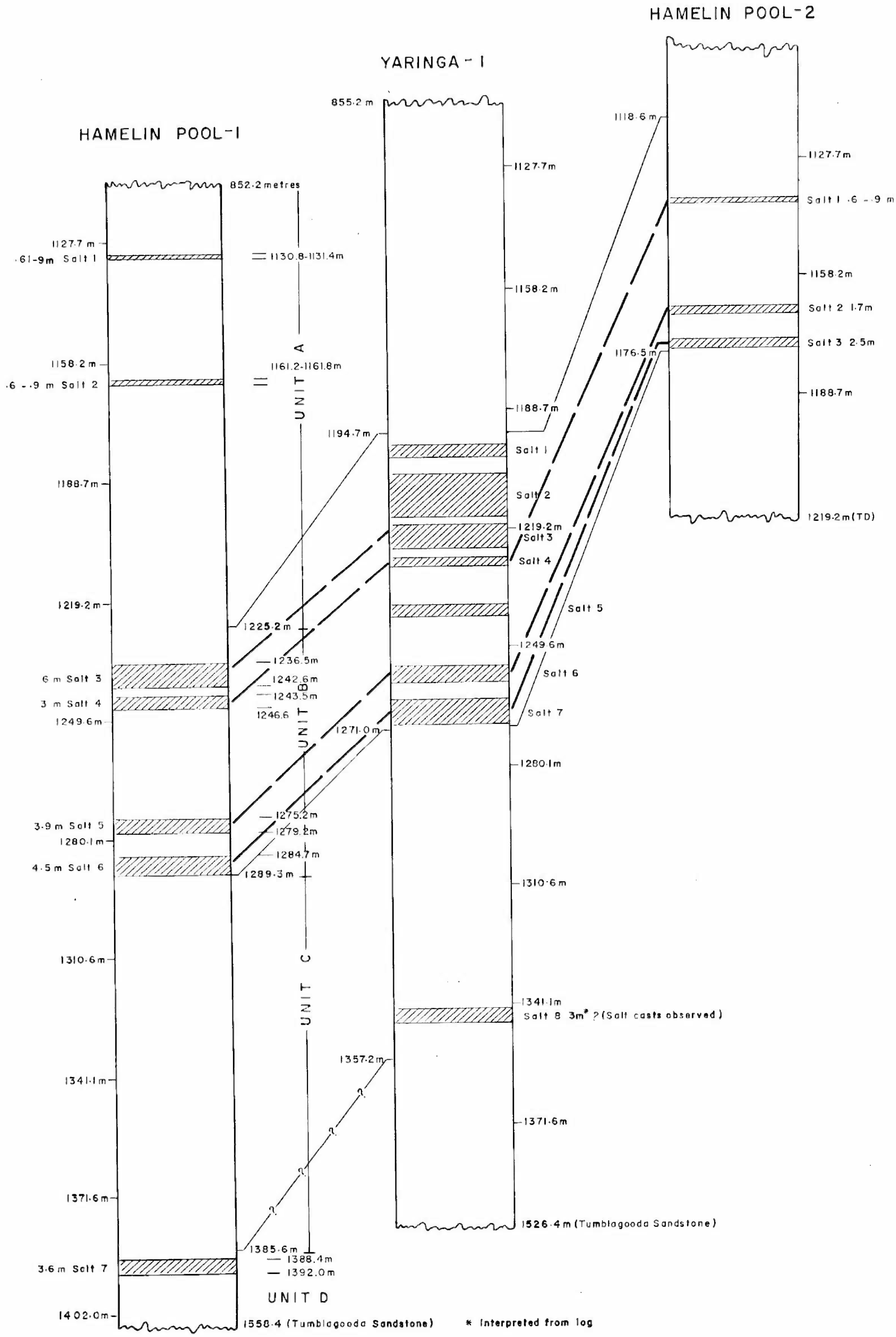


Fig 16 Location of wells penetrating Silurian evaporites - Carnarvon Basin

FIG 17- WELL CORRELATIONS OF SALT BEDS IN THE DIRK HARTOG FORMATION, CARNARVON BASIN. (After Pendery et al., 1969)



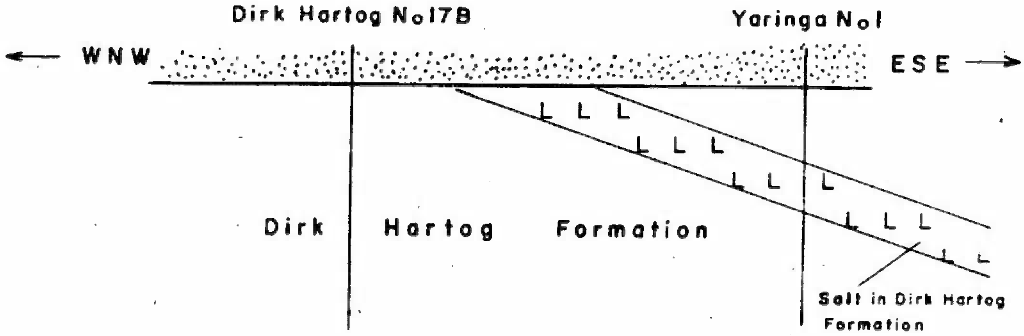


FIG 18-SEQUENCES OF DIRK HARTOG FORMATION (LUDLOW) PENETRATED IN DIRK HARTOG 17B AND YARINGA WELLS-CARNARVON BASIN

To accompany Record 1973/170

W/A 248

Formation	Hamelin Pool No. 1	Yaringa No. 1	Hamelin Pool No. 2
Surface deposits			8.8 m
Toolonga Calcilutite (Senonian)	129.5 + m	64.9 m	55.5 m
Alinga Fm. (Albian-Cenomanian)	51.8 m	50.9 m	61.0 m
Birdrong Fm. (Aptian)	20.4 m	25.0 m	66.8 m
Unknown A (?)	136.2 m	179.8 m	128.3 m
Unknown B (?)	506.6 m	529.1 m	466.0 m
Dirk Hartog A) Upper Silurian	873.1 m	339.5 m	327.4 m
Dirk Hartog B) Upper Silurian	64.0 m	76.2 m	59.4 m
Dirk Hartog C) Upper Silurian	96.3 m	87.8 m	41.1+m
Dirk Hartog D) Upper Silurian	172.8 m	167.6 m	-
Tumblagooda Sandstone (Ordovician?)	-	762.0+m	-
T.D.	1595.3 m	2288.4 m	1219.2 m

OFFICER BASIN

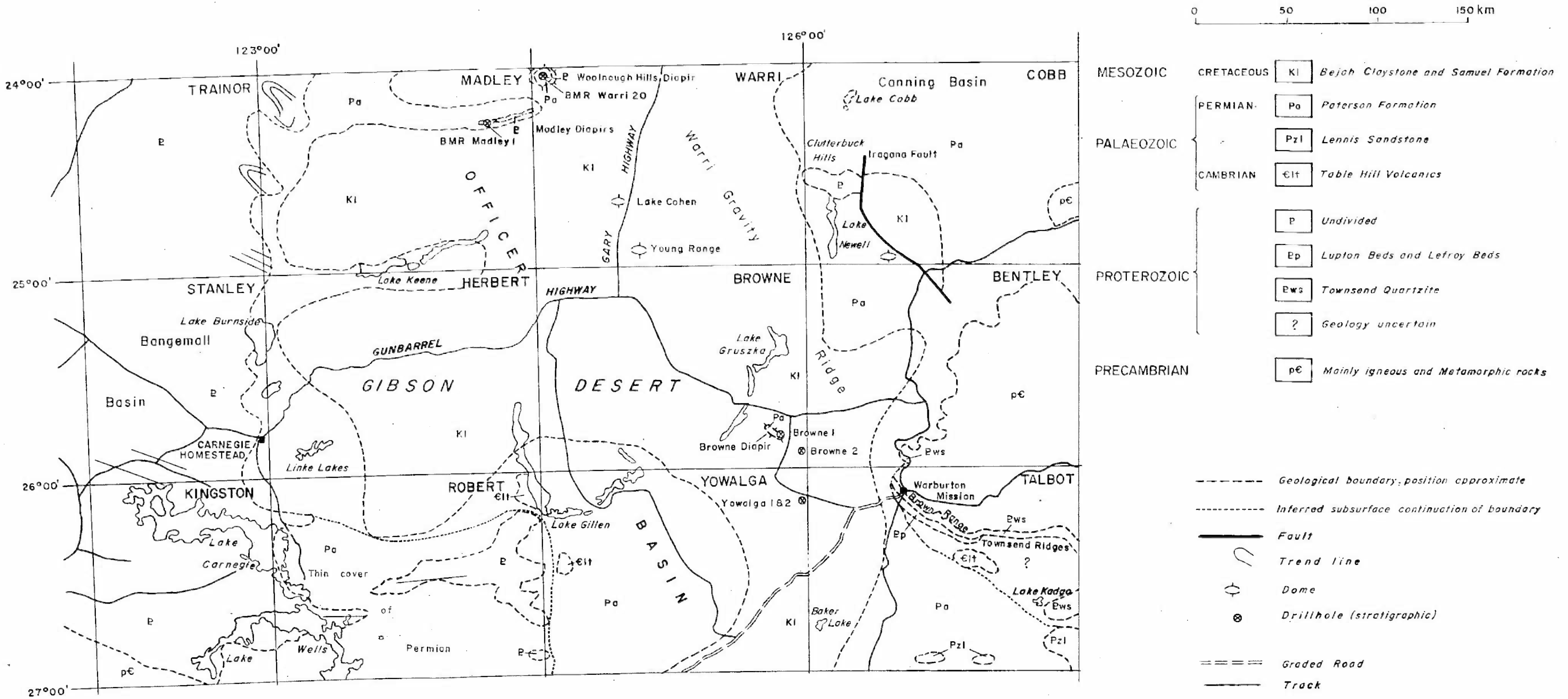
Surface deposits of evaporites in the Officer Basin were first discovered in the centre of Woolnough Hills in 1956 during geological reconnaissance mapping of the southern Canning Basin by geologists of the BMR. The occurrence was recognized as possibly constituting the core of a salt dome (Veevers & Wells, 1959, 1960), and subsequently Leslie (1961) made a regional geological investigation of the Gibson Desert area in the Officer Basin and made further observations of Woolnough Hills. Wells (1963) reported the occurrence of other diapiric structures, some with cores of exposed evaporites, arranged in an arcuate line a few kilometres southwest of the Woolnough Hills. Wilson (1967) considered that at least twelve domal structures, occur along this southwest-trending line, which he called the Madley Diapiric Trend (Figs. 19, 26 and 27). The best exposed of these diapirs occur in a central zone and for ease of reference have been numbered 1 to 6 from east to west. They all have cores of Proterozoic rocks with rim rocks of Permian and Mesozoic strata.

The Woolnough Hills (Fig. 20) and Madley Diapirs (Figs 26 and 27) occur in a northwestern lobe of the Officer Basin, here informally called the Gibson Depression, because it lies in the area of the Gibson Desert. Evidence for its presence is mainly from regional geophysical surveys. The age and history of movements of the intrusive evaporitic cores is not known with certainty, but the latest movements of the diapirs probably continued into mid-Tertiary times.

It was generally considered that the evaporites were Precambrian because of similarities between the overlying stromatolitic dolomite and the Precambrian dolomites in neighbouring basins, notably the Bitter Springs Formation of the Amadeus Basin. Recent re-interpretation of seismic work for the Hunt Oil Co. has suggested that there are possibly two levels of evaporites, both of Precambrian age. The probable younger evaporite sequence has been called the Babbagoola Beds (defined from the Yowalga No. 2 well). The presumed older sequence, called Browne Beds, was defined by Lowry et al, (1972) in the Browne No. 1 well, where it forms the intrusive core of the Browne Diapir. Evaporites lithologically similar are exposed in the diapiric cores of some of the domes along the Madley Diapirs and in the Woolnough Hills Diapir. Interpretation of the seismic cross-section through the Browne No. 2 well suggests that the evaporitic sequence may be part of the Babbagoola Beds. The assumed age of both the Browne and Babbagoola Beds depends on isotopic age determinations carried out on volcanic rocks in the sequence.

The Table Hill Volcanics (described by Talbot & Clarke, 1917 and named by Peers, 1969) are interbedded in the succession and are thought to lie stratigraphically above both evaporite sequences; they are tentatively regarded as Early Cambrian in age. The dolomite at Woolnough Hills (Figs 20 and 21) is interbedded with thinly bedded siltstone (with holomorphs after halite) and unconformably overlain, in turn, by Permian fluvioglacial deposits and Cretaceous sediments. Poorly exposed lateritized Lower Cretaceous lutite crops out in the distal parts of the dome and in neighbouring outcrops. The geological succession in the Madley Diapirs (Figs 25, 26, 27) is somewhat similar (Wells, 1963; Wilson, 1967). The evaporites in outcrop at Woolnough Hills and Madley consist mainly of secondary friable gypsum in contact with scattered blocks of brecciated dolomite. A few fresh exposures of tightly folded and in part brecciated gypsum are exposed in sink holes at Woolnough Hills and in some of the Madley Diapirs. Several shallow stratigraphic drill holes, BMR Madley No. 1 at Madley Diapir No. 6, and BMR Warri Nos 1-20 at Woolnough Hills, showed conclusively that the intrusive

FIG 19-LOCATION OF DIAPIRIC STRUCTURES IN THE NORTHERN PART OF THE OFFICER BASIN



To accompany Record 1973/170

AUS 1/222A

FIG 20-VERTICAL AIR PHOTOGRAPH OF THE WOOLNOUGH HILLS DIAPIR
(Enlargement from Warri Run I, Photo 70)

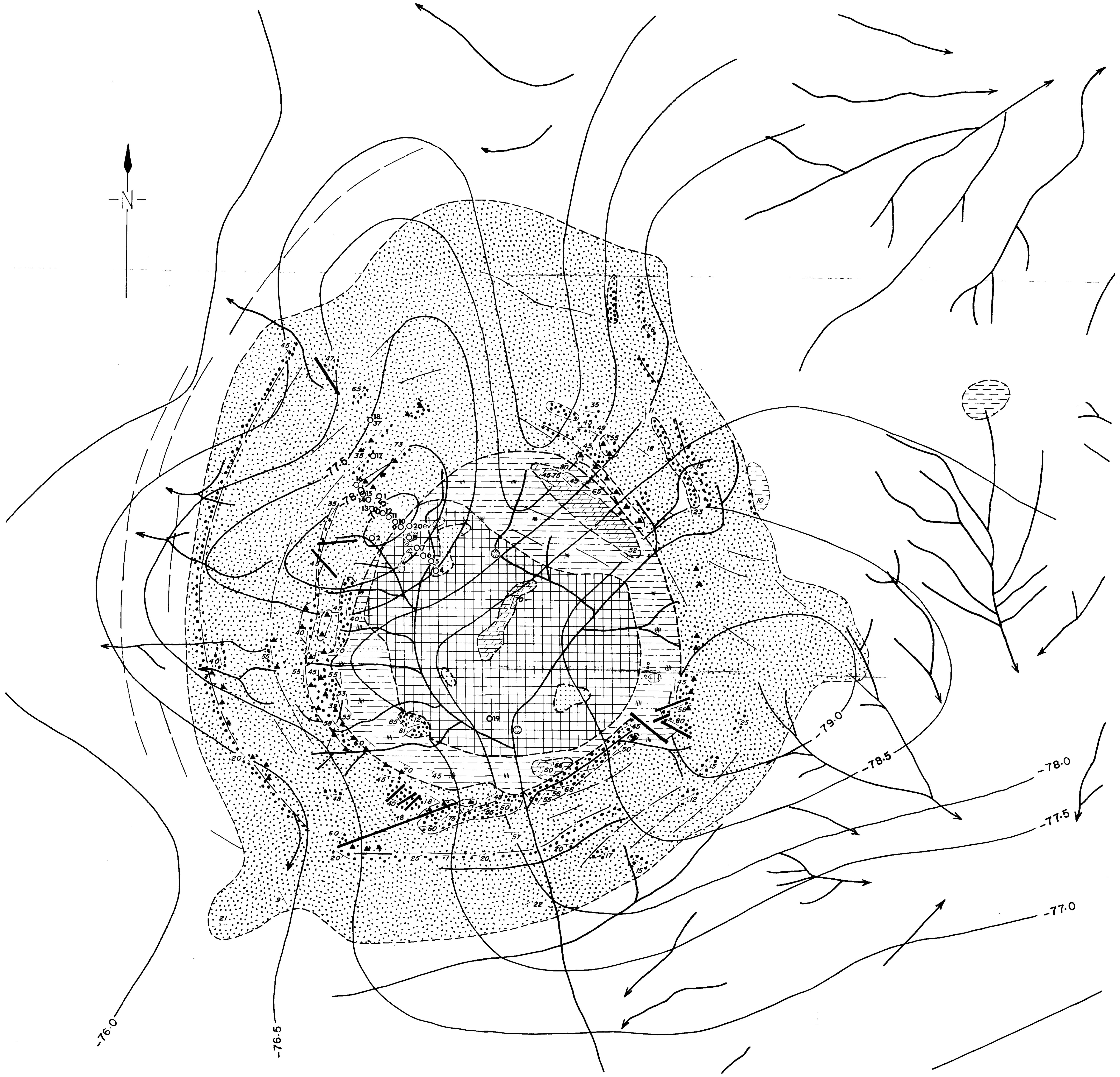


FIG 21-GEOLOGICAL MAP OF WOOLNOUGH HILLS WITH BOUGUER ANOMALIES

after W.J.E. von de Graaff (GSWA)

0 — 1 Kilometre appro. — 0 — 1 M

CRETACEOUS	Claystone	Samuel Formation ? Bejah Claystone	
PERMIAN	Undifferentiated; Sandstone, Siltstone, Shale, Tillite	Paterson Formation	
	Tillite		
	Sandstone		
	Chert, Siltstone etc.		Proterozoic, including Browne Beds ?
	Dolomite		
	Sandstone		
	Gypsum Core		

— 77.0 Gravity contours, interval 0·5 milligals

O9 Stratigraphic hole

O ev Evaporite hole (B M R Warri No 20)

Geological boundary

Fault

20 Strike and dip of strata, measured

Strike and dip of bed, vertical

Trend lines

Sinkhole

NOTE: B M R Warri No 3 is water well about 12 km Southeast of Woolnough Hills

To accompany Record 1973/170

G 51/A3/2

beds are halite, which is overlain by cap rocks of mixed carbonate and sulphate rocks, tens of metres thick. A detailed gravity survey over the dome by BMR suggested that the intrusive evaporite plug is probably double-crested (Fig. 21). The gravity values obtained over the structure are in general consistent with a salt dome model with rock salt (density 2.1) in a body 1000 m in diameter and 5000 m in height intruding rocks of density 2.3 in an area where the total thickness of sediments is about 7000 m and the assumed basement density is 2.5-2.6. Other geophysical surveys in the region show that the Gibson Depression contains at least 4500 m and perhaps as much as 7500 m of sediment and is separated from the Kidson Sub-basin to the north by a buried basement ridge. Woolnough Hills are on the southwest flank of the ridge.

Other less well defined domes are present in the Gibson Depression (Fig. 19), particularly in the Madley and Warri Sheet areas. They include poorly defined domes in Permian and Mesozoic rocks at Lake Cohen, in Cretaceous rocks at the eastern end of the Young Range and another in Permian, Mesozoic and Cretaceous rocks near the Iragana Fault (Wells, 1963). Several closely spaced doubly plunging anticlines and synclines lie in a northwest-trending zone between Lake Breaden and the Baker Range. A seismic cross-section (Jackson, 1966b, fig. 23), indicated the presence of a diapiric core underlying the fold zone and the structure has been termed the Browne Diapir (Figs 22, 23, and 24); evaporitic sequences were subsequently penetrated in Hunt/Placid Browne Nos 1 and 2 stratigraphic wells (Jackson, 1966b) (Fig. 24).

Hunt Oil Co. seismic lines (Hunt Oil Co., 1966) 12D and 12E show possible diapiric masses which may trend parallel to the Browne Diapir axis.

Seismic record sections in Turpie (1967) show possible diapirs along the Gunbarrel Highway - one is a possible continuation of the Browne Diapir trend and the other occurs a few kilometres farther west.

Mack & Herrmann (1965) described a sequence of 8500 m of late Precambrian to ?Cambrian sediments in the Runton-Carnegie area. The two members of the sequence are in places separated by an angular unconformity. The lower member consists of sandstone, shale, carbonate rocks, and evaporites, and the upper of sandstone, shale and evaporites. The evaporites consist mostly of gypsum but are poorly exposed. Mack & Herrmann (1965) correlate the sequence, which is now thought to be part of the Bangemall Basin, with the Carnegie Sandstone - Maurice Formation interval in the western part of the Amadeus Basin, but whatever its age it has been used as evidence of widespread evaporitic sedimentation. Because the sequence occurs in areas near salt lakes some doubt has been expressed as to whether the evaporites are actually interbedded with the sediments; the cursory examination during the present study did not resolve these doubts.

Thin evaporite beds were intersected in two shallow stratigraphic test holes and a petroleum exploration well drilled by Hunt/Placid Oil Company (Jackson, 1966a). In the Yowalga No. 2 well evaporites occur in Unit B of the Babbagoola Beds, which lie unconformably beneath the Table Hill Volcanics. Poorly preserved fossil spores (leiospheres) from cores in Units B & C of the formation suggest a late Precambrian age (Balme, in Jackson, 1966a).

The succession penetrated in the well is:

Age	Formation	Thickness	
Cainozoic	laterite	3.7 m	
Lower Cretaceous	Samuel Formation	86.9 m	
	---unconformity---		
Permian	Paterson Formation	312.4 m	
(Sakmarian)	(Yowalga Sandstone of Jackson, 1966a)		
	---unconformity---		
Lower Palaeozoic	Lennis Sandstone	321.6 m	
	---unconformity---		
Lower Cambrian	Table Hill Volcanics	117.3 m	
	---unconformity---		
Proterozoic?	Babbagoola Beds		
	Unit A	41.1 m)	
	Unit B	6.1 m)	143.6 m
	Unit C	96.3 m)	
	T.D.	989.4 m	

Unit A in the Babbagoola Beds consists of interbedded fine to very coarse-grained sandstone and dark red-brown micaceous shale. Anhydrite occurs in these rocks as fracture and joint fillings. Unit B consists of silicified, anhydritic dolomite with gypsum and anhydrite veins and fracture fillings. Unit C is interbedded siltstone and shale.

FIG 22–VERTICAL AIR–PHOTOGRAPH NORTHERN PART OF THE BROWNE DIAPIR, OFFICER BASIN. (Enlargement from Browne Run 9, Photo 5120)

SEISMIC LINE 13-C

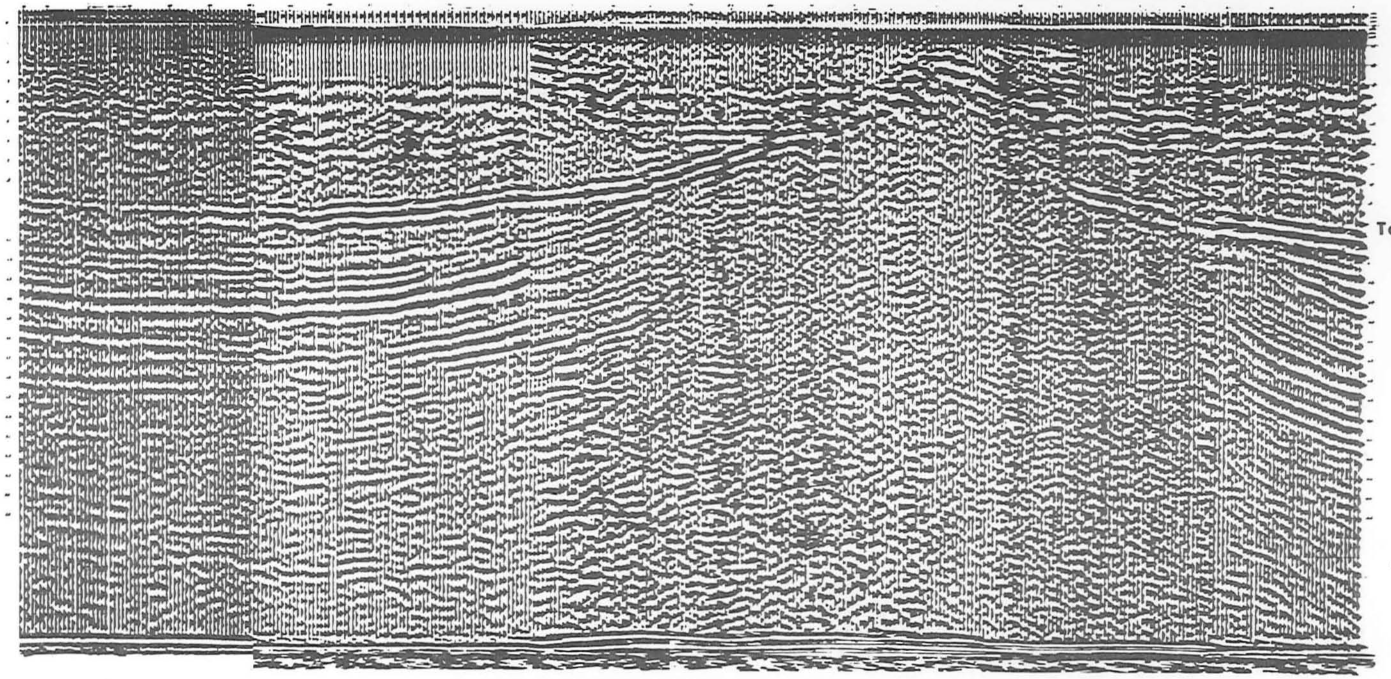
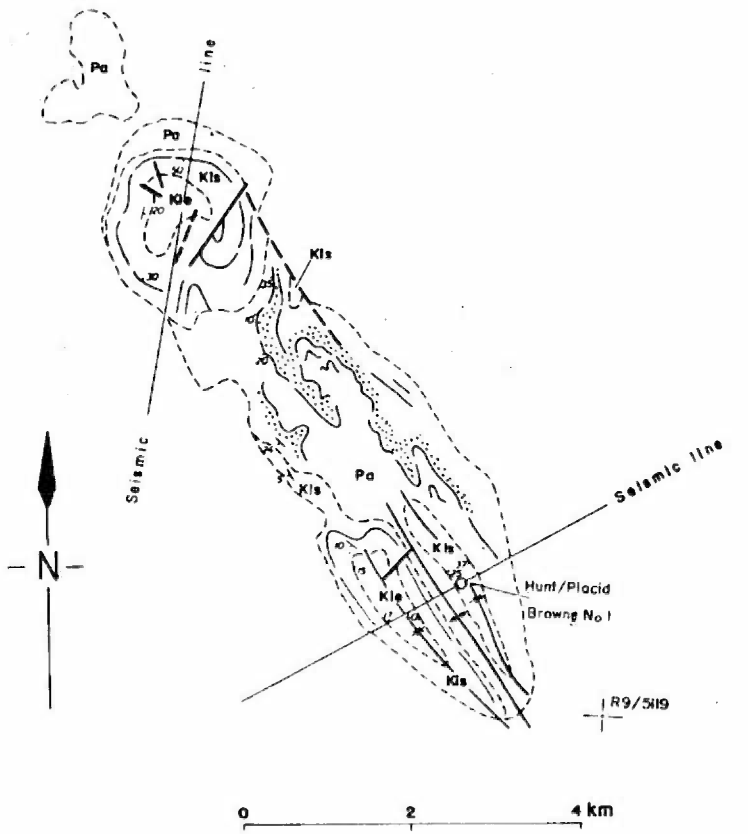


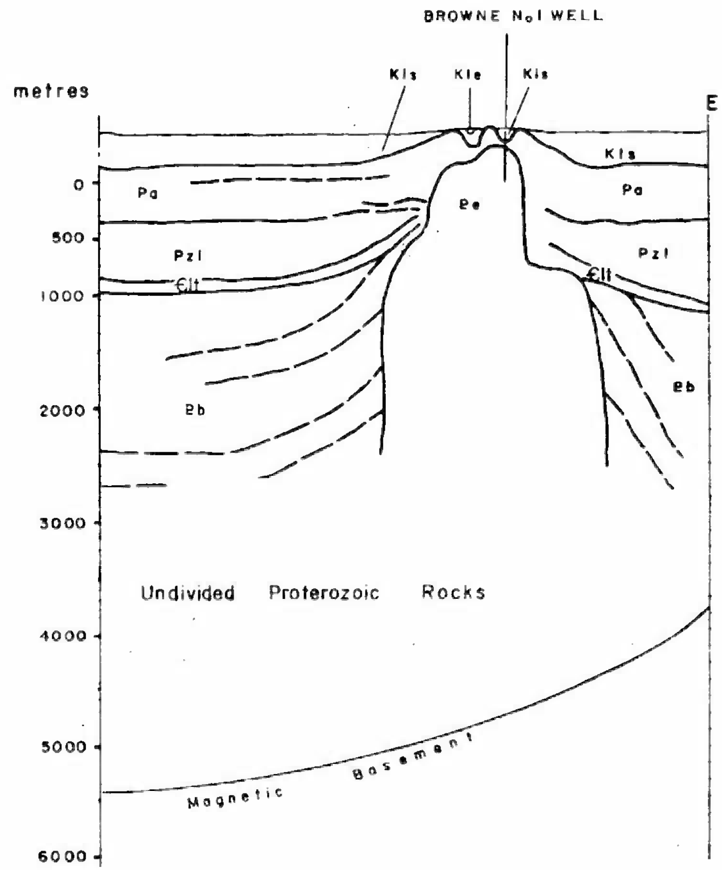
FIG 23-SEISMIC CROSS-SECTION OF THE BROWNE DIAPIR, OFFICER BASIN
WESTERN AUSTRALIA (after Jackson, 1966 b)

51

FIG 24-GEOLOGICAL SKETCH MAP AND CROSS-SECTION OF THE BROWNE DIAPIR



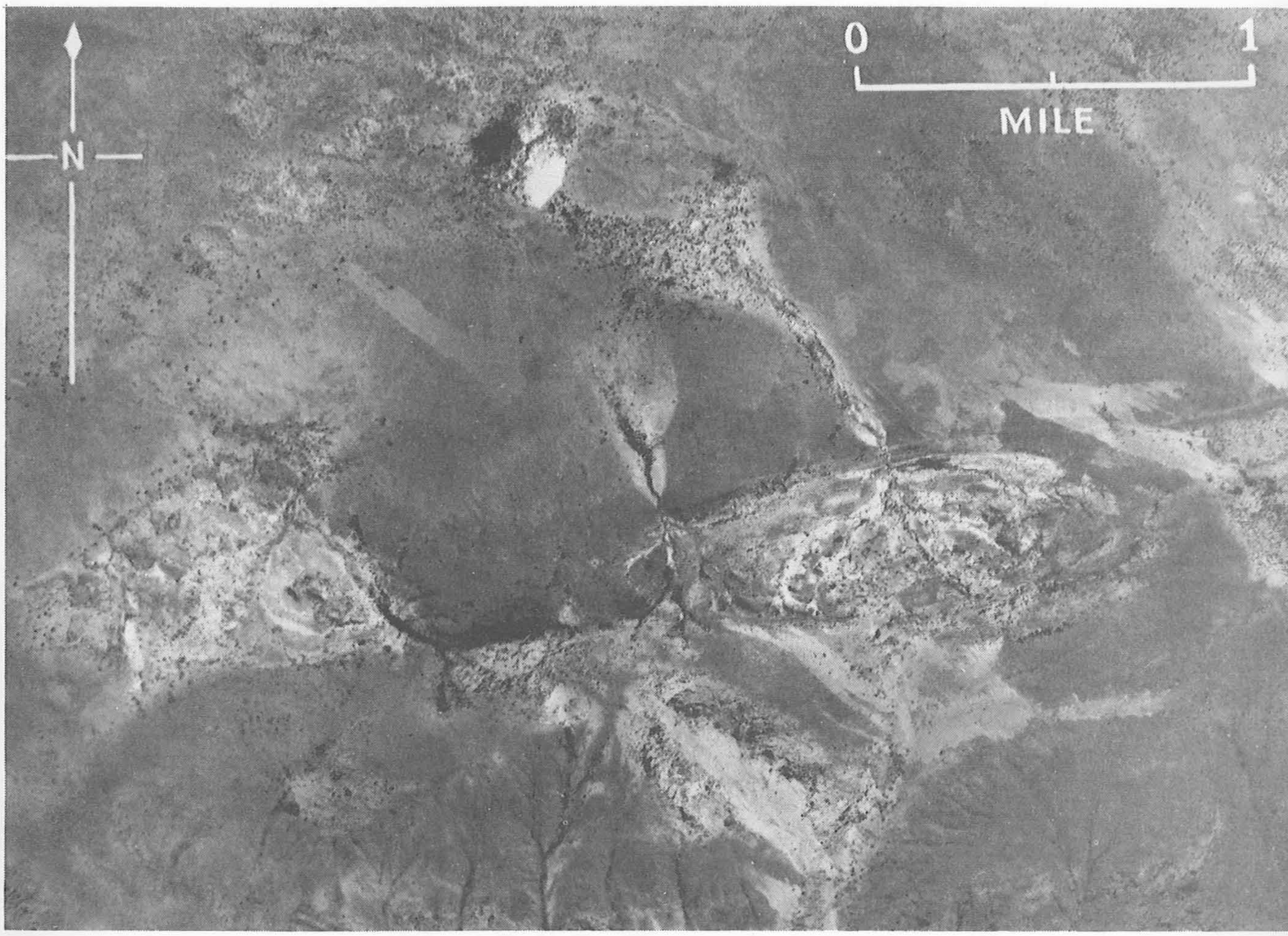
Kle	*Bejah Claystone*		*Geological boundary, position approximate*
Kls	*Samuel Formation*		*Anticline*
Pa	*Paterson Formation*		*Syncline*
	Strongly ferruginised sandstone of Paterson Formation		*Fault*
Pzl	*Lennis Sandstone*		*Fault, position approximate*
€lt	*Table Hill Volcanics*		*Strike and dip of strata, measured*
Pb	*Babbagoola Beds*		*Trend lines; interpreted from seismic reflections in cross-section*
Pe	*Browne Beds*		*Air-photo centre point*



CROSS-SECTION FROM BROWNE GEOLOGICAL SHEET
SG/51-8 PRELIMINARY EDITION 1972

To accompany Record 1973/170

G51/A8/3



G/5472

FIG 25-VERTICAL AIR-PHOTOGRAPH OF DIAPIRS Nos. 5 & 6 (East to West)
IN THE MADLEY TREND, MADLEY SHEET AREA, OFFICER BASIN

0 1 km

FIG 26- AIRPHOTO MOSAIC OF THE MADLEY DIAPIRIC TREND
(AIRPHOTOS, MADLEY RUN 2, Nos. 23, 26, 30)

FIG 27-GEOLOGICAL MAP OF THE MADLEY DIAPIRS 1 to 6, (after Wilson, 1967) GIBSON DESERT, WESTERN AUSTRALIA

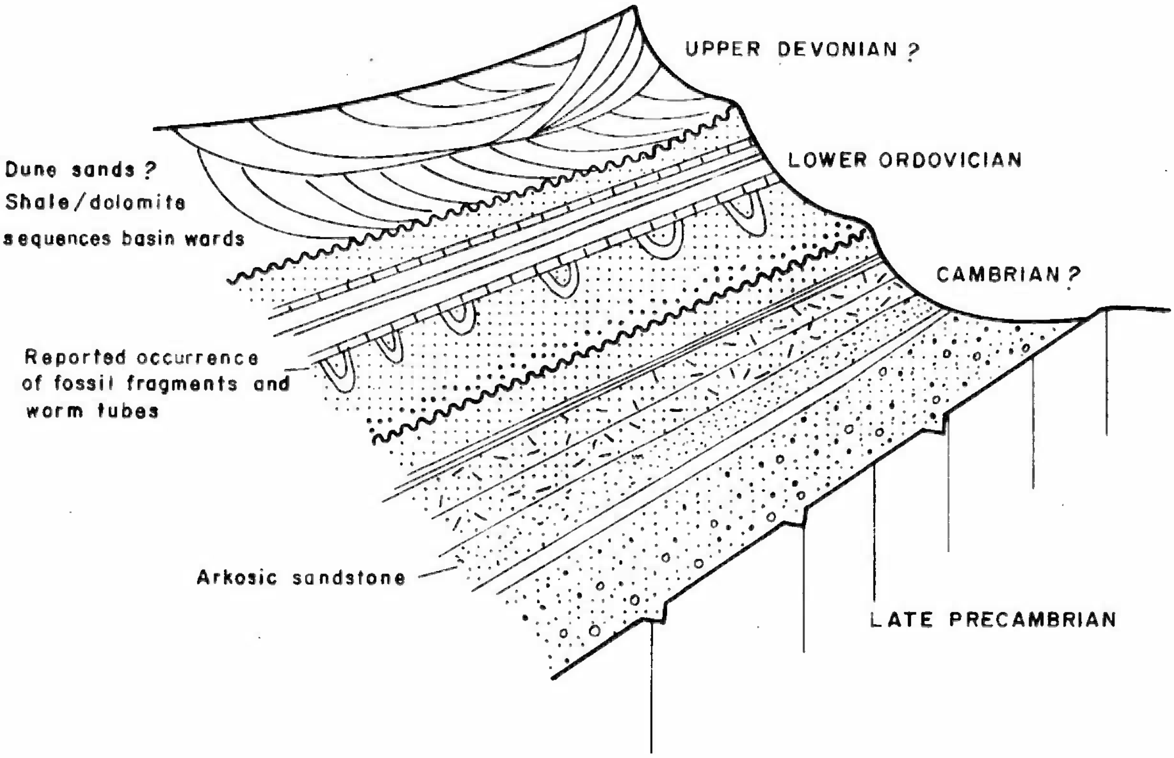


FIG 28 - SEQUENCE ABOUT 60 m THICK UNCONFORMABLY OVERLYING LATE PRECAMBRIAN SEDIMENTS AT THE NORTHEASTERN EDGE OF THE OFFICER BASIN

Evaporites were encountered in the Browne Beds sequence of uncertain age (?Proterozoic) in the Hunt/Placid Browne Nos 1 and 2 shallow stratigraphic holes drilled on the Browne Diapir between Lake Breaden and the Todd Range, in the Browne Sheet area (Jackson, 1966a).* The sequences penetrated in the two wells were-

Age	Formation	Thickness	
		Browne No. 1	Browne No. 2**
Lower Cretaceous	Samuel Fm.	84.4 m	140.2 m
Lower Permian	Paterson Formation ("Yowalga Sandstone" of Jackson, 1966a)	48.2 m	121.9 m
Proterozoic?	Browne Beds	254.2 m	30.5 m
	T.D.	386.8 m	292.6 m

In Browne No. 1 the evaporites occur in the Browne Beds (132.6 - 386.8 m) in a sequence consisting of 152 m of limestone, gypsum, and shale overlying 101 m of gypsum banded with varying amounts of black and grey waxy shale. In Browne No. 2 they occur over the interval 262.1 - 292.6 m in a sequence consisting of 26 m of limestone and a little shale overlying 4.5 m of gypsum with lath-like crystals and shale partings. The evaporite minerals are anhydrite, gypsum, and halite; they occur as thin beds or as secondary fracture fillings. Minor shows of hydrocarbons were encountered in both wells in the Browne Beds.

In the northeastern part of the Officer Basin, in South Australia, about 350 km east-southeast of the Browne Diapir area, a Palaeozoic sequence about 60 m thick unconformably overlies Proterozoic sediments on the south side of the Musgrave and Mann Ranges (Fig. 28). The Devonian sandstones in outcrop pass into shale/dolomite sequences basinwards, but the westerly extent of this sequence is unknown. The Cambrian sediments in outcrop are predominantly marginal arkosic sandstone but some anhydrite has been reported interbedded in Cambrian sediments in Emu No. 1 in the northeastern part of the Officer Basin (Krieg, 1969).

The Continental Birksgate No. 1 well in the eastern Officer Basin penetrated about 500 m of Lower Palaeozoic sediments and over 1200 m of unnamed siltstone, sandstone,

* The formation names used informally by Jackson (1966a), have been changed to conform with those proposed by Lowry et al. (1972) and Peers & Trendall (1968).

** It has been suggested (see p. 28), on the basis of interpretation of seismic reflection sections in the Browne Diapir-Yowalga No. 2 area, that the sequence in the Browne No. 2 well may be, in fact, Babbagoola Beds.

and some limestone of presumed late Precambrian age. Anhydrite constitutes up to 10% of a small interval in the siltstone and limestone.

The available evidence suggests that there are possibly two major evaporite sequences of probable late Precambrian age in the Officer Basin. The precise outlines of the evaporite basin remains to be defined, but the Woolnough Hills and Madley Diapirs indicate that the evaporite sequence must be several hundred metres thick. The surface occurrences should be investigated first, and other domes in the northwest drilled. The presence of hydrocarbons in the Browne Beds drilled in the Browne Diapir has particular significance for the formation of sulphur, especially as sulphate is common in the evaporitic sequence (see p.

ARCKARINGA BASIN AND THE BOORTHANNA TROUGH

Evidence for the presence of evaporites in the Arckaringa Basin comes from interpretation of surface structures and from the results of drilling for oil and minerals.

An inlier of strongly dislocated Lower Permian and Upper Jurassic sediments at Mount Toondina (Fig. 29) near the centre of the Arckaringa Basin (Fig. 30) occurs in an area of slightly tilted Lower Cretaceous rocks. Seismic surveys indicate that the sedimentary sequence in the Arckaringa Basin apart from that in the Mount Toondina area, is only mildly deformed. An isolated small positive gravity anomaly coincides approximately with the Permian inlier, and a small relatively low reversal corresponds approximately with the centre of the structure. The anomalous structure at Mount Toondina is explained by Freytag (1965) as probably being caused by the elevation of blocks of Permian and Jurassic sediments above a piercement with a core of incompetent rocks of unknown age and composition. Although the Mount Toondina structure is dissimilar to the diapirs in the Flinders, and Peake and Denison Ranges (Coats, 1964), sediments of Willouran age, which are considered to contribute the breccia-core complexes of the diapirs, crop out in the Peake-Denison-Mount Dutton trend, only 48 km to the east of Mount Toondina (Freytag, 1965). The Toondina piercement is certainly younger than Early Cretaceous and there is some evidence for Quaternary movement. The numerous mound springs scattered in and around Mount Toondina owe their development to the formation of the structure. H. Wopfner (pers. comm.) described cone structures at Mount Toondina and suggests that they are similar to shatter cones. These should be re-examined to verify that the structure is not of impact origin.

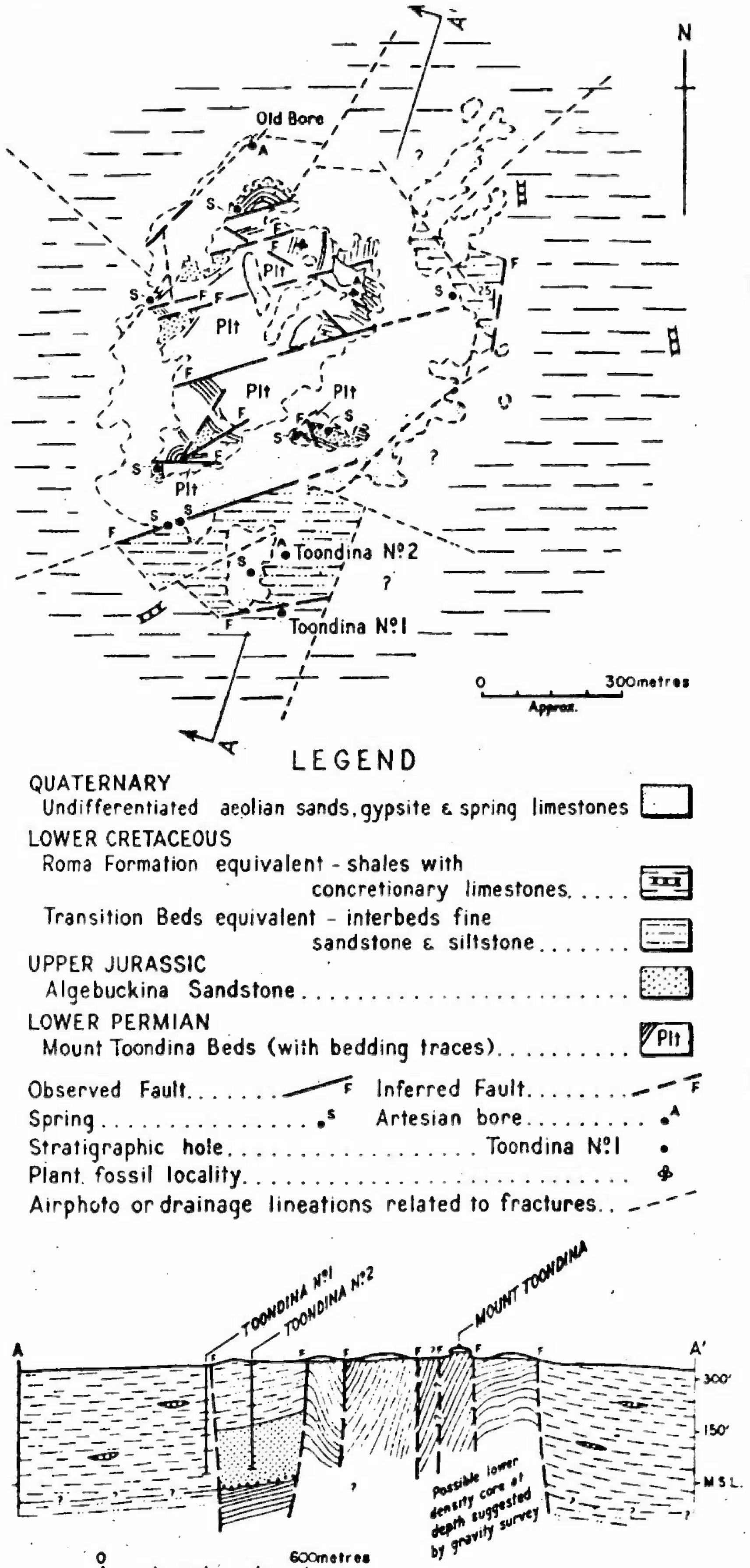


FIG 29-GEOLOGICAL MAP AND CROSS-SECTION OF THE MOUNT TOONDINA STRUCTURE (after Freytag,1965)

To accompany Record 1973/170 M(s)243

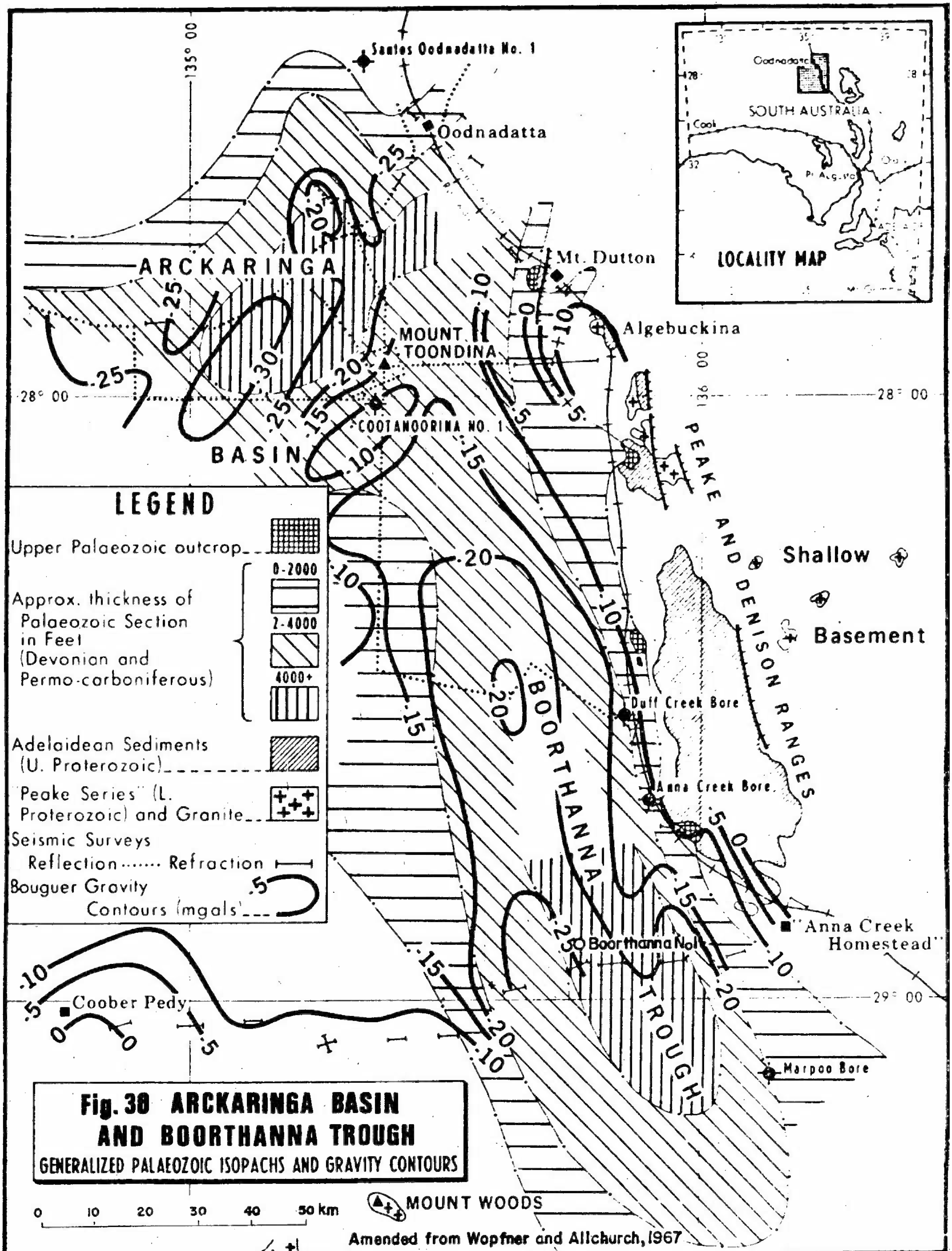


Fig. 38 ARCKARINGA BASIN AND BOORTHANNA TROUGH
GENERALIZED PALAEOZOIC ISOPACHS AND GRAVITY CONTOURS

Occidental Minerals Special Mining Lease (329) was taken up after the discovery of Devonian evaporites in the South Australian Department of Mines Cootanoorina No. 1 well (Wopfner & Allchurch, 1967) about 53 km south-southwest of Oodnadatta, i.e. about 5 km south of Mount Toondina. Devonian rocks (identified by palynology) penetrated in this well proved to be a prominent and widespread seismic reflector previously recorded in reconnaissance geophysical studies. These studies indicated that Devonian rocks are widespread in the subsurface within the Arckaringa Basin and the Boorthanna Trough. The Devonian cores from the Cootanoorina well consist of alternations of black shale and anhydrite, probably deposited in a restricted environment. The anhydrite is commonly pink and occurs in pods. Holmes (1970) considered that if, in the Devonian, a connection to the open seas lay to the north or west, then the southerly parts of the Arckaringa Basin and the Boorthanna Trough would be the most prospective for accumulations of bittern salts. Geophysical surveys suggested a southerly tongue of Devonian sediments and, at the northern end of an elongate trough, a lip which would inhibit the flow of brines. The Boorthanna Trough is a narrow half-graben which formed at the time (Devono-Carboniferous) of the Alice Springs Orogeny. By contrast the sequence in the Adelaide Geosyncline was folded much earlier (by Ordovician movements, possibly equivalent to the Rodingan Movement in the Amadeus Basin), and the Flinders Range diapirs presumably ceased movement at or soon after this event.

On the basis of the interpretation of Holmes (1970), Boorthanna No. 1 (Holmes & Rayment, 1970), 111 km south-southeast of Cootanoorina No. 1, was drilled by Occidental Minerals to a total depth of 1225.6 m. No identifiable Devonian rocks were encountered, and Precambrian metavolcanics were intersected at 1158.2 m.

The sequence penetrated in the Boorthanna No. 1 well is as follows:

Age	Formation	Interval	Thickness
Lower Cretaceous (Neocomian to Aptian)	Cadna-Owie Formation	0-46 m	46 m +
Lower Permian (Artinskian to Kungurian?)	Mount Toondina Beds	46-643 m	597 m
Carboniferous to Lower Permian (Sakmarian)	Unit One Beds	643-863 m	220 m

	Unit Two? Beds (Lake Phillipson Beds?)	863-1158 m	295 m
Precambrian	Metavolcanic Sequence	1158-1225 m	

The absence of Devonian rocks suggests that deposition may not have extended into the southern part of the Boorthanna Trough or was confined to the eastern side of the trough at this latitude.

Weedina No. 1 (Lat. 28°28'31"S; Long. 135°39'20" E), sited on the Warrangarrana structure in the northern section of the Boorthanna Trough, was drilled by Pexa Oil N.L. It reached a total depth of 1624.3 m and penetrated 800-900 m of dolomite, dolomitic sandstone, and shale of probable Devonian age. A few minor anhydrite occurrences were noted. The dolomite in Weedina No. 1 is believed to have originated as an algal mat facies in an intertidal zone. The dolomite occurs in the interval 726.3 - 1609.0 m and is probably Devonian, but no fossils have been found. The small amount of anhydrite in the sequence commonly occurs in pods. Quartzite at total depth is possibly Ordovician.

NGALIA BASIN

In outcrop the Treuer Member of the basal Vaughan Springs Quartzite in the Ngalia Basin consists of interbedded white siltstone and thin-bedded grey silicified, in part glauconitic, sandstone up to 1370 m thick. It may contain interbedded evaporites at depth and a powdery efflorescence is commonly present on the outcrops of siltstone. Coarsely crystalline selenite commonly occurs as a surface crust, notably near Eva Springs and on the north side of the Hann Range, near the Stuart Highway.

EROMANGA BASIN

Some gypsum has been found in the Lower Cretaceous Rolling Downs Group and other Mesozoic rocks of the Eromanga Basin, but the deposits are thin (less than 5 cm thick) and there is little indication that any substantial thicknesses are present.

Minor occurrences of evaporites including gypsum were deposited in Cainozoic depressions in the Eromanga Basin and were penetrated in the BMR Barrolka No. 1 and BMR Canterbury No. 3 stratigraphic drill holes. The sediments are over 100 m thick and the evaporites were possibly the result of seasonal evaporation of floodwaters during Tertiary and Quaternary time (Senior, 1970).

Evaporite (halite) has been recorded from the Hutton Sandstone of the Eromanga Basin in Queensland (Wells, 1971). The salt occurs in a white siltstone exposed at the back of a large cave situated in the Canaga Creek area near Jandowae (26°38'S, 157°03'E) on the Chinchilla Sheet area. The salt is most probably secondary in origin.

SYDNEY BASIN

Exotic evaporite minerals are present in the Triassic of the Sydney Basin, e.g., dawsonite.

BANCANNIA TROUGH

Probably the main area of interest for evaporites in New South Wales is in the western part of the State, where Middle and Upper Devonian sediments are present. Minor evaporitic intersections and red-bed sequences have been reported by Planet Exploration in their well sections Bancannia North No. 1, Bancannia South No. 1 and Jupiter No. 1 in the Broken Hill area. The Late Devonian age of these sediments has only recently been determined, from collections of fish fossils. Devonian sediments up to 4500 m thick are present in western New South Wales and this has discouraged exploration by petroleum companies.

BONAPARTE GULF BASIN

Until mid-1972 the evidence for evaporites in the Bonaparte Gulf Basin mainly revolved around the interpretation of the origin of several anomalous structures on seismic cross-sections. Only when the Sandpiper No. 1 and Pelican Island No. 1 wells were drilled was the presence of evaporites in the basin established.

Seismic surveys carried out for Arco Ltd. and Australian Aquitaine Petroleum in the offshore part of the Bonaparte Gulf Basin (Arco, 1965, 1966, 1967, and 1969 and Australian Aquitaine Petroleum, 1968a) have shown very strong discontinuities in the sedimentary sequence. Over large areas the beds are otherwise undisturbed or only mildly tilted. The seismic section shows wide areas of no reflections with apparently homogenous material intruded into the sedimentary section. The distribution of these intrusive bodies is shown in Figures 31A and B. Aquitaine suggested before any of the features were drilled that the intrusive bodies were salt domes. The intrusions have remarkably straight sides and the sedimentary beds continue uninterrupted but domed across the top of the intrusion and, lower down, terminate abruptly against the vertical walls of the intrusive body. The tops of the domes are covered by about 1200 m of sediments. The core material may originate in the Devonian, but the 'mother salt' is older than Late Devonian and younger than Middle Ordovician (Arenigian).

A seismic cross-section of one of these structures is illustrated by Caye (1968). He says-

'In the southern part of the Sahul Shelf anomalous intrusive bodies have been recognised on the seismic sections. These intrusions are not randomly spread, being found along zones regarded as fault-controlled Palaeozoic sub-basin margins. A negative magnetic anomaly of 1 gamma maximum has been recorded over these by airborne magnetometer surveys indicating the intrusive material is either salt, clay or acid lava. The location of these structures on fault zones and the seismic log appearance suggests a comparison with structures due to diapiric salt bodies found in Germany (Trusheim, 1960) and in Gabon.'

The following extract, which describes the nature of the intrusive phenomena, is taken from the completion report on the Hyland Seismic Survey (Australian Aquitaine Petroleum, 1968a).

'INTRUSIVE PHENOMENA

Although it is difficult to specify their nature the following facts were established -

- They are generally related to faults (P1, P2, P4 and P5 for example)

- They produce moderate to very sharp breaks underlined with diffracted reflections on the deep horizons. They are generally unsymmetrical with one side steeper than the other (see P1, P4, and P2 on Line TS16)

- No deep horizon crosses them and no reflection was recorded underneath

- Shallow horizons are continuous but either distorted (anticlinal domes) or faulted above them. This was noticed on Horizon 1a which was followed over all the intrusive anomalies and on Horizon 2 which forms a continuous dome over P2 but presents faulted structures over P1 and P4.

- These phenomena are noticeable on very shallow sediments recorded on the subot sections. Diffractions appearing on P1 and P3 could indicate the presence of hard and roughly surfaced formations. However, subot sections of lines Cb13 and Cb15 show only domes over P2 and P4.

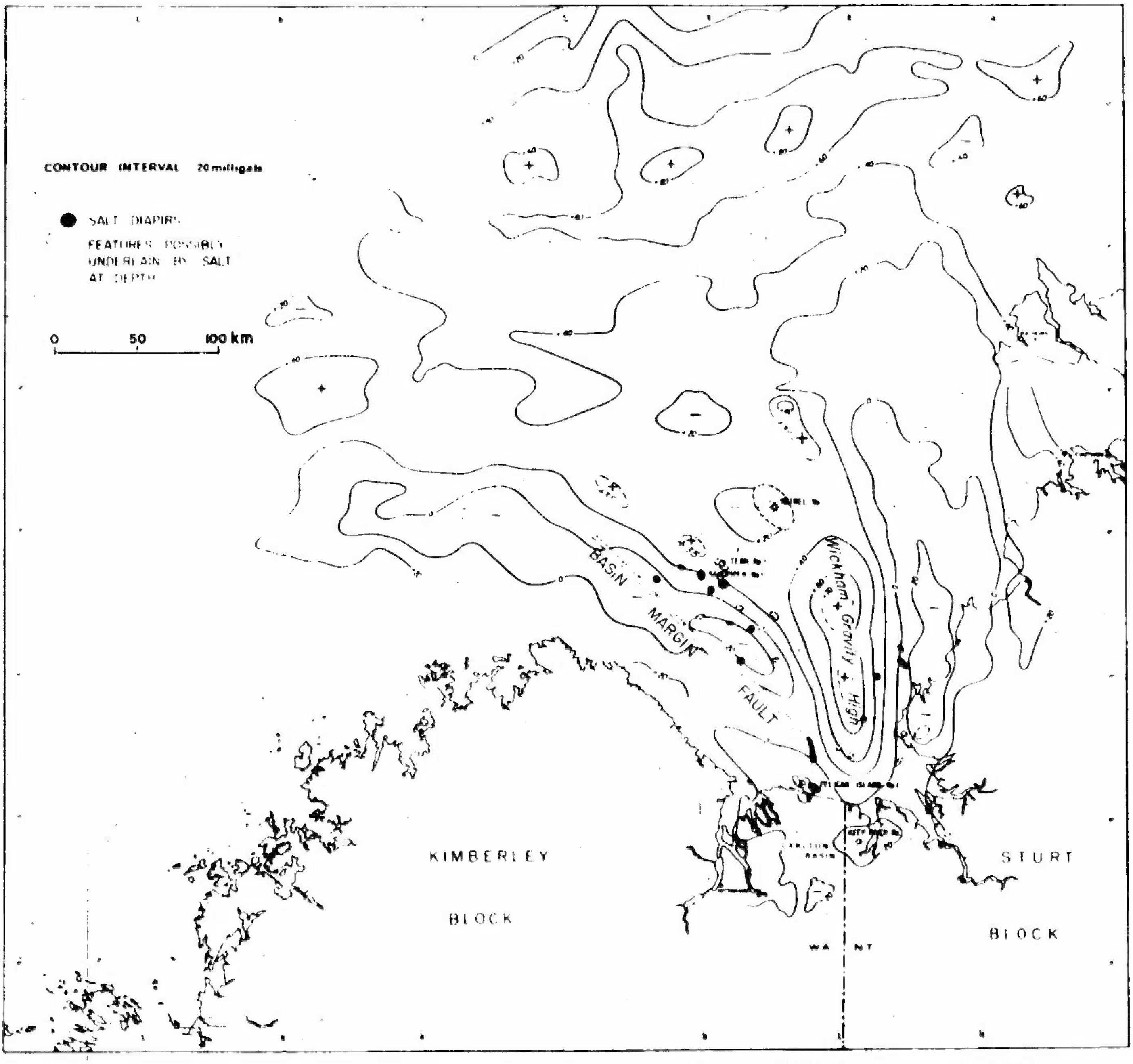


FIG 31A - BOUGUER ANOMALIES, AND LOCATION OF SALT DIAPIRS AND PROBABLE SALT CONTROLLED STRUCTURES IN THE BONAPARTE GULF BASIN, W.A. AND N.T.
(after Crist and Hobday, 1973)

Record 1973/170

Aus 6/119

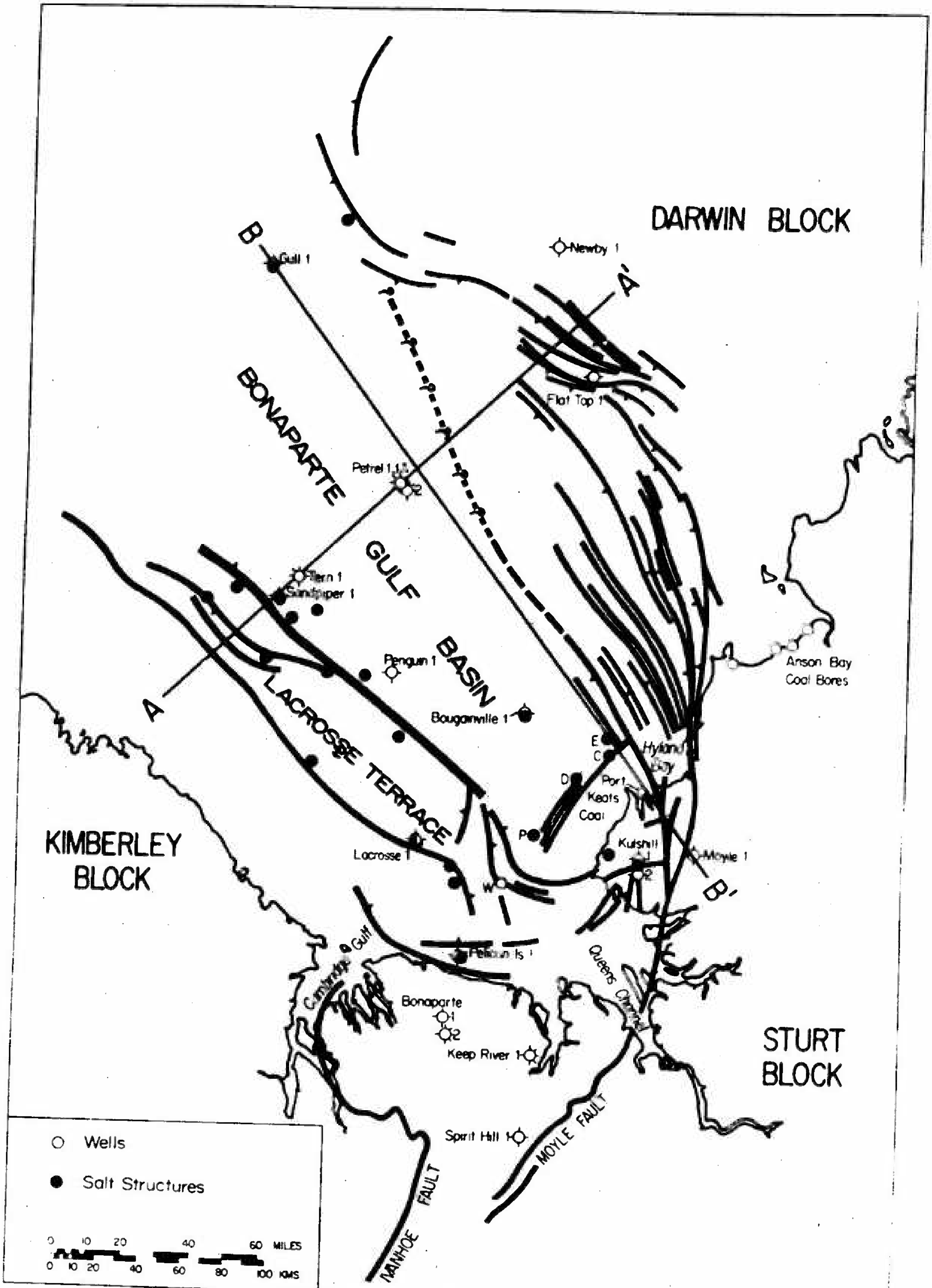


Fig. 31 B. Tectonic framework of the Southeast Bonaparte Gulf Basin (from Edgerley & Crist, 1974)

Record 1973/170

These facts lead one to believe that the anomalies are caused by intrusive phenomena. Further information is necessary to define the nature of the intrusive rocks.'

Crist & Hobday, (1973) give up-to-date information on the diapiric intrusions in the offshore Bonaparte Gulf Basin. The authors suggest that salt has migrated laterally in the basin towards boundary faults and movement has taken place at several times from Late Permian to Holocene. At least fourteen diapirs have been mapped by seismic methods.

The Sandpiper No. 1 well intersected a cap-rock zone of disturbed sediments 809 m thick (944-1753 m) and reached TD after penetrating 139 m of halite (1753-1892 m). According to the well completion report 'Sandpiper No. 1 was the first well in the Bonaparte Gulf - Timor Sea area to penetrate into the core material of an indicated intrusive feature thereby confirming the original seismic interpretation of a series of diapiric salt features in the southern portion of the basin.'

The cap rock is considered to be Upper Devonian to Lower Carboniferous and the underlying halite Upper Devonian (Famennian). The cap rock is about the same age as the Ningbing Limestone of the onshore Bonaparte Gulf Basin. Movement of the diapir is thought to have ceased at least before the deposition of the Cretaceous-Jurassic Petrel Formation.

Pelican Island No. 1 (approx. lat. 14°46'19"S, long. 128°46'27"E) was drilled by Arco Australia Ltd to a total depth of 1981.2 m and the interval 1791.3-1981.2 m consisted of massive halite. No conventional cores were attempted in the halite sequence, but sidewall cores were obtained at 1890 m and 1966 m. The first recovered 3 cm of light grey transparent to translucent fractured halite and the deeper sample recovered 2 cm of similar halite. The sediments above the salt are identified as the Lower Carboniferous Bonaparte Beds; so the halite could also be Lower Carboniferous but is more likely to be Devonian or older.

A seismic cross-section of one of the intrusive bodies in the offshore Bonaparte Gulf Basin is shown in Figure 32.

Recent papers describing the regional geological setting of the Bonaparte Gulf Basin include those of Laws & Brown (in prep.) and Laws & Kraus (1974). Edgerley & Crist (1974) have concluded the following concerning the important tectonic events associated with salt and diapiric structures in the Bonaparte Gulf Basin (citations omitted) -

'1. Middle Ordovician to Middle Devonian uplift and subsequent erosion of the area between the Kimberley and Darwin Blocks, followed by subsidence. The pattern of subsidence was such that the basin flanks to the west and south were separated from the central collapsed areas by tilted fault blocks or terraces that foundered to depths intermediate between platform and basin. The platform areas retain minor structural disturbances.

2. The proto-ocean that invaded these areas was restricted in size and depth and salt was deposited across the terraces and central basin.

3. Further subsidence in the Frasnian and Famennian times permitted reef growth on the margins of the platform areas. The basin-margin fault was a buttress against salt that crept down the inclined base of the Lacrosse Terrace. Salt rose up against the base of the fault plane. Salt ridges within the deep basin may also have started to form under the influence of salt migration due to creep.

4. Epeirogenic movements caused Carboniferous sediments to thicken towards the central graben. When the critical load of overburden was reached and the salt attained plasticity, flowage was initiated on the Lacrosse Terrace and within the deep basin. The result was the formation of sinks and complimentary salt ridges parallel to the western margin of the central graben. Local uplifts of salt occurred along faults.

5. The basin continued to founder in the Permian and Triassic. The movement of salt within the basin accentuated the salt ridges and the attendant sinks. Lateral migration of salt occurred in the central areas of the basin. Late Triassic-Early Jurassic tectonism caused rapid intrusion of salt in diapirs which penetrated the sedimentary overburden along the hinge zone of the Lacrosse Terrace. In contrast, salt on the southern terrace continued to rise gradually and may have pierced Lower Permian sediments.

6. Repeated cycles of uplift, erosion and deposition resulted in a number of unconformities in the Jurassic, Cretaceous and Tertiary sediments. Salt may have been injected into the diapirs and salt structures at a late stage to cause uplift of these beds'.

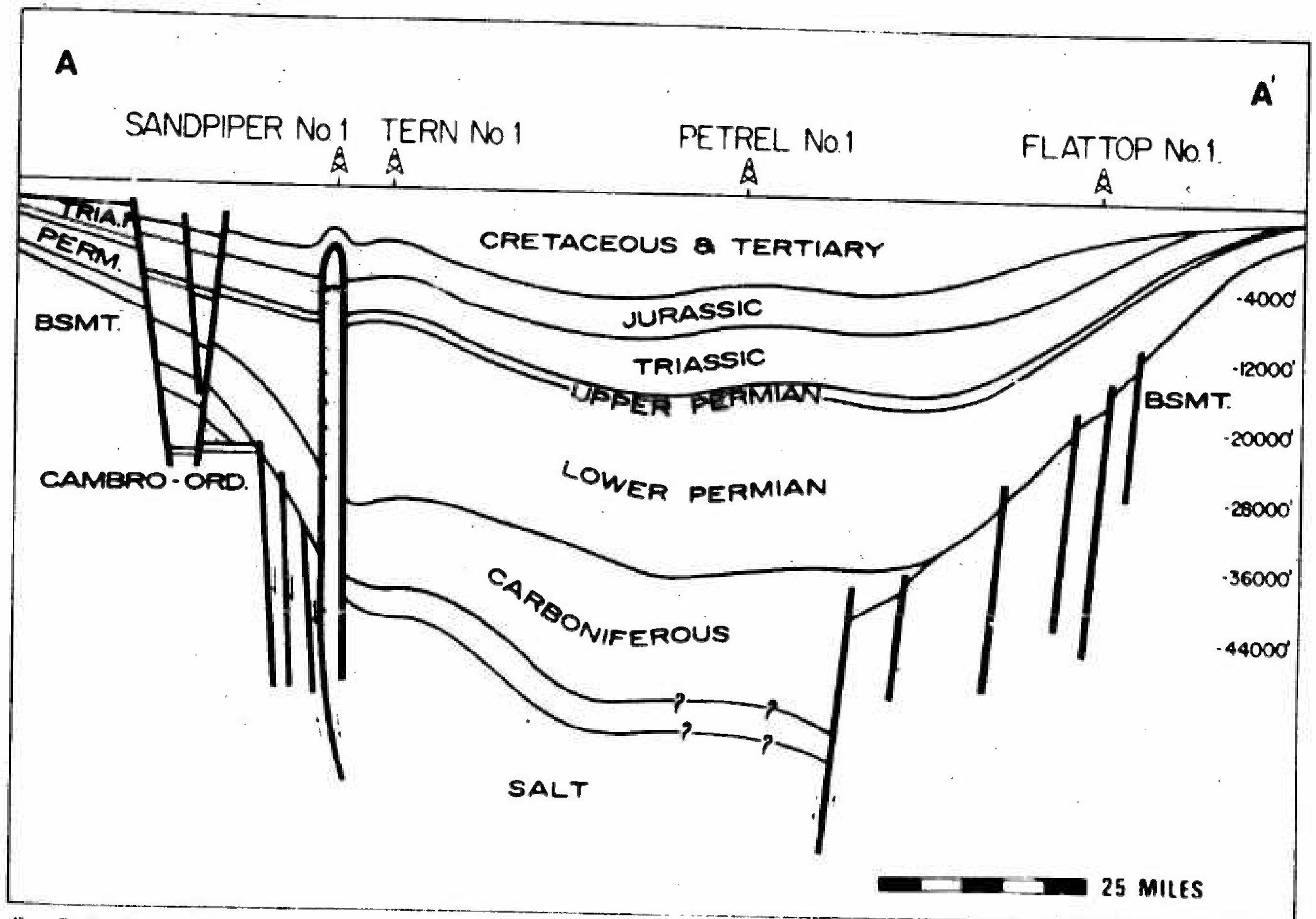


Fig. 31 C. East-West geological cross section across Southeast Bonaparte Gulf Basin (from Edgerley & Crist, 1974)

Record 1973/170

AUS/6/287

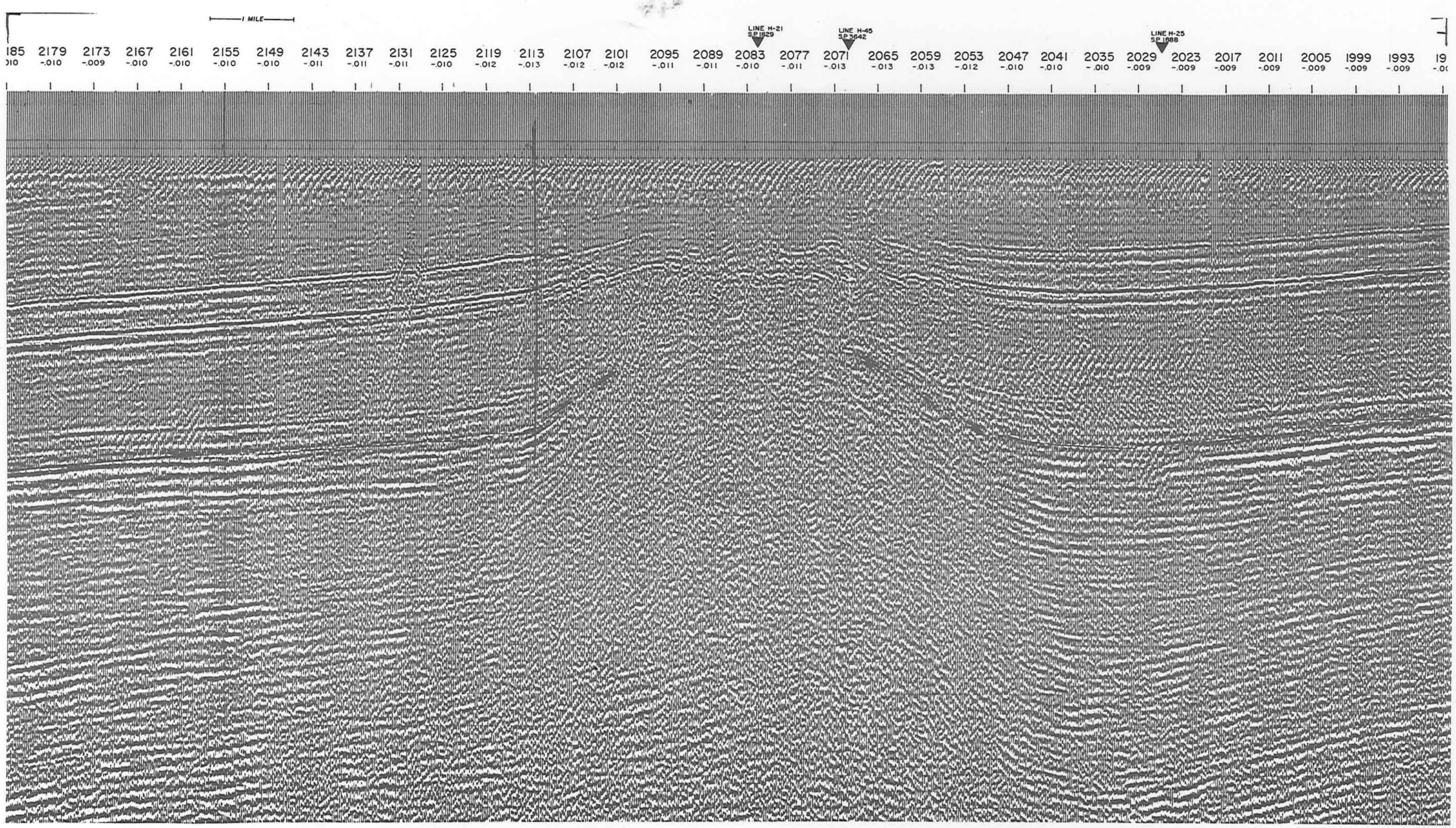


FIG 32-SEISMIC CROSS-SECTION OF INTRUSIVE BODY, OFFSHORE BONAPARTE GULF BASIN
A.A.P. HYLAND SEISMIC SURVEY, LINE H22 (from Australian Aquitaine Petroleum)

83

ADELAIDE GEOSYNCLINE

Numerous diapiric structures with cores of intrusive siltstone breccia occur in the Flinders Ranges (Fig. 33) of South Australia and have been well documented; the chief references are Webb (1960, 1961), Coats (1964, 1965), Dalgarno & Johnson (1968), and Binks (1971). During deposition of the uppermost Precambrian and Lower Cambrian sediments, which together exceed 15 000 m in thickness, an incompetent dolomite-siltstone sequence (Callanna Beds) formed piercement structures which influenced sedimentation. More than thirty diapiric structures occur along linear trends which are regarded as a basement fault system. Their distribution is shown in Figure 33. The injected material is a carbonate-siltstone breccia with abundant exotic blocks, and there is no conclusive evidence of interbedded evaporites except that the grey siltstone in the core complex, probably equivalent to the Willouran Series, contains abundant pseudomorphed halite. The red micaceous siltstone, also from the Willouran Series, and well bedded quartzite of unknown affinities both contain rare pseudomorphs after halite.

Many and varied mineral occurrences are known from the diapirs; some of the intrusions have been investigated in detail by the South Australian Mines Department (Barnes, 1969, 1970; Johns, 1969; Langsford, 1969).

A mildly evaporitic 'redbed' environment followed the Lower Cambrian regression in the Adelaide Geosyncline, and a further reversal to a 'redbed' environment, but with greater clastic contributions, characterized most of the Middle to Upper Cambrian Lake Frome Group and its lithostratigraphic equivalents (Parkin, 1969, p. 85) (Parkin, 1969, p. 105).

'On Yorke Peninsula the Lower Cambrian Hawker Group is followed by a break in sedimentation and some erosion resulting from the Cassinian Uplift. Subsequently clastic sediments including conglomerates of the White Point type were deposited on a shallow shelf followed by silts, red beds and evaporites and marine Middle Cambrian limestones.' (Parkin, 1969, p. 105).

This sequence is described by Watts, Gausden, & Heisler (1966) in the Stansbury West No. 1 Well completion report. The well which is at the southern end of the Yorke Peninsula, (34°54'02"S; 137°42'46"E) reached a total depth of 1745 m and penetrated 244 m of Cambrian upper redbeds, which lie unconformably beneath Permian rocks in the interval 335-579 m. The lower redbed sequence is 97 m thick over the interval 828-925 m. Both these sequences are clastic, but traces of gypsum were recorded in the top part of the underlying Parara Limestone, which is 363 m thick over the interval 925-1288 m.

Cambrian redbed sequences were also intersected 10.5 km north of Stansbury West well, in the Minlaton well, which reached a total depth of 994 m and intersected 750 m of Cambrian section including redbed clastics.

Stansbury stratigraphic well, 6 km east-southeast of Stansbury West, penetrated 140 m of Cambrian redbeds and was still in this sequence at total depth of 417 m.

DALY RIVER BASIN AND OTHER NORTHERN AND CENTRAL AUSTRALIAN OCCURRENCES

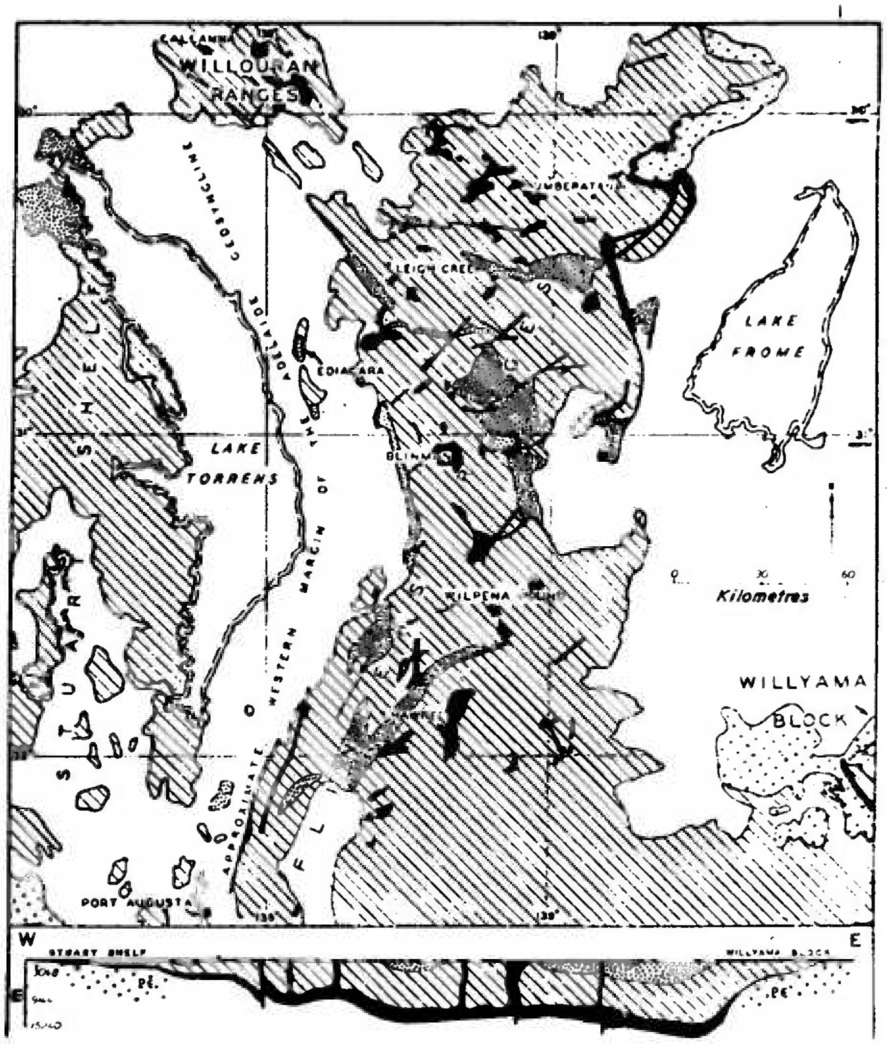
Thin anhydrite beds occur in the Cambrian of the Daly River Basin. They are of small extent and only a few centimetres thick.

Many exposures of Precambrian sedimentary rocks in the northern part of the Northern Territory contain pseudomorphs or moulds after halite, but there are no confirmed reports of interbedded evaporites. Several domes are also present, but there is no evidence to suggest that they are caused by diapirism.

The McArthur Group (mid-Proterozoic - about 1 800 m.y. old) of the Northern Territory (Smith, J.W., 1964; Walpole et al., 1965; M.C. Brown, pers. comm.) includes a sequence of continental sediments and evaporites. Environments represented are supratidal flats and ephemeral lakes, intertidal flats with barrier islands, shallow sea, and deep water. The sequence consists predominantly of dolomite and shale.

Halite pseudomorphs occur in a fine-grained sandstone of the Tooganinie Formation in the Bauhinia Downs Sheet area (Smith, J.W., 1964). The sequence consists of fine-grained sandstone, chert, siltstone, dolomite, and fine bands of rhythmically interlaminated dolomitic sandstone and pebble conglomerate.

The Pungalina Member of the Masterton Formation in the Carpentarian (mid-Proterozoic) Tawallah Group (Yates, 1963) also contains halite pseudomorphs, and Paine (1963) recorded halite and pyrite pseudomorphs in dolomitic beds of the Wollogorang Formation of the Tawallah Group.



CAMBRIAN—MIDDLE AND LOWER		
LATE PRECAMBRIAN	ADELAIDEAN	
		Local Unconformity
		Callanna Beds; in diapirs
		Regional Unconformity
	OLDER PRECAMBRIAN	*Metamorphic Basement*

FIG 33–DIAPIRS IN THE ADELAIDE GEOSYNCLINE (after Geological Survey of South Australia and Coats, 1964)

The McCaw Formation of the Katherine River Group, also of Carpentarian age, contains in places halite pseudomorphs in a purple, dolomitic siltstone (Roberts & Plumb, 1965). A younger carbonate-evaporite assemblage is known in the Victoria River area (Sweet et al., 1971).

Anhydrite has been reported from drill holes penetrating the Central Mount Stuart Beds in the Alcoota area of central Australia but no details have been released. Gypsum reported to be of secondary origin has been described from the Grant Bluff Formation by K.G. Smith (1964).

A minor occurrence of gypsum has been recorded in the Frewena No. 1 bore (lat. $19^{o}22'00"S$; long. $135^{o}30'00"E$) from the early Middle Cambrian Wonarah Beds in the Georgina Basin. The age of the beds has been determined from fossils collected from outcrops. In subsurface the beds consist of carbonate rocks with minor siltstone and sandstone. The Barkley Oil Co. Pty Ltd (Pemberton & Webb, 1965 unpubl; in K.G. Smith, 1972) recorded limestone and dolomite with some red and purple shale to 149 m in Frewena No. 1, and dolomite from 149 - 312 m (T.D.). Gypsum is abundant in the interval from 110 - 149 m and also in the upper half of the dolomite interval.

Minor deposits of gypsum occur in vugs in siltstone and dolomite of the early Middle Cambrian Merrina Beds in shallow stratigraphic drill holes in the Wiso Basin (Milligan et al., 1966).

BROWSE BASIN

Substantial patches and veins filled with anhydrite have been reported in Core No. 2 (1895.8-1897.4 m) from the Rob Roy No. 1 Well in the offshore Browse Basin. The anhydrite occurs in a Sakmarian sandstone (see Table III).

RECENT EVAPORITES OF CONTINENTAL AREAS

There are numerous thin deposits of evaporites (chiefly halite and gypsum) in playa lakes scattered across the continent. Some of those close to the coast and accessible to transport facilities have been exploited. In addition, brine from sea water that is naturally concentrated in areas such as at the head of a gulf or on shallow shelves in tropical zones is, in places, further concentrated in solar evaporation pans. Descriptions of some overseas salt plants and solar evaporation methods are given in Rau (Ed., 1966).

Groundwaters rich in dissolved salts are common in Australia, particularly in the desert areas of central and Western Australia. In the southern part of the Northern Territory, for example, brines from some water bores contain up to 100 000 ppm total dissolved salts and many bores contain about 30 000 ppm. Salt springs are also common throughout the more arid areas of Australia, but only a few have been exploited for their dissolved salts.

The principal areas of salt production are as follows (Bureau of Mineral Resources, 1973, and unpublished information supplied by the Mineral Economics Section of the Bureau of Mineral Resources).

Company	Area	Production (tonnes)		
Queensland		1969	1970	1971
I.C.I.A.N.Z.	Bajool (near Rockhampton)	245 289 (total for ICIANZ & CQSI)	288 860	219 060
Central Queensland Salt Industries Ltd	"		63 437	27 098
N.I.*	Bowen	N.I.	6600 (1970-71)	
Victoria				
Cheetham Salt Ltd	Laverton (Port Phillip Bay) N.I. Lara & Geelong (Corio Bay)	N.I.	(e) 81 300	(e) 50 800

Some small-scale production has been recorded from saline lakes in west and northwest Victoria.

Company	Area	1969	1970	1971
South Australia				
I.C.I.A.N.Z.	Dry Creek	422 700 (Solar evaporation of sea water)	343 400	340 400
B.H.P.	Whyalla	47 700	36 600	68 100
Ocean Salt	Port Price		92 500)	
Waratah Gypsum	Stenhouse Bay		69 100)	288 600
Others	Lakes Fowler & MacDonnell		10 700)	
Total		572 485		

* N.I.: no information;
(e): estimate

Company	Area	Production (tonnes)		
Western Australia				
Leslie Salt	Port Hedland	292 631	562 384	655 352
(Concentrating and crystallizing ponds)				
Texada Mines	Lake MacLeod	299 559	1 157 800	1 407 200
(Potash production began late in 1973)				
Lefroy Salt	Lake Lefroy		125 000	142 200
(Production began in 1970)				
Dampier Salt	Dampier - tidal flats			
(Production began in 1971; first shipments for export early 1972)				
Exmouth Salt	Exmouth Gulf - east shore			
Shark Bay Gypsum	Shark Bay	N.I.	(e) 280 000	(e) 200 000
Export total		592 190		

* N.I.: no information;

(e): estimate

Production in Western Australia alone could reach 10 million tonnes annually by the mid-1970s.

Shark Bay Gypsum has a potential capacity of 1 million tonnes per year and Dampier Salt more than 3 million tonnes per year. Leslie Salt Co. mill has a designed capacity of 1.27 million tonnes per year. Texada Mines sold 1.63 million tonnes in the year ended March 1972.

Potash is reported from the Texada Mines workings at Lake MacLeod, and is the only locality in Australia where there is production of other evaporites in addition to halite and gypsum. The company commenced langbeinite ($K_2Mg_2(SO_4)_3$) production towards the end of 1973. Initial recovery was expected to be 80 000 tonnes which would be only a fraction of the plant capacity. It was anticipated that the plant, situated at Cape Cuvier, 25 km from Lake MacLeod, would be fully operative and reach its planned annual capacity of 200 000 tonnes in early 1974.

The principal areas of gypsum production are:

Company	Area	Production (tonnes) 1969	1970	1971
New South Wales				
C.S.R.	Hay and Hillstone Mining Divisions		32 137	
Others	Hay Mining Division		198	
	Bourke " "		41	
	Hillstone" "		944	
	Others		5 670	
Total		32 145	38 990	36 386
Victoria				
Brunswick Plaster Mills	Millewa, Nowingi		19 164	
Mildura Plaster Mills	Yatpool		12 367	
Geelong Plaster Mills	Hattah		2 040	
Murray Valley Gypsum	Cowangi		1 391	
	Hattah		5 661	
	Others		7 031	
Total		85 737	47 654	46 304
South Australia				
C.S.R.	Lake MacDonnell (Eyre Peninsula)		11 200	
	'Salt Lake' (Kangaroo Is.)		187 000	
	Lake Fowler		15 200	
Waratah Gypsum	Lake MacDonnell		271 100	
	Stenhouse Bay		154 400	

Company	Area		Production (tonnes)	
		1969	1970	1971
Dry Creek Plaster	Craigie Plain			
Others			28 700	
Total		728 799	667 600	652 659
Western Australia				
	Yellowdine & Lake Brown (Yilgarn Mineral Field)	54 470		
	Lake Cowcowing, Nukarni and Yebeni (SW part of state)	10 727		
	Norseman (Dundas mineral field)	234		
Ajax Plaster Co. Pty Ltd	Yellowdine		8 829	18 589
West Australian Plaster Mills	"		23 456	21 876
H.B. Brady & Co.	Lake Brown		14 922	15 914
Norseman Plaster Works	Norseman		305	-
Garrick Agnew Pty Ltd	Gascoyne		37 201	111 183
Gypsum Industries of Australia Pty Ltd	Lake Cowcowing		5 446	417
Others	Kellerberin Nukarni		1 273	1 466
Total		65 431	91 432	169 445

South Australia

Short accounts of South Australian surface occurrences of evaporites are given in Parkin (1969) and brief resumes of salt and gypsum occurrences and production in the State are given in the Mineral Information Series issued by the South Australian Department of Mines and Geological Survey.

Seasonal deposits are harvested regularly from Lakes MacDonnell, Fowler, and Bumbunga, and other small lakes are periodically scraped. Lake Bumbunga, the closest natural salt lake to Adelaide, lies 112 km to the north. Lakes Eyre, Gairdner, and Hart, and Island Lagoon contain large untapped reserves. At Peesey Swamp natural brines are spread into artificial ponds and evaporated to dryness for salt production. Most salt production comes from solar evaporation of sea water at Whyalla, Port Paterson, Port Price, and Dry Creek. At Dry Creek I.C.I. Alkali (Australia) Pty Ltd harvest 500 000 tonnes of salt annually. Total South Australian production has exceeded 600 000 tonnes annually in recent years.

Probably most of the near-coastal salt lakes in South Australia had marine connections at one time or another. One of the most notable is Lake MacDonnell, which contains the largest gypsum deposits in Australia, reaching a thickness of 8-10 m. The deposits occur just above sea level and it has been estimated that they contain 500 million tonnes of practically pure rock gypsum. The production rate is about 300 000 tonnes per year, some of which is exported to Japan. The deposit is large enough to satisfy Australian consumption for many years. The production of gypsum in South Australia in 1969 was over 700 000 tonnes, 90% of Australian production. No known gypsum deposits in South Australia are thicker than 10 m.

The large inland lakes north of Spencers Gulf have had no marine connections. Lake Torrens, for example, contains mainly gypsiferous clays and the magnesium content is much lower than sea water. The surface of Lake Torrens is 34.1 m above sea level and it is normally a dry salina. It has been the site of accumulation of some 300 m of lacustrine sediments since Eocene time. The succession consists of Eocene carbonaceous mudstone, sand, and siltstone, a ?Miocene dolomite-mudstone sequence, and Quaternary red-brown siltstone, clay, gypsum, sand, and mud. The brines enclosed by the lake sediments are chloride waters without useful concentrations of salts other than sodium chloride.

In Lake Eyre the deposits are thinner: modern lake sediments in the Lake Eyre Basin are only 4.5 m thick in the deflated lake floor. They overlie a 30-45 m dolomite sequence of the Tertiary Etadunna Formation, which crops out to the east of Lake Eyre and is underlain by a lacustrine sequence of carbonaceous sand, silt, and clay to the total depth of boring, 299.6 m. Sedimentation appears to have been continuous from the Cretaceous Winton Formation into the Lower Tertiary. The salt crust in the lake may reach 50 cm, and trace element analyses have shown that strontium and barium values are higher in areas where the evaporites begin to form. Structurally the lake has formed in a synclinal sink, and horsts of Middle Tertiary age occur on the east side of the basin. Radiocarbon dates indicate that it took 20 000 years for the lake floor to deflate to a level of 18 m below sea level. Tilting of the present lake surface suggests that the region is tectonically active; it is certainly seismically active.

The presence of nodular gypsum and sulphur in the southeastern part of Lake Eyre is described by Bonython & King (1956), and their origin discussed by Baas-Becking & Kaplan (1956). The source bed is an early Holocene clay lying between Pleistocene and late Holocene sediments. The nodules consist of a shell of coarsely crystalline gypsum around a core partly filled by gypsum and the remainder consisting of over 90% sulphur as orthorhombic crystals, with traces of selenium and arsenic. The relative abundances of sulphur isotopes suggest an organic origin, with the gypsum crust formed by bacterial oxidation of the core sulphur. The known sulphur occurrence occupies an area of about 0.4 ha and the sulphur content of the bed is only about 1%. C_{14} determinations on a composite sulphur sample showed an age of 20 000 years.

Lake Eyre was investigated by Bonython (1956) and Johns & Ludbrook (1963), and a similar report on Lakes Torrens and Gairdner is given by Johns (1968). The geomorphology and stratigraphic record of Lake Eyre North are described by King (1956).

Western Australia

Salt up to 25 cm thick is harvested from playa lakes in the goldfields area. In many of the lakes up to about 5 cm of seasonal salt may accumulate and then be concentrated by wind action. At Lake Lefroy, near Widgiemooltha salt is worked by Norseman Gold Mines and estimated capacity of production is 500 000 tonnes annually. Reserves are placed at several hundred million tonnes.

At Lake MacLeod, on the west coast, figures up to 2 million tonnes have been quoted as the projected annual salt harvest. The salt occurs in brine which is replenished as evaporation proceeds by salt springs on the east side of the lake. Lake MacLeod lies below sea level and it has been presumed that the salt brines are derived from sea water. The floor of the lake is composed of impermeable clastic sediments and brine flows into the lake when this barrier is broken by, for instance, trenching in the lake bed. The reported presence of potash as well as salt in the springs may indicate, on the other hand, the presence of interbedded evaporites in formations at depth. The average composition of the brine (apart from the high sodium chloride fraction) in Lake MacLeod is reported by Texada Mines Pty Lty to be as follows:

KCl	0.56%	
$MgCl_2$	4.72%	
SO_4	1.63%	
Br	0.07%	(one sample)
S.G.	1.200	

Large gypsum deposits have been announced by Texada Mines on the east side of the lake.

Gypsum is known to occur in wind-blown dunes around salt lakes in many parts of the State. An account of the gypsum deposits in Western Australia is given by de la Hunty & Low (1958).

Potash has been produced from alunite-bearing muds in Lake Chandler. The mud contains up to 60% alunite. A production rate of 1 000 tonnes per year was attained, but proved to be uneconomic, and the plant was closed in 1949 (Noakes, 1972).

Queensland (Dep. Nat. Dev., 1969)

The bulk of Queensland's salt production comes from the Port Alma area, where underground brines have been exploited by Central Queensland Salt Industries Ltd since 1958. Average annual production since 1960 has been of the order of 26 500 tonnes. Production in 1967 was 37 711 tonnes.

The company recently became associated with Imperial Chemical Industries of Australia and New Zealand (ICIANZ) in a major expansion program estimated to cost \$2 500 000. Initial capacity of the saltworks will be

150 000 tonnes per annum, with provision for expansion to 450 000 tonnes. The salt will be shipped from Port Alma to the ICIANZ plant at Botany Bay, New South Wales, for the production of caustic soda and chlorine.

Dow Chemical (Aust.) Pty Ltd is investigating the extent of the brine horizon over a wide area of the Fitzroy delta.

In a report on the Burdekin-Townsville Region by the Department of National Development (1972) the following information is given on Bowen-Guthalungra area. 'Salt works have been operated at Bowen and Guthalungra for the production of salt by solar evaporation of sea water. There has been no production from Guthalungra for a number of years. All output from Bowen, where 6600 tonnes were harvested in 1970-71 is used locally.

Salt deposits which form seasonally in Lake Buchanan are worked intermittently during the dry winter months to provide salt for local agricultural uses.'

In the far Western Division a number of lakes have a high salt content. Several lakes in the Mulligan River/ Eyre Creek area, in the southwestern corner, are reported to contain extensive deposits of salt. One of the largest, Kalidawarry Waterhole, is 19 km long and 90 m wide. It is reported to have, in places, 1.2 m of salt partly buried beneath alluvium. Highly concentrated brine was located at a depth of 3 m in an excavation near Lake Machattie, 129 km north-northeast of Birdsville.

Other lakes reported to contain salt deposits include Lake Mueller, 26 km northeast of Aramac, and Lake Galilee, 80 km northeast of Aramac.

Strontianite was reported many years ago from the Eastern Boyne River, 42 km south of Gladstone, but nothing further is known about it.

Small lenses of celestite crop out near Dunbar Creek, Elderslie, 72 km west-northwest of Winton.

Svanbergite had been reported near Pigeongah Waterhole, Coorabulka, about 113 km south-southwest of Boulia. This mineral is mainly of academic interest because of its rarity.

Underground brines occur in Pleistocene beds at the mouth of the Fitzroy River in Queensland and are known over a wide area centred on Casuarina Island. Brines occur in separate beds, and concentration increases in each with depth. Central Queensland Salt Industries Ltd exploits the salt on the mainland south of Casuarina Island. Total salt production to the end of 1968 was 276 790 tonnes. The salts are high in magnesium but low in potassium.

NOTES ON, AND COMPARISONS WITH, DEPOSITS OUTSIDE AUSTRALIA

The following notes on evaporite deposits outside Australia include information collected during discussion with Dr G. Richter-Bernburg and with geologists of other organizations. They are given here because in several cases comparisons were made with Australian deposits and some of the major features of overseas deposits are pertinent to the interpretation of origin and significance of local deposits. In addition new information on some of the deposits is not available in published form. Mention will be made of deposits in Germany, Iran, Canada, the Dead Sea, Sicily and Texas, together with brief extracts of papers dealing with potash concentration, geochemistry, and prospecting.

PLAYA AND ALKALINE LAKES

In general it is considered that the likelihood of obtaining large commercial quantities of potash and trona from Australian playa lake deposits is small, though important occurrences have been discovered in several overseas countries and there is still plenty of scope for further detailed investigations of Australian deposits. One notable example is the Searles Lake in California, the surface water of which is rich in boron and potassium as well as lithium and phosphorus. The geology of the lake is described by Smith (in Rau, ed., 1966), the mineral equilibria in the lake are described by Eugster & Smith (1965) and production by Ryan (1961). A new production method will be used whereby brines at various depths in the lake are selectively extracted and concentrated by evaporation in solar ponds. It is hoped that any combination of salt components can be extracted, and salt cake, potash salts, and other minerals will be produced. The salts occur in a chain of lakes and it appears that flow of brines between the lakes, and fractional crystallization may have been the main mechanism for differentiation of the salts.

Leonardi (1954) has described the Searles Lake salt succession. There are two cycles of evaporite precipitation in the bottom salts and an intervening phase of brine dilution. In each cycle there is a succession upwards from sodium carbonate through sodium sulphate to halite.

Numerous analyses of evaporites from the large lakes in South Australia failed to indicate any significant concentration of bittern salts. Perhaps it is not surprising that there are no concentrations of other salts in these lakes when climatic factors and the provenance areas are considered. Sodium carbonate for example, is derived from a source, especially of volcanic rocks, subjected to humid weathering. Sodium sulphate is produced chiefly by erosion of igneous rocks or from sediments deposited in a continental environment. Similarly borates are mostly derived from weathering of igneous rocks and from hot springs, and nitrates originate by oxidation of organic matter in the presence of potassium and sodium salts, or from volcanic sources. Nitrate and caliche deposits in Chile originate from rising ground water which is evaporated at the surface, although concentration of nitrate by this method is not common. Very few lakes in Australia contain concentrations of anything other than halite and gypsum. A small salt lake in the southwestern part of the Northern Territory near Mount Redvers contains a high proportion of sodium sulphate, which was presumably formed by erosion of igneous rocks of the surrounding Precambrian basement, and Lake MacLeod on the Western Australian coast contains minor potash (0.56% KCl) in the brine.

Some of the more notable examples of alkali lakes in the USA are Owens Lakes and Mono Lake in the western States and Sand Hills in Nebraska. The evolution of these closed basin waters is discussed by Jones (in Rau, Ed., 1966). The potash in Sand Hills is thought to have been derived from plant ashes produced when the Indians burned down areas of coniferous forest and accompanying vegetation each year. In Australian salt lake areas the contribution of potash would be negligible because the vegetation burnt by Aborigines amounts mostly to scant native grasses.

Vast trona deposits are present in alkaline lakes in the East African Rift Valley; the largest deposit is in Lake Magadi (Eugster, 1967). Hydrous sodium silicates, e.g. magadiite, are probably precipitated from alkaline brines, and percolating ground waters convert magadiite to kenyaite and then to chert. The reaction sequence is -

$NaSi_7O_{13}(OH)_3 \cdot 3H_2O$	$NaSi_{11}O_{20.5}\ (OH)_4 3H_2O$	$SiO_2 nH_2O$
(magadiite)	(kenyaite)	(chert)

Thus a mechanism for the inorganic precipitation of chert to form bedded deposits has been outlined. Alternating silica-rich and iron-rich bands of iron formations may be due to concentration cycles in alkaline lakes.

Volcanic and igneous terrains are obvious sources for bicarbonate waters, and Lake Magadi lies in such a terrain. Extensive volcanic terrains were common in the Precambrian and trona-rich lakes could possibly have been more abundant. This would explain the large number of banded iron formations found in the Precambrian.

The Eocene deposits of the Green River Formation of Wyoming have been described in detail by Bradley & Eugster (1969). Evaporites and other sediments were deposited in an ancient playa called Gosiute Lake. The saline facies contains trona, halite, and lesser amounts of shortite, northupite, pirssonite, gaylussite, nahcolite, thermonatrite, wegscheiderite, and tychite. Shortite is the most abundant after trona and halite. The trona and mixed trona and halite underlie 2600 km^2 and range from thin films to beds 11.5 m thick. The beds are chemical deposits laid down on the lake floor during stages of very low water level in the lake. About 7.5×10^{10} metric tons of trona are present. Bradley & Eugster conclude that ...'all the constituents in the brines from which trona and halite precipitated were brought in by streams, were leached from new falls of volcanic ash, and were derived from the mineral springs known to have existed in the watershed.'

Evaporation of a closed system rich in bicarbonate must eventually lead to trona + natron assemblages, but if the atmosphere buffers the brine and replenishes the CO_2 then trona will continue to deposit until dryness. Such a system must have operated for the Green River Formation. The solubilities of trona and nacholite are more affected by P_{CO_2} than by temperature. Hence undersaturated sodium solutions can precipitate trona by introduction of CO_2; this can be accomplished biogenically.

The most important mechanism for the production of trona is evaporation in equilibrium with the atmosphere, and because deposition is slow there is ample time to maintain the equilibrium.

If a sodium carbonate/bicarbonate/chloride brine continuously evaporites in equilibrium with air and has a bicarbonate quotient of 0.15, 80% of the potential trona crystallizes out before halite saturation point. In places within the pores of a trona bed, the greater the depth below the surface and the less access it has to the atmosphere, the less likely will the occluded brine be to become saturated with halite. Trona crystallization will continue with addition of biogenic CO_2. These findings account for the thick monomineralic beds of trona in the Green River Formation. The occluded brine is the obvious source of all the authigenic minerals. The concentration of minerals in zones may be caused by migration of pore water during compaction. The large volume of this water has been estimated by Emery & Rittenburg (1952). Shortite on the other hand is randomly distributed and the crystals probably formed after compaction.

There are two reported sodium carbonate deposits in Australia, one at Hill End Station in Western Australia and the other at a playa lake in Queensland. No details are available of these isolated, and unsubstantiated deposits.

Germany - The Northwest German Basin

The following summary of the geology of the German Salt Basin from Richter-Bernburg & Schott (1959) is given as a background to later, more detailed, discussions under the heading of Zechstein salt domes on p.

Exploratory drilling of the northwest German Basin began in the late 1850s after oil seeps were discovered near many of the salt domes. The basin contains 6-8000 m of upper Palaeozoic, Mesozoic, and Cainozoic sediments which are bounded on the south by Variscan folded basement and in the north by crystalline rocks of Scandinavia.

The sediments were mostly deposited in a shallow sea which once had oceanic connections through the present North Sea. Jurassic and Lower Cretaceous sands are the main oil reservoirs. Salt occurs in the basal part of the section, from which over 200 salt domes project. Most of the salt is Upper Permian and occurs in the Zechstein units 2, 3 and 4. The pre-saline Zechstein 1 is largely a carbonate/sulphate facies and its halite facies is restricted to the marginal areas of the basin. The evaporites lie conformably on the Lower Permian Rotliegend Series which in turn unconformably overlies Variscan folds and older rocks. The Lower Permian is generally regarded as constituting part of the basement. The Rotliegend beds pass into saline formations in the general region of the lower course of the Elbe River in the Holstein district.

The Rotliegends beds are 500-1000 m thick - perhaps as much as 1500 m in the centre of the basin - but they have not been penetrated in the depocentre and are known only from the diapirs. The salt of Zechstein units 2, 3 and 4 may be as much as 1200 m thick with intercalations of clay and anhydrite developing at the expense of the halite and effectively reducing its thickness by some 100 m. Salt changes to anhydrite over a short distance laterally.

Diapirs occur only where the salt thickness is greater than 400 m, but halokinesis ('Halokinese' of Trusheim, 1957) or salt movements may occur where the salt is less than 400 m thick.

Pressures of about 100 kg cm^2 are sufficient to make salt behave like a viscous liquid and therefore a sedimentary load of much less than 2000 m could be considered sufficient to cause flow; but this premise is not supported by field observations and the flow mechanics of such masses are much more complicated than generally supposed.

Stratigraphic sequences are still preserved in the salt in the diapirs and no laminar flow is apparent. The intrusion of the salt bodies apparently took place in an eruptive fashion. The term 'eruptive' is used by Richter-Bernburg & Schott (1959) to indicate the rate of movement relative to that experienced in the first two phases of salt movement-accumulation followed by diapirism. Evidence for this type of intrusion is indicated by the mushroom folds with a peripherally rolled overhang, and the formation of dilatation faults in rocks covering the salt mass. Stille (1925) and others considered that orogenic stress alone caused diapiric movement.

At the other extreme, Lachman (1911) and Trusheim (1957) both considered that the salt was autoplastic and that halokinesis was the major cause of the deformation. However, in northwest Germany, salt diapirs follow well defined trends which are in line with faults that extend outside the salt province. Hence the regional arrangement of the diapirs and 'salt walls' closely follow tectonic lineaments. These conclusions are supported by a study of the history of the Gifhorn region, which shows the genetic connection between epeirogenic subsidence and salt dome growth. The salt was under extremely high pressures (700 kg/cm^2) in deep troughs aligned with the regional north-northeast lineament of geotectonic instability. Dilatation faults then disrupted the cover rocks and the relief in pressure facilitated rapid diapirism along salt lines and in salt plugs.

In the Holstein district the lines of salt intrusions of the older Rotliegends salt came from the deep part of the trough and form the cores of diapirs, whereas the Zechstein salt is tightly folded and is overturned against the walls of the salt intrusions.

The three phases in the growth of salt structures, then, can be summarized as accumulation, diapirism, and finally uplift and subsequent movements. The accumulation phase, which can lead to formation of salt pillows (in loci for salt migration the increase in salt thickness forms lenses or pillows), is caused by variation in thickness of sediment cover. The diapiric phase takes place rapidly and salt is commonly extruded at the surface. Salt movement, or migration without piercement, took place almost continuously but diapirism was bound to a few orogenic movements. Final uplift and other movement may be slow and continuous or intermittent (by diapiric movements). Uplift of the salt may accompany subrosion; the amount of upwards movement depends partly on the amount remaining in the reservoir. Further epeirogenic subsidence may reactivate the salt, and, if there is a regional displacement in the position of sedimentary troughs diapirism or salt activity recurs.

A similar sequence of events has been described by Golov & Solov'yev (1966) from the Peri-Caspian Depression of the USSR, which is reputed to be the largest salt dome area in the world.

The accumulation of petroleum in the salt dome fields depends primarily on the tectonic structure of the dome, the distribution of reservoir beds around it, and the attitude of the porous beds. Most accumulations occur on the flanks of the dome, but some occur in crossfolds whose axes strike across the salt masses (transverse anticlines). The latter may be older than the diapirism and hence there may be no connection between the oil accumulation and the salt dome. The time of migration will therefore depend largely on the historical development of the oil-bearing salt structure. Production from salt dome fields accounts for nearly half the production of petroleum in Germany.

Zechstein Salt Domes

The German Zechstein salt domes may be up to 50 km long and from 1-5 km wide (Fig. 34).

The cap rock of the domes (Fig. 34) is about 200 m thick. The interval in which the cap rock is formed is known as the subrosion zone (Fig. 36). The cap rock contains small pods of sulphur, but no large deposits. In general sulphur is commonly found in the lower part of the limestone and the top of the gypsum of the cap rock (Borchert & Muir, 1964, pp 253-4). The cap rock is internally cavernous and part of its calcium sulphate may be bacterially reduced to sulphur. In some places, eg in Sicily, the initial gypsum was associated with carbonates, and the sulphur is therefore usually disseminated throughout cellular limestones. Euhedral quartz is common in cap rocks and probably formed during or after the latest movements of the dome. Quartz crystals up to 10 microns long have been found in inclusions in evaporites.

The stratigraphical significance of idiomorphic quartz crystals in the evaporites of northwestern Germany is discussed by Schettler (1972), who found that the characteristics of the crystals can be used locally for stratigraphic correlation. Silica is readily transported in salt deposits and bipyramidal crystals are very common in cap rocks; much of the quartz is derived from the exposed cap rocks. The silica has been derived from or remobilized by downward percolating meteoric water, which produced retrograde metamorphic effects and was responsible for the formation of the insoluble cap rock of the domes. The composition of the cap rock is related to the character of the original evaporites; so calcium sulphates predominate where the original salts were marine. Contemporaneous crystallization of anhydrite and idiomorphic quartz has been described by Nissembaum (1967). The upward plastic movement of salt in the domes has been calculated as about 2 mm per year, but no movement is apparent in any of the mine workings. Comparative figures for the Gulf Coast salt domes are given in Appendix VI. The outside wall of the domes consist mainly of an impervious anhydrite layer (Figs 36 & 37), which must not be breached during mining outward towards the wall because the surrounding sediments contain much water. Microseismic surveys can be used to predict where the wall of the dome is.

The salt in the domes contains anhydrite zones, and subsidence in the dome leaves them in relief as small hills. Subsidence is commonly caused by removal of the soluble salts from the domes by leaching and by pumping of salt brines.

Peat bogs commonly form in the eroded and subsided surface over many salt domes (Figs 37 & 38). A similar subsidence over salt may be present in central Australia (but with no evidence of peat bogs); for instance in the Lake Amadeus area salt deposits are predicted beneath the salt lake chain (See p.). Several years ago many of the houses in the town of Luneburg in Germany were found to be gradually subsiding. At the time the town was built it was not known that it was underlain by a salt dome. The subsidence and tilting of the houses was caused by pumping of brines from wells and the formation of hard residual ridges of the less soluble anhydrite beds. In some houses considerable reconstruction was necessary but subsequently these houses were removed and the areas over the dome are now car-parking areas (Dresher, Hildebrand and Schmidek,

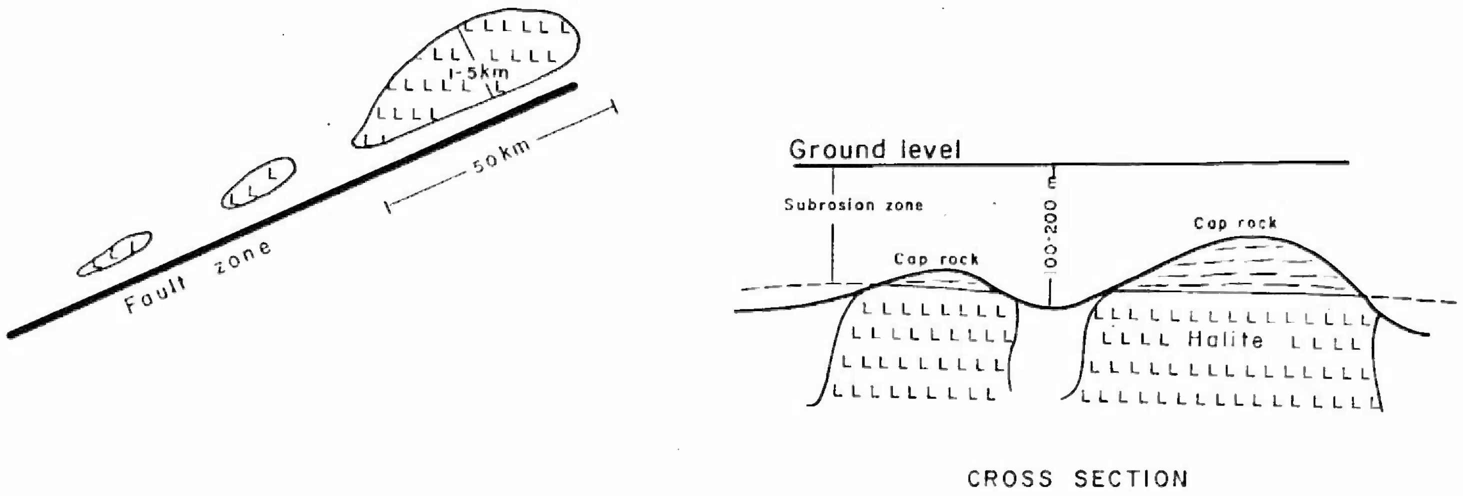


FIG 34-DISTRIBUTION AND SIZE OF SALT DOMES IN PLAN AND CROSS-SECTION

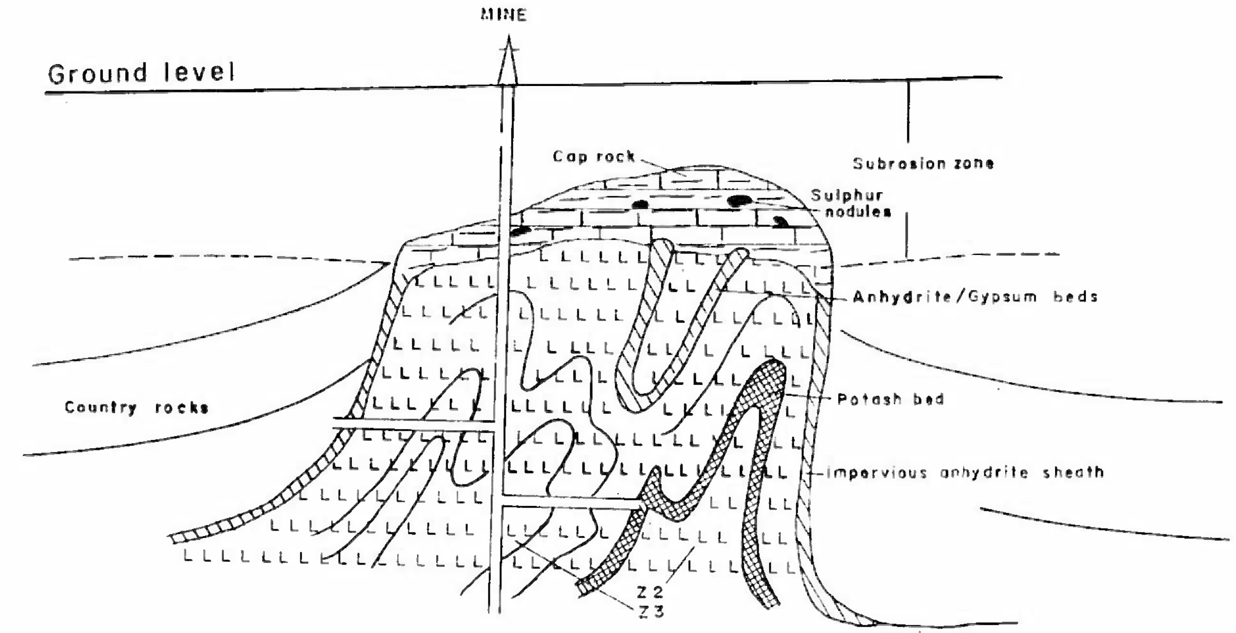


FIG 36-GENERALISED CROSS-SECTION OF GERMAN SALT DOME

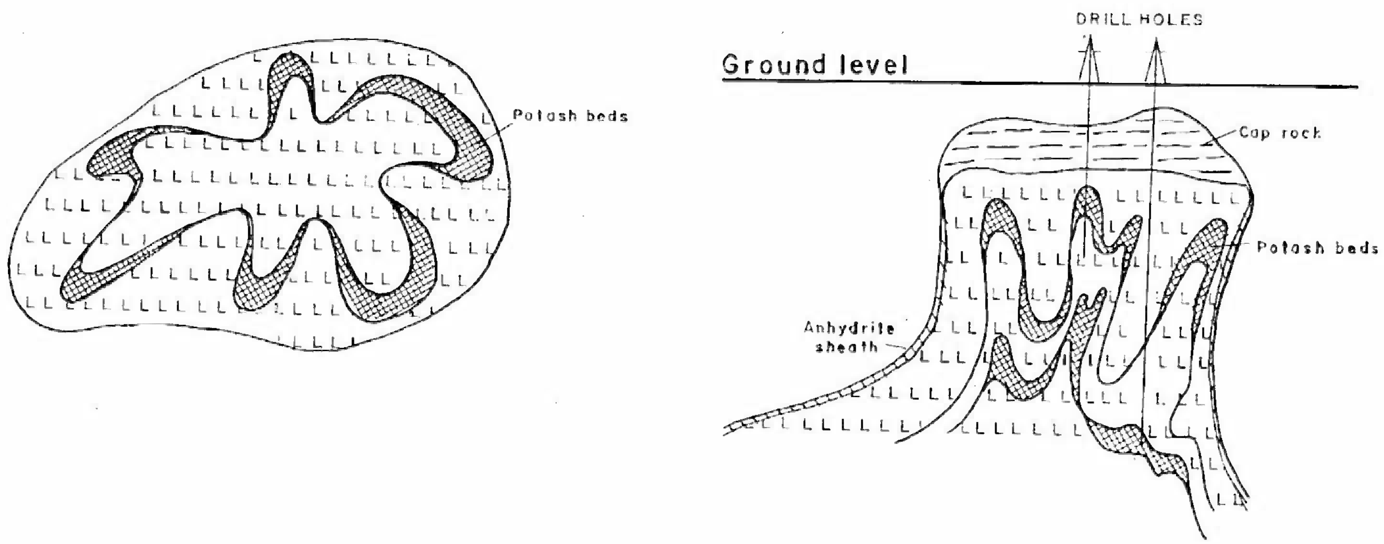


FIG 35-SKETCH PLAN AND CROSS-SECTION OF ZECHSTEIN SALT DOME SHOWING DISTRIBUTION OF POTASH BEDS

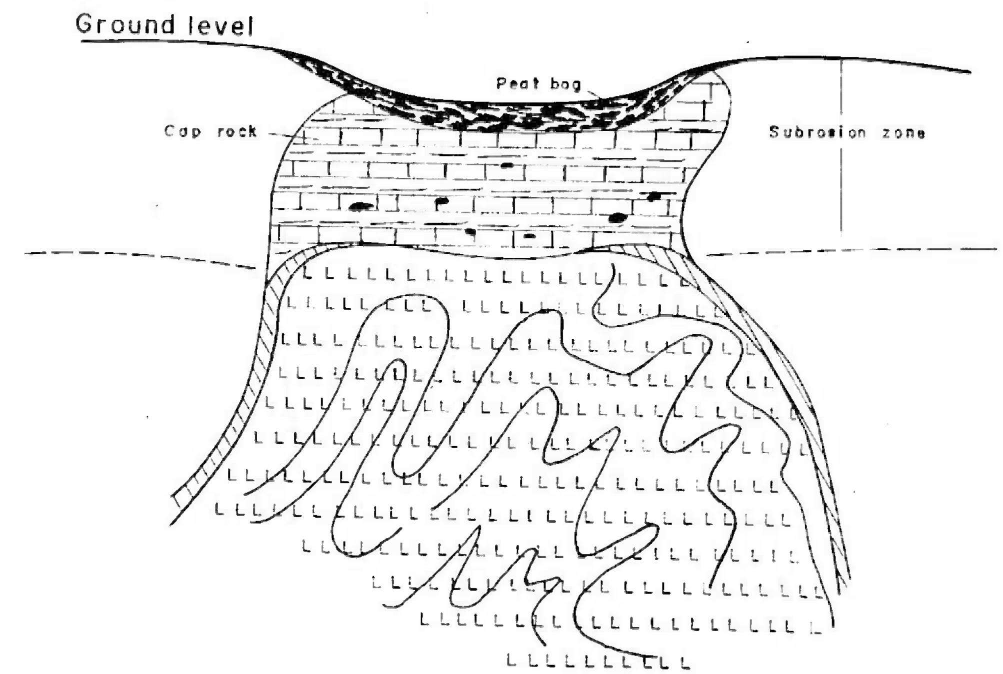


FIG 37-CROSS-SECTION OF CIRCULAR DEPRESSION OVER SALT DOME SHOWING LOCATION OF PEAT BOG

1973). A similar example of subsidence and collapse of buildings over salt domes is shown in Figure 38. The results of subsidence over evaporites and other soluble rocks and related geological and engineering problems has been the subject of a recent symposium conducted by the International Association of Engineering Geology (1973).

Potash beds in salt domes are selectively mined (Figs 35 & 36). Potash is also worked in undisturbed sediments where salt domes are not present, at depths of 400 to 800 m from beds of Zechstein 1 about 6 m thick (Fig. 39). A short historical summary of potash mining in Germany, together with a description and a discussion of the origin of the Zechstein salt and potash deposits, is given by Richter- Bernburg (1972a). Secondary replacement processes in oceanic evaporite deposits with examples from the German Zechstein are described by Borchert (1972).

The potash deposits are worked by one company in Germany. The cut-off grade in the mine is about 15% K_2O, but in places where seams are favourably disposed or very wide, 13% K_2O can be mined. Some mines in which a seam is strongly folded have had to be closed because of difficult mining conditions even though the grade is high. Either differential crystallization or flotation methods are used to concentrate the potash which is beneficiated to about 50-60% K_2O practically pure KCl.

The structure of the beds is complicated and synformal folds are commonly present (Fig. 40). The potash commonly thickens in the axes of the folds in many German salt domes (Figs 35 & 40); similar thickening, which was first erroneously interpreted as the original thickness of the beds, was outlined in the Texas Gulf Coast salt deposits (Fig. 40). Because of the extensive underground mining very close correlation, using the anhydrite beds, has been possible in the salt domes.

Generally the oldest salt is at the core (salt of Zechstein 2) enclosed by the younger Zechstein 2, 3 and 4. The salt is intensely folded, with near vertical axes and normal or inverted inclination (Fig. 35). The comparatively undisturbed basement beneath is composed of Zechstein 2, 1 and older formations. Recent references that describe the internal structures of some salt domes include Muehlberger (1968), Hofrichter (1968), Kupfer (1968), and Muehlberger & Clabaugh (1968).

Indications of the presence of potash in sub-surface evaporites can be gained from the composition of brines from wells and bores in the region and by monitoring drilling fluid during evaporite drilling (Anderson & Majeske, 1970). Thick halite sequences (at least up to 100 m) are generally a prerequisite for precipitation of the bittern salts, but no strict halite/potash ratio has been established.

Deposition of such thick evaporites in silled or barred basins was originally envisaged by Ochsenius. A high evaporation rate and loss of water behind the barrier was replaced by an adequate influx of new oceanic water. This model has seen wide application to many examples and is probably in operation in such areas as the Red Sea and Persian Gulf where the region of recent evaporite formation behind the barrier on supratidal flats is called a sabkha (salt flat). The barrier itself is generally formed by organic reefs. This type of environmental model has been suggested by Richter-Bernburg (1972b) for the Lower Triassic of the German Basin and he indicates a lateral transitory evaporite series over a shallow shelf area or 'mega-sabkha'. A similar model showing the ideal gradation of salt precipitation in silled basins is shown in figure 42 (Richter-Bernburg, 1972b). It shows the distribution of similar saline facies in deeper shelf areas with the local and regional influence of shallow water ridges. The different chemical phases are formed by fractionated precipitation. The rate of salt precipitation in a basin is about 2-10 cm per year and a solar cycle of 11 years can be measured in halite and anhydrite beds: the eleventh bed is thickest (Richter-Bernburg, 1963a, 1968). The German Zechstein is one of the most enriched formations in S^{32} so far found.

The palaeogeography of a salt basin is the key to understanding the distribution of facies changes. In the German Zechstein sulphate (anhydrite) occurs only at the margins of the basin, where there is high evaporation, and as a direct result of the high marginal evaporation the bituminous sediments including some carbonate rocks in the centre are commonly succeeded by halite.

Palaeogeographical studies suggest that the Zechstein sea was no deeper than the thickness of the salt; the deepest parts were 600-700 m. The salt filled up pre-existing troughs and was not deposited in shallow pans. A similar situation prevailed in the Sicilian deposits (described later). Generally the German salt series, including the carbonates, sulphates, and chlorides, are 600 m thick, but in some places they reach a maximum thickness of 1000 m. The cycle of deposition consists of a bituminous clastic phase at the base, followed by grey anhydrite, red and brownish salt, and red salt (containing

FIG 38- CRATER CAUSED BY COLLAPSE OF CAPROCK ROOF OVER SALT-MINE CAVITY, BLUE RIDGE SALT MINE, TEXAS. (FROM HANNA, 1958).

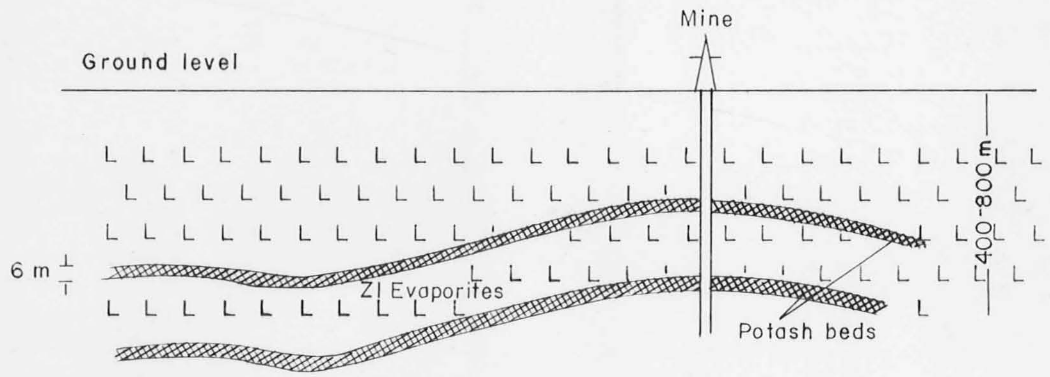


FIG 39-DIMENSIONS OF POTASH BEDS IN RELATIVELY UNDISTURBED AREAS NORTHWEST GERMAN SALT BASIN

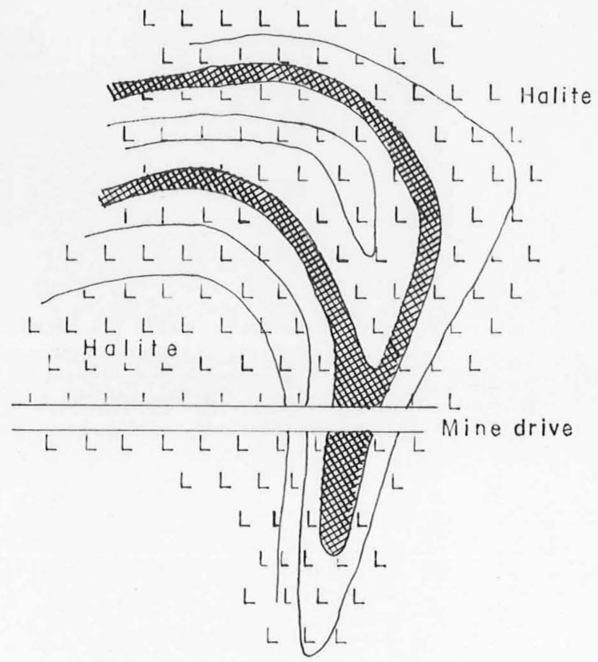


FIG 40-SYNFORMAL OCCURRENCE OF POTASH BED IN DOME SHOWING THICKENED POTASH ZONE

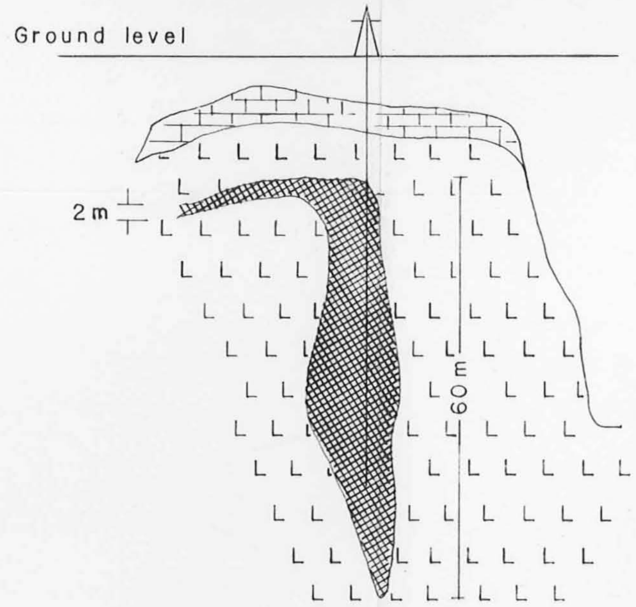


FIG 41-ABNORMAL THICKNESS OF POTASH IN TEXAS GULF COAST SALT DOME

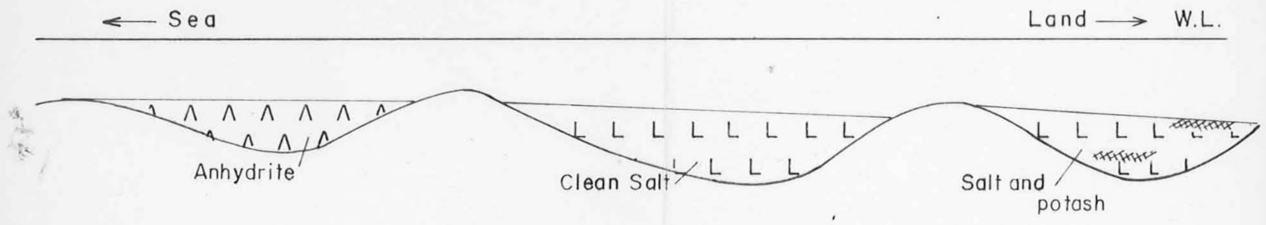


FIG 42-SILLED BASINS AND SEQUENCE IN EVAPORITE DEPOSITION

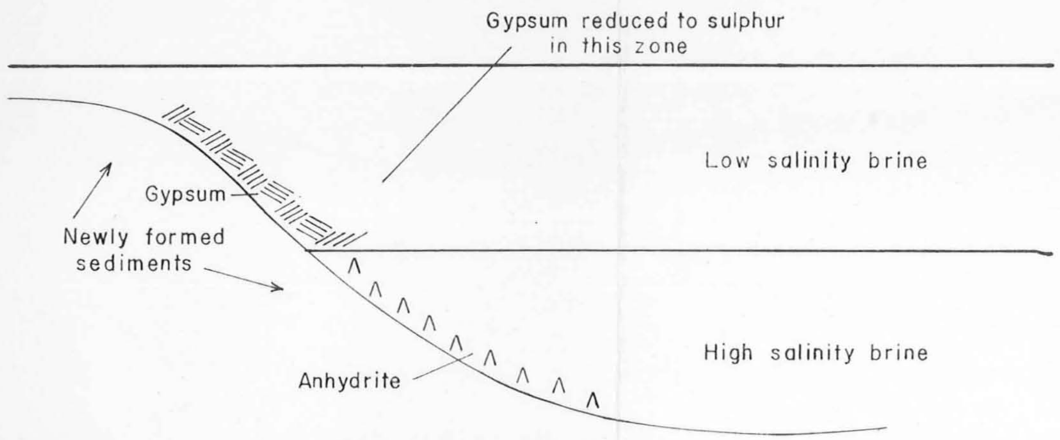


FIG 43-GYPSUM/ANHYDRITE EQUILIBRIUM IN EVAPORITE BASIN hematite) at the end of the cycle. Pyrite crystals are common at the base of the salt. In some salt lakes red bacteria (Phycobylin) cause a red coloration, but this organism has not been found in any of the German red salts. Deposition of potassium and magnesium sulphate and chlorides succeed the large thicknesses of halite and thin recessive sequence of halite and anhydrite intevened before a new cycle commenced. The facies variations in evaporite basins are described by Richter-Bernburg (1963b, 40-1; 1968, 413-4; 1972a, 33-9; and 1972b, 275-87).

In the margins and in shallow water in the central parts, considerable thicknesses of carbonates and sulphates were deposited; they commonly contain algal and bryozoan reefs. Towards deeper water the massive light carbonate rocks ('Hauptdolomit') pass into dark, well stratified limestones or dolomites, and at the bottom of the basin may be replaced by highly bituminous fetid shale ('Stinkschiefer').

The marginal carbonate rocks following the coastline are normally accompanied by a wall of light-coloured massive anhydrite 300-500 m thick on the deep water side. Towards the centre of the basin it changes to thin laminated dark anhydrite.

In the Zechstein 2-3-4, cycles of halite each 200-600 m thick were deposited in the large basin, but in Zechstein 1 cycle the halite was only deposited in a trap behind an anhydrite barrier (Richter-Bernburg, 1972b). Precipitation of the halite is considered to have taken place comparatively rapidly and supporting evidence is given in Richter-Bernburg (1950, 1955). The potash salts are mostly in beds 2-10 m thick within the thicker halite. The Stassfurt seam of maximum 25 m in Zechstein 2 is the thickest potash.

The German Basin, in which the important saline deposits of the Zechstein originated, is considered to be a large embayment of the Scandic Ocean. In the late Permian this ocean ingressed from the north-west flooding a large part of Germany and covering the Lower Permian continental basin.

The rock salt in evaporite deposits, which shows clear regular stratification, indicates calm conditions and only seasonal changes. Red salt with clay intercalations is normally observed at the basin margin; it passes progressively towards the centre of the basin into white salt with thin strata of dark clay or anhydrite, and white salt with fine flakes of anhydrite and a C-H-S gas content. Salt beds with a well defined anhydritic base and decreasing sulphate form a progressive microsequence, whereas beds with a poorly defined base and increasing sulphate form a recessive sequence, and are evidence for re-solution in a saline sedimentary basin. Any irregularities in salt stratification result from changes in concentration of brine as a consequence of desiccation.

Studies of such features in Australian evaporite basins would enable the palaeogeography and the prevailing climatic conditions to be reconstructed. This interpretation would, in turn, help to evaluate the economic potential of a salt deposit and enable prospective areas to be delineated.

An interesting note on the behaviour of brines was described from the German potash mines: brines of different composition can be pumped through the same pipe with little intermixing. A carnallitic brine of 400 g/l and a sodium chloride brine from another part of the mine are pumped 1.5 km through a 15-20 cm pipe to the shaft, and on arrival the soda brine in the top half of the pipe has not intermixed with the magnesium brine in the lower half.

A concise review of the saline deposits of Germany with a summary of stratigraphy, palaeogeography, sedimentation, tectonics, and subrosion is given by Richter-Bernburg (1972b).

SICILY

The Sicilian deposits have recently been studies by Richter-Bernburg and provide an excellent example of facies variations and transitions in a saline environment. An abstract of a paper by Richter-Bernburg on the Sicilian sulphate deposits and their environmental significance is given in Bersticker (1963, ed.).* The evaporites are of Miocene age and were deposited in deep channels, and facies variations, for instance from gypsum to salt, occur over a distance of about 2 km.

A cross-section of the basin is shown in Figures 44 and 45. Massive, white, limestone up to 5 m thick which is present in the near-shore areas in a shallow platform environment contains algal reefs. Basinward the limestone passes into 'swallow tail' or 'sword' gypsum which contains thin beds of clay and laminae of anhydrite. The gypsum

* A more recent paper on the Sicilian evaporites (Richter-Bernburg, 1973) has been published since this report was written.

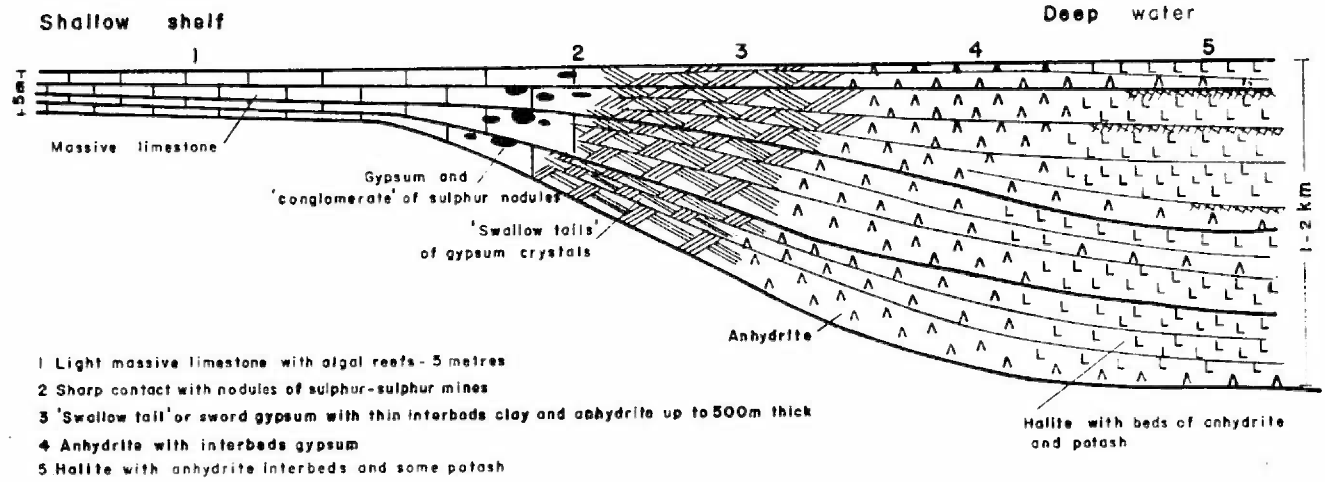


FIG 44-RECONSTRUCTED DIAGRAMMATIC CROSS-SECTION OF THE SICILIAN MIOCENE EVAPORITE BASIN

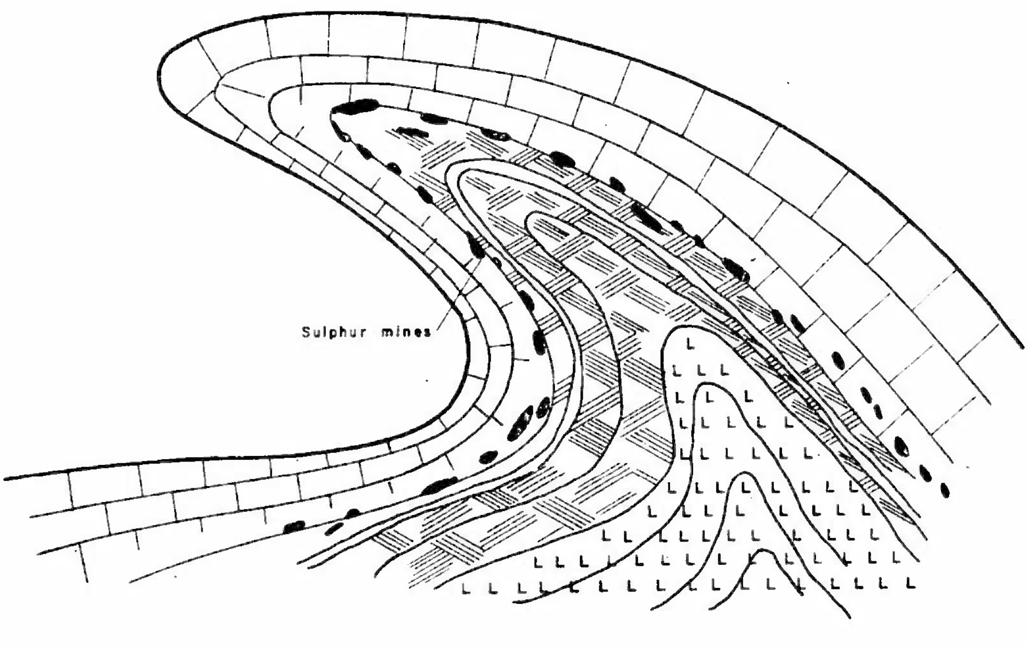


FIG 45-DIAGRAMMATIC PLAN OF THE SICILIAN EVAPORITE BASIN AND SULPHUR DEPOSITS occurs in 'monocrystalline' beds (the gypsum is crystallographically continuous across the thickness of the bed) from 1 cm to 1 m thick and reaches a total maximum thickness of about 500 m. Thin laminae of clay and anhydrite occur in the gypsum, but no anhydrite is present, however, where the gypsum beds reach a thickness of one metre. The outer basin ward, zone consists of fine bedded anhydrite and salt with some potash and reaches a thickness of one to two kilometres.

The contact of shelf limestone with gypsum is sharp and is marked by a zone of sulphur nodules; the old sulphur mines occur along the sulphate/carbonate transition. Bacteria introduced by surface waters have reduced sulphate to sulphur in the shallow water. A similar process of sulphide oxidation by bacteria is known to exist in the Louisiana salt domes. A list of selected representative references to the origin of sulphur is included after the general references. It is noteworthy that one recent paper (Davis et al., 1970) presents evidence against the production of elemental sulphur in salt domes by oxidation of hydrogen sulphide by sulphate ions. As an alternative Davis et al. suggest that dissolved oxygen of groundwater or sea water may be the oxidizing agent, which tends to limit the depth at which deposits of native sulphur could form.

Pressure and temperature conditions in the basin and salinity of the brine determine whether anhydrite or gypsum is deposited (Fig. 43). In the relatively shallow, low salinity part of a basin shelf, gypsum is deposited and may be reduced by bacteria to sulphur. Sulphur may be formed in water as deep as 50 m. Farther from the shore, where water pressure is higher and high-salinity brine is found, anhydrite is deposited. Fluctuations in sea level would be responsible for interbedding of gypsum and anhydrite.

Secondary sulphur veins in Sicily are caused by redistribution in hot volcanic waters, mostly derived from volcanism at Mt Etna. These deposits contain large bright yellow crystals of sulphur in masses, veins, and lenses. There appears to be no doubt that the sulphur is redistributed from the primary deposits and not volcanic in origin (Richter-Bernburg, pers. comm.). Jensen (1968) discusses the origin of the Sicilian deposits and suggests a bacterial origin for the native sulphur and associated calcite.

IRAN

The Kuh-e-Namak salt dome in the Central Iranian Salt basin has been studied in detail. Gansser (1955) considers that salt was extruded from the dome and flowed at the surface. Mapping of fold axes has shown that they are essentially vertical; but if horizontal movement had occurred at the surface they would be expected to be also nearly horizontal and therefore Richter-Bernburg (pers. comm.) considers that salt did not penetrate to the surface. Nevertheless, in some south Persian salt plugs there are several well documented examples of subaerial extrusion and salt 'glaciers' are preserved.

The Persian Gulf is one of the few areas where modern evaporites are being formed; further references to these occurrences, which have materially assisted in the interpretation of evaporite precipitation, are listed on p.

CANADA

Over the past few years Canada has come to the fore as a potential giant potash producer. Indeed, her deposits are the thickest so far discovered and potash production comes from depths as great as 1800 m. The potash-rich zones and intervening barren zones of the Middle Devonian Prairie Evaporite Formation (Elk Point Group) beds in the Saskatchewan Sub-basin, are together about 60 m thick. Thickness and richness of the beds vary: for example a 4.5 m potash zone is known to average 29% K_2O yielding more than 3 million tonnes K_2O per km^2, and a 2.4 m potash zone averages 35% K_2O yielding more than 1.6 million tonnes K_2O per km^2 (Gorrell & Alderman, 1968). The shallowest potash beds being worked are at depths of about 900 m below ground level. It has been possible to correlate thin beds over hundreds of square kilometres by methods similar to those described by Richter-Bernburg (1968). An interesting feature of the exploitation of these deposits is that it is necessary to freeze the Cretaceous aquifers to enable shafts to be sunk into the potash deposits, which occur at greater depths.

The geology of the Prairie Evaporite Formation of the Elk Point Basin as revealed by recent test drilling in the Saskatchewan Sub-basin is described by Holter (1972). The formation is the youngest of the three major evaporite cycles of the Elk Point Group and the only one to be deposited in the Sub-basin.

TEXAS

Like the German deposits, the potash-bearing beds of the Permian Leonard, Guadalupe, and Ochoa Stages of Texas are tightly folded. Potash beds in the domes may be only 2 m thick, but when drilled the potash interval may be 70 m thick because of the steep dip of the bed and thickening on the axes of folds. (Fig. 41). Mansfield & Lang (1935) describe the Texas and New Mexico potash deposits, and the mineralogy of drill core obtained from drilling for potash in Texas is described by Schaller & Henderson (1932) and Sellards & Schoch (1928). The stratigraphy and the internal structures of some of the Texas salt domes is described by Muehlberger (1968) and Hofrichter (1968).

EVAPORITE DEPOSITS IN MODERN MARINE AND CONTINENTAL BASINS

Papers describing recent deposits include Bramkamp & Powers (1955); Butler (1965, 1969); Curtis et al. (1963); Evans (1966); Evans et al. (1964 a and b); Evans & Shearman (1964); Friedman et al. (1973); Hassan & El-Dashlouty (1970); Holser (1966a); Kendall & Skipwith (1969); Kinsman (1964 a & b, 1966, 1969); Morris & Dickey (1957); Phleger (1969); Phleger & Ewing (1962); Shearman (1963, 1966, 1970); and Thompson (in press). The Gulf of Suez and Persian Gulf are the two best known loci of recent evaporites; brines are subjected to high temperatures, and because gypsum dehydrates to anhydrite at 45°C, primary anhydrite would be expected at times, though it is apparently not being formed now.

There are no known modern deep basins in which evaporite salts are actively precipitating. Modern basins in which evaporites may have been deposited in deep sea conditions in the past include the Mediterranean Sea, Piano del Sale (Danakil Depression), and Gulf of Mexico (Schmatz, 1969). By contrast Hsu (1972) and Hsu et al. (1973) present evidence for the presence of a desiccated deep basin at the present site of the Mediterranean Sea to explain the occurrence of late Miocene evaporites.

Deep-sea evaporites have possibly formed in the Gulf of Mexico in water depths of 1-2 km in the late Palaeozoic or early Mesozoic. Formation of evaporites in the present Gulf is prevented by low evaporation rate and excessive flow of seawater into it.

The Tertiary deposits of the Dead Sea Basin, and chemical processes in the lake waters, provide examples of continental evaporite deposition.

The earliest formation that was restricted to the Dead Sea graben is 1000-4000 m of Plio-Pleistocene rock salt. Halite of this age occurs in outcrop at Mt Sedom and occurs in boreholes. Nearly 4000 m of rock salt was penetrated in one bore hole and was still in salt at T.D. The composition of the formation suggests that it was deposited from waters with affinities to the ocean. Other rock salt in the sedimentary sequence is Early to Middle Pleistocene and Late Pleistocene to Recent in age but present salt deposition is restricted to marginal hypersaline pools.

The salts in the lake waters are derived from recycled old brines brought in by the Jordan River, from subaerial and subaqueous springs, and from upward ion diffusion from the lower waters of the lake. Waters from springs in the Mount Sedom area contain about 380 gm/l total salinity and are enriched in potassium so much that the ionic equivalent ratio of Na/K averages 1.6 and may be even as low as 1.1.

The lake water has a low pH (6.4) and calcium carbonate is precipitated in irregular cycles after prolonged evaporation which concentrates bicarbonate to a point where CO_2 is expelled. Gypsum crusts occur in the littoral zones of the Dead Sea floor but is subordinate to calcium carbonate in deeper zones even though gypsum is being precipitated continuously from the surface of the Dead Sea in excess of carbonate, occassionally 10 to 20 times greater. The gypsum beneath the wave influenced zone is reduced by bacteria to H_2S and the remaining calcium combines with CO_2 to form calcite. The H_2S diffuses into the upper water layers where it oxidises to sulphate that is reprecipitated with calcium as gypsum. Some of the H_2S precipitates with iron as pyrite. The calcium carbonate is deposited more commonly as calcite in the sediments rather than aragonite.

No dolomite or anhydrite are found in the sediments. Halite and carnallite are extracted from the Dead Sea brines; the crystallization process has been described by Kenat (1966); the waters contain 1% KCl.

Recent data on the salt deposits of the Dead Sea area are presented by Zak & Bentor (1972), Bentor (1968), and the depositional processes and environments of evaporites are in Neev & Emery (1967).

POTASH GEOCHEMISTRY

'Among the many geochemical mysteries of our times, perhaps one of the most thoroughly studied and documented by physical chemistry and geological data, and yet one that is still very far from a satisfactory solution, is the chemistry and origin of potash deposits.' (Garrett, 1970).

The main problem is that sylvinite (Sylvite-halite rock) represents perhaps 75 to 80% of the K_2O content of known oceanic evaporite occurrences. The mere presence of KCl in the deposits is hard to explain, let alone its being the dominant mineral. Another unusual characteristic is the relatively small amounts of $MgSO_4$ in or near the deposits.

Large quantities of sulphate must have been removed from the system to enable potassium to precipitate as chloride. Previous explanations for the mechanism have been:

1. that the sulphate could be precipitated, in sea water, as calcium sulphate, by calcium brought in by groundwater. To account for the Canadian deposits would need a river the size of the Mississippi with mineralization equal to that of the Colorado River.

2. the sulphate is removed by sulphate-reducing bacteria, the mechanism being

$$SO_4^{--} + 2C + 2H_2O \xrightarrow{\text{bacteria}} H_2S + 2CO_2 + 2OH^- \longrightarrow H_2S + 2HCO_3^-$$

The carbon dioxide is reabsorbed, such a mechanism being the basis of the popular theory for the origin of sodium carbonate. The formation of the soda ash/trona deposits in the Wadi-Natroun of Egypt has been explained by this theory.

This reaction, however, is not supported by evidence from measurements of sulphur isotope ratios. As bacteria select S^{32} this isotope should be depleted in H_2S, sulphides etc, and the remaining sulphate should be high in S^{34} or have a high S^{34} value. But this is not the case.

Most of the modern theories of potash precipitation (that is, as sylvinite) postulate primary carnallite in the bittern phase of evaporation, altering metasomatically to sylvite. This process has been demonstrated in the Saskatchewan deposits, where there are abrupt lateral and vertical changes in red carnallitite (carnallite-halite rock) and red sylvinite in the Prairie Evaporite Formation (Wardlaw, 1968). The carnallitite has been altered to sylvinite by depletion of $MgCl_2$: the process has been substantiated by Br/Rb studies and by bed thickness relationships. The red carnallitite beds are 15 m thicker than red sylvinite beds. Seismic methods, which can determine bed thickness, have been used as a prospecting aid, but allowance must be made for regional variations in thickness.

The process by which carnallite is metasomatically replaced is not at all clear. There are two main theories.

The first envisages irregularities on the gypsum floor, high points of which are the loci for water released by the transition of gypsum to anhydrite. The volume reduction in gypsum triggers structural changes and metasomatism within the overlying evaporites. The mineral assemblages produced depend largely on the amount of sulphate present in the basin. Metasomatic replacement processes with a similar mechanism to this in the Stassfurt potash bed have been described by Borchert (1972).

A second theory proposes extensive limnological stratification in evaporating closed sea water basins (Garrett, 1970). Minerals such as schoenite, leonite, and kainite ($K_2SO_4MgSO_46H_2O$; K_2SO_4. $MgSO_4.H_2O$; $KCl.MgSO_42.75 H_2O$), which formed in the upper basin water layers, are converted to carnallite as they pass downward through brines of higher concentration. The $MgSO_4$ would crystallize in shallow zones during low temperature periods and be flushed out together with the $MgCl_2$ from the carnallite to leave sylvite (KCl). The solution of the sulphate is accounted for by the higher temperatures at depth. Halite would crystallize continuously and would be present with carnallite and then form sylvinite in the final mixture. The potash depositional cycle could be terminated by an influx of sea water into the basin, which by now would be fairly shallow. The dilute brines would be effective in decomposing the carnallite into sylvite, and the high $MgCl_2$ brine produced would form a layer to protext the KCl from being leached.

The following points tabulated under geological and geophysical aids in the exploration for potash deposits have been suggested by Goldsmith (1966).

Geological Aids in Exploration

1. The palaeogeography and depositional history of the basin can be used to determine the significance of dolomite, gypsum, and anhydrite outcrops.

2. Regional structure may suggest salt movement into domes and anticlines.

3. Collapse structures indicate salt solution.

4. Helium is commonly found in salt.

5. Recognition of post-depositional changes can be significant especially where drilling in evaporites -

a. blue halite is generally associated with potassium salts.

b. Large chloride crystals are indicative of recrystallization.

c. Increased thickness of salt sections may indicate domes and flexures conducive to the accumulation of rich potash beds.

d. Bromine analyses of salt may indicate the direction in which brines of higher concentration precipitated and may lead to potassium -bearing chloride.

e. Bromine discontinuity may indicate renewed deposition or solution of overlying salt and removal of the ores.

f. Rapid separation of marker beds indicates removal of salt and direction in which original undisturbed mass is preserved, which may be ore bearing.

g. Wind-borne clay scattered in salt deposits suggests that no salt has been removed, but discontinuous clay seams may indicate salt removal and disappearance of adjacent potassium chlorides.

Geophysical Aids in Exploration

1. Gravimetric surveys can be used to outline major salt basins and structures.

2. Resistivity surveys can be used, particularly where salt is shallow.

3. Seismic surveys are used to determine structures and floor of salt deposits.

4. Well logs are invaluable where no core is available.

References to the use of well logs for the interpretation of evaporite deposits include Alger & Crain, (1966); Bird, (1966); Fons, (1969); Jones, Bowles & Bell, (1960); Knutson & Walther, (1965); Spicer, (1946); Timko, (1964); and Tixier & Alger, (1967).

a. Gamma Ray Log. K^{40} emits gamma radiation and sylvite yields a theoretical response of 16 API units per 1% K_2O, or 1008 API units for pure sylvite (Goldsmith, 1966). Clay beds can be readily distinguished from K-bearing beds when other logs are available.

b. Neutron Log. This is a measurement of hydrogen ion concentration and can be used to distinguish minerals with water of crystallization.

c. Density Log. This is useful for identification of minerals in beds.

Potash Concentration

The ideal physical conditions envisaged by Goldsmith (1966) for potash concentration are a large complex deep basin, with a forebasin, main basin, and satellite basins. A shallow basin is less promising because the rate of subsidence would have to be rapid and constant. Upward changes in the sequence suggest shallowing of water as salt fills the basin. In many basins irregularities with relief as much as 60 m existed on the floor and potash was concentrated in the depressions. This has been shown in the Carlsbad and Delaware Basins in the USA. By contrast the potash limit in the Paradox Basin (Four Corners Area of the USA) follows the outline of the basin margin.

In general it appears that potash salts are concentrated within restricted pockets of a basin. Where there is a series of basins, the one with no connection with the sea furnishes the most favourable depositional environment.

Adams (in press) has tabulated a useful guide for the exploration and assessment of potash deposits. The following summary is from the unedited manuscript of his paper*:

'The study and exploration of an evaporite deposit should be based on (1) the thorough study of its stratigraphy and mineralogy, and then (2) on the interpretation of these features in the context of the chemistry of the salt systems. The search for new evaporite deposits requires the use of subsurface and indirect surficial evidence because the soluble chloride minerals rarely crop out at the surface. Evaporites of intracratonic basins are commonly associated with extensive chemical, biochemical and clastic sediments such as shelf carbonates, fringing reefs and red beds. Evaporite deposits at the continental margins occur

* Citations omitted

where crustal extensions developed during the Mesozoic and Cenozoic periods. The proximity of buried evaporites may be inferred from saline waters in springs and wells, thick outcrops of gypsum or anhydrite and domal or collapse structures or geophysical anomalies such as those associated with the piercement salt structures under and around the Gulf of Mexico. Surface geophysical techniques, particularly gravity and seismic methods may be useful in determining the distribution and shape of evaporite bodies.

Initial exploration of a known evaporite section may require the evaluation of geophysical logs from wildcat oil and gas exploration. Gamma-ray, neutron, sonic, caliper, density and resistance logs are useful in the interpretation of evaporite lithology, stratigraphy and mineralogy. The gamma-ray log is particularly useful as it detects the gamma radiation from the natural potassium isotope K^{40}, hence it provides a continuous measure of the potassium content of the salt section. Initial exploration core holes are drilled on several mile centers using a sodium chloride saturated brine. If a natural brine is not available rock salt can be added to the drilling fluid. Where potash salts are present the brine must be saturated with respect to all the readily soluble minerals with due allowance for possible higher temperatures (hence greater solubilities) in deep holes. If the composition of the brine cannot be rigorously controlled a petroleum based drilling fluid is used.

Less than ten percent of the salts in sea water yield potash-rich mineral assemblages. Minable potash deposits, therefore, are generally associated only with thicker halite deposits. The potash-bearing assemblages moreover, commonly occur in the younger, upper portions of the thick halite deposits since the potash salts are precipitated late in the evaporation sequence. Multiple potash horizons may occur in the upper one quarter to one third of major halite deposits, (unless they are precipitated in adjacent sub-basin) reflecting the cylic nature of precipitation.

The principal potash deposits of a district may occur directly over the thickest halite sections, peripheral to them or in nearby sub-basins, depending on the tectonic history of the area.... Thick halite deposits in some basins do not have associated potash deposits, the potash-rich brines having been lost by reflux before potash precipitation or the precipitated salts having been subsequently dissolved by refreshened brines.

The exploration for potash deposits in known evaporite sections is based on studies of the chemical and physical characteristics of the salt beds. Stratigraphic criteria favourable to the occurrence of potash deposits include a) halite sequences in excess of two to three hundred feet in thickness, b) the presence of potassium in sulfate beds (possibly as polyhalite), in clastic horizons (possibly as illite or mixed layered potassium clays) or as disseminated grains of potassium chloride or sulfate minerals in halite beds and c) the interbedding of "insoluble" - bearing clastic horizons toward the top of the evaporite section. The presence of insoluble material interbedded with and disseminated within the salt beds indicates a closer source for detrital material and a decreasing rate of chemical relative to clastic sedimentation. The clastic source is closer because the size of the basin has been reduced through evaporation. The rate of chemical sedimentation has decreased due to the lower vapor pressure of the residual concentrated brines. Both conditions infer higher brine concentration, hence the possibility of potash deposition. In the Prairie Evaporite formation of Saskatchewan not only do the insolubles increase toward the top of the formation but the concentration of insolubles within the three potash-bearing members increases from the lowest to the highest. The insolubles of the potash beds in the Yorkton area of Saskatchewan include anhydrite, gypsum, dolomite, quartz, hematite and micas or illite. In the Salado formation of New Mexico both insoluble-rich beds and polyhalite beds are more common with the potash deposits in the upper portion of the formation.

The bromine content of halite may be used to infer the favourability of a salt deposit for potash horizons. The substitution of bromine for chlorine in the halite structure increases as the concentration of the brine increases, hence halite in and near potash beds contains more bromine. In deposits formed from the simple evaporation from sea water the absolute bromine content of halite is an indication of the stage of evaporation, hence the likelihood of a potash deposit being present. Potash beds might be expected when the bromine concentration in halite exceeds 150 parts per million bromine. Halite beds formed by the dissolution and reprecipitation of salt beds or the mixing of marine and non-brines will contain lower bromine concentration. For example, halite in potash assemblages in the Salado formation, largely a second cycle evaporite deposit, contains as little as 70 ppm Br. In the exploration of an evaporite deposit, therefore, bromine data are useful when interpreted in the context of other mineralogical and stratigraphic information.

EVALUATION OF DEPOSITS

The selection of appropriate mining and milling methods and the economic exploitation of a potash deposit will depend upon the accurate characterization of the physical and chemical features of the deposit. Similarities between deposits render much of this evaluation routine. The recognition and evaluation of features peculiar to a deposit may, however, determine the success of the operation. Some general guidelines are listed in Table IV.

NX or NC cored drill holes are the basis for the initial appraisal of a deposit. Due to the coarse grainsize of salt assemblage smaller core is generally unrepresentative. Development drill holes are spaced on one quarter to one mile centers depending on the depth and complexity of the deposit. The salt cores are logged with attention to all mappable stratigraphic, lithologic and mineralogic features (a logging scale of one inch equals ten feet is appropriate for the halite section; one inch equals one foot for potash horizons). The potash horizons should be sampled by geological unit for chemical analysis and determinative mineralogy without compositing dissimilar mineral assemblages. It is generally sufficient to analyze for K, Na, Ca, Mg, Cl, SO_4 and H_2O after drying to constant weight at $90^{\circ}C$. The accuracy of the sampling and analytical procedures may be confirmed if the megascopic mineralogy of the sample, estimated from hand specimen and thin section, can be calculated from the chemical analyses within the accuracy of the estimates and the analytical methods. The geological interpretation of these data in terms of the factors listed in Table IV should indicate the potential for a minable deposit or the need for additional drilling or metallurgical tests.'

TABLE IV. Guides to the evaluation of potash deposits (after Adams, 1973)

Factor to be considered	Potential Problem	Observation to be made
Structure of ore horizon	Faulting, folding or flowage of ore horizon complicating or precluding room and pillar mining method	a) correlation of stratigraphy between drill holes b) examination of core for evidence of deformation and recrystallization
Stratigraphy	Incorrect correlation of ore horizons; salt thickness above is insufficient to protect deposit from water; slabbing and ore dilution from clay beds above ore horizon	Detailed core logging and correlation of beds between drill holes
Ore Depth	Low mine extraction or excessive development and mining costs	Mining method and size of mine openings designed on basis of rock mechanics and geology
Ore Thickness	Local systematic or random thinning of ore zone	a) isopach maps of stratigraphic units and mineralization in ore zone b) inspection core for evidence of metasomation and potash leaching, i.e., recrystallized halite, clay in intergranular clots, and horizontal mineral zoning

TABLE IV. (cont.)

Factor to be considered	Potential Problem	Observation to be made
Ore Mineralogy	Assemblages incompatible with proposed mill circuit; certain assemblages reduce stability of mine openings; high insoluble content requires extra desliming capacity.	Determinative mineralogy of core
Ore Grade	Grade may be too low or erratic to maintain acceptable mill feed; recoverable K_2O may be significantly less than total K_2O	Correlation and interpretation of drill hole; comparison of chemical analyses with determinative mineralogy
Ore Continuity	Erratic barren or thin areas in ore zone	Correlation of stratigraphic units and mineralization in ore zone; inspect core for evidence of recrystallization and horizontal mineral zoning
Ore Crystallinity	Inclusion of contaminants within potash minerals; fine-grained assemblages requiring finer grind	Correlation of microscopic examination of ore samples with chemical analyses of mineral separates
Ore Reserves	Insufficient reserves or excessive mining and milling costs	Accurate geological description of deposit for mining and metallurgical studies

The following extract from Ingerson (1968) is a summary of a discussion on potash formation, and major unsolved problems in the study of evaporite deposits.

'Potassium mineralization

Primary deposits

1. In both the German and the English evaporites much of the potassium appears to have been deposited originally as primary carnallite.

2. Little of the original carnallite remains in either series, however. In the English deposit the outlines of original carnallite crystals are preserved by hematite and clay flakes that coated their surfaces.

3. In the German deposits much of the carnallite now present appears to have been formed late in the alteration series by a process called "recarnallitization."

4. No primary potassium minerals have been described from Carlsbad, New Mexico, but from the general description, the indicated paragenesis, and the bromine content of the minerals, the chances appear excellent that here also a good part of the potassium was originally deposited as carnallite.

5. Sharp tops and bottoms of the beds appear to be characteristic of primary deposits.

Secondary deposits

1. In all the areas described the minerals of the potassium zones appear to have been extensively recrystallized, replaced, altered, and, at Carlsbad at least, transported laterally over considerable distances.

2. Potassium salts replace pre-existing minerals, in part by simple reaction with the bitterns, in part by reaction with earlier (primary ?) potassium minerals.

a. In the German deposits, for example, the "Q brines" (rich in $MgSO_4$) take K from early-formed carnallite and replace anhydrite with polyhalite. The whole sequence is largely K-bearing sulfates, the chloride freed from the carnallite joining that of the bitterns to form "reaction halite", a secondary mineral very low in bromine.

b. In the English deposits, on the other hand, the potassium minerals replace and react with halite, so the sequence is mostly chlorides (including the rare rinneite), with very little kieserite or other sulfates.

3. The sequences are very complicated in some cases, and they vary from one layer to another even in the same deposit. Hence, no detailed, or even general, outline of the mineral paragenesis is possible in a summary account of this kind.

4. Although no primary potassium minerals have been identified at Carlsbad, the opinion was expressed that the potassium mineralization occurred shortly after deposition.

Salt mines are very dry because salt formations are "tight", that is, they are highly impervious to water. How, then, did the solutions move around to effect the changes mentioned above?

1. Much, if not most, of the motion of and changes effected by the solutions probably took place before final consolidation, while parts of the layers concerned still consisted largely of a crystal network or mush with interstitial solutions, like the upper part of Searles Lake, California.

2. Cavities and channelways can remain open in salt to depths of 900-1500 m for considerable lengths of time.

3. After deep burial, elevated temperatures could allow the solutions to dissolve out channelways for themselves. Some mineral assemblages give evidence of such elevation of temperature.

4. Tectonic movements may move solutions along shear zones and allow them to move along faults or joints.

<u>Physical-chemical data on equilibrium and nonequilibrium processes</u>

Most of the discussion on this topic took the form of listing published material (without specific references) on equilibrium studies and citing individuals (mostly without addresses) who are continuing such studies.

Some pertinent observations were also made:

1. There is great need for a careful modern repetition of the work of Usiglio on evaporation of sea water, together with detailed quantitative work on each phase that separates.

2. Nonequilibrium studies are important, especially in the operation of chemical plants; but comparatively little work has been done in this field.

3. In the large, natural systems we are studying, it sometimes appears that the processes were nonequilibrium; but it is more likely that there were considerable gradations of temperature and composition over the distances involved rather than failure to attain equilibrium at any given point.

4. One of the least-known parts in the overall system is the temperature range 46°-$100^{\circ}C$, with low $MgCl_2$ content. Good data in this area would be most welcome.

Major unsolved problems

Each member of the work group was asked to list what he considered to be the most important unsolved problems in the deposition and geochemistry of evaporites. Of the 20 or more problems suggested the "top 10" were selected by preferential ballot for presentation to the larger study group. These are as follows:

1. The palaeogeography of evaporite-depositing basins and their relation to the open ocean.

2. Restudy of the evaporation of sea water, including study of trace elements and isotopes.

3. Dynamics of evaporite crystallization and deposition in a basin containing (a) non-layered brine and (b) layered brine.

4. The distribution of primary saline mineral facies in a basin.

5. Origin of major layering (layers 1-100 feet thick) in evaporite deposits.

6. Mechanics of solutions moving through evaporite deposits.

7. Are there equilibrium conditions (a) during primary precipitation of saline minerals and (b) during transformations of saline minerals at later stages?

8. What is the proportion of marine, deep-water saline deposits to shallow-water deposits? Of marine to continental deposits?

9. What is the relative importance of the sources of evaporite constituents; relict marine, airborne, leached from weathered rocks, or other possible sources?

10. The extent and mode of removal of salt from evaporite deposits.

NOTE ON SULPHUR ISOTOPES

Fractionation of sulphur isotopes takes place by the following exchange reaction:

$$^{32}SO_4^{-2} + H_2{}^{34}S \qquad {}^{34}SO_4^{-2} + H_2{}^{32}S$$

At equilibrium H_2S is enriched in ^{32}S by 73 per mil more than that of the SO_4^{-2} (i.e. it has been calculated to be 7.3% at 24^oC). Hence sulphides and native sulphur are enriched in ^{32}S and sulphates in ^{34}S. Anaerobic bacteria are possibly the only natural medium for this reduction at near-surface earth temperatures.

Sulphur isotope ratios are expressed by comparison with a meteorite standard. The ratio in meteorites is remarkably constant. The ratio is expressed by -

$$^{34}S\,^o/_{oo} = \frac{(^{34}S/^{32}S)_S - (^{34}S/^{32}S)_{ST}}{(^{34}S/^{32}S)_{ST}} \times 1000$$

ST is the standard ratio for meteorites and S is the ratio for the sample. Samples with positive and negative values are enriched and depleted, respectively, in ^{34}S with respect to meteoritic sulphur.

The $^{34}S/^{32}S$ ratio is highest in cap rock sulphates and lowest in sedimentary sulphides. The ratio is constant in sea water (^{34}S = +20.1) and there is no isotope fractionation during evaporation of sea water. However, evaporites show changes due probably to bacterial reduction of sulphate to sulphur enriched in ^{32}S. For example, in Gulf Coast salt domes ^{34}S values are about +66.

Fractionation of sulphur isotopes during the crystallization of sulphate, in particular of calcium sulphate from aqueous solutions, is very small, around 1% enrichment of ^{34}S in the crystals, and little fractionation occurs in the deposition of gypsum in an evaporite basin.

Few Precambrian evaporites are known, but many of the older deposits have probably been eroded, and also few wells have been drilled into the Precambrian. Studies carried out on gypsum and anhydrite from Precambrian deposits show quite different sulphur isotope ratios from those found in Cambrian evaporites; the biggest change in isotope ratio is always found between Cambrian and Precambian deposits. For example the sulphur isotope ratios determined on sulphates from Siberia and Pakistan are similar, but they are quite different from those determined on sulphates from the Adelaidean Bitter Springs Formation. The Zechstein sulphate is one of the formations most enriched in ^{32}S.

The results of some of the investigations of sulphur isotope geochemistry are discussed by Holser & Kaplan (1966) and Nielsen (1972). Some results of sulphur isotope studies made on evaporitic anhydrite, including examples from Australia, are tabulated in Solomon et al. (1971).

MINOR ELEMENT CONCENTRATIONS IN EVAPORITES

Minor element concentration has been used in some evaporite deposits as an indication of the depositional environment and particularly to indicate the stage which brine composition and concentration had reached in the evaporite basin. The significance of bromine and in some cases rubidium, particularly as an indicator of the environment, has been discussed by many authors. Some of the more recent references are Raup, Holser, Baar and Braitsch (all in Rau, ed., 1966); and the following included in selected references to potash deposits: Schwerdtner & Wardlaw, (1963); Adams, (1969); Kuhn, (1968, 1972); Lainina & Anoshin, (1962); Lindberg, (1946); Ogienko, (1959); Schock & Puchelt, (1970); Valyashko, (1956a, b); and Wardlaw, (1970).

The proportion of bromine increases proportionately with increase in concentration of the parent brine, and brine capable of precipitation of potash may contain between 175-350 ppm bromine.

By contrast, Holser, Wardlaw & Watson (1972) have recently described extraordinarily low bromine contents in salt rocks of the Lower Elk Point salt in Canada. Secondary cycles involving leaching or re-solution by fresh water have been invoked by the authors to explain this phenomenon.

Bromine content can also be used to determine if the salts are syngenetic or epigenetic; secondary chlorides contain less bromine than primary chlorides. In addition salts of identical age or stage of formation that precipitate from a concentrating brine should have an equal bromine content. Hence a bromine discontinuity may show renewed deposition, or if bromine content is high it may indicate re-solution of the overlying salt and removal of the ores. Detailed analyses of bromine content over salt sections in several wells may show the direction in which brines of higher concentration precipitated and may lead to potassium bearing chlorides (Goldsmith, 1966).

CURRENT STUDIES OF AUSTRALIAN EVAPORITES AND ALLIED ACTIVITIES

Companies that have been active in exploration of basin evaporite deposits in Australia are Occidental Minerals Corporation of Australia, Mines Exploration Pty Ltd, Newmont Pty Ltd, Magellan Petroleum Corporation, and West Australian Petroleum Pty Ltd. The CSIRO is investigating the formation of evaporites and the biogenesis of sulphur.

Occidental Minerals has drilled one well in the Boorthanna Trough and, at the time of writing (1974), is still engaged in an appraisal of Australian deposits. Mines Exploration has reviewed local occurrences and undertaken comprehensive analysis of many evaporite cores, particularly from the Adavale Basin. Newmont investigated and drilled in the southeast Lake Amadeus region, but have ceased that operation. Magellan Petroleum prepared a report on the Amadeus Basin (Banks, 1964) and, in collaboration with Continental Oil Company of Australia and the Australian Sun Oil Company, investigated the Dirk Hartog deposits, but at present are inactive in this field. Wapet drilled the Doran Structure, and their future program includes drilling the Logue Structure, a possible salt dome (see discussion under Canning Basin).

CSIRO has investigated the formation of evaporites by the leaching of cations from sediments. Experiments showed that weathering of shales resulted in the formation of large gypsum crystals. Sulphur isotopes in naturally occurring sulphates have been studied by CSIRO, and the more specialized aspects of this work include a study of Precambrian sulphates, the time of introduction of sulphate-reducing bacteria, and the implications with regard to the beginning of the oxygen cycle and the origin of life.

CSIRO is also studying the occurrence and composition of fluid inclusions in evaporites. In Germany Dombrowsky (1966) has cultivated bacteria from fluid inclusions. However, most workers view the results with scepticism and consider that contamination probably occurred during the experiment. It is very doubtful whether bacteria can move through rock salt, as it is most impermeable, but it has been shown that they can move metres through other rock types. Fluid inclusions have not been studied systematically in German salt deposits; the comparison between inclusions in gypsum and halite was mentioned as a possible starting point for this type of investigation. The composition of fluid inclusions has been discussed in the series on geochemical data published by the US Geological Survey (Roedder, 1972). This paper reviews the world literature on analysis of fluid inclusions, applicability and limitations of the methods used, published and unpublished data obtained, and their geological significance.

There is an unconfirmed report that Thiess Bros have drilled for evaporites in the Fortescue Valley in Western Australia. The valley is underlain by Quaternary and Tertiary sediments, but no evaporite deposits are known, and there does not appear to be any evidence of evaporites at the surface. The location of this exploratory drilling and the results are unknown.

CONCLUSIONS

In general terms, exploration in Australia should be directed to the discovery of shallow deposits of high grade at locations within reach of transport and labour. Transport facilities commonly determine the economic viability of a deposit. For example, the potash deposits of Canada are inland and consequently at a disadvantage in export markets compared with deposits in Ethiopia which are near the sea. Deposits in Canada are, of course, favourably located to satisfy local markets in the form of existing chemical complexes. Such considerations would have important implications if potash was found in Australian deposits. Long-range plans should, therefore, incorporate an exploration program for potash in areas that will at least compete with established producers.

Most known Australian evaporite deposits have been discounted, even though they may contain large quantities of sulphur and potash, because they are either too deeply buried or too far from seaboard transport. Nevertheless, deposits are economically worked overseas to a depth of about 1200 m, but in these areas transport facilities are more favourable than they would be in Australia.

The review of the basin deposits in Australia has shown that there are four major onshore bedded evaporite deposits; in the Canning, Officer, Amadeus, and Adavale Basins. The Bonaparte Gulf Basin includes a thick evaporite sequence onshore, and diapiric structures are numerous. Several other basins have indications of bedded evaporites, but their full extent and potential as major deposits are not known at present. The majority of the more accessible surface or near surface deposits in Australia still remain to be investigated thoroughly.

Canning Basin

The Canning Basin has the thickest known sequence of evaporites: 740 m of halite was penetrated in the McLarty No. 1 well. The basin is so wide that satellite sub-basins could have developed during the evaporite phase and potash concentration would be enhanced in those separated, and farthest removed, from the open sea. Several closed structures in the basin are probably the result of a combination of salt solution by groundwater and thickening of sediments in the resulting depressions. Remobilization and leaching of the salt by percolating fluids may also lead to concentrations of potash in certain zones.

Amadeus Basin

Two formations contain evaporites. The less soluble evaporites in the Precambrian Bitter Springs Formation crop out; the Lower Cambrian evaporites are known only from the subsurface but deposits may occur at shallow depth in many areas. The limited information on the distribution of minerals in the Precambrian evaporites suggests that a peripheral zone of gypsum surrounds a core of halite. The most prospective area for residual liquors would be in the depressions in the halite. The halite zone is not well defined but apparently lies within the central eastern part of the Amadeus Basin. The Lower Cambrian evaporites are restricted to the northeastern part of the basin and grade westwards into shale and sandstone.

Adavale Basin

The evaporite deposits in the Adavale Basin are the most interesting economically as they contain the only known occurrence of potash in Australia. The area near the Warrego Fault, adjacent to the Pleasant Creek Arch, where the evaporites are thick and relatively shallow, is the most prospective. Salt solution, postulated in this basin, may result in sylvite concentration.

Officer Basin

Several diapiric structures with exposed cores of caprock gypsum have been discovered. Recent shallow drilling has shown that the caprock is underlain by halite (Wells & Kennewell, in prep.). Evaporites may be of two ages, according to the evidence from seismic cross sections which increases the prospects in the area. The diapiric structures with exposed evaporite cores present attractive, and easily investigated, exploration targets.

Offshore Bonaparte Gulf Basin

Many diapiric structures were detected on seismic cross-sections in the offshore Bonaparte Gulf Basin and subsequently halite was intersected in the bottom 180 m of Pelican Island No. 1 and bottom 140 m of Sandpiper No. 1; both wells were drilled on the crests of diapiric structures and provided indisputable evidence for the composition of the diapir cores. The precise extent of the evaporites is not known and as there are no proved onshore deposits it is probably the least attractive of the basins for mineral exploration.

Continental Deposits

Deposits of halite in modern salt lakes are the main source of domestic consumption. Basin deposits are unlikely ever to be a competitive source of halite, and, conversely, salt lakes are unlikely to provide competitive sources of potash and sulphur. The only exception is Lake MacLeod in Western Australia where potash will be produced as a byproduct of mainly halite recovery. Nevertheless, salt lakes are of significance in the study of the origin of evaporite basins, as has been discussed by Valyashko (1972); who gives several examples of modern evaporite formation in playa lakes, including one of carnallite precipitation in Tsarkhan playa in the Tsaidam depression of the USSR.

RECOMMENDATIONS

Further work in the investigation of Australian evaporite deposits can be divided into several stages:

1. Additional geological investigations of surface evaporite occurrences and palaeogeographic studies of evaporite sequences in the more prospective basins.

Geological mapping should be confined to the Officer and Amadeus Basins, where diapirs are known and there are surface occurrences of evaporites. Lithofacies studies to determine the palaeogeography of an evaporite deposit would necessarily be limited in other basins to a study of well sections. Detailed mapping of the Bitter Springs Formation in the Amadeus Basin could form part of this program but would pose special problems because of the complexity of incompetent folding in the formation.

2. Stratigraphic drilling of surface or near-surface occurrences and shallow pattern drilling of diapir cores; geochemical studies of the evaporite cores, particularly bromine analysis, which gives an indication of the stage the evaporite cycle has reached.

The Officer and Amadeus Basins offer several targets for shallow stratigraphic drilling. The Woolnough, Madley, and Browne Diapirs are prime targets in the Officer Basin and some preliminary shallow test drilling has already been attempted. Many other possible diapiric structures in the basin have been outlined by recent photo-interpretation. There are several outcrops of evaporites in the Amadeus Basin, but the caprock gypsum should first be located by mapping and drilled, because they are more likely to signify evaporite mineralization at shallow depth.

In South Australia the most interesting target for exploration is the Mount Toondina Structure. The composition of the intrusive core is unknown and could probably be established by shallow drilling.

3. Geophysical investigations; detailed gravity and seismic traverses of known diapirs, and other areas to solve specific problems.

Geophysical studies can be used to solve specific problems in some basins; for example the precise minimum depth to the top of the evaporites in the Adavale Basin may be determined by detailed gravity and seismic surveys. Similarly a detailed gravity survey of the Lake Amadeus area in the Amadeus Basin has been suggested as a method of determining the distribution of low density evaporites which were postulated to underlie the salt lake belt. However, it is probably more expedient to establish, by shallow stratigraphic drilling, that evaporites do in fact extend into the southern part of the basin.

Of fundamental importance is the detailed geophysical study of known diapiric structures to establish the attitude, depth, source, and dimensions of the mostly buried or largely concealed evaporite bodies. These investigations could in many areas indicate the age and origin of the intrusive material.

4. Further drilling to detail targets outlined by geophysical surveys and ground mapping.

Most of the evaporite basins are being explored for petroleum and during the course of this exploration the basin is normally investigated by seismic surveys. These surveys may indicate shallow diapiric structures, areas where salt bearing formations approach ground level or areas of sedimentary cover where saline beds are buried at shallow depth. These types of deposits would present accessible drilling targets.

ACKNOWLEDGMENTS

Geologists of the following companies and State Geological Surveys kindly supplied information and made available data from their unpublished results of seismic surveys and drilling.

BRISBANE

Mr J.T. Woods, Chief Government Geologist:
Mr R.J. Allen, Petroleum Geologist:
Mr C.F. Swarbrick, Geological Survey of Queensland

Dr R. Wise, Manager of Australian Operations;
Mr K.A. Olson, Senior Geologist:
Mr J.O. Erickson, Geophysicist, Phillips Australian Oil Company

Mr G.F. Bryant, Manager;
Mr G. Patrick,
Mr R. Boone (2ic), Texaco (Australia) Ltd

Mr R. Hopkins, Manager;
Mr A. Sabitay, Geophysicist, Magellan Petroleum Australia Ltd

Mr M.M. Carval, Managing Director;
Mr R. Heilammer,
Mr K. Creevey, Australia Aquitaine Petroleum Pty Ltd

SYDNEY

The Manager, Mr J. Olaf Sund,
Mr D. Holmes, Occidental Minerals Corporation of Australia

Mr A.G. Rose, Chief Government Geologist;
Mr J. Stunz, N.S.W. Geological Survey

Mr M.A. Condon, General Manager;
Mr R. Butcher, Geophysicist;
Mr G. Auchincloss, Geologist, Hartogen Exploration Pty Ltd

Mr E. Erickson, Senior Geologist;
Mr J. Wonfor, Australian Gulf Oil Co

Mr I. McFarlane, Director;
Mr J. Ivanac, Senior Geologist;
Mr J. Best;
and Mr A. Lindner, (Southern Pacific Petroleum),
Central Pacific Minerals N.L.

Dr Geoff Taylor,
Dr Graham Taylor,
Dr I.R. Kaplan, CSIRO,
Division of Mineral Chemistry

Dr G. Bishoff,
Geology Department,
Macquarie University

<u>PERTH</u> Mr S.W. Totten, Managing Director;
Dr R. Alexander,
E. Horstman,
D. Bozanic and R. Storlings,
West Australian Petroleum Pty Ltd

Mr J.H. Lord, Director;
Dr A. Trendall, Dr P. Playford, Dr R. Cope,
Geological Survey of Western Australia

<u>ADELAIDE</u> Mr L. Parkin, Director;
Mr G. Whitten, Chief Geologist;
Mr K. Miles, Dr H. Wopfner,
Department of Mines

Mr R. Russel, Manager;
Dr R. George,
Mines Exploration

Mr F.R. Hartley, Director;
Mr Dickson, Dr Brown, Dr G. Smith,
The Australian Mineral Development Laboratories

<u>MELBOURNE</u> The Manager, (Bruce Webb, Greg Cochrane),
Newmont Pty Ltd Australia

The Manager (Jim Cundill, Bill Meyers),
Cundill Meyers and Associates, (Consultants for
Newmont Pty Ltd Australia)

APPENDIX 1 - DOCUMENTATION OF DRILL CORES BY PHOTOGRAPHY

All drill cores obtained by West Australian Petroleum are slabbed and the flat polished surface is photographed in colour. All photos are taken and processed by the one photographer, who ensures uniform toning. The photographs are filed at head office, are readily available for inspection, and provide most of the structural details of the core. It then becomes unnecessary, for most purposes, for the geologist to spend time in travelling to the core store to inspect material or wait for delivery from store. The procedure does not, of course, supplant the initial detailed description of the mineralogy, texture, and structure of the core.

This method could have been applied very successfully to the study and description of evaporite cores from the Amadeus Basin. The structures displayed by the heterogeneous cap rocks are complex and vary considerably and in addition the field descriptions of rock types had to be modified after microscopic and X-ray diffraction studies (Wells & Kennewell, 1972). If colour photos had been available the graphic logs of the core could have been produced much more easily without having to resort to re-examination of all the material.

Richter-Bernburg commented that most of the translucent evaporite cores from the German salt basin are photographed in transmitted light; this enables easy recording of the structure and texture of the evaporites.

APPENDIX 2 - COMMERCIAL AND INDUSTRIAL USE OF SALT RESERVOIRS

A salt reservoir, being impermeable, is an ideal site for petroleum storage. It is cheaper - only about half as expensive than a tank farm; it does not occupy expensive land; it does not disfigure the landscape; and it is less vulnerable to attack.

Storage caverns in salt are in use in West Germany; the main purpose is to keep in reserve at least 20 million tonnes of crude and refined products, sufficient for 90 days or more, to compensate for delays, in obtaining oil stocks, which might result from protracted negotiations on oil pricing, transport holdups, and so on.

Large cylindrical caverns can be made by disolving salt through a small diameter hole drilled deep into the salt mass. Caverns have been partly filled at Ruestringen in Germany. They lie about 1200 m below the surface and are shaped like bottles with a drill hole running from the neck to the surface. Each bottle is 25 m in diameter and 400 m high and can hold about 170 000 tonnes of oil.

The savings in cost of this type of storage are considerable. Conventional tanks cost between \$US16 and \$US27 a cubic metre (1.2 m^3 equals 1 tonne of oil or about 8 barrels). Caverns in salt cost at the most only \$US9.50/m^3; at Ruestringen the cost will probably only be \$US3. In addition the cost of the land for tank farms near cities may also mean a large capital outlay. To store 10 million tonnes of oil will require 60 cavities of the dimensions given above. In future larger cavities with a capacity of 350 000 tonnes may be feasible.

As large quantities of water are required and brine must be disposed of it is essential that the caverns be excavated near the coast. The plant used for constructing the reservoir remains on the site: the oil can be extracted by pumping sea water to the base of the cavern and forcing it to the surface.

When completed in 1979, the caverns in the Ruestringen salt dome near Wilhelmshaven will be the world's largest, (Petroleum Information Bureau, 1973). In early 1973, the 10 caverns completed had a capacity of 12.5 million barrels, and at the end of the project there will be 52 caverns with a capacity of 100 million barrels. Similar storages with 5.5 million barrel capacity are planned at Hamburg and Bremen.

At Manosque, in France, about 80 km from Marseilles, similar leached storage caverns in salt will be completed by 1976, with an ultimate capacity of 63 million barrels of oil and diesel fuel. The storages produced so far have a capacity of 19 million barrels.

At Fort Saskatchewan in Canada caverns being leached in salt 1500 m below ground level will store 2 million barrels of propane and butane. Construction costs are reported to be 1/50th of those for above-ground storage.

Another ingenious use of salt caverns is for storage of electrical power in off-peak periods (Whitehouse, Council, & Martinez, 1968; Martinez, 1971). Air is compressed in the cavern using electric pumps and the electrical energy recovered in peak periods by release of the air through a reversible compressor-expander. The high temperatures in the salt mass add to the efficiency of the system.

Many papers describing the use of salt caverns for storage of gases and liquids are published in Bersticker (ed., 1963), and Rau (ed., 1966).

Disposal of industrial waste materials has become an ever-increasing problem over the past few years and a partial solution has been to dispose of them in rock salt deposits. In particular, radioactive materials have been stored in this way (see Pierce & Rich, 1962; Galley, ed., 1968; and Gera, 1972). Gera concludes that 'In relation to the safety of radioactive waste containment, the risk of excessive deformation can be kept acceptably low if the disposal formation meets the following requirements: (1) bedded salt located in a geologically stable area; (2) subhorizontal salt beds exposed to very limited differential loading; (3) thickness of the salt beds of the order of 100 to 300 m; and (4) depth of the salt beds between 300 and 700 m.'

Because of the remoteness of the present known evaporite deposits in Australia it seems unlikely that any of these methods of storage and disposal will be used in the foreseeable future. Even so there is the possibility that the more accessible deposits may assume strategic use for fuel storage and for disposal of waste products. More accessible deposits may be discovered in the meantime.

APPENDIX 3 - INCIDENCE OF SALINE DEPOSITS IN GEOLOGIC TIME

Modified after Kozary, Dunlap, & Humphrey (1968), with some additional information

Precambrian

Australia	- Amadeus Basin, central Australia; Officer Basin, Western Australia
North America	- Ontario (Grenville Series); Arctic Islands; Idaho-Montana (Belt Series), British Columbia
Asia	- Persian Gulf?; southwest Pakistan

Cambrian-Ordovician

Australia	- Amadeus Basin, central Australia
Asia	- Lena-Jenissei; Eastern Siberia; Aden to India and Pakistan (Hormuz Series)
Africa	- Spanish Sahara
North America	- Mackenzie Basin in North West Territories; Williston Basin; Southern Illinois; Arctic Islands
South America	- Southern Bolivia

The largest salt basin occurs in Siberia with potash in the south. Potash is also known in Pakistan.

Silurian

Australia	- Carnarvon Basin, Western Australia
Asia	- Ob-Jenissei
Europe	- Northern Baltic
North America	- Williston Basin; Michigan Basin in Michigan, Ohio, Pennsylvania, New York, West Virginia and Virginia; Arctic Islands

Devonian

Australia	- Adavale Basin, Queensland; ?Canning Basin - Western Australia

Asia	- Mongolia, Tana Tuva; Southern Siberia; Tamyr Peninsula; Lena - Jenissei
Europe	- Baltic, Novgorod; Ukraine
North America	- James Bay; Michigan Basin; Southern Iowa; Western Canada, Saskatchewan; Arctic Islands

The Devonian deposits are very extensive and include two of the worlds largest potash deposits, one in Saskatchewan, the other in southeast USSR.

Carboniferous

Asia	- Tana Tuva; Sinkiang; Inner Mongolia; Shantung; Java
Africa	- Tindouf Basin
Europe	- Spitzbergen
North America	- Arctic Islands; Williston Basin; Paradox Basin; Illinois Basin; Michigan Basin; Southern Iowa; Maritine Provinces; Greenland, Cape Franklin.
South America	- Lower Amazon; Southern Peru; N.E. Venezuela

Mississippian deposits occur in north, central and eastern USA, maritine provinces of Canada and possibly in south central USSR and in the Arctic Islands. Potash occurs in the maritime provinces. Pennsylvanian deposits are not widespread. They occur in the Paradox Basin USA where large potash deposits are known, and Amazon Basin Brazil).

Permian

Asia	- Central Siberia; Fergana Basin; Pamir Turkestan
Europe	- North Sea, German Plains - England; Alpine Basins; Central Russia
North America	- Mid continent; Colorado Plateau; British Columbia; Mackenzie; Ellesmere Island; Greenland, Scoresby Sound
South America	- Sub-Andean Basin; Pedro del Fogo Basin

Giant deposits occur in the Permian including potash basins in USSR.

Triassic

Asia	- Lebanon, Syria; Persian Gulf; Pamir, Tadjikistan; East China; Khorat Plateau
Europe	- Iberian Basins; Aquitanian Basin; northwestern Europe; Danubian Basin, Balkans; Appenines, Sicily
Africa	- Maghreb; Ethiopia; West Congo, Angola; Possibly Somalia and Tanzania (?Jurassic)
North America	- British Columbia; northwest Arizona; Williston Basin
South America	- Pucara Basin, Peru; S. Bolivia; Sierra Pampeanas; Caxias

Potash occurs in the Moroccan sub-basins.

Jurassic

Asia	- Foreland of Arabian Shield; Black Sea, Pamir, Sinkiang; Northern Pakistan; ?Thailand
Europe	- England, Lowlands, NW Germany
Africa	- Maghreb, Saharan Atlas; Lower Nigeria; Ethiopia, Shoa; Tanganyika, Lindi
North America	- Central Utah - Montana; northern New Mexico, Nebraska; Gulf of Mexico, northern Cuba, Bahama Platform
South America	- Southern Andean Belt; Arica; Pucara; Huallaga; Chapiza; Giron; Mareval

The western part of the Gulf of Mexico includes one of the world's largest deposits and minor potash occurs in the U.S.A. and Tehuantepec portions of the basin.

Cretaceous

Asia	- Sinai, Tadjikistan Belt; Zagros Mountains; Madras, Sri Lanka; ?China

Africa	- Maghreb, Libya; Senegal; Nigeria; Gabon, Angola; Ethiopia, Somalia; South Africa
North America	- Gulf of Mexico Belt
South America	- Andean Belt; Commodoro Rivadavia; Sergipe, Alagoas; Araripe Basin

Potash occurs in Brazil and west central Africa. The Congo deposits are under development and those in Angola and Brazil are currently being investigated.

<u>Lower Tertiary</u>

Asia	- Mesopotamia, Persian Gulf; Central Iran; Caspian Sea; Fergana Basin; Sinkiang; Kohat Basin
Europe	- Paris Basin; Rhine Graben; Iberian Basins
Africa	- Maghreb; Sirte Embayment; Sinai; Taoudeni Basin; Nigeria; Somalia; Mozambique
North America	- Yucatan; Florida; Jamaica
South America	- Sub Andean Belt

<u>Upper Tertiary</u>

Asia	- Cyprus, Levant; Mesopotamia, Persian Gulf; Anatolia, Central Iran; Trans-caspian Basins; Kutch Peninsula; Sinkiang; Central China
Europe	- Iberian Basins; Appenines; Alps; Dinarides; Transylvania; Carpathians
Africa	- Maghreb; Cyreneica; Red Sea Graben; Nigeria
North America	- Oriente, Cuba; Hispaniola; southern Nevada, northwest Arizona

Tertiary potash production occurs in Spain, France, Sicily, and Russia and deposits have recently been discovered in Ethiopia and in sediments underlying the Dead Sea. Potash deposits on the flanks of the Carpathians are being investigated.

APPENDIX 4 - THEORETICAL AND OBSERVED SALT SUCCESSIONS FROM SEA WATER COMPARED WITH EVAPORITE DEPOSITS

Theoretical salt successions from sea water (After Stewart, 1963)

A. Up to stage of saturation with potassium-free magnesium sulphates ($25^{o}C$).

1. Carbonates of calcium and perhaps magnesium
2. Gypsum
3. Anhydrite
4. Anhydrite + halite
5. Polyhalite + halite

B. If the early salts remain in contact with residual liquids at all stages and react freely with them, the final products of crystallization of the bittern salts are:

$17.5^{o}C$ - $110^{o}C$: kieserite + carnallite + bischofite + halite + anhydrite

C. If early salts are isolated, then stages of precipitation are (at $25^{o}C$), with relative volumes expressed as percentages of total salts, excluding halite and calcium salts -

1. Bloedite (Astrakanite) - 0.4%

   (Na_2SO_4. $MgSO_4$. $4H_2O$)
2. Epsomite - 8.4%

   ($MgSO_4$. $7H_2O$)
3. Epsomite - 4.2%/Kainite - 5.2%

   (KCl. $MgSO_4$. $3H_2O$)
4. Kainite - 18.6%/Hexahydrite - 1.8%

   ($MgSO_4$. 6_H2O)
5. Kainite - 2.8%/Kieserite - 0.8%

   ($MgSO_4$. H_2O)

6. Kieserite - 4.8%/Carnallite - 4.6%

($KCl.MgCl_2.6H_2O$)

7. Kieserite - 4.9%/Carnallite - 0.9%/Bischofite - 42.6%

($MgCl_2.6H_2O$)

Halite is deposited at all stages in the succession above.

VOLUME OF SALTS IN SEAWATER AND PARAGENETIC SEQUENCES OF SALTS COMPARED WITH THOSE OF EVAPORITE DEPOSITS

(Schmalz, 1966)

Approximate volumes of major salts precipitated isochemically from one liter of seawater compared with relative volumes of the same salts in an "average" evaporite deposit of the same thickness.

a) From normal seawater:

Salt	Volume (cm^3)	Percentage of original brine remaining at start of precipitation
$MgCl_2$	1.48	0.5
KCl	0.43	1.0
$MgSO_4$	0.94	1.5
NaCl	12.87	10.0
$CaSO_4$	0.59	85.0
$CaCO_3 + CaMg(CO_3)_2$	0.06	90.0

b) In an average evaporite deposit:

$MgCl_2$	0.02
KCl	0.23
$MgSO_4$	0.30
NaCl	10.89
$CaSO_4$	4.29
$CaCO_3 + CaMg(CO_3)_2$	1.04

Theoretical and observed paragenetic sequences of salts.

	25°C		70°C
Theoretical (1)	Observed (2)	Observed (2)
Bishofite	Bishofite	Bishofite
Kieserite-Carnallite	Carnallite	Carnallite
Kieserite-Kainite	Kieserite-Carnallite	Kieserite-Carnallite
Hexahydrite-Kainite	Kainite	Kainite
Epsomite-Kainite	Kieserite-Epsomite-Hexahydrite	Kieserite
Epsomite	Epsomite	Loweite
Astrakanite-Polyhalite	Halite (continues)	Halite (continues)
Polyhalite		
Halite (continues)	Gypsum	Gypsum
Gypsum	Carbonates	Carbonates
Carbonates		

(1) Phillips, 1947

(2) Borchert and Muir, 1964

The sharply bedded sequences in evaporites cannot be reproduced in the laboratory. In addition, the abundance of carbonates deposited in evaporitic environments compared to the absence or meagre amount of actual evaporite deposited poses many problems. Much thicker evaporite sequences would be expected if the evaporites and carbonates were deposited in a ratio proportional to their concentration in sea water.

APPENDIX 5 - SOME SALT DOME AND EVAPORITE STATISTICS

A. Gulf Coast Area, U.S.A. (after Hanna, 1958)

Largest offshore dome - 12 km x 7 km; may be 13 km high.

Modest size - 40 km^3 of salt.

Largest - 300 km^3 of salt.

Volume of salt in Gulf Coast area - 20-40 km^3 of 90-95% purity salt.

Original thickness of mother salt bed may be as much as 1500 m.

Located - by mounds, lakes, paraffin beds, and in one case by rock salt outcrop.

Flow rate - maximum estimate 4 km^3 of salt in 50-75 000 years or 20 000 cm /second in some conduits.

Upward growth - 30 cm/100 years in some domes

B. Magnitude of Evaporation - Mediterranean Sea Example (after Goldsmith, 1966)

Area - 2.6 million km^2

Evap. Rate - 140 cm/year

Sea Loss - 3500 km^3/year (half replenished by rainfall and rivers and half from Atlantic inflow)

Salt Content - 3.65% (higher than Atlantic)

Median Depth - 1400 m

Evap. to dryness in 2000 years (with no replenishment from Atlantic)

Salt layer residual - 24 m thick

C. Russian Salt Dome

The largest salt dome area in the world lies in the Peri-Caspian depression in the U.S.S.R. (Golov & Solov' yev, 1966).

An underground salt dome over 1 km thick and 200 sq. km in area has been discovered in Kazakhstan near the Caspian. It contains more than 1000 million tons of salt, which can be exploited. The gypsum cap is several tens of metres thick. Over 1000 such domes have been found in the USSR and exploitation of many of them is to begin soon.

APPENDIX 6 - CHEMICAL ANALYSES

YARINGA NO 1 AND HAMELIN POOL NOS 1 AND 2, CARNARVON BASIN

(from Pendery, 1970a)

YARINGA NO. 1

Depth	Br (ppm)
1213.1 - 1216.2 m	330
1216.2 - 1219.2 m	210
1219.2 - 1222.2 m	200
1222.2 - 1225.3 m	200
1225.3 - 1228.3 m	170
1228.3 - 1231.4 m	210

HAMELIN POOL NO. 1

(Depths have been adjusted to conform with Schlumberger readings.)

Salt 1	1149.1 - 1149.7	No analyses
Salt 2	1165.0 - 1165.6	No analyses
Salt 3	1236.9 - 1243.6	

Depth (m)	Sample No.	Br(ppm)	K(%)	Mg%	Li(ppm)	Ca%	S%
1236.9 to 1239.9	No samples	-					
1240.2	1-2	255	0.008				
1240.5	2-2	245	0.008				
1240.8	3-2	240	0.009				
1241.1	4-2	240	0.009				
1241.5	5-2	290	0.009				
1241.8	6-2	300	0.010				
1242.1	7-2	270	0.010				
1242.4	8-2	270	0.010				
1242.7	9-2	265	0.010				
1243.0	10-2	265	0.010				
1243.3	11-2	270	0.011				
1243.6	12-2	265	0.011				

Depth (m)	Sample No.	Br (ppm)	K (%)	Mg%	Li (ppm)	Ca%	S%
Salt 4 (1245.1 - 1247.5 : 2.4)							
1245.4	1-3	105	0.020				
1245.7	2-3	130	0.014				
1246.0	3-3	160	0.013				
1246.3	4-3	165	0.015				
1246.6	5-3	140	0.013				
1246.9	6-3	185	0.013				
1247.2	7-3	160	0.014				
1247.5	8-3	140	0.030				
Salt 5 (1274.7 - 1277.7 : 3.0)							
1275.0	1-4	265					
1275.3	2-4	265					
1275.6	3-4	210					
1275.9	4-4	265					
1276.2	5-4	280					
1276.5	6-4	280					
1276.8	7-4	270					
1277.1	8-4	240					
1277.4	9-4	255					
1277.7	10-4	245					
Salt 6 (1283.8 - 1288.7 : 4.9)							
1284.1	16	190	0.07	0.19	8	0.93	0.12
1284.4	28	20	0.05	0.15	2	0.71	0.19
1284.7	25	30	0.47	1.40	44	22.6	18.3
1284.7	30	270	0.04	0.11	4	0.43	0.14
1285.0	24	240	0.04	0.07	2	1.40	0.45
1285.3	20	220	0.07	0.18	6	0.64	0.07
1285.6	18	260	0.04	0.05	4	0.50	0.10
1286.0	22	340	0.04	0.07	2	0.43	0.79
1286.3	27	130	0.54	1.0	54	6.90	2.30
1286.3	29	280	0.06	0.22	6	1.10	0.30

Depth (m)	Sample No.	Br(ppm)	K(%)	Mg%	Li(ppm)	Ca%	S%
1286.3	15	90	0.41	0.84	36	10.40	5.20
1286.6	23						
1286.6	23	230	0.05	0.15	6	6.00	2.30
1286.9	13	260	0.03	0.07	4	2.10	0.81
1287.2	21	260	0.03	0.10	2	0.79	0.20
1287.5	19	170	0.02	0.07	6	1.00	0.31
1287.8	17	180	0.02	0.07	4	1.10	0.31
1288.1	14	240	0.05	0.07	4	1.90	0.67
1288.4	12	10	0.15	0.94	12	10.70	5.30
1288.4	26	300	0.05	0.13	4	1.40	0.36
Salt 7 (1388.7 - 1391.7 : 3.0)							
1389.0	9	450	0.04	0.19	10	0.79	0.19
1389.3	3	280	0.05	0.11	1	0.86	0.27
1389.6	7	- No recovery -					
1389.9	5	250	0.03	0.11	6	0.21	0.04
1390.2	10	10	0.95	1.50	104	6.70	4.40
1390.2	11	10	1.30	1.70	168	6.70	0.90
1390.5	2	230	0.22	0.87	36	4.00	1.20
1290.8	8	220	0.04	0.14	6	1.20	0.30
1391.2	6	170	0.03	0.15	1	1.10	0.27
1391.4	4	130	0.11	0.41	18	1.80	0.28
1391.7	1	100	1.90	1.80	200	8.90	1.90

HAMELIN POOL NO. 2

1165.9	1	290	0.027
1166.2	2	170	0.170
1166.5	3	190	0.087
1166.8	4	250	0.020
1167.1	5	220	0.030
1167.4	6	120	0.110

Depth (m)	Sample No.	Br(ppm)	K(%)	Mg%	Li(ppm)	Ca%	S%
1174.4	7	190	0.018				
1174.7	8	190	0.029				
1175.0	9	230	0.018				
1175.3	10	250	0.017				
1175.6	11	240	0.017				
1175.9	12	150	0.016				
1176.2	13	230	0.016				
1176.5	14	290	0.016				
1142.1	1	80	0.054				
1142.1	2	80	0.021				
1142.6	3	80	0.018				
1143.3	4	50	0.021				

APPENDIX 7. ECONOMICS OF POTASH AND SULPHUR-PRODUCTION AND IMPORTS

Figures for world and Australian production and consumption of potash, sulphur and other evaporite minerals and references to future demand and prices are given by Roskill Information Services (1971), US Bureau of Mines (1970), U.S. Bureau of Mines - Commodity Data Summaries (1973), Annual Survey of the Mining Journal (1973), Annual Survey of the Engineering and Mining Journal (1973), Overseas Trade Bulletins of the Commonwealth Bureau of Census and Statistics (1973), Bureau of Mineral Resources (1973), Lefond (1969), Pendery (1970a, b), United Nations Industrial Development Organization (1973), and British Sulphur Corporation (1974).

Potash

The following summary has been abstracted partly from an unpublished report prepared by Pendery (1970a).

Future demand for potash should maintain a 7.5% growth rate, and supply capacity should increase about 75% by 1977; about half of this will be from new Canadian mines. Capacity utilization was estimated at about 80-85% in 1969-70, and was predicted to gradually increase to a balance in 1974-75. Two other influencing factors are an estimated expansion of mill capacity at the Canadian mines which could increase by about 3 million tonnes K_2O per year, and whether or not the Communist Bloc creates large surpluses.

The world resources of potassium compounds are sufficient for several thousand years (Bureau of Mines, 1970). The world indicated reserves are about 118 875 million tonnes of K_2O (or 99 140 million tonnes of K). World production showed only a 1.7% increase from 1967 to 1968 with the USSR now the largest producer.

The potash industry is currently overexpanded and a world surplus should remain until 1975 at least. Over the past 20 years domestic demand in the US has shown an annual average growth rate of 7.2%. The US demand for the year 2000 has been predicted to fall in the range of 7.7-14.1 million tonnes which gives a minimum growth rate of 2.77% or maximum of 4.71%. The rest of the world demand for the year 2000 is predicted at 36-54 million tonnes.

If an economic method of recovering potassium from sea water is found then there will be self-sufficiency world-wide, virtually forever. The problems involved in this method are discussed by Hadzeriga (1966).

The chief problem in the potash industry is how to translate large surplus production in a few countries into shipments to the countries in need.

Sulphur

World sulphur resources are enormous and ample to supply any probable demand within the foreseeable future. The average annual increase is 7.4% for the world-wide production of sulphur and 2.5% for the increase in production of sulphur from pyrites.

The threat to profitable marketing of sulphur is partly the use of alternative materials. Otherwise there is a problem of location of new sources of elemental sulphur, to find new uses, improve technology, and develop cheaper production methods.

Australian Trade and Production in Sulphur and Potash

(B.M.R. 1973)

Potassium Imports (1970/71)

Chemical Grade 9520 tonnes, value f.o.b. $1 534 000

Fertiliser Grade 155 729 tonnes, value f.o.b. $4 859 000

Sulphur Imports (1971)

268 515 tonnes, value f.o.b. $4 756 000

Local production of pyrites concentrates was 230 767 tonnes with a sulphur content of 105 386 tonnes.

REFERENCES

ADAMS, S.S., in press - INDUSTRIAL ROCKS AND MINERALS - POTASH. Am. Inst. Min. Metall. Eng.

ALGER, R.P., and CRAIN, E.R. 1966 - Defining evaporite deposits with electrical well logs: in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 2, 116-30.

ANDERSON, R.J., and MAJESKE, E.C., 1970 - Detection of potash zones by drilling fluid analysis; in CHEMICAL AND INDUSTRIAL ROCKS AND MINERALS. Proc. 6th Forum Geol. Ind. Min. Misc. 1, Geol. Surv. Div., Michigan Dept Nat. Res., 34-6.

ANGOVE, R.V., and DOUGLASS, J.L., 1972 - Hickey Hills seismic survey; for Aust. Aquitaine Petrol. Pty Ltd by Austral United Geophys. Pty Ltd (unpubl.).

ARCO, 1965 - Timor Sea seismic survey, 1965. Sparker survey for Arco Ltd and Aust. Aquitaine Petrol. Pty Ltd by Geophysical Assoc. Pty (unpubl.).

ARCO, 1966 - Sahul Shelf marine seismic survey, sparker method. Compagnie Generale de Geophysique for Arco Ltd and Aust. Aquitaine Petrol. Pty Ltd (unpubl.).

ARCO, 1967 - Lesueur seismic survey, sparker method, for Arco Ltd and Aust. Aquitaine Petrol. Pty Ltd, by Compagnie Generale de Geophysique (unpubl.).

ARCO, 1969 - Londonderry Rise seismic survey, final report. Compagnie Generale de Geophysique for Arco Ltd and Aust. Aquitaine Petrol. Pty Ltd (unpubl.).

AUSTRALIAN AQUITAINE PETROLEUM, 1968a - Hyland seismic survey OP2 - OP83, N.T. Interpretation report by Aust. Aquitaine Petrol. Pty Ltd (unpubl.).

AUSTRALIAN AQUITAINE PETROLEUM, 1968b - Terry Range magneto-telluric survey, final report. Aust. Aquitaine Petrol. Pty Ltd Rep. 9517A6/1 (unpubl.).

BAAS-BECKING, L.G.M., and KAPLAN, I.R., 1956 - The microbiological origin of the sulphur nodules of Lake Eyre. Trans. Roy. Soc. S. Aust., 79, 52-65.

BANKS, J.E., 1964 - Mineral reconnaissance in the Amadeus Basin, Northern Territory, Australia. Rep. for Magellan Petrol. Corp. (unpubl.).

BARNES, L.C., 1969 - Exploration of the Mount Coffin diapir, northern Flinders Ranges. S. Aust. Dept. Mines Miner. Resour. Rev. 131, 62-83.

BARNES, L.C., 1970 - Geological investigation of the Burra crush zone. S. Aust. Dept. Mines Miner. Resour. Rev., 132, 7-35

BENTOR, Y.K., 1968 - Salt deposits of the Dead Sea region in SALINE DEPOSITS. Geol. Soc. Am. Spec. Paps 88, 139-56.

BERSTICKER, A.C., ed., 1963 - SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland

BINKS, P.J., 1971 - The geology of the Orroroo 1:250 000 map area. Geol. Surv. S. Aust. Rep. Invest. 36

BIRD, J.M., 1966 - Well log applications and interpretation in a brine field; in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc., Inc. Cleveland, 2, 57-69.

BONYTHON, C.W., 1956 - The salt of Lake Eyre - its occurrence in Madigan Gulf and its possible origin. Trans. Roy. Soc. S. Aust., 79, 66-92

BONYTHON, C.W., and KING, D., 1956 - The occurrence of native sulphur at Lake Eyre. Trans. Roy. Soc. S. Aust., 79, 121-30.

BORCHERT, H., 1972 - Secondary replacement processes in salt and potash deposits of oceanic origin; in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences, 7, 61-8

BORCHERT, H., and MUIR, R.O., 1964 - SALT DEPOSITS. The origin, metamorphism and deformation of evaporites. Van Nostrand, London

BRADLEY, W.H., and EUGSTER, H.P., 1969 - Geochemistry and palaeolimnology of the trona deposits and associated authigenic minerals of the Green River Formation of Wyoming. U.S. geol. Surv. prof. Pap., 496-b

BRAMKAMP, R.A., and POWERS, R.W., 1955 - Two Persian Gulf Lagoons. abstract in J. sediment. Petrol., 25, 139-40

BRAUNSTEIN, J., and O'BRIEN, G.D., eds, 1968 - DIAPIRISM AND DIAPIRS, a symposium. Amer. Assoc. Petrol. Geol. Mem. 8

BRITISH SULPHUR CORPORATION, 1974 - Sulphur. Brit. Sulph Corp. Ltd, 110, Jan.-Feb. 1974

BUREAU OF MINERAL RESOURCES, 1973 - AUSTRALIAN MINERAL INDUSTRY, 1971 Review. Bur. Miner. Resour. Aust.

BUREAU OF MINES, 1970 - Mineral facts and problems. U.S. Dept. Int. Bur. Mines Bull. 650

BUREAU OF MINES, 1973 - Commodity data summaries. U.S. Bur. Mines.

BUTLER, G.P. et al., 1965 - Recent evaporite deposits along the Trucial Coast of the Arabian Gulf. Proc. geol. Soc. Lond., 1623, 91-2.

BUTLER, G.P., 1969 - Modern evaporite deposition and geochemistry of co-existing brines, the Sabkha, Trucial Coast, Arabian Gulf. J. sediment. Petrol. 39. (1), 70-89

CAYE, J.P., 1968 - The Timor Sea - Sahul Shelf area. J. Aust. Petrol. Explor. Assoc., 35-41

COATS, R.P., 1964 - The geology and mineralization of the Blinman Dome Diapir. Geol. Surv. S. Aust., Rep. Invest., 26

COATS, R.P., 1965 - Diapirism in the Adelaide Geosyncline. J. Aust. Petrol. Explor. Assoc., 1965, 98-102

COMMONWEALTH BUREAU OF CENSUS AND STATISTICS, 1973 - Overseas trade bulletins, 1972-73. Comm. Bur. Census and Stats.

CONDON, M.A., 1965 - The geology of the Carnarvon Basin, Western Australia. Part 1 - pre-Permian stratigraphy. Bur. Miner. Resour. Aust. Bull. 77

CONDON, M.A., 1967 - Ibid., Part 2 - Permian Stratigraphy.

CONDON, M.A., 1968 - Ibid., Part 3 - post-Permian stratigraphy; structure; economic geology.

CREEVEY, K.J., 1971 - Recent information and prospects in the Kidson Sub-basin. J. Aust. Petrol. Explor. Assoc., 53-8

CRIST, R.P., and HOBDAY, M., 1973 - Diapiric features of the offshore Bonaparte Gulf Basin, Northwest Australian Shelf. Bull. Aust. Soc. Explor. Geophys., 4(1), 43-66.

CURTIS, R., EVANS, G., KINSMAN, D.J.J., and SHEARMAN, D.J., 1963 - Association of dolomite and anhydrite in the recent sediments of the Persian Gulf. Nature, Lond., 197, 679-80

DALGARNO, C.R., and JOHNSON, J.E., 1968 - Diapiric structures and late Precambrian-early Cambrian sedimentation in Flinders Ranges, South Australia; in DIAPIRS AND DIAPIRISM, a symposium. Amer. Assoc. Petrol. Geol. Mem. 8

DAVIS, J.B., STANLEY, J.P., and CUSTARD, H.C., 1970 - Evidence against oxidation of hydrogen sulphide by sulphate ions to produce elemental sulphur in salt domes. Bull. Amer. Assoc. Petrol. Geol. 54, (12), 2444-7

DAVIS, J.B., and KIRKLAND, D.W., 1970 - Native sulphur deposition in the Castile Formation, Culberson County, Texas. Econ. Geol. 65, 107-21

DE LA HUNTY, L.E., and LOW, G.H., 1958 - The gypsum deposits of Western Australia. Geol. Surv. W. Aust. Bull., 6

DEPARTMENT OF NATIONAL DEVELOPMENT, 1969 - RESOURCES AND INDUSTRY OF CENTRAL QUEENSLAND. Rept. by Comm. Dept Nat. Dev. and Qld Dept Indus. Devel. April, 1969

DEPARTMENT OF NATIONAL DEVELOPMENT, 1972 - Geology and minerals - Burdekin-Townsville Region, Queensland. Resour. Ser., Geograph. Sect., Dept. Nat. Dev., Canberra

DOMBROWSKI, H.J., 1966 - Geologic problems in the question of living bacteria in Palaeozoic salt deposits. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 215-20.

DRESCHER, J., HILDEBRAND, G., & SCHMIDEK, R., 1973 - Subsidences in the centre of Lueneburg: proposals for constructional sanification. In SINK-HOLES AND SUBSIDENCE. Proc. Hanover Symp., Internat. Assoc. Engng. Geol., T4-G, 1-7.

EDGERLEY, D.W., and CRIST, R.P., 1974 - Salt and diapiric anomalies in the southeast Bonaparte Gulf Basin. Aust. Petrol. Explor. Assoc. J., 14, (1), 85-94.

EMERY, K.O., and RITTENBURG, S.C., 1952 - Early diagenesis of California basin sediments in relation to origin of oil. Bull. Amer. Assoc. Petrol. Geol., 36, 735-806.

ENGINEERING AND MINING JOURNAL, 1973 - Annual survey and outlook. Eng. Min. J. 174, (3)

EUGSTER, H.P., 1967 - Hydrous sodium silicates from Lake Magadi, Kenya; precursors of bedded chert. Science, 157, (3793), 1177-80

EUGSTER, H.P., and SMITH, G.E., 1965 - Mineral equilibria in the Searles Lake evaporites, California. J. Petrol. 6, 473-522

EVANS, G., 1966 - The recent sedimentary facies of the Persian Gulf region. Roy. Soc. Lond. philos. Trans., ser. A., 259, 291-8

EVANS, G., KENDALL, C.G. St. C., and SKIPWITH, P.A.d'E., 1964a - Origin of the coastal flats, the Sabkha of the Trucial Coast, Persian Gulf. Nature, Lond. 202, 759-62

EVANS, G., KINSMAN, D.J.J., and SHEARMAN, D.J., 1964b - A reconnaissance survey of the environment of recent carbonate sedimentation along the Trucial Coast, Persian Gulf; in DEVELOPMENTS IN SEDIMENTOLOGY, 1: Deltaic and shallow marine deposits. 129-35. Elsevier, Amsterdam

EVANS, G., and SHEARMAN, D.J., 1964 - Recent celestine from the sediments of the Trucial Coast of the Persian Gulf. Nature, Lond. 202, 385-6

FONS, L., 1969 - Geological applications of well logs. Soc. Pet. Well Log Analysts. 10th Ann. Logging Symp. 44p

FREYTAG, I.B., 1965 - Mount Toondina Beds - Permian sediments in a probable piercement structure. Trans. Roy. Soc. S. Aust., 89, 61-76

FRIEDMAN, G.M., AMIEL, A.J., BRAUN, M., and MILLER, D.S., 1973 - Generation of carbonate particles and laminites in algal mats - examples from sea-marginal hypersaline pool, Gulf of Aqaba, Red Sea. Amer. Assoc. Petrol. Geol. Bull. 57, (3), 541-557

GALLEY, J.E., ed., 1968 - Subsurface disposal in geologic basins - a study of reservoir strata. Amer. Assoc. Petrol. Geol. Mem. 4, 253 p

GALLOWAY, M.C., 1970 - Adavale, Queensland - 1:250 000 geological series. Bur. Miner. Resour. Aust. explan. Notes SG/55-5

GANSSER, A., 1955 - New aspects of the geology in central Iran. Proc. 4th World Petrol. Congr. Section I/A/5, Reprint 2

GEARY, J.K., 1970 - Offshore exploration of the southern Carnarvon Basin. J. Aust. Petrol. Explor. Assoc. 10, (2), 9-15

GERA, F., 1972 - Review of salt tectonics in relation to the disposal of radioactive wastes in salt formations. Bull. Geol. Soc. Amer. 83, 3551-74

GLENISTER, B.F., 1962 - Conodonts and fish plates from Frome Rocks No. 1 well. in Bur. Miner. Resour. Aust. Petrol. Search Subs. Act. Publ. 8, 30-1

GLOVER, J.E., 1973 - Petrology of the halite-bearing Carribuddy Formation, Canning Basin, Western Australia. J. geol. Soc. Aust., 20,(3), 343-59

GOLDSMITH, L.H., 1966 - Some fundamentals of potash geology as a guide to exploration. Soc. Prof. Well Log Analysts, 7th ann. Logging Symp. Trans. 15p

GOLDSMITH, L.H., 1969 - Concentration of potash salts in saline basins. Bull. Amer. Assoc. Petrol. Geol., 53,(4), 790-97

GOLOV, A.A., and SOLOV'YEV, B.A., 1966 - Genetic types of salt structures in the Peri-Caspian Depression and their oil-gas prospects. (English trans. of Geolog. Nefti i Gaza) Petrol. Geol. 10, (4), 157-61.

GORRELL, H.A., and ALDERMAN, G.R., 1968 - Elk Point Group saline basins of Alberta, Saskatchewan, and Manitoba, Canada. in SALINE DEPOSITS. Geol. Soc. Amer., Spec. Paps., 88, 291-317

GRIEVE, R.O., 1955 - Leaching(?) of Silurian salt beds in southwestern Ontario as evidenced in wells drilled for oil and gas. Trans. Canad. Min. Metall., 55, 10-16.

GROSS, W., 1971 - Unterdevonische Thelodontier - und Acanthodier-schuppen aus Westaustralien. Palaont. Z., 45(3-4), 97-106

HADZERIGA, P., 1966 - Considerations on the recovery of potash from sea water bitterns. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland 2, 204-11

HANNA, M.A., 1958 - SALT DOME STRUCTURES. Petroleum indoctrination course, Gulf Oil Corp. (unpubl.).

HASSAN, F., and EL-DASHLOUTY, 1970 - Miocene evaporites of Gulf of Suez region and their significance. Bull. Amer. Assoc. Petrol. Geol., 54,(9), 1868-96.

HENDERSON, S.W., and SHANNON, P.H., 1966 - Yaringa No. 1, Western Australia, well completion report. Continental Oil Co. Aust. Ltd (unpubl.)

HITE, R.J., 1967 - Distribution and geologic habitat of marine halite and associated potash deposits. U.S. Geol. Surv. open file rep., 41 pp

HOFRICHTER, E., 1968 - Stratigraphy and structure of the Palangana Salt dome, Duval County, Texas. in SALINE DEPOSITS. Geol. Soc. Amer. Spec. Paps., 88, 365-79

HOLMES, D.A., 1970 - South Australian potash project (612), special mining lease 329. Occidental Miner. Corp. Aust. (unpubl.)

HOLMES, D.A., and RAYMENT, P., 1970 - Well completion report, Oxy Min Boorthanna No. 1, South Australia potash project. Occidental Miner. Corp. Aust. (unpubl.)

HOLSER, W.T., 1966a - Diagenetic polyhalite in recent salt from Baja California. Amer. Miner., 51, 99-109

HOLSER, W.T., 1966b - Bromide geochemistry of salt rock. in SECOND SYMPOSIUM ON SALT, N. Ohio, geol. Soc., Cleveland, 1, 248-75.

HOLSER, W.T., WARDLAW, N.C., and WATSON, D.W., 1972 - Bromide in salt rocks: extraordinarily low content in the Lower Elk Point Salt, Canada. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 69-75

HOLSER, W.T., and KAPLAN, I.R., 1966 - Isotope geochemistry of sedimentary sulphates. Chem. Geol., 1, 93-135

HOLTER, M., 1972 - Geology of the Prairie Evaporite formation of Saskatchewan, Canada. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences, 7, 183-9

HSU, K.J., 1972 - Origin of saline giants a critical review after the discovery of the Mediterranean evaporite. Earth-Sci. Rev., 8, 371-96

HSU, K.J., RYAN, W.B.F., and CITA, M.B., 1973 - Late Miocene desiccation of the Mediterranean, Nature, 242, (5395), 240-4

HUNT OIL CO., 1966 - Yowalga seismic survey, Western Australia. Rep. by Ray Geophysics (Aust.) Pty Ltd (Mickleberry R.K.) for Hunt Oil Co., Bur. Miner. Resour. Aust. Petrol. Search Subs. Acts. Rep. (unpubl.)

INGERSON, E., 1968 - Deposition and geochemistry work sessions. in SALINE DEPOSITS. Geol. Soc. Am., Spec. Paps., 88, 671-81.

INTERNATIONAL ASSOCIATION OF ENGINEERING GEOLOGY, 1973 - SINK-HOLES AND SUBSIDENCE. Proc. Hanover Symp.

IVANOV, A.A., 1953 - Fundamentals of the geology of evaporites and their prospecting, investigation and evaluation. Gosgeolisdat., Moscow

IVANOV, A.A., 1960 - Geologiya galogennyka otlozhenity (formatsiy) SSSR: Trude Vsesbyuzuogo Naucho-Issledovatel skogo Gedogicheskogo Instituta (VSEGEI). Ministerstva Geologii i Okhrany Nedr SSR Novaya Seriys Tom 35

IVANOV, M.V., 1968 - Microbiological processes in the genesis of native sulphur deposits. (English translation from Russian) I.P.S.T. Cat. No. 1850, U.S. Dept. of Commerce, 298 pp

JACKSON, P.R., 1966a - Well completion report, No. 2 Yowalga, Officer Basin, Western Australia. Hunt Oil Co., Placid Oil Co. (unpubl.)

JACKSON, P.R., 1966b - Geology and review of exploration, Officer Basin, Western Australia. Hunt Oil Co. Rep. (unpubl.)

JENSEN, M. Le R., 1968 - Isotopic geology and the origin of Gulf Coast and Sicilian sulphur deposits. in SALINE DEPOSITS. Geol. Soc. Amer. Spec. Paps., 88, 525-36

JOHNS, R.K., 1968 - Investigations of Lake Torrens and Gairdner. Dept Mines, S. Aust. Geol. Surv., Rep. of Invest., 31

JOHNS, R.K., 1969 - Exploration for copper in the Oraparinna and Enorama diapirs, Dept. Mines S. Aust., Miner Resour. Rev. 131, 104-14.

JOHNS, R.K., and LUDBROOK, N.H., 1963 - Investigations of Lake Eyre. Dept Mines, S. Aust. Geol. Surv. Rep. of Invest., 24

JONES, C.L., BOWLES, C.G., and BELL, K.G., 1960 - Experimental drill hole logging in potash deposits of the Carlsbad District, New Mexico. U.S. geol. Surv., Open File Rep. (unpubl.)

KEEVERS, R.E., 1968 - Marine basinal evaporite deposits in Australia. Confid. rep. for Mines Explor. Pty Ltd (unpubl.)

KENAT, J., 1966 - The production of potassium chloride from the Dead Sea by crystallization. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc., Inc., Cleveland, 2, 195-203.

KEMP, A.L.W., and THODE, H.G., 1968 - The mechanism of the bacterial reduction of sulphate and of sulfite from isotopic fractionation studies. Geochim. Cosmochim. Acta 31, (1), 71-91

KENDALL, C.G. St. C., and SKIPWITH, A. d'E, 1969 - Holocene shallow water carbonate and evaporite sediments of Khor al Bazam, Abu Dhabi, southwest Persian Gulf. Bull. Amer. Assoc. Petrol. Geol. 53, (4), 841-69.

KING, D., 1956 - The Quaternary stratigraphic record at Lake Eyre North and the evolution of existing topographic forms. Trans. Roy. Soc. S. Aust., 79, 93-103

KINSMAN, D.J.J., 1964a - Recent carbonate sedimentation near Abu Dhabi, Trucial Coast, Persian Gulf. Ph.D. Thesis, London Univ., 302 pp.

KINSMAN, S.J.J., 1964b - Dolomitization and evaporite development, including anhydrite in lagoonal sediments, Persian Gulf. Geol. Soc. Amer. Programme 1964 meeting, 108-9

KINSMAN, D.J.J., 1966 - Gypsum and anhydrite of recent age, Trucial Coast, Persian Gulf. in SECOND SYMPOSIUM ON SALT, N. Ohio Geol. Soc., Inc. Cleveland, 302-6

KINSMAN, D.J.J., 1969 - Modes of formation, sedimentary associations, and diagnostic features of shallow-water and supratidal evaporites. Bull. Amer. Assoc. Petrol. Geol. 53, (4), 830-40

KNUTSON, C.F., and WALTHER, H.C., 1965 - Evaluation of potash deposits with oil field logs. Continental Oil Co. (unpubl.)

KOOP, W.J., 1966 - Recent contributions to Palaeozoic geology in the south Canning Basin, Western Australia. J. Aust. Petrol. Explor. Assoc., 105-109

KOZARY, M.T., DUNLAP, J.G., and HUMPHREY, W.E., 1968 - Incidence of saline deposits in geologic time. in SALINE DEPOSITS. Geol. Surv. Amer. Spec. Paps. 88, 43-58

KRIEG, C., 1969 - Geological developments in the eastern Officer Basin of South Australia. J. Aust. Petrol. Explor. Assoc., 9(2)

KUHN, R., 1972 - Combined evaluation of Br - and Rb - contents for the genetic characterization of carnallites and sylvite rocks. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 77-89

KUPFER, D.H., 1968 - Relationship of internal to external structure of salt domes. in DIAPIRISM AND DIAPIRS, a symposium. Amer. Assoc. Petrol. Geol. Mem. 8, 79-89

LACHMANN, R., 1911 - Der salzauftrieb, geophysikal studien uber den Bau der Salzmassen Norddeutschlands. Kali, 6, Halle

LANGSFORD, N.R., 1969 - Mineral exploration of the Windowarta diapir. Dept. Mines S. Aust. Miner. Resour. Rev., 131, 77-9

LAWS, R.A., and BROWN, R.S., in prep. - Petroleum geology of the south-eastern Bonaparte Gulf Basin. in Petroleum Volume of ECONOMIC GEOLOGY OF AUSTRALIA AND PAPUA NEW GUINEA. Aust. Inst. Min. Metall., Melbourne

LAWS, R.A., and KRAUS, G.P., 1974 - The regional geology of the Bonaparte Gulf Timor Sea area. Aust. Petrol. Explor. Assoc. J., 14, (1), 77-84.

LEFOND, S.J., 1969 - HANDBOOK OF WORLD SALT RESOURCES. Plenum Press, New York

LEONARDI, M.L., 1954 - American Potash and Chemical Corporation, main plant cycle, Min. Engng, N.Y., 6, 203

LESLIE, R.B., 1961 - Geology of the Gibson Desert area, Western Australia. Frome-Broken Hill Co. Rept. 3000-G-38 (unpubl.)

LOHMANN, H.H., 1972 - Salt dissolution in subsurface of British North Sea as interpreted from seismograms. Bull. Amer. Assoc. Petrol. Geol. 56, (3), 472-9

LOTZE, F., 1964 - The distribution of evaporites in space and time; in NAIRN, A.E.M., ed., PROBLEMS IN PALAEOCLIMATOLOGY. New York, Wiley, 491-507

LOWRY, D.C., JACKSON, M.J., van der GRAAF, W.J.E., and KENNEWELL, P.J., 1972 - Preliminary results of geological mapping in the Officer Basin, Western Australia, 1971. Ann. Rep. Geol. Surv. W. Aust. for 1971, 50-56 and Bur. Miner. Resour. Aust. Rec. 1972/66 (unpubl.)

MACK, J.E., and HERMANN, F.A., 1965 - Reconnaissance geological survey of the Alliance Gibson Desert block PE 205H, 206H, 207H, Western Australia. Union Oil Develop. Corp., G.R. 18 (unpubl.)

MAJOR, R.B., and TELUK, J.A., 1967 - The Kulyong Volcanics. Geol. Surv. S. Aust. Quart. Geol. Notes, 22

MANSFIELD, G.R., and LANG, W.T.B., 1935 - The Texas - New Mexico potash deposits. in THE GEOLOGY OF TEXAS, 2, (3). Univ. Texas Bull., 3401, 641-832

MARTINEZ, J.D., 1971 - Environmental significance of salt. Bull. Amer. Assoc. Petrol. Geol., 55, (6), 810-25

MATTOX, R.B., ed, 1968 - SALINE DEPOSITS, Geol. Soc. Amer. Spec. Paps. 88

McWHAE, J.R.H., PLAYFORD, P.E., LINDNER, A.W., GLENISTER, B.R., and BALME, B.E., 1958 - The stratigraphy of Western Australia. J. geol. Soc. Aust., 4(2)

MINING JOURNAL, 1973 - Annual survey. Min. J.

MILLIGAN, E.N., SMITH, K.G., NICHOLS, R.A.H., & DOUTCH, H.F., 1966 - Geology of the Wiso Basin, Northern Territory. Bur. Miner. Resour. Aust. Rec. 1966/47 (unpubl.)

MORRIS, R.C., and DICKEY, P.A., 1957 - Modern evaporite deposition in Peru. Bull. Amer. Assoc. Petrol. Geol. 41, 2467-74

MUEHLBERGER, W.R., 1968 - Internal structures and mode of uplift of Texas and Louisiana salt domes. in SALINE DEPOSITS, Geol. Soc. Amer. Spec. Paps. 88, 359-64

MUEHLBERGER, W.R., and CLABAUGH, Patricia S., 1968 - Internal structure and petrofabrics of Gulf Coast salt domes. in DIAPIRISM AND DIAPIRS, a symposium. Amer. Assoc. Petrol. Geol. Mem. 8, 90-8

NEEV, D., and EMERY, K.O., 1967 - The Dead Sea; depositional processes and environments of evaporites. Geol. Surv. Israel, Bull. 41, 147pp

NIELSEN, H., 1972 - Sulphur isotopes and the formation of evaporite deposits. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 91-102

NISSENBAUM, A., 1967 - Anhydrite inclusions in idiomorphic quartz in gypsum concretions from Makhtesh Ramon, Israel. Israel J. Earth Sci., 16, 30-3

NOAKES, L.C., 1972 - Mineral resources of Australia. Bur. Miner. Resour. Aust. Rec. 1972/12 (unpubl.)

OCHSENIUS, C., 1877 - Die Bildung der Steinsalzlager und ihrer Mutterlangensalze. Halle

OCHSENIUS, C., 1888 - On the formation of rock-salt beds and mother-liquor salts. Acad. Nat. Sci. Phil. Proc., 181-7

PAINE, A.G.L., 1963 - Tanumbirini, N.T., 1:250 000 geological Series. Bur. Miner. Resour. Aust. explan. Notes SE/53-2

PARKIN, L.W., ed., 1969 - HANDBOOK OF SOUTH AUSTRALIAN GEOLOGY. Geol. Surv. S. Aust.

PEERS, R., 1969 - A comparison of some volcanic rocks of uncertain age in the Warburton Range area. Ann. Rep. Geol. Surv. W. Aust. for 1968, 57-61

PEERS, R., and TRENDALL, A.F., 1968 - Precambrian rocks encountered during drilling in the Main Phanerozoic sedimentary basins of Western Australia. Ann. Rep. Geol. Surv. W. Aust. for 1967, 69-77

PEMBERTON, R.L., and WEBB, E.A., 1965 - Frewena No. 1 well completion report. Barkley Oil Co. Pty Ltd, (unpubl.)

PENDERY, E.C., 1970a - Final completion report, temporary reserves 4186H and 4187H, Western Australia. Confid. Rep. for Magellan Petrol. (Aust.) Ltd (unpubl.)

PENDERY, E.C., 1970b - Distribution of salt and potash deposits: present and potential effect on potash economics and exploration. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 2, 85-95

PENDERY, E.C., CAMPBELL, M.D., FARMER, R.T., and McDANIEL, K.W., 1969 - Well completion report, Hamelin Pool No. 2, and summary report - potash potential - Carnarvon Basin, temporary reserves 4186H and 4187H, Western Australia. Magellan Petroleum Pty Ltd (unpubl.)

PETROLEUM INFORMATION BUREAU, 1973 - Oil goes underground again. Petroleum Gazette, 17,(6), 172-5.

PHILIP, G.M., 1969 - Silurian conodonts from the Dirk Hartog Formation, Western Australia. Proc. Roy. Soc. Vic., 82, 287-97

PHILLIPS, F.C., 1947 - Oceanic salt deposits. Quart. Revs. (London), 1, 91-111

PHLEGER, F.B., 1969 - A modern evaporite deposit in Mexico. Bull. Amer. Assoc. Petrol. Geol., 53, (4), 824-9.

PHLEGER, F.B., and EWING, G.C., 1962 - Sedimentology and oceanography of coastal lagoons in Baja California, Mexico. Bull. Geol. Soc. Amer. 73, 145-82

PIERCE, W.G., and RICH, E.I., 1962 - Summary of rock salt deposits in the United States as possible storage sites for radioactive waste materials. U.S. Dept. Int., Geol. Surv. Bull., 114B, 91 pp

PLAYFORD, P.E., and COPE, R.N., 1971 - The Phanerozoic stratigraphy of Western Australia: A correlation chart in two parts. Ann. Rep. Geol. Surv. W. Aust. for 1970, 32-3

PLAYFORD, P.E., and LOWRY, D.C., 1966 - Devonian reef complexes of the Canning Basin, Western Australia. Geol. Surv. W. Aust. Bull., 118

RAU, J.L., ed., 1966 - SECOND SYMPOSIUM ON SALT, N. Ohio geol. Soc. Inc., Cleveland

RICHTER-BERNBURG, G., 1950 - Zur frage der absoluten Geschwindiqkeit geologischer Vorgange. Naturwiss., 37, (1), 1-8.

RICHTER-BERNBURG, G., 1955 - Uber salinare Sedimentation. Z. dtsch. geol. Ges., 105, p. 593-645

RICHTER-BERNBURG, G., 1963a - Solar cycle and other climatic periods in varvitic evaporites. in NAIRN, A.E.M., - PROBLEMS IN PALAEOCLIMATOLOGY. 510-20, New York, Wiley

RICHTER-BERNBURG, G., 1963b - Zechstein (Upper Permian) at the southern border of the Harz Mountains. 6th World Petrol. Cong., Excursion Guide-Bk II, 39-48

RICHTER-BERNBURG, G., 1968 - Problems of bedding and stratification in saline formations. abstract in SALINE DEPOSITS. Geol. Soc. Amer. Spec. Paps., 88, 413-4.

RICHTER-BERNBURG, G., 1972a - Sedimentological problems of saline deposits. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 33-9

RICHTER-BERNBURG, G., 1972b - Saline deposits in Germany: a review and general introduction to the excursions. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 275-87

RICHTER-BERNBURG, G., 1973 - Facies and palaeogeography of the Messinian Evaporites in Sicily. in MESSINIAN EVENTS IN THE MEDITERRANEAN. Geodynamics Scientific Rept. 7, 124-41.

RICHTER-BERNBURG, G., and SCHOTT, W., 1959 - The structural development of northwest German salt domes and their importance for oil accumulation. Proc. 5th World Petrol. Cong., New York, Sec. 1, Pap. 4, 81-94.

ROBERTS, H.G., and PLUMB, K.A., 1965 - Mount Marumba, Northern Territory - 1:250 000 geological Series. Bur. Miner. Resour. Aust. explan. Notes. SD/53-6

ROEDDER, E., 1972 - Composition of fluid inclusions. U.S. Geol. Surv. Prof. Pap. 440 - JJ, 164 pp.

ROSKILL INFORMATION SERVICES, 1971 - SALT: WORLD SURVEY OF PRODUCTION AND CONSUMPTION WITH SPECIAL REFERENCE TO FUTURE DEMAND AND PRICES. Roskill Information Service Ltd.

RYAN, J.E., 1961 - Industrial Salts. Production at Searles Lake. Trans. Amer. Inst. Metall. Engrs. 190, 447-52

SCHALLER, W.T., and HENDERSON, E.P., 1932 - Mineralogy of drill cores from the potash fields of New Mexico and Texas. U.S. geol. Surv. Bull., 833, 124 p

SCHETTLER, H., 1972 - The stratigraphical significance of idiomorphic quartz crystals in the saline formations of the Weser - Ems area, north-western Germany. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 111-27

SCHMALZ, R.F., 1966 - Environments of marine evaporite deposition. Mineral Industries. 35,(8), 1-7

SCHMALZ, R.F., 1969 - Deep water evaporite deposition: a genetic model. Amer. Assoc. Petrol. Geol. Bull. 53,(4), 798-823

SELLARDS, E.H., and SCHOCH, E.P., 1928 - Core drill tests for potash in Midlands County, Texas. Univ. Texas. Bull. 2801, 159-201

SENIOR, B.R., 1970 - Barrolka, Queensland - 1:250 000 geological Series. Bur. Miner. Resour. Aust. explan. Notes. SG/54-11

SHEARMAN, D.J., 1963 - Recent anhydrite, gypsum, dolomite and halite from the coastal flats of the Arabian shore of the Persian Gulf. Proc. Geol. Soc. Lond. 1607, 63-5

SHEARMAN, D.J., 1966 - Origin of marine evaporites by diagenesis. Trans. Inst. Min. Metall., Sect. B., 75, (717), 208-15.

SHEARMAN, D.J., 1970 - Recent halite rock, Baja California, Mexico, Ibid., 79, (765), 155-62.

SMITH, D.B., 1972a - Foundered strata, collapse-breccias and subsidence features of the English Zechstein. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 255-69

SMITH, J.W., 1964 - Bauhinia Downs, Northern Territory - 1:250 000 geological Series. Bur. Miner. Resour. Aust. explan. Notes SE/53-3

SMITH, K.G., 1964 - Progress report on the geology of the Huckitta 1:250 000 sheet, Northern Territory. Bur. Miner. Resour. Aust. Rep. 67

SMITH, K.G., 1972b - Stratigraphy of the Georgina Basin. Bur. Miner. Resour. Aust. Bull. 111

SOLOMON, M., RAFTER, T.A., and DUNHAM, K.C., 1971 - Sulphur and oxygen isotope studies in the northern Pennines in relation to ore genesis. Trans. Inst. Min. Metall. Sect. B, 80, Bull. 777, 259-75

SOUTH AUSTRALIA DEPARTMENT OF MINES AND GEOLOGICAL SURVEY - Salt in South Australia. Miner. Inf. Ser.

SPICER, A.C., 1946 - Gamma ray studies of potassium salts and associated geologic formations. U.S. geol. Surv. Bull., 950

STEWART, A.J., 1969 - Completion report, BMR Alice Springs No. 3 (Ringwood) Northern Territory. Bur. Miner. Resour. Aust. Rec. 1969/7 (unpubl.)

STEWART, F.H., 1963 - Marine evaporites. U.S. geol. Surv. Prof. Pap. 440Y

STILLE, H., 1925 - The upthrust of the salt masses of Germany. Bull. Amer. Assoc. Petrol. Geol., 9, (3), 417-41. in GEOLOGY OF SALT DOME OIL FIELDS, 1926, Tulsa, Oklahoma, Amer. Assoc. Petrol. Geol. 142-66

STURMFELS, E.K., 1952 - Report on investigation on evaporites in the Northwest Basin, W.A., during May, June, and July, 1951. Aust. Min. and Smelting Co. Ltd (unpubl.)

SWEET, I.P., MENDUM, J.R., BULTITUDE, R.J., and MORGAN, C.M., 1971 - The geology of the Waterloo, Victoria River Downs, Limbunya and Wave Hill 1:250 000 Sheet areas, Northern Territory. Bur. Miner. Resour. Aust. Rec. 1971/71 (unpubl.)

TALBOT, H.W.B., and CLARKE, E. de C. 1917 - A geological reconnaissance of the country between Laverton and the South Australian border. Geol. Surv. W. Aust. Bull. 75

TALLIS, N.C., and FJELSTUL, C.R., 1966 - The Lake Dartmouth seismic survey, 1965. Phillips Petrol. Co. (unpubl.)

THODE, H.G., and MONSTER, J., 1965 - Sulphur - isotope geochemistry of petroleum, evaporites and ancient seas. in FLUIDS IN SUBSURFACE ENVIRONMENTS - a symposium. Amer. Assoc. Petrol. Geol. Mem. 4, 367-85

THOMPSON, R.W., in press - Tidal-flat sedimentation of the Colorado River delta, northwestern Gulf of California. Geol. Soc. Amer. Mem. 107

TIMKO, D.J., 1964 - Potash evaluation using well logs. The Log Analyst, 5, (1), 31-5

TIXIER, M.P., and ALGER, R.P., 1967 - Log evaluation of non-metallic mineral deposits. Soc. Pet. Well Log Analysts, Ann. Well Logging Symp. Trans. 1-23

TRUSHEIM, F., 1957 - Uber halokinese und ihre bedeutung fur strukturelle entwicklung Norddeutschlands Z. deutsch. geol. Ges., 109, 111-58

TRUSHEIM, F., 1960 - Mechanism of salt migration in northern Germany. Bull. Amer. Assoc. Petrol. Geol. 44, (9), 1519-40

TURPIE, A., 1967 - Giles-Carnegie seismic survey, Western Australia 1961-1962. Bur. Miner. Resour. Aust. Rec. 1967/123 (unpubl.)

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, 1973 - World sulphur supply and demand, 1960 - 1980. Unit. Nat Ind. Devel. Org., U.N., New York, 165 pp

VALYASHKO, M.G., 1972 - Playa lakes - a necessary stage in the development of a salt-bearing basin. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 41-51

VEEVERS, J.J., and WELLS, A.T., 1959 - Probable salt dome at Woolnough Hills, Canning Basin, Western Australia. Aust. J. Sci., 21, (6), 193-4

VEEVERS, J.J., and WELLS, A.T., 1960 - Probable salt dome at Woolnough Hills, Canning Basin, Western Australia. Bur. Miner. Resour. Aust. Rep. 38, 97-112

WALPOLE, B.P., DUNN, P.R., and RANDAL, M.A., 1968 - Geology of the Katherine-Darwin region, Northern Territory. Bur. Miner. Resour. Aust. Bull. 82

WALPOLE, B.P., ROBERTS, H.G., and FORMAN, D.J., 1965 - Geology of the Northern Territory in relation to mineralization. in GEOLOGY OF AUSTRALIAN ORE DEPOSITS (2nd edition). 8th C'wealth Min. Metall. Cong. 1, 160-7

WARDLAW, N.C., 1968 - Carnallite - sylvite relationships in the Middle Devonian Prairie Evaporite Formation, Saskatchewan. Bull. geol. Soc. Amer. 79, (10), 1273-94

WATTS, T.R., GAUSDEN, J., and HEISLER, H.H., 1966 - Stansbury West No. 1 well completion report. Beach Petrol. N.L. (unpubl.)

WEBB, B.P., 1960 - Diapiric structures in the Flinders Rangers, South Australia. Aust. J. Sci., 22, (9), 390-1

WEBB, B.P., 1961 - The geological structure of the Blinman Dome. Trans. Roy. Soc. S. Aust. 85, 1-6

WELLS, A.T., 1963 - Reconnaissance geology by helicopter in the Gibson Desert, Western Australia. Bur. Miner. Resour. Aust. Rec. 1963/59 (unpubl.).

WELLS, A.T., and KENNEWELL, P.J., 1972 - Evaporite drilling in the Amadeus Basin - Goyder Pass, Gardiner Range and Lake Amadeus, Northern Territory. Bur. Miner. Resour. Aust. Rec. 1972/36 (unpubl.)

WELLS, A.T., & KENNEWELL, P.J., in prep. - Evaporite exploration in the Officer Basin, Western Australia. Bur. Miner. Resour. Aust. Rec. 1974/194 (unpubl.).

WELLS, B.E., 1971 - An occurrence of common salt near Jandowae. Qld Govt Min. J. 369

WHELAN, J.A., 1972 - Ochsenius bar theory of saline deposition supported by quantitative data, Great Salt Lake, Utah. 24th Int. Geol. Cong., 1972 Sect. 10, 296-303

WILSON, R.B., 1967 - Woolnough Hills and Madley diapiric structures, Gibson Desert, W.A. J. Aust. Petrol. Explor. Assoc., 94-102

WOPFNER, A., and ALLCHURCH, P.D., 1967 - Devonian sediments enhance petroleum potential of Arckaringa Sub-basin. Aust. Oil and Gas J., 14, (3), 18-32

WHITEHOUSE, G.D., COUNCIL, M.E., and MARTINEZ, J.D., 1968 - Peaking power with air. Power Engng. 72, (1), 50-2

YATES, K.R., 1963 - Robinson River, Northern Territory, 1:250 000 geological Series. Bur. Miner. Resour. Aust. explan. Notes SE/53-4

ZAK, I., and BENTOR, Y.K., 1972 - Some new data on the salt deposits of the Dead Sea area, Israel. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp. UNESCO, Earth Sciences 7, 137-46

SELECTED BIBLIOGRAPHY ON THE ORIGIN AND DESCRIPTION OF SULPHUR

AULT, W.U., 1959 - Isotope fractionation of sulphur in geochemical processes. In ABELSON, P.H., ed RESEARCHES IN GEOCHEMISTRY. John Wiley & Sons, Inc., N.Y., 241-59

AULT, W.U., and KULP, J.L., 1959 - Isotopic geochemistry of sulphur. Geochim. Cosmochim, Acta, 16, (4), 201-35

AULT, W.U., and KULP, J.L., 1960 - Sulphur isotopes and ore deposits. Econ. Geol., 55, 73-100

BAAS-BECKING, L.G.M., and KAPLAN, I.R., 1956 - The microbiological origin of the sulphur nodules of Lake Eyre. Trans. Roy. Soc. S. Aust., 79, 52-65.

BASTIN, E.S., and GREER, F.E., 1930 - Additional data on sulphate reducing bacteria in soils and waters of oil-fields. Bull. Amer. Assoc. Petrol. Geol., 14, 153-9

BONYTHON, C.W., and KING, D., 1956 - The occurrence of native sulphur at Lake Eyre. Trans. Roy. Soc. S. Aust., 79, 121-30

DAVIS, J.B., and KIRKLAND, D.W., 1970 - Native sulphur deposition in the Castile Formation, Culberson County, Texas. Econ. Geol. 65, 107-21

DAVIS, J.B., STANLEY, J.P., and CUSTARD, H.C., 1970 - Evidence against oxidation of hydrogen sulphide by sulphate ions to produce elemental sulphur in salt domes. Bull. Amer. Assoc. Petrol. Geol. 54, (12), 2444-7

DESSAU, G., 1958 - Sul Cosidetto Minerale "Soriato" dei Giacimenti Solfiferi della Sicilia. Rivista Lo Zolfo, 11, 11-18

DESSAU, G., 1962 - Indagini Sull'origine dei Giacimenti Solfiferi della Sicilia. Consiglio Nazionale delle Richerce, Ric. Sci., 32, (1), 13-22

DESSAU, G., JENSEN, M.Le R., and NAKAI, N., 1962 - Geology and isotopic studies of Sicilian sulfur deposits. Econ. Geol. 57, 410-38

ELLISON, S.P., 1971 - Sulphur in Texas. Univ. Texas, Austin, Bur. Econ. Geol. Handbook 2

EL SHAZLY, E.Y., and MANSOUR, A.O., 1962 - Note on the occurrence of native sulphur at Um Reigha, Red Sea Coast. J. geol. UAR, 6, (2), 133-6

FEELY, H.W., and KULP, J.L., 1957 - Origin of Gulf Coast salt dome sulphur deposits. Bull. Amer. Assoc. Petrol. Geol. 41, (8), 1802-53

FENCHEL, T.M., and RIEDL, R.J., 1970 - The sulphide system: a new biotic community underneath the oxidized layer of marine sand bottoms. Marine Biol., 7, 255-68

GAHL, R., and ANDERSON, B., 1928 - Sulphate-reducing bacteria in California oilfield waters. Cbl. Bakteriol, 73, 331-

GOLDMAN, M.I., 1953 - Deformation, metamorphism and mineralization in gypsum-anhydrite cap, Sulphur Salt Dome, Louisiana. Geol. Soc. Amer. Memoir, 50, 169p

GOLEVA, G.A., 1963 - Hydrogeologic features of the origin of the sulphur deposits of the Carpathian foothills. abstract in Int. Geol. Rev. 5, (9), 1072

HANNA, M.A., and WOLF, A.G., 1934 - Texas and Louisiana salt-dome cap-rock minerals. Bull. Amer. Assoc. Petrol. Geol., 18, 212-35

HAWKINS, M.E., and JIRIK, C.J., 1966 - Salt domes in Texas, Louisiana, Mississippi, Alabama, and offshore tidelands. U.S. Bur. Mines Inf. Circ. 8313

HARRISON, A.G., and THODE, H.G., 1958 - Mechanism of the bacterial reduction of sulphate from isotope fractionation studies. Farad. Soc. Trans., 54, 84-92

HOLSER, W.T., and KAPLAN, I.R., 1966 - Isotope geochemistry of sedimentary sulphates. Chem. Geol., 1, 93-135

IVANOV, M.V., 1968 - Microbiological processes in the genesis of native sulphur deposits. I.P.S.T. Cat. No. 1850, U.S. Dept. Commerce, 298 pp

JENSEN, M. Le R., 1968 - Isotopic geology and the origin of Gulf Coast and Sicilian sulphur deposits. in SALINE DEPOSITS. Geol. Soc. Amer. Spec. Paps. 88, 525-36

JONES, G.E., STARKEY, R.L., FEELY, H.W., and KULP, J.L., 1956 - Biological origin of native sulphur in salt domes of Texas and Louisiana; Science, 123, 1124-5

KAPLAN, I.R., and RITTENBERG, S.C., 1964 - Microbiological fractionation of sulphur isotopes. Gen. Microbiol. J., 34, 195-212

KAPLAN, I.R., SWEENEY, R.E., and NISSENBAUM, A., 1969 - Sulphur isotope studies on Red Sea geothermal brines and sediments. in HOT BRINES AND RECENT HEAVY METAL DEPOSITS IN THE RED SEA. Springer Verlag, 474-98

KEMP, A.L.W., and THODE, H.G., 1968 - The mechanism of the bacterial reduction of sulphate and of sulfite from isotopic fractionation studies. Geochim. Cosmochim. Acta, 32, (1), 71-91

MACNAMARA, J., and THODE, H.G., 1951 - The distribution of sulphur 34 in nature and the origin of native sulphur deposits. Research, 4, (12) 582-3

MARX, A.H., 1936 - Hoskins Mound salt dome, Brazoria County, Texas. Bull. Amer Assoc. Petrol. Geol. 20, (2), 155-78; also in GULF COAST OIL FIELDS, 833-56

McNEAL, R.P., and HEMENWAY, G.A., 1972 - Geology of Fort Stockton sulphur mine, Pecos County, Texas. Bull. Amer. Assoc. Petrol. Geol. 56, (1), 26-37

NAKAI, N., and JENSEN, M. Le R., 1960 - Biogeochemistry of sulphur isotopes. J. Earth Sci., 8, 181-96

NAKAI, N., and JENSEN, M. Le R., 1963 - Sulphur isotope meteorite standards, results, and recommendations. in BIOGEOCHEMISTRY OF SULPHUR ISOTOPES, Yale University. Nat. Sci. Found. Symp.

NAKAI, N., and JENSEN, M. Le R., 1964 - Sulphur isotope fractionation by bacterial oxidation and reduction of sulphur. Geochim. Cosmochim. Acta, 7, (1)

NETTLETON, L.L., 1955 - History of concepts of Gulf Coast salt-dome formation. Bull. Amer. Assoc. Petrol. Geol. 39, 2373-83

NIELSEN, H., 1972 - Sulphur isotopes and the formation of evaporite deposits. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 91-102

SCHOUTEN, C., 1946 - The role of sulphur bacteria in the formation of the so-called sedimentary copper ore and pyritic ore bodies. Econ. Geol. 41, 517-38

SHUKRI, N.M., and NAKHLA, F.M., 1955 - The sulphur deposits of Ras Gemsa, Red Sea Coast, Egypt. Symp. Appl. Geol. in the Near East, Ankara, 114-23

SUBBA, RAO, M.S., IYA, K.K., and SREENIVASAYA, M., 1947 - Microbiological formation of elemental sulphur in coastal areas. 4th Inter. Congr. Microbiol., 494-

THODE, H.G., KLEEREKOPER, H., and McELCHERAN, D., 1951 - Isotope fractionation in the bacterial reduction of sulphate. Research, 4, (12), 581-2

THODE, H.G., MACNAMARA, J., and FLEMING, W.H., 1953 - Sulphur isotope fractionation in nature and geological and biological time scales. Geochim. Cosmochim. Acta 3, 235-43

THODE, H.G., and MONSTER, J., 1965 - Sulphur-isotope geochemistry of petroleum, evaporites, and ancient seas. in FLUIDS IN SUBSURFACE ENVIRONMENTS - A Symposium. Amer. Assoc. Petrol. Geol. Mem. 4, 367-77

THODE, H.G., WANLESS, R.K., and WALLOUCH, R., 1964 - The origin of native sulphur deposits from isotope fractionation studies. Geochim. Cosmochim. Acta, 5, (6) 286-98

TRUPER, H.G., 1969 - Bacterial sulphate reduction in the Red Sea hot brines. in HOT BRINES AND RECENT HEAVY METAL DEPOSITS IN THE RED SEA. Springer Verlag, 263-71

VINOGRADOV, A.P., 1959 - THE GEOCHEMISTRY OF RARE AND DISPERSED CHEMICAL ELEMENTS IN SOILS, 2nd Ed. Consultants Bureau, New York, 1-209

VINOGRADOV, A.P., GRINENKO, V.A., and USTINOV, V.I., 1961 - Origin of Pre-Carpathian sulphur deposit as revealed by S^{32}/S^{34} and C^{12}/C^{13} ratios. Geokhimiya, 10, 999

VOITESTI, J.P., 1926 - Geology of the salt domes in the Carpathian region of Rumania. in GEOLOGY OF SALT DOME OIL FIELDS. Amer. Assoc. Petrol. Geol., 87-122

ZOBELL, C.E., and RITTENBERG, S.E., 1948 - Sulphate - reducing bacteria in marine sediments. J. Mar. Res., 7, 602-17

SELECTED BIBLIOGRAPHY ON THE ORIGIN AND DESCRIPTION OF POTASH DEPOSITS

ADAMS, S.S., 1968 - Potassium reserves in the world. in KILMER, V.J., YOUNTS, S.E., and BRADY, N.C., eds - THE ROLE OF POTASSIUM IN AGRICULTURE. Amer. Soc. Agron., Crop Sci. Soc. Amer., Soil Sci. Soc. Amer. 1-21

ADAMS, S.S., 1969 - Bromine in the Salado Formation, Carlsbad potash district, New Mexico. New Mexico State Bur. Mines and Min. Res., Bull. 93, 122p

ADAMS, S.S., 1970 - Ore controls, Carlsbad potash district, southeast New Mexico. in THIRD SYMPOSIUM ON SALT, N. Ohio geol. Soc. Inc., Cleveland, 246-57

ANDERSON, R.J., and EGLESON, G.C., 1970 - Discovery of potash in the A-1 Salina salt in Michigan. in CHEMICAL AND INDUSTRIAL ROCKS AND MINERALS, Proc. 6th Forum Geol. Ind. Min., Misc. 1, Geol. Surv. Div., Michigan Dept. Nat. Res., 15-19

ANDERSON, R.J., EGLESON, G.C., MATTHEWS, R.D., and MAJESKE, E.C., 1972 - The recent discovery and probable distribution of extensive deposits of potash in the Silurian of Michigan. Proc. 24th Int. Geol. Cong., Section 4, 445-52

ANDERSON, R.J., and MAJESKE, E.C., 1970 - Detection of potash zones by drilling fluid analysis. in CHEMICAL AND INDUSTRIAL ROCKS AND MINERALS. Proc. 6th Forum Geol. Ind. Min., Misc. 1, Geol. Surv. Div., Michigan Dept. Nat. Res., 34-6

ARMSTRONG, G., DUNHAM, K.C., HARVEY, C.O., SABINE, P.A., and WATERS, W.F., 1951 - The paragenesis of sylvine, carnallite, polyhalite and kieserite in Eskdale borings Nos. 3, 4 and 6, Northeast Yorkshire. Miner. Mag., 29, 667-89

BAAR, A., 1952 - Methods of study of the physical-chemical reworking of potassium salt deposits; the significance of such studies in mining. Min. Technol. (Bergbautechnik) 2, (6), 274-7

BANNATYNE, B.B., 1960 - Potash deposits, rock salt, and brines in Manitoba. Winnipeg Dept. Mines. and Nat. Resour. Publ. 59-1

BARTLEY, E.M., 1966a - Potash. In CANADIAN MINERALS YEARBOOK 1965. Mines Branch and Miner. Resour. Div., Dept. Energy, Mines and Resour., Ottawa, Canada. 11p

BARTLEY, E.M., 1966b - Canadian potash developments in 1965. Amer. Inst. Min. Metall. and Petrol. Eng., 1966, 10p.

BORCHERT, H., 1972 - Secondary replacement processes in salt and potash deposits of oceanic origin. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 61-8

BORCHERT, H., and MUIR, R.O., 1964 - SALT DEPOSITS. The origin, metamorphism and deformation of evaporites. Chap. 17, The potash deposits of the Rhine Graben, 193-203. Van Nostrand London

BRAITSCH, O., 1966 - Bromine and rubidium as indicators of environment during sylvite and carnallite deposition of the upper Rhine Valley evaporites. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 293-301

BRITISH SULPHUR CORPORATION, 1967 - World survey of potash. Brit. Sulphur Corp. Ltd, London 93p

BRITISH SULPHUR CORPORATION - Phosphorus and potassium. Brit. Sulphur Corp. Ltd, London

CAMERON, A.L., 1949 - Salt, potash and phosphate in Manitoba. Bull. Manitoba Dept Mines and Nat. Res. 48-9, 13p

CLARKE, A.R., and SCHWERDTNER, W.M., 1966 - Petrofabric analysis of potash rocks, Esterhazy, Saskatchewan. in SECOND SYMPOSIUM ON SALT, N. Ohio geol. Soc. Inc., Cleveland, 1, 102-21

COLE, H.L., 1948a - Potash discoveries in western Canada. Trans. Canad. Inst. Min. 51, 83-99

COLE, H.L., 1948b - Potash discoveries in western Canada. Bull. Canad. Min. Metall. 41, 149-58

COLORADO SCHOOL OF MINES RESEARCH FOUNDATION, INC., 1967 - Potash. Miner. Ind. Bull., 10 (3), Colorado School of Mines, 18p

DUBININA, V.N., 1951 - On the genesis of sylvite. Dok. Akad. Nauk S.S.S.R., 80, (2), 233-36

DUBININA, V.N., 1954 - Mineralogy and petrography of the upper Kama potash deposits. Trudy Vsesoyuz. Nauchno-issled. Inst. Galurgii, 29, 3-128

DUNLAP, J.C., 1951 - Geological studies in a New Mexico potash mine. Econ. Geol., 46, 909-23

DYER, B.W., 1945 - Discoveries of potash in eastern Utah. Min. Tech. 9, (1), 56-61: Amer. Inst. Mining and metall. Eng. Tech. Pub. 1755, 6p; Trans. 173

ELLSWORTH, H.V., 1926 - Chemistry of potash-bearing horizon of the Malagash salt deposits, Nova Scotia. Can. geol. Surv. Sum. Rept., 1924, Pt C, 181-98

EVANS, R., 1970 - Genesis of sylvite and carnallite-bearing rocks from Wallace, Nova Scotia. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 239-45

FIVEG, M.P., 1955 - Conditions of formation of potash salts. Byull. Mosk. Obshch. Isp. Prirody. Ser. Geol. 30, (3)

FULDA, E., 1938a - Steinsalz und Kalisalze. in Beyschlag, F., Krusch, P. & Vogt, J.H.L., (eds), DIE LAGERSTATTEN DER NUTZBAREN MINERALIEN UND GESTEINE, 3, (2) Stuttgart

FULDA, E., 1938b - Kainite formation. Kali und Steinsalz, 46-7

GARRETT, D.E., 1966 - The chemistry and origin of potash deposits. Amer. Chem. Soc. ann. Mtg. 152, MS 66-487 (unpubl.)

GARRETT, D.E., 1970 - The chemistry and origin of potash deposits. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 211-22

GOLDSMITH, L.H., 1966 - Some fundamentals of potash geology as a guide to exploration. Soc. Prof. Well Log Analysts, 7th ann. Logging Symp. Trans. 15p.

GOLDSMITH, L.H., 1969 - Concentration of potash salts in saline basins. Bull. Amer. Assoc. Petrol. Geol., 53, (4), 790-97

GOUDIE, M.A., 1957 - Middle Devonian potash beds of central Saskatchewan. Saskatchewan Dept Min. Res. Rept. (unpubl.)

GOUDIE, M.A., 1959 - Saskatchewan potash deposits. Trans. Amer. Inst. Metall. Engrs. San Francisco Meeting 1959, TP 59 H 16

GREAT NORTHERN RAILWAY COMPANY, 1961 - Potash occurrences in the Williston Basin. Min. Res. and Devel. Dept. Gt N. Rlwy, Co. Rep. 15, 11p.

HADZERIGA, R., 1966 - Considerations on the recovery of potash from sea water bitterns. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 2, 204-11

HITE, R.J., 1961 - Potash-bearing evaporite cycles in the salt anticlines of the Paradox Basin, Colorado and Utah. in Short papers in the geological sciences. U.S. Geol. Surv. Prof. Pap. 424-D, Art. 337, D 135-38

HITE, R.J., 1967 - Distribution and geologic habitat of marine halite and associated potash deposits. U.S. Geol. Surv. Open file Rep. 41p

HITE, R.J., and GERE, W.C., 1958 - Potash deposits of the Paradox basin. in Guidebook to the geology of the Paradox Basin. Intermountain Assoc. Petrol. Geol., 9th Ann. Field Conf., 221-25

HOLSER, W.T., WARDLAW, N.C., and WATSON, D.W., 1972 - Bromide in salt rocks: extraordinarily low content in the Lower Elk Point Salt, Canada. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO. Earth Sciences 7, 69-75

HOLTER, M., 1972 - Geology of the Prairie Evaporite formation of Saskatchewan, Canada. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 183-9

HOLWERDA, J.G., and HUTCHINSON, R.W., 1968 - Potash bearing evaporites in the Danakil area, Ethiopia. Econ. Geol., 63, (2), 124-50

HOOTS, W.H., 1925 - Geology of a part of western Texas and southeastern New Mexico with special reference to salt and potash. U.S. Geol. Surv. Bull., 780 B, 33-126

HURD, D., and SHAW, W.W., 1966 - The carnallite problem in the Saskatchewan potash field - some empirical relations as determined by seismic isopachs. Min. Eng., 18, (8), 44 (Abstract)

ILYINSKI, V.P., 1948 - On the production of halite, potassium and magnesium chlorides and sulphates, and bromine by evaporation of sea water. Rukovod. Gosinst. Prikl. Khim., 40

INGERSON, E., 1968 - Deposition and geochemistry work sessions. in SALINE DEPOSITS. Geol. Soc. Am., Spec. Paps., 88, 671-81

IVANOV, A.A., 1932 - On the genesis of sylvinite in the Verchnekamsk potash deposits. Zapiski vsesoyuz. mineralog. obshch., 61, (2) IVANOV, A.A., 1935 - Carnallite in the Upper Kama deposits. in THE SOLIKAMSK CARNALLITE. ed. N. Kupnakov., Moscow, p5

IVANOV, A.A., 1945 - Potash in the pre-Carpathian evaporites. Zh. f. chem. Ind. 12

IVANOV, A.A., 1950 - Potash in the Angara-Lena salt basin. Zapiski vsesoyuz, mineralog. obshch. 79, (4), 297-8

JONES, C.L., 1954 - The occurrence and distribution of potassium minerals in southeastern New Mexico. Guidebook of southeastern New Mexico, 5th field Conf. New Mexico geol. Soc., 107-12

JONES, C.L., 1959 - Potash deposits in the Carlsbad region, southeastern New Mexico (abs.), Econ. Geol., 54, 1349; Bull. geol. Soc. Amer., 70, 1625

JONES, C.L., 1972 - Permian basin potash deposits southwestern United States. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 191-201

JONES, C.L., BOWLES, C.G., and BELL, K.G., 1960 - Experimental drill hole logging in potash deposits of the Carlsbad district. New Mexico, USGS File Rep. Jan, 15, 1960

JONES, C.L., and MADSEN, BETH M., 1968 - Evaporite geology of the fifth ore zone, Carlsbad district, southeastern New Mexico. U.S. Geol. Surv. Bull., 1252-B, 21p

KALIUM-SYMPOSIUM, 1955 - Internationales Kali-Institut, Berne

KENAT, J., 1966 - The production of potassium chloride from the Dead Sea by crystallization. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 2, 195-203

KEYES, D.A., 1966 - Geology of the IMC potash deposit, Esterhazy, Saskatchewan. Trans. Amer. Inst. Mining metall. Eng., 235, 186-91

KEYES, D.A., and WRIGHT, J.Y., 1966 - Geology of the IMC potash deposit, Esterhazy, Saskatchewan. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Cleveland, 1, 95-101

KING, R.H., 1946 - Carnallite filled mud cracks in salt clay. J. sed. Petrol., 16, (1), 14

KLINGSPOR, A.M., 1966 - Cyclic deposits of potash in Saskatchewan. Bull. Canad. Petrol. Geol., 14, 193-207

KNUTSON, C.F., and WALTHER, H.C., 1965 - Evaluation of potash deposits with oil field logs. Continental Oil Co., Develop. and Res. Dept. Produc. Res. Div. Rep., 568-2-1-65

KROENLEIN, G.A., 1939 - Salt, potash and anhydrite in Castile Formation of south-east New Mexico. Bull. Amer. Assoc. Petrol. Geol., 23, 1682-93

KOPNIN, V.I., 1966 - Distribution of constant components in the sediments of the Upper Kama potassium deposits. Geochem. Internat., 3, (3), 536-45

KUHN, R., 1953 - Mineralogische fragen der in den Kalisalzlagerstatten vorkommenden salze. in POTASSIUM, POTASIO, KALIUM, - 1954. Berne, Switzerland. Inter. Potash Inst., 51-105

KUHN, R., 1968 - Geochemistry of the German potash deposits. in SALINE DEPOSITS. Geol. Soc. Amer. Spec. Paps., 88, 427-504

KUHN, R., 1972 - Combined evaluation of Br- and Rb- contents for the genetic characterization of carnallites and sylvite rocks. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences 7, 77-89

KURNAKOV, N.S., ed., 1935 - THE SOLIKAMSK CARNALLITE. Moscow

LAININA, I.N., and ANOSHIN, G.N., 1962 - Some regularities of distribution of rubidium, thallium and bromine in the process of formation of potassium salt deposits. Dok. Akad. Nauk S.S.S.R., Sibir. Sekt. Geol. and Geophys., (3), 64-74 (Russian)

LANG, W.B., 1942 - Basal beds of the Salado Formation in Fletcher potash core test, near Carlsbad, New Mexico. Bull. Amer. Assoc. Petrol. Geol., 26, 63-79

LEPESHKOV, I.N., 1946 - Theory of formation of salt basins and the genesis of the potash salts of the Volga - Emba district. Dok. Akad. Nauk S.S.S.R. Inst. Obshch. i Neorgan. Khim. 85, 451-

LEPESHKOV, I.N., and BODALEVA, N.V., 1940 - Kieserite, bischofite and other salts discovered in salt deposits on the southern part of the Permian sea. Dok. Akad. Nak S.S.S.R., 27, 978-

LEWIS, R.W., 1966 - Potash. In Bur. Mines Miner. yearbook 1965. U.S. Bur. of Mines. 15p

LEWIS, R.W., 1967 - Potash in 1966. Miner. Ind. Surv. Letter. U.S. Bur. of Mines. 4p

LINDBERG, M.L., 1946 - Occurrence of bromine in carnallite and sylvite from Utah and New Mexico. Amer. Miner., 31, 486-494

LINN, K.O., and ADAMS, S.S., 1966 - Barren halite zones in potash deposits, Carlsbad, New Mexico. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 59-69

LOBANOVA, V.V., 1949 - Petrography of the eastern Carpathian potash deposits. Dok. Akad. Nauk S.S.S.R., 66, (6)

LOBANOVA, V.V., 1953 - On the genesis of langbeinite. Dok. Adad. Nauk S.S.S.R., 88, (2), 145-8

LOTZE, F., 1938 - STEINSALZ AND KALISALZE. Berlin, Verlag Gebruder Borntraeger, 936p

LOTZE, F., 1957 - STEINSALZ AND KALISALZE, 2nd edition. I. Teil; Berlin, Verlag Gebruder Borntraeger, 465 p

MANSFIELD, G.R., and LANG, W.T.B., 1935 - The Texas-New Mexico potash deposits. in THE GEOLOGY OF TEXAS, 2, (3). Univ. Texas Bull., 3401, 641-832.

MATTHEWS, R.D., 1970 - The distribution of Silurian potash in the Michigan Basin. in CHEMICAL AND INDUSTRIAL ROCKS AND MINERALS. Proc. 6th Forum on Geol. Ind. Min., Misc. 1, Geol. Surv. Div., Michigan Dept. Nat. Res., 20-33

MAYHEW, E.J., and HELYMUN, E.B., 1966 - Complex salts and brines of the Paradox basin. in SECOND SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 221-35

MORACHEVSKII, I.V., 1935 - Accessory minerals and insoluble residues in the Solikamsk carnallite. in THE SOLIKAMSK CARNALLITE. Moscow, 13-

NOVA SCOTIA DEPARTMENT OF MINES, 1950 - Salt and potash in Nova Scotia. Nova Scotia Dept Mines

NOYES, R., 1965 - Potash and potassium fertilizers. Chem. Process Monograph, 15. Noyes Devel. Corp., Park Ridge, N.J., 210 p.

ODDO, G., 1949 - Experimental data on the simultaneous formation of sulphur, oil and soluble sodium, potassium and magnesium salts from sea water. Ann. Chim. appl. Ital., 39, (2-3)

O'DONNELL, R.W., 1966 - Separation and extraction of the alkali metal halites from Saskatchewan potash. M.Sc. thesis, Dept of Chem. and Chem. Eng., University of Saskatchewan, Saskatoon, 132 p

OGIENKO, V.S., 1959 - Distribution of bromine in the rock salt of the Angara-Lena salt basin and the possibility of finding potassium salts. Geochemistry 1959 (translated from Russian), 8, 893-900

PEARSON, W.J., 1960a - Developments in potash in Saskatchewan. Canad. Min. Inst., 63, 510-15

PEARSON, W.J., 1960b - Western Canada potash and its future prospects. Engng. J., 43, (8), 68-72

PENDERY, E.C., 1970 - Distribution of salt and potash deposits: present and potential affects on potash economics and exploration. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 2, 85-95

PERTHUISOT, J.P., 1971 - Recent polyhalite from Sebkha el Melah (Tunisia). Nature, Lond. (Phys. Sci.), 232, 186-7

PICKARD, F.C., 1967 - Potash. Eng. Min. J., 173-4

RAYMOND, L.R., 1953 - Some geological results from the exploration for potash, in north-east Yorkshire. Quart. J. geol. Soc. Lond., 108, 283-310

RYKOVSKOV, A.E., 1932 - The problem of the absence of sulphate in the Solikamsk potash deposits. Arb. d Hauptamtes f. geol. Erkundung, 43

SCHALLER, W.T., and HENDERSON, E.P., 1932 - Mineralogy of drill cores from the potash fields of New Mexico and Texas. U.S. geol. Surv. Bull., 833, 124p

SCHOCK, H.H., and PUCHELT, H.R., 1970 - Distribution of Rb and Cs in potassium salts - experimental and analytical investigations. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 232-8

SCHULZE, G., 1960 - Contribution to the genesis of polyhalite in salt minerals of the German Zechstein. Z. angew. Geol., 6, (7), 310-17

SCHWERDTNER, W.M., 1964 - Genesis of potash rocks in Middle Devonian Prairie Evaporite Formation of Saskatchewan. Bull. Amer. Assoc. Petrol. Geol. 48, (7), 1108-15

SCHWERDTNER, W., and WARDLAW, N.C., 1963 - Geochemistry of bromine in some salt rocks of the Prairie Evaporite Formation of Saskatchewan in SYMPOSIUM ON SALT N. Ohio. geol. Soc. Inc., Cleveland, 240-6

SELLARDS, E.H., and SCHOCH, E.P., 1928 - Core drill tests for potash in Midlands County, Texas. Univ. Texas Bull. 2801, 159-201

SCHCHERBINA, V.N., 1960 - Rhythms and cycles of sedimentation in the section of the salt series of the Starobinsk potash deposit. Dok. Akad. Nauk S.S.S.R., 131, 398-401

SMITH, D.B., 1973 - The origin of the Permian middle and upper potash deposits of Yorkshire: an alternative hypothesis. Proc. York geol. Soc., 39, (3), 16, 327-46

SMITH, H.I., 1938 - Potash in the Permian salt basin. Industr. Engng. Chem. Industr. edit., 30, 854-60

SMITH, H.I., 1949 - Potash. Industrial minerals and rocks. Amer. Inst. Min. Engng. Publ., 684-713

SPICER, H.C., 1946 - Gamma-ray studies of potassium salts and associated geologic formations. U.S. geol. Surv. Bull., 950, 143-161

STEWART, F.H., 1956 - Replacement involving early carnallite in the potassium-bearing evaporites of Yorkshire. Mineral. Mag., 31, 127-35

TAZIEFF, H., 1969 - Potash-bearing evaporites - Danakil area. Econ. Geol., 64, (2), 228-9

TCHERVINSKII, P.N., 1943 - Petrochemistry of the carnallite and sylvinite facies in the Verchneckamsk deposits. Zapiski Vsesoyuz. Mineralog. Obshch., 72, (2)

TCHERVINSKII, P.N., 1946 - Alkaline replacement of carnallite in the Solikamsk deposits. Zapiski Vsesoyuz. Mineralog. Obshch., 75, (2), 149-

THE GEOLOGY OF SALT DEPOSITS, 1960 - Amer. Chem. Soc. Monogr. Ser., 145

TIMKO, D.J., 1964 - Potash evaluation using well logs. The Log Analyst, 5, (1), 31-5

TOMPKINS, R.V., 1955 - Potash in Saskatchewan. Trans. Canad. Min. Inst., 58, 38-41

URAZOV, G.G., 1932 - Succession of evaporites in the Solikamsk potash deposits. Arb. d. Hauptamtes f. geol. Erkundung, 43

VALYASHKO, M.G., 1951 - Volumetric relationships of the liquid and solid phases during evaporation of sea water as a factor in formation of potash deposits. Dok. Akad. Nauk S.S.S.R., 77, (6), 1055-8

VALYASHKO, M.G., 1956a - Geochemistry of bromine in halogenation processes and utilization of its content in salts as a criterion for genesis and prospecting. 20th Int. geol. Congr., Mexico 1956, Resumenes trab. present., 378

VALYASHKO, M.G., 1956b - Geochemistry of bromine in the process of salt deposition and use of the bromine content as a genetic and prospecting criterion. Geochem. (translated from Russian), 1, (6), 570-89

VALYASHKO, M.G., 1956c - The geochemistry of potash deposits. Dok. Akad. Nauk S.S.S.R., 182-

VALYASHKO, M.G., 1957 - Physico-chemical conditions of the formation of potassium salt deposits in the earth's past. Dok. Akad. Nauk S.S.S.R. Geokhimia, 6, 470-

VALYASHKO, M.G., 1957 - Physico-chemical conditions of the formation of potassium salt deposits of the past. Geochem. 6, 553-65 (Eng. trans.)

VALYASHKO, M.G., 1972 - Playa lakes - a necessary stage in the development of a salt-bearing basin. in GEOLOGY OF SALINE DEPOSITS. Proc. Hanover Symp., UNESCO, Earth Sciences, 7, 41-51

VALYASHKO, M.G., and NECHAYEVA, A.A., 1951 - Experimental data on the conditions of formation of polyhalite. Miner. Handb. Lvov. Geol. Soc., 5

VAN DER PLANK, A., 1962 - Petrology and geochemistry of some diamond drill cores from the Saskatchewan potash deposits. Master's thesis (geology), Univ. Wisconsin

VORONOVA, M.L., 1954 - Polyhalite and sylvite in the Usun-Suu sulphate deposits. Dok. Akad. Nauk S.S.S.R., 99, 449

WARDLAW, N.C., 1968 - Carnallite-sylvite relationships in the Middle Devonian Prairie Evaporite Formation, Saskatewan. Bull. geol. Soc. Amer., 79, (10), 1273-94

WARDLAW, N.C., 1970 - Effects of fusion rates of crystallization and leaching on bromine and rubidium solid solutions in halite, sylvite and carnallite. in THIRD SYMPOSIUM ON SALT. N. Ohio geol. Soc. Inc., Cleveland, 1, 223-31

WARDLAW, N.C., and SCHWERDTNER, W.M., 1963 - Fibrous koeninite in carnallite and sylvine from the Prairie Formation of Saskatchewan. Neues Jahrbuch Geol. Monatsh., 76-7

WILLIAMS, A.J., 1947 - Report on Saskatchewan potash deposits. Canad. Chem. Metall., 31, (5), 410-

WILLIAMS, A.J., 1952 - Further potash discoveries in Saskatchewan. Trans. Canad. Min. Inst., 55, 170-1

YARZHEMSKII, Y.Y., 1945 - Potassium salts of the Inder uplift. Dok. Akad. Nauk S.S.S.R., 48, 191-

ZEHNOWITZER, E.W., 1935 - Plasticity of crystals of sylvine. Nature, 135, 1076

ZIEGLER, V., 1915 - Potash deposits of the Sand Hills region, northwestern Nebraska. Colorado School of Mines Quart. 10, (3), 6-26

PART II

A SHORT REPORT ON EVAPORITE DEPOSITS OF AUSTRALIA

by G. Richter-Bernburg

This general review of evaporite deposits is the result of a brief visit to Australia from 21st April to 18th May, 1971 at the request of BMR. A short field trip was made to the Amadeus Basin but most information was derived from a study of reports, logs and cores from drill holes and from discussions with geologists and geophysicists from BMR, State Geological Surveys, and exploration companies. Though this report is based on some of my own experience on salt geology, the four weeks available for studying the problem was sufficient only for giving a broad generalized outline of the problems involved.

Salt deposits (NaCl, K- and Mg-salts) can be exploited from two different types of occurrences:

1. Recent or superficial salt deposits

2. Fossil or underground salt formations.

1. Recent salt deposits

Australia is one of those countries where in some areas the evaporation rate is so high that mineralized water evaporates and dissolved substances are precipitated. Many salt lakes are present in the southern and western parts of the continent. None of these salt deposits have attracted industrial development although in parts of coastal South Australia and Western Australia an abundance of salt is produced by solar evaporation of sea water, both for local consumption and export.

It may be emphasized that the production of any other salts from sea water is out of discussion at this moment.

2. Underground salt formations

Rock salt has been found in several places in Australia, within the last 10 years, mainly by oil exploration wells. It is present in the Adavale Basin in Queensland, in the Carnarvon and Canning Basins in Western Australia and in the Amadeus Basin in the Northern Territory.

The exact ages of the evaporite-bearing formations in some of the basins are uncertain.

(a) Adavale Basin

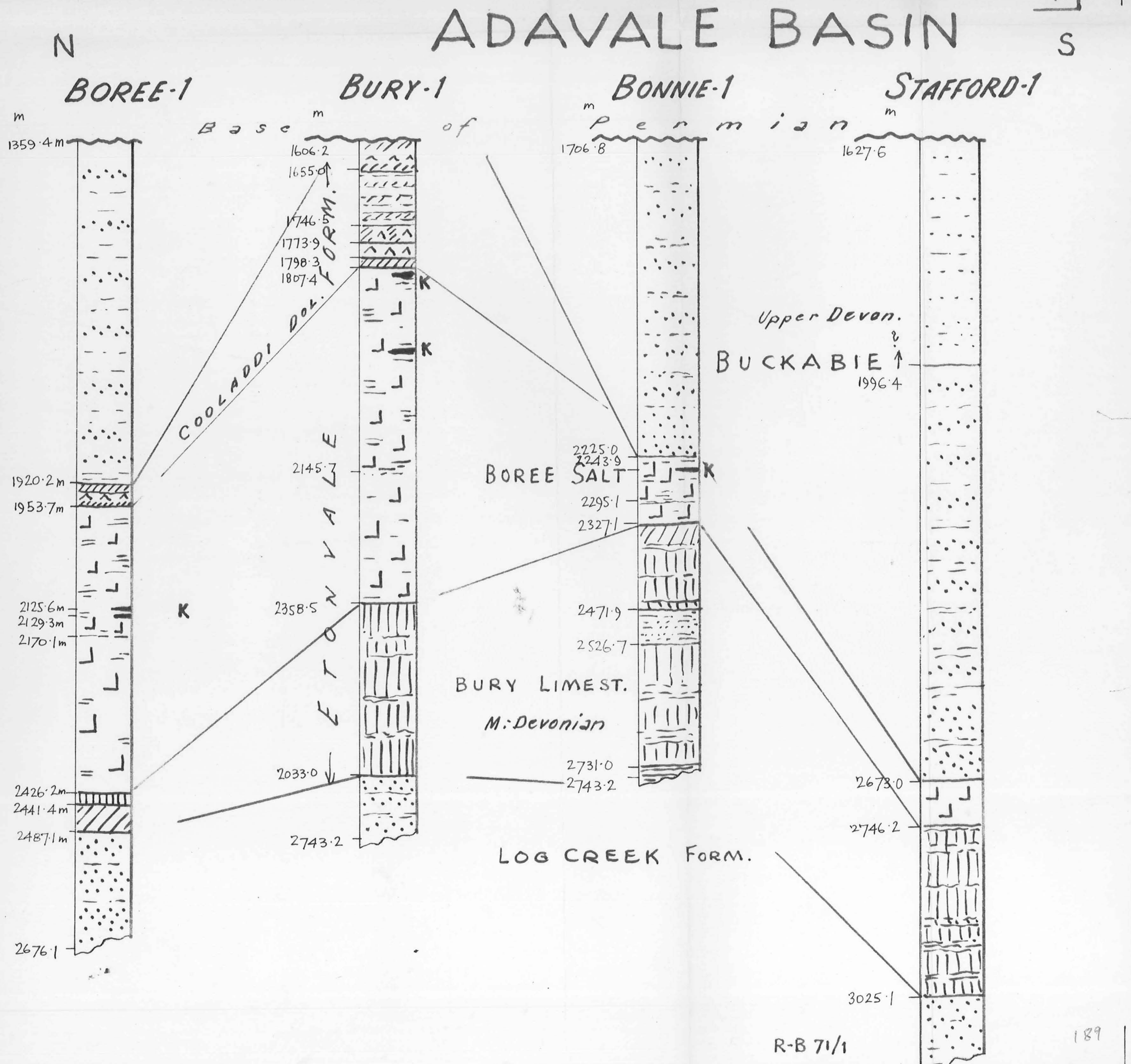
Within this sub-basin of the Great Artesian Basin, four oil wells penetrated rock salt: Boree No. 1, Bury No. 1, Bonnie No. 1, and Stafford No. 1. The stratigraphy of the basin is summarized in Table 1. The graphic logs of the evaporite-bearing parts of the sequences are shown on Figure 1. In Bury No. 1 where the salt is closest to the surface (1807.4 m), the depth to the base of Permian is also the least (201.1 m), but the salt thickness is greatest at 551.0 m. In Boree No. 1, a similar thickness (472.4 m) is present but in Bonnie No. 1 and Stafford No. 1 wells the halite section is considerably thinner - 102.1 m and 73.1 m respectively.

From the limited core evidence the sequence is the same in all wells. The upper part, in Boree No. 1 (185.9 m) thick, in Bury No. 1, (33.5 m), in Bonnie No. 1, (70.1 m), consists of medium crystalline, rather transparent, smoke-brown halite with numerous bands of dark brown anhydrititic clay. The lower part is, in general, purer and the clay or anhydrite is restricted to very thin interbeds.

The gamma ray logs of the four wells (Fig. 2) show that the twofold subdivision is a regional feature. Although the wells are more than 50 km apart a peak in the log (X on Fig. 2) can be recognized everywhere. This indicates uniform uninterrupted sedimentation in the basin.

TABLE I - ADAVALE BASIN STRATIGRAPHY

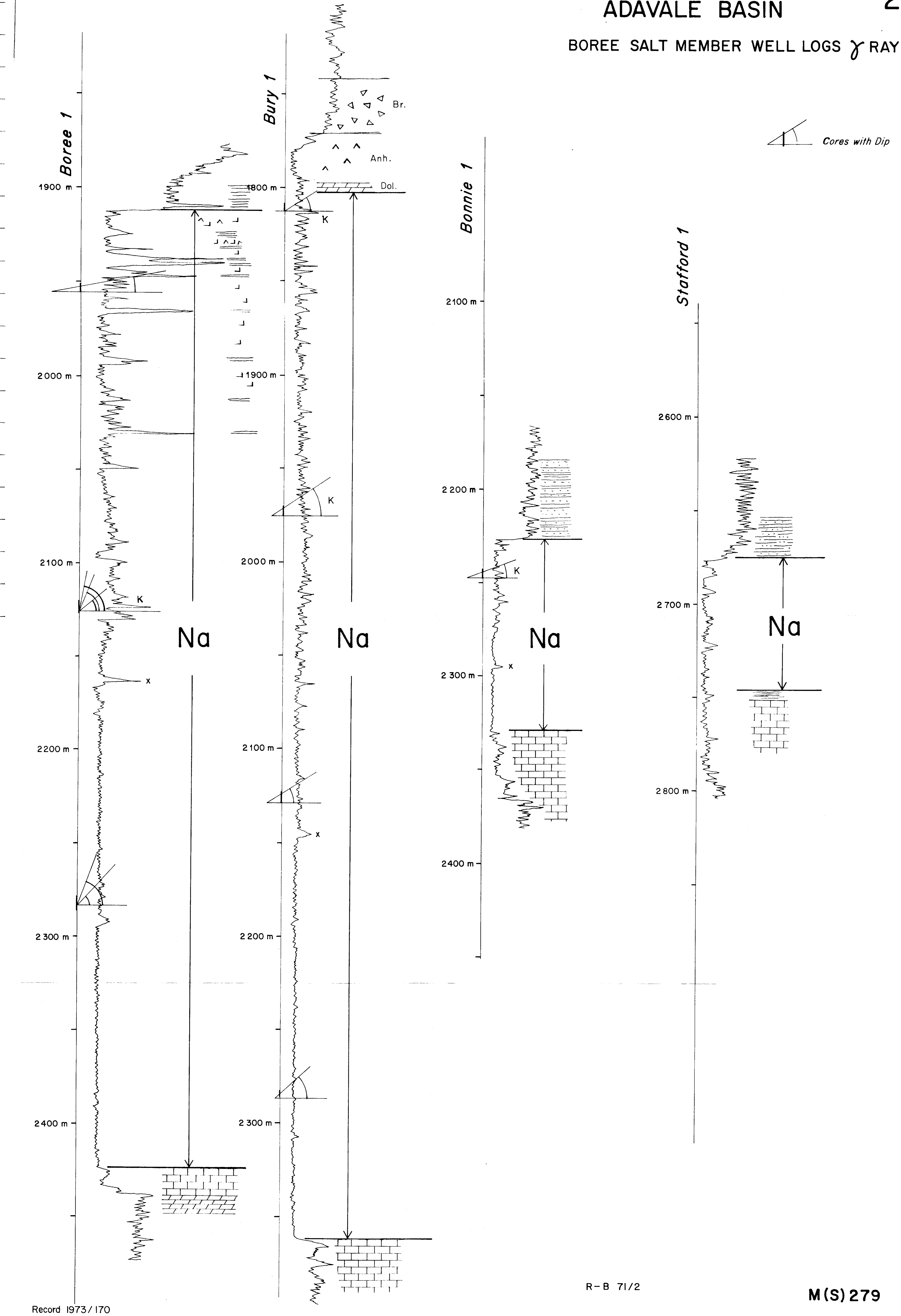
	Permian			
MAIN UNCONFORMITY				
U. DEVON.	Buckabie Fm	Continental sandstone		3050 m
M. DEVON.	Etonvale Fm	'D1'	Silts + shales	150 m
		'D2'	West Cooladdi-Dolom. East	300 m
		'D3' South		Boree-Salt Bury-Limestone
L. DEVON.	Log Creek-Fm. ('Gilmore')	'D4'	Arkosic Sdst	370 m
			Shale-Member	370 m
	Gumbardo-Fm.		Volcanics	



ADAVALE BASIN
1.
N
S
BOREE-1
BURY-1
BONNIE-1
STAFFORD-1
m
Base of Permian
1359·4m
1920·2m
1953·7m
2125·6m
2129·3m
2170·1m
2426·2m
2441·4m
2487·1m
2676·1
K
1606·2
1655·0
1746·5
1773·9
1798·3
1807·4
2145·7
2358·5
2033·0
2743·2
COOLADDI DOL.
ETONVALE FORM.
1706·8
2225·0
2243·9
2295·1
2327·1
2471·9
2526·7
2731·0
2743·2
BOREE SALT
BURY LIMEST.
M. Devonian
LOG CREEK FORM.
Upper Devon.
BUCKABIE
1627·6
1996·4
2673·0
2746·2
3025·1
3142·4
R-B 71/1

ADAVALE BASIN

BOREE SALT MEMBER WELL LOGS γ RAY



Record 1973/170

R-B 71/2

M(S) 279

Thin beds of sylvinite (a mixture of halite and sylvite) are present (shown as K in Fig. 2): in Bury No. 1 at 1810.5 - 1810.7 m and 1970.37 - 1970.45 m; in Boree No. 1 at 2125.6 m and 2129.3 m the beds are about 2.5 cm and 7.6 cm thick respectively; in Bonnie No. 1 at 1243.9 m is a bed about 10 cm thick. The sylvite is milky white and can easily be distinguished from the darker halite. In all three wells the potash occurs in the upper third of the sequence. The beds are too thin to show up well on the gamma ray log. Thus, it is unlikely that important potash beds have been overlooked.

The possibility of the presence of thicker potash deposits in the basin has now to be discussed. In this respect the facies and the thickness of the salt have to be considered. Within the halite facies itself no obvious variations are apparent. However the Bury Limestone Member thins towards the north (Boree No. 1) and is interbedded with clastics towards the west (Bonnie No. 1). The Cooladdi Dolomite which forms the roof of the salt thins out towards the west and seems to be represented by sandy beds. The facies distribution, shown in Figure 3 is based on seismic data and other work by oil companies. It suggests that the salt extends only a short distance west of the Boree and Bonnie wells; the wells Fairlea and Carlow did not penetrate salt. The absence of salt in Ravensbourne No. 1 well is thought to be due to its being eroded in pre-Permian times. However it is uncertain whether the arkosic sandstone below the Permian in the Ravensbourne well belongs to the base or to the roof of the Boree Salt Member.

Another problem is the structure of the Boree Salt Member. The cores of the Bury No. 1 well show a continuous dip of about 45°. In Bonnie No. 1 the salt dips from 10-25°. However in Boree No. 1, although the dip in the upper part is only 5-15°, the core at 2125.0 - 2131.1 m shows a dip of 40-90°, and the core at 2280.5 - 2286.9 m a dip of 45-60°. This shows that the drilled thickness in Boree No. 1 has been increased by flowage. Seismic surveys by Phillips Oil Co. in the southern part of the Adavale Basin, give an idea of the present thickness (Fig. 4). Although the isopachs are based on sparse evidence there appears to be ample evidence that the thickest salt succession lies close to the southwest boundary near the Warrego Fault. The migration of salt towards faults is common. Thus it seems likely that the salt forms a kind of long diapir, that has moved more-or-less upwards, as shown in Figure 5. The top of the thick salt body would have to be investigated, but the salt could extend to mineable depths.

Seismic work farther north (Fig. 6) indicates a fairly constant thickness of the Boree Salt Member. Consequently, the facies of the Middle Devonian should be studied farther north. Here the shelf, which occurs on the western side of the geosynclinal trough of east Australia, could find a north or south continuation; its western border is marked by unprospective clastic sediments.

(b) Carnarvon Basin

In the Carnarvon Basin the wells intersecting evaporites are spread over a distance of about 800 km in a north-south direction (Fig. 7). The only well with a true salt member is Yaringa No. 1 where the 71.6 m of halite penetrated has been called the "Yaringa Member". The nearby well, Dirk Hartog No. 1, proved only a carbonate-sulphate evaporite series, 252.9 m thick. It is, as in Yaringa No. 1, interbedded with a thick sequence of limestone and dolomite, the whole being called "Dirk Hartog Formation". It has a total thickness of 739.1 m in the Dirk Hartog No. 1 and 671.1 m in Yaringa No. 1 (Fig. 9). Both Quail No. 1 and Wandagee No. 1 penetrated a comparable succession in the Dirk Hartog Formation, which includes, in the middle, the dolomitic-anhydritic Yaringa Member about 90 m thick (Fig. 9). In the offshore well, Pendock No. 1, this evaporitic member is missing, and only carbonate rocks are present.

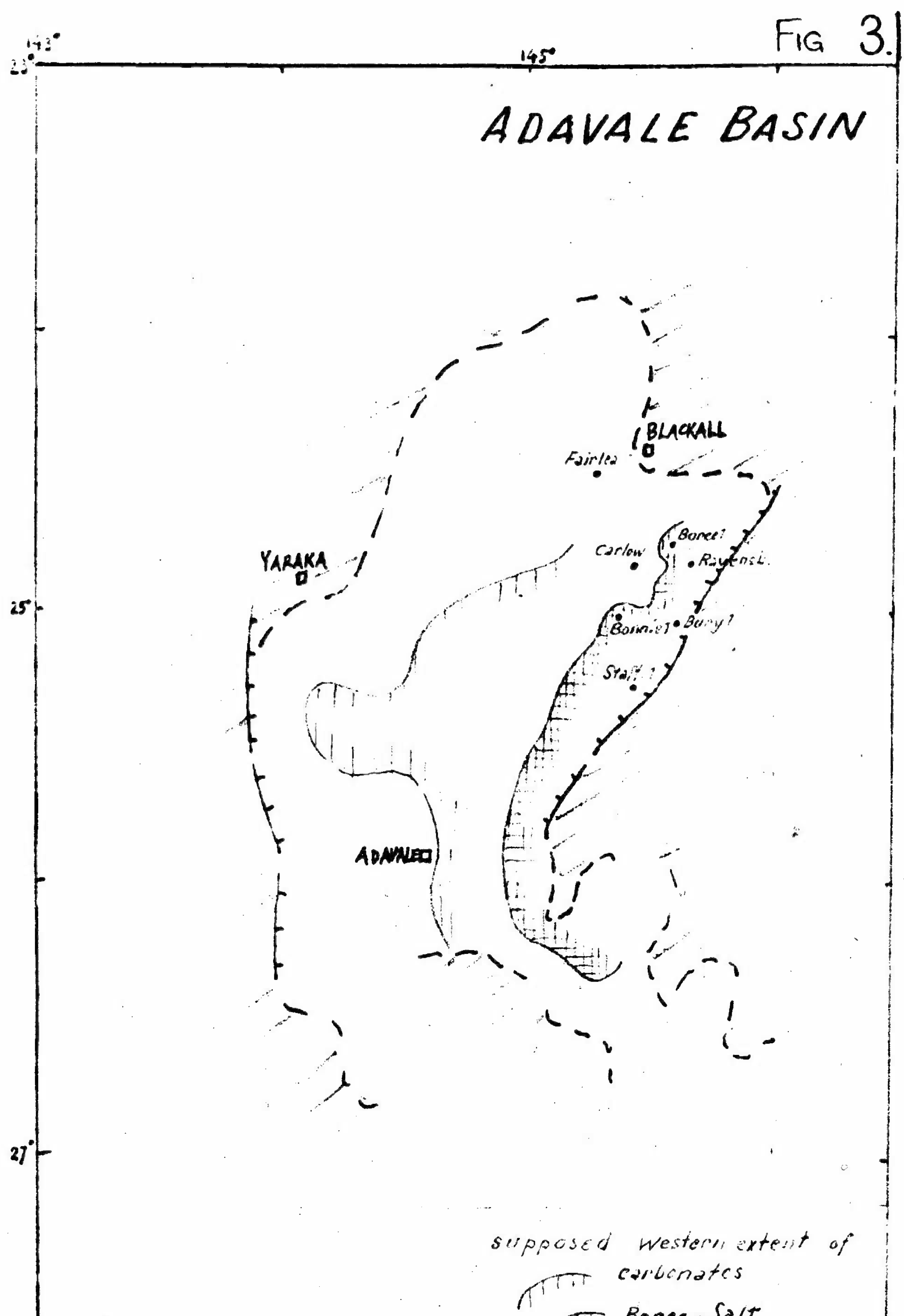
In Yaringa No. 1, Quail No. 1, and Pendock No. 1 a reddish brown sandstone, the Nanyarra Sandstone, overlies the Dirk Hartog Formation. The Nanyarra Sandstone is overlain by another carbonate sequence, which is dated by marine fossils as lowermost Upper Devonian (Frasnian). In part, it has developed as thick reef limestone. Rough Range No. 1 penetrated more than 1200 m of carbonate rocks but it is uncertain whether this is equivalent to the Upper Devonian reef, the Dirk Hartog Formation, or both.

The evaporitic Yaringa Member probably extends between Quail No. 1 and Yaringa No. 1, and farther south, but there are no indications that it is developed better than in the Yaringa No. 1 well. Its age is late Silurian.

No structural feature is known.

(c) Canning Basin and Fitzroy Trough

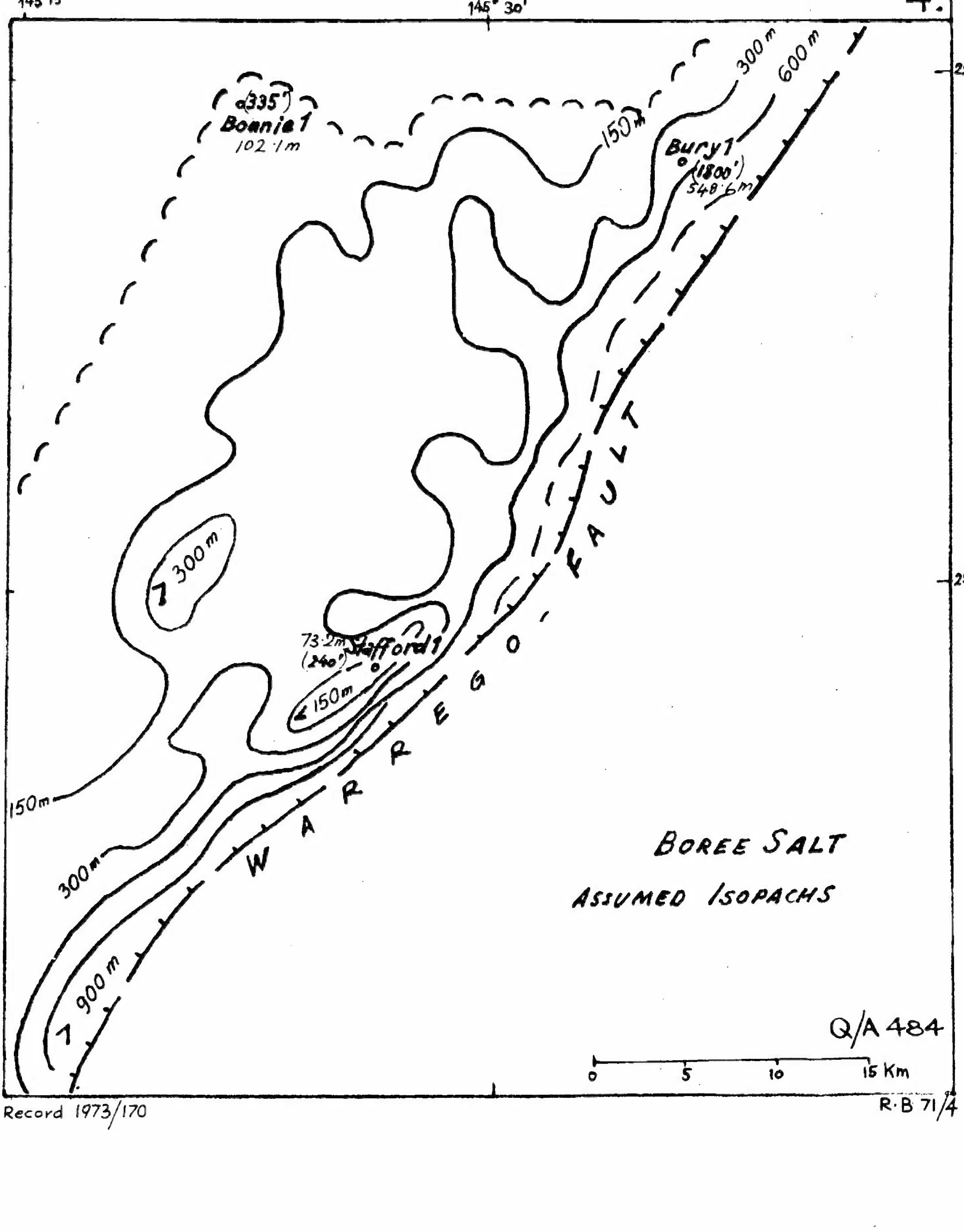
The evaporite deposits of the Canning Basin (Fig. 7) are of greater interest. Five wells have penetrated salt deposits of considerable thickness (Fig. 8). In the northwesternmost well, Parda No. 1, the salt itself is missing. Here, the unconformity of Thangoo Limestone above basement



Record 1973/170

PART OF ADAVALE BASIN

4.

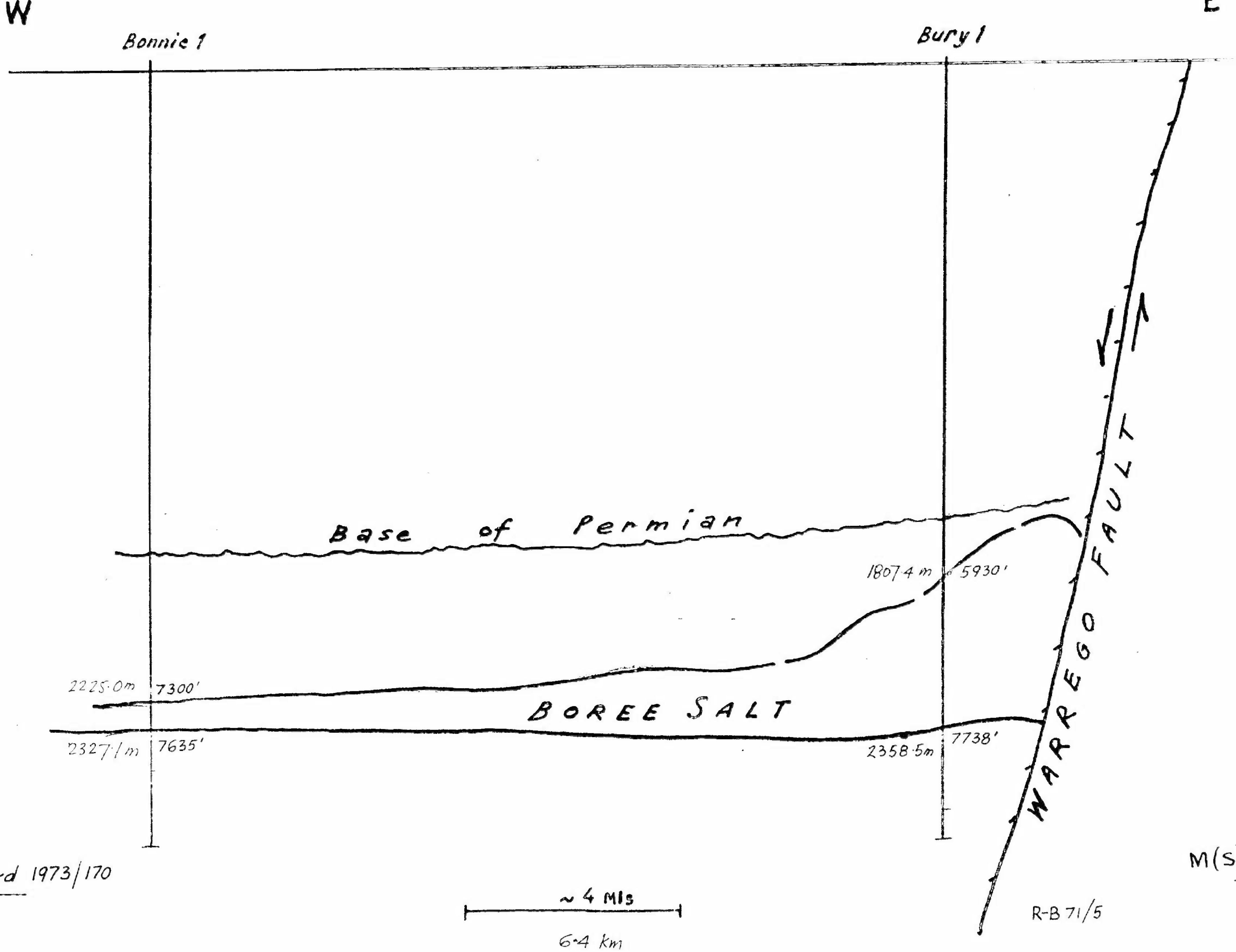


Record 1973/170

R·B 71/4

ADAVALE BASIN

SCHEMATIC CROSS SECTION



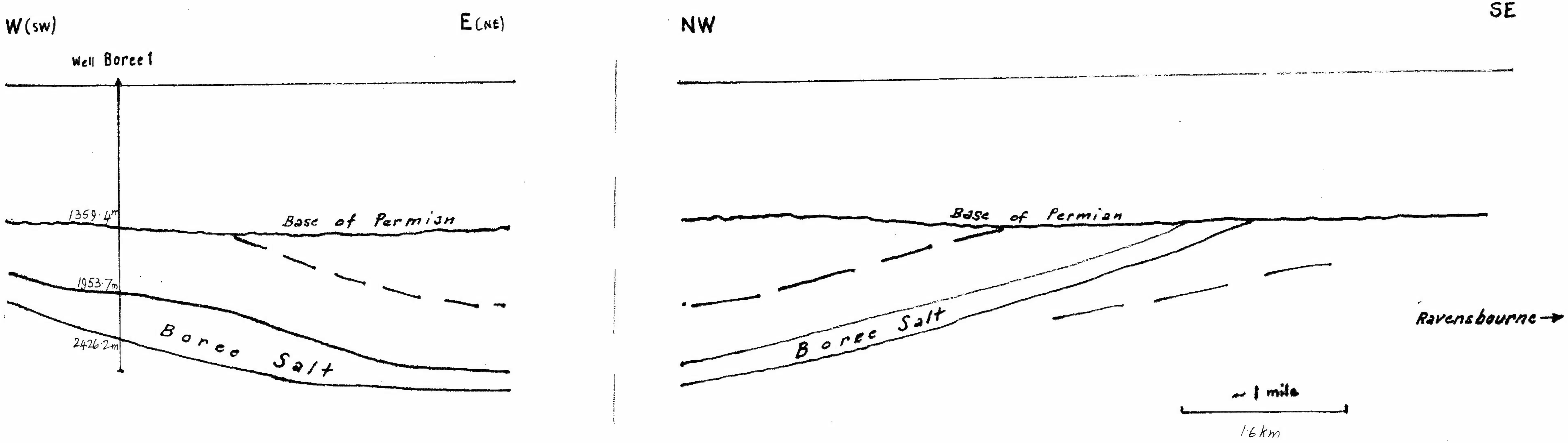
Record 1973/170

M(S)280

R-B 71/5

NORTHERN PART OF ADAVALE BASIN

ROUGH INTERPRETATION OF 2 SEISMIC PROFILES

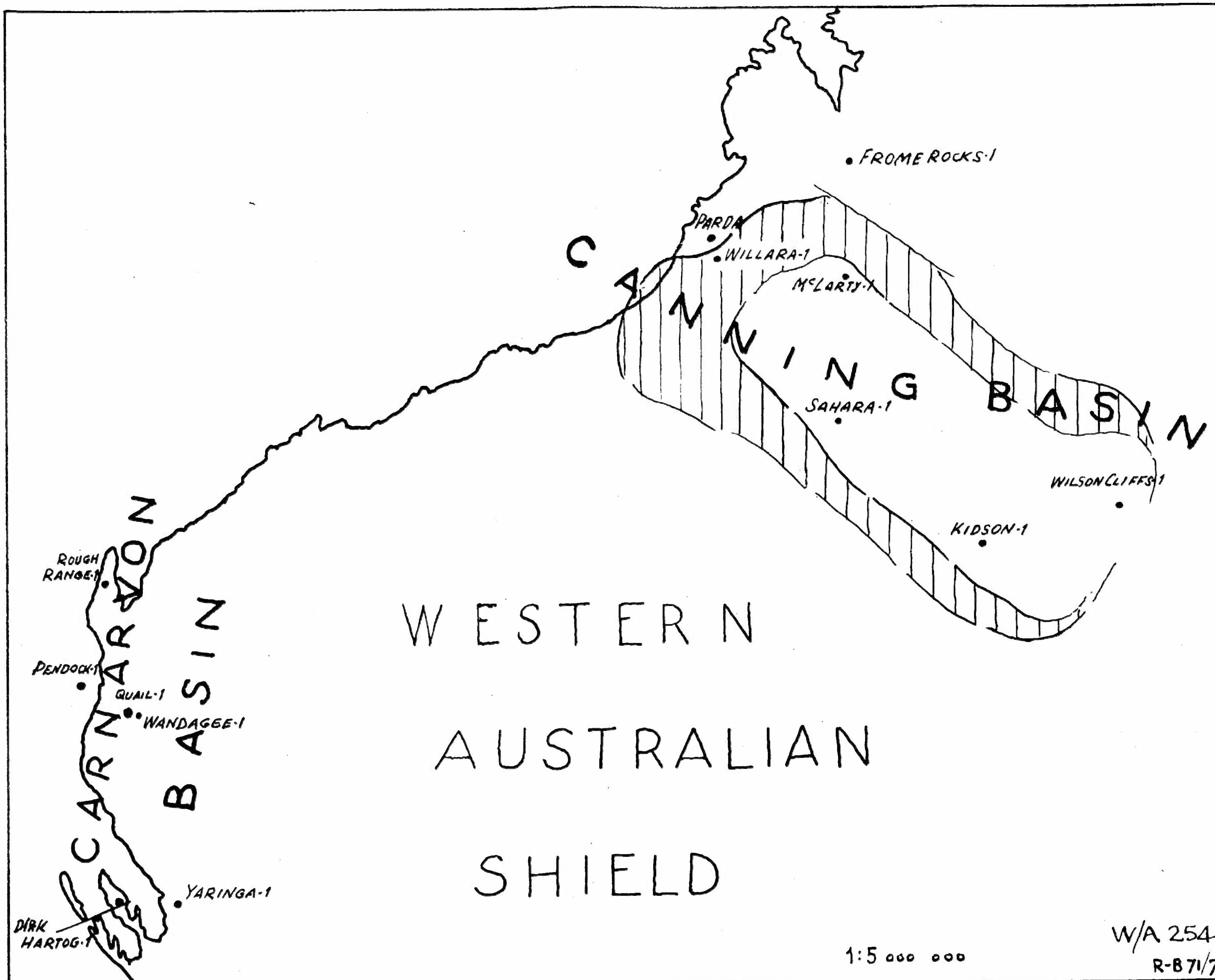


R-B 71/6

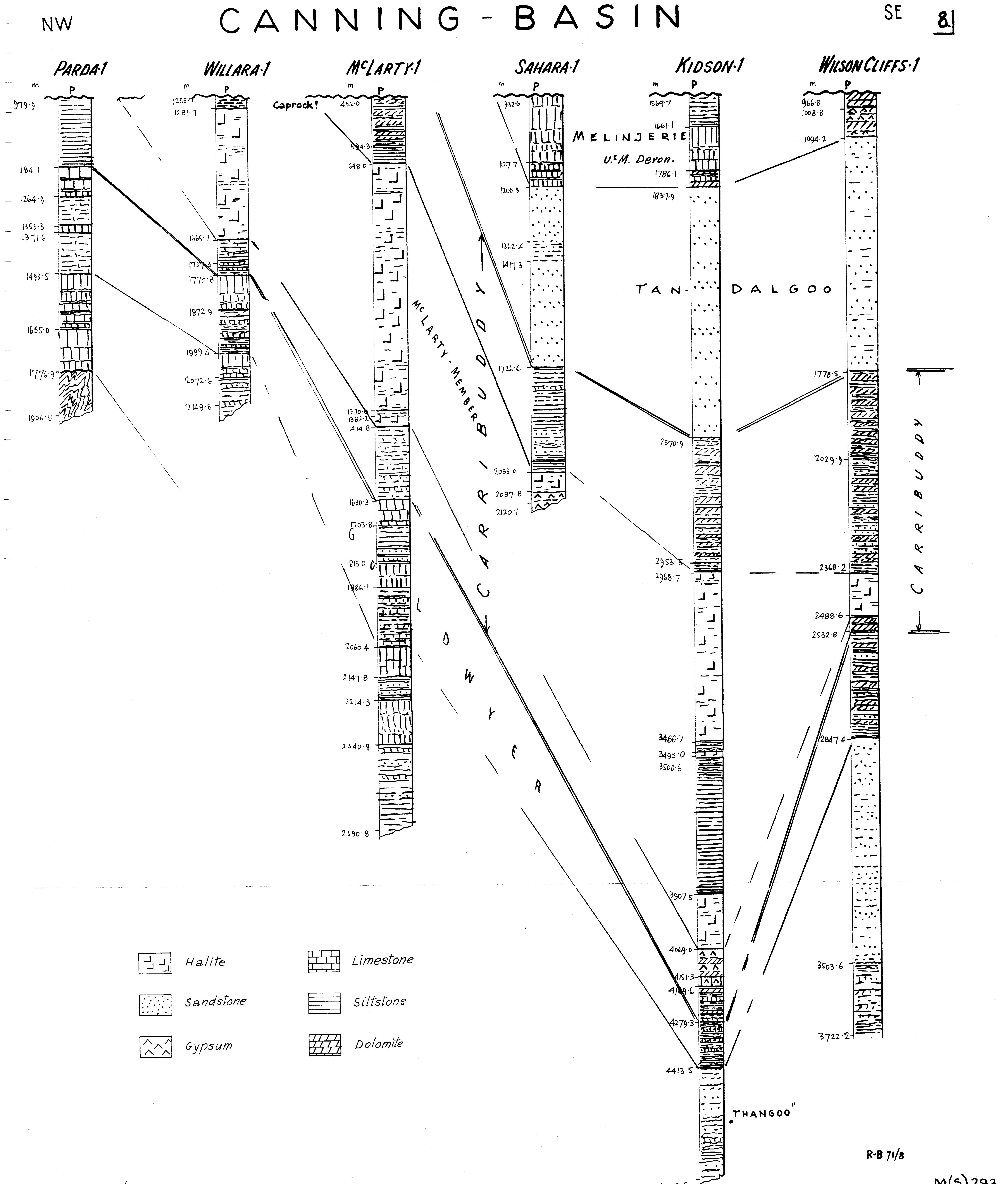
Record 1973/170

M(S)281

CANNING AND CARNARVON BASINS — WELLS PENETRATING EVAPORITES, AND SUBCROP OF SALT BELOW PERMIAN IN CANNING BASIN.

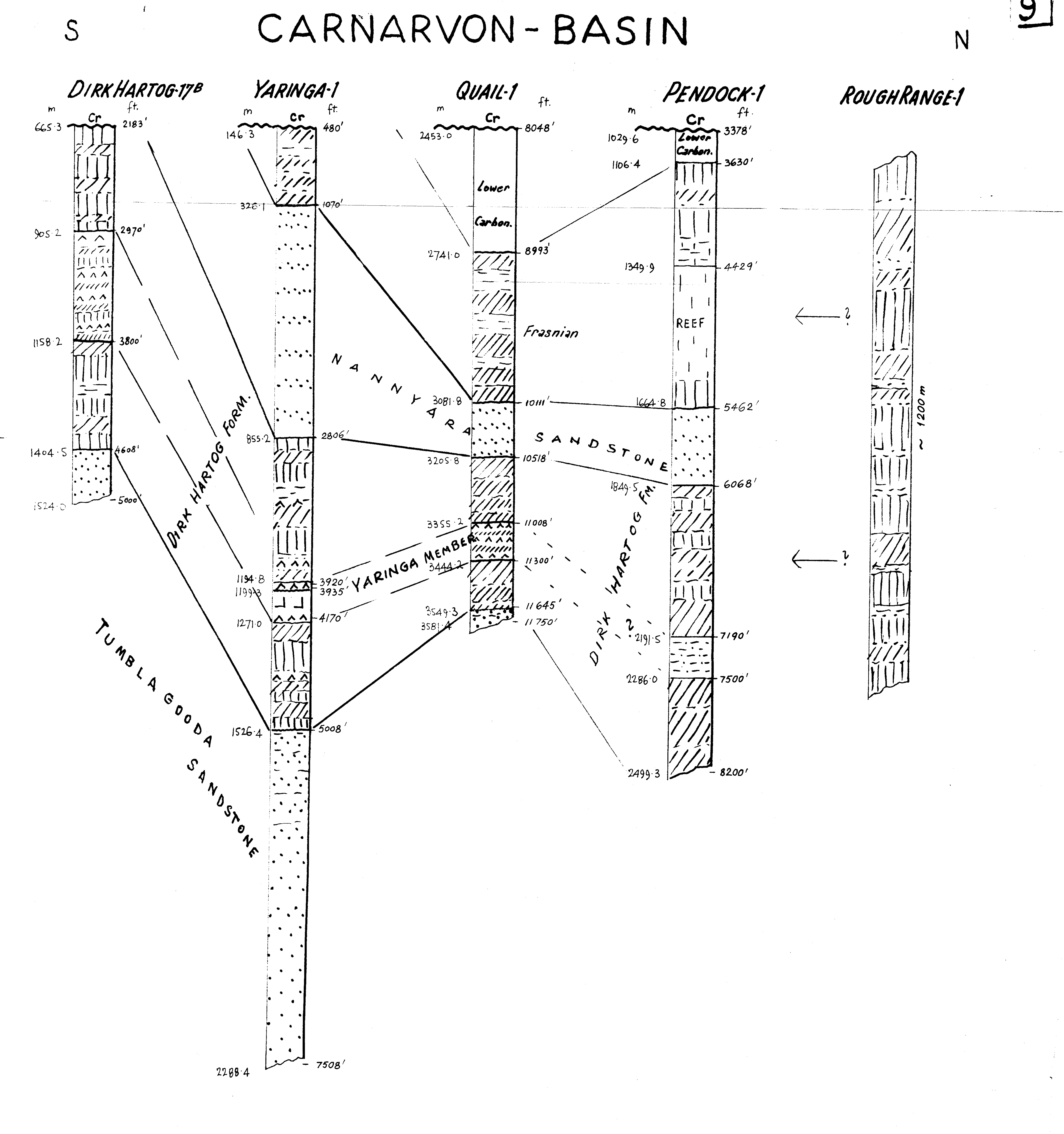


SE 81



Record 1973/170

M(S)283


S
CARNARVON-BASIN
N
DIRK HARTOG-17B
YARINGA-1
QUAIL-1
PENDOCK-1
ROUGH RANGE-1
Lower Carbon.
Frasnian
REEF
NANNYARRA SANDSTONE
DIRK HARTOG FORM.
YARINGA MEMBER
DIRK HARTOG FM.
TUMBLAGOODA SANDSTONE
~1200 m

gneiss has been drilled. Above the Thangoo Limestone the Upper Ordovician Goldwyer Formation forms the base for an evaporite member of the Carribuddy Formation. The salt in the 5 wells occurs in the middle part of the Carribuddy Formation and is stratigraphically well defined.

The McLarty No. 1, Kidson No. 1 and Wilson Cliffs No. 1 wells penetrated the salt in its true thickness of 766.8 m, 914.4 m (with interbedded shales), and 120 m respectively. In Willara No. 1 where 384.0 m of salt was drilled, the Permian unconformity cuts across the salt thickness (Fig. 10). Above that a shaly caprock of pre-Permian or Permian age and 26 m thick is developed. The Sahara No. 1 well stopped shortly after reaching the salt member which we may call "McLarty Member" for it is probably best developed in McLarty No. 1 well.

A NW-SE section (Fig. 10) below the Permian unconformity shows the interfingering of the salt member with the interbedded shale member towards the SE. This is undoubtedly approaching the margin of primary salt deposition.

The subcrop of the salt below the Permian is shown, from seismic information, in Figure 7. In the south-east the salt margin is not well defined because it becomes thinner towards its primary depositional margin. The boundary of the salt elsewhere is an erosional edge caused by pre-Permian denudation.

The salt rock is a typical "Haselrock" (in German: Haselgebirge) i.e. it is composed of halite and mostly red to greenish claystone or pelite. This type of rock is common in the northwest European Lower Permian as well as in the Triassic of the Alps, i.e. in more or less continental formations. In some parts of the salt sequence halite predominates, in other parts clay. The salt occurs in crystalline cubes, with cavernous faces, of 15 cm^3 size and more, spread irregularly over the pelite mass.

No evidence of potash could be found within the relatively small amounts of core and the gamma-ray logs do not indicate its presence. It is unlikely to occur in this type of salt.

Stratigraphically, there is a similarity to the Carnarvon Basin sequence. The correlation of the Nanyarra Sandstone with the Tandalgoo Sandstone and of the Carribuddy Formation with the Dirk Hartog Formation seems to be acceptable but so far there is no confirmatory palaeontological dating. Then the evaporitic "Yaringa Member" in the Carnarvon Basin and the "McLarty Member" in the Canning Basin could easily be contemporaneous sediments. Even the correlation with the "Boree Salt" in the Adavale Basin is a possibility.

I should add that the facies of the salt may change in the same manner as the facies of any other sedimentary rock. But we should study the geology of the whole of the basin for indications of where higher salinities are to be expected. For the Devonian that is surely not the area of central Australia which mainly includes the Amadeus Basin. Predominantly clastic sediments were deposited here during the Devonian.

The Fitzroy Trough is separated from the Canning Basin by the Broome Swell. I do not know whether there is a palaeogeographical separation too. But there is one interesting feature shown by the Frome Rocks No. 1 well. Below the Jurassic cover between 223.7 m and 769.9 m the well penetrated a dolomite-anhydrite caprock and then rock salt to 1220.1 m (T.D.). This uniform salt is lithologically distinct from the "McLarty Member" and other halite rocks. It is more a breccia where light grey dolomite in pieces of walnut size - also bigger or smaller - is more or less abundant. No bedding can be seen. However, the salt is remarkably stressed, as shown by the parallel orientation of the crystals. Salt of this type has undergone extraordinary movement. Even in normal salt domes such kind of stress structure is generally missing. The age of the salt and the formation from which it originated are not known.

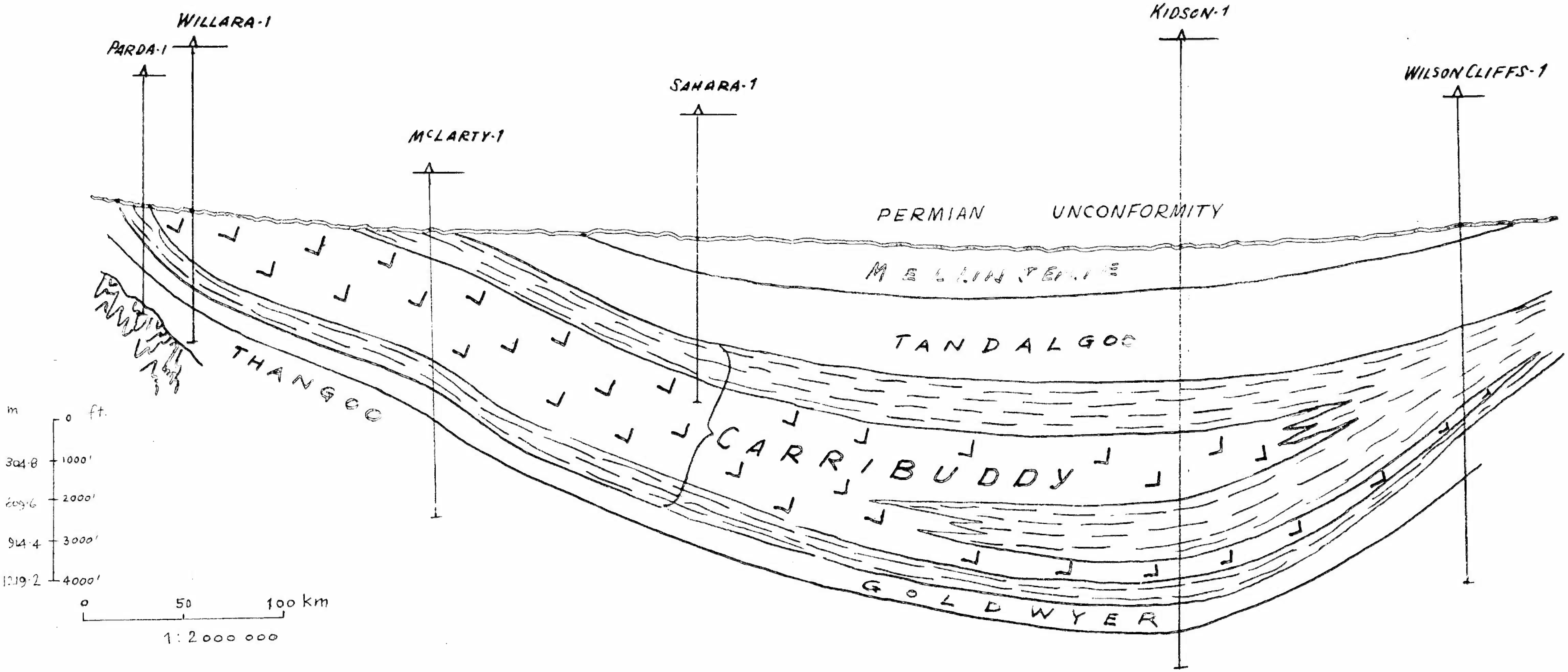
The Frome Rocks salt body has been explained, probably correctly, as a salt dome. Its position in relation to the regional structure (Fig. 11) indicates a diapiric movement along the northwest trending step fault, the "Barlee Fault". Seismic surveys northwest of the Frome Rocks Dome have indicated other similar structures suspected to be salt domes. However within the Doran structure, 13 km northwest of Frome Rocks, a well drilled to 823 m gave no evidence of a salt diapir, and other structures show gravity highs instead of minima. Thus, the explanation for these possible diapiric structures is still open.

(d) Amadeus Basin

In the Amadeus Basin, geological mapping has shown the presence of salt formations in the lower part of the very thick sedimentary sequence. The Goyder Pass, Illamurta, and similar structures can only be explained

CANNING BASIN

SECTION



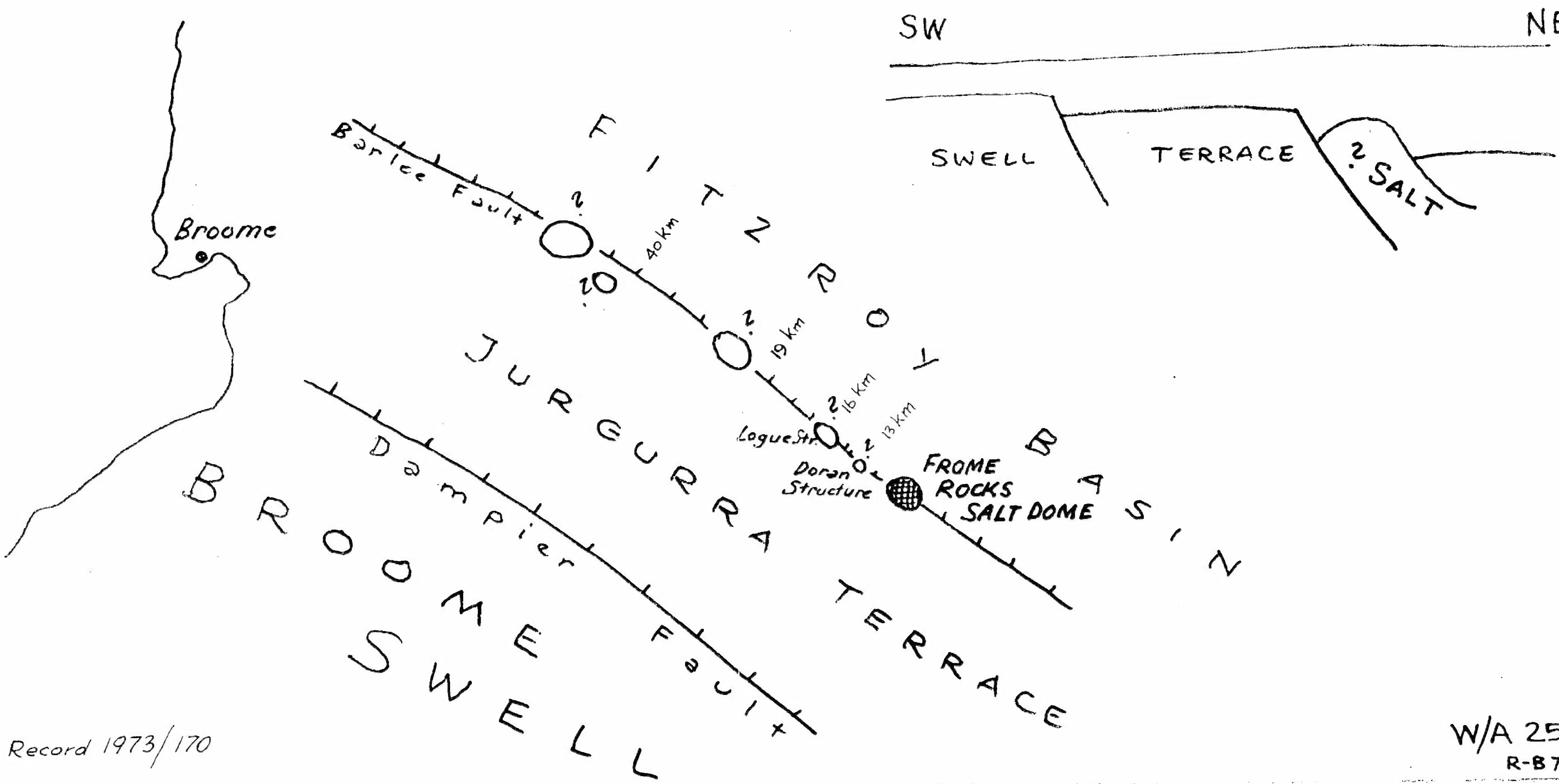
R·B 71/9

M(S) 282

Record 1973/170

FITZROY TROUGH

ROUGH TECTONIC SKETCH



Record 1973/170

W/A 255
R-B 71/10

adequately by the diapirism of considerable amounts of salt. Gypsum and clay alone will not produce such structures. From field work, the late Precambrian Bitter Springs Formation was suspected as the main evaporite sequence of the Amadeus Basin. In this formation, it is the older Gillen Member which contains, besides carbonate rocks, masses of gypsum and red shale at the surface, while the younger part, the Loves Creek Member, mainly consists of dolomite and limestone.

Some wells have proved this suspicion. Ooraminna No. 1 well penetrated red shale and salt from 1804.4 m - 1859.2 m (T.D.). Erldunda No. 1 well has more than 51.8 m rock salt from 1612.3 m - 1665.1 m (T.D.). No salt cores were available for study in these wells. BMR Mt Liebig No. 1 well located in the Bitter Springs Formation penetrated halite from 92.0 - 299.9 m. It is a pink, rather uniform, medium crystalline halite with interstitial light grey dolomitic claystone. The percentage of impurities changes only slightly and is low in general. (The salt is for instance, cleaner than the McLarty Salt Member). However, there are also beds where the ratio NaCl/Clay is about 1:1, and there is interbedded anhydrite of 30 - 60 cm thickness as well. At 298.7 m the dip is about 45°.

The salt is overlain by a very typical subrosion breccia (Richter-Bernburg, 1972b) composed of pink dolomitic marl with pieces of light grey dolomite. The whole rock can be called a marly caprock. Recognition of this rock on the surface could be useful in the search for a favourable location for another salt well.

Much higher in the Amadeus sequence another evaporite formation, the Chandler Limestone, is present. Halite has been penetrated in the wells -

Mt. Charlotte No. 1	Alice No. 1	Orange No. 1
Interval		
710 - 936.3 m	2063.4 - 2181.7 m	2314.6 - 2502.4 m
Evaporite thickness		
225.5 m halite	118.8 m halite with shale	187.7 m halite

No cores from these well sections were examined by me.

It may be of interest for further research that in the easternmost well, McDills No. 1 about 460 m of Todd River Dolomite has been drilled, and Chandler Limestone evaporite normally overlies the Todd River Dolomite. The Todd River Dolomite is missing in the Mt. Charlotte No. 1 well. It is possible that the carbonate facies predominates towards the east although a more salty facies increases in this member towards the west. The investigation of the Chandler Member should therefore be concentrated in the western area.

With respect to the search for larger amounts of Bitter Springs Formation salt in the Amadeus Basin, a working model is needed for discussion. Undoubtedly all folds and other structures of the well documented basin can be explained by high mobility at a deeper tectonic level. At least, the style of the deformation is the result of a mobile basal formation - comparable in smaller scale with the Swiss Jura. It could be that the Bitter Springs Formation accumulated by salt migration (halokinesis). This sub-surface accumulation could have been subroded in the belt of maximum thickness, more or less in a large zone which coincides with the northwest-southeast lineation of the large salt lakes, Lake Hopkins, Lake Neal, Lake Amadeus and so on. If it is intended to sink wells for salt exploration in this region, an airborne gravimetric survey could help to find the gravity minumum where the greatest and highest salt accumulation will exist.

It is almost impossible to make more recommendations over such a complex area like the Amadeus Basin, after such a short time.

(e) <u>Arckaringa Sub-basin</u>

The Arckaringa Sub-basin lies south of the eastern part of the Amadeus Basin. In the central part of this area Mt Toondina shows a very remarkable circular uplift structure, within the Permian, which looks like a salt dome, although there is no surface indication of salt in the area. However, about 8 km south of the Toondina uplift the well Cootanoorina No. 1 has been drilled. The sequence in this well is 0-187.4 m Cretaceous and Jurassic, 187.4-891.5 m Permian, 891.5-948.2 m (T.D.) dolomite and interbedded nodular anhydrite of probable Devonian age.

The Permian sediments do not show any indication of salt interbeds. The Devonian is of at least penesaline facies. Whether or not there was a connection to the Adavale Basin during the Devonian is unknown. In the Amadeus area, salt deposition was unlikely during the Devonian.

3. Summary

Generally, some points should be emphasized: conventional mining of rock salt or potash salt is only possible if the deposit -

(1) is high grade (rock salt more than 99% NaCl, potash salt at least 20% K_2O).

(2) occurs in this quality in sufficiently large amounts to allow mechanisation of mining.

(3) is less than 750 m below the surface.

(4) does not have to be transported long distances on land.

Solution mining of rock salt requires enormous quantities of water. If this is available the energy supply for refining or for using the brine in chemical industries should be guaranteed.

Mining potash by solution is only possible in extremely favourable situations.

Summarizing my report, and disregarding recent salt deposits, I may conclude :

1. Halite

The Yaringa salt in the Carnarvon Basin is of lowest interest. The information from every new occurrence of salt should be added to the total information up to date.

The McLarty salt in the Canning Basin seems to me a significant deposit. The prospects for exploitation will depend on the depth of the salt and on the distance from the sea. In the Willara No. 1 well the top of salt is at a depth of 1256 m, in the McLarty No. 1 well at only 648 m. Taking into consideration that Broome Harbour is not too far away, a possibility for exploitation could exist. The salt itself could be mineable by solution.

In the Adavale Basin the Boree Salt could also be extracted by solution mining as it occurs at considerable depths. Special seismic work should prove the upper limit of the salt northwest of the Warrego Fault. The economical and also the hydrological situation requires specific research.

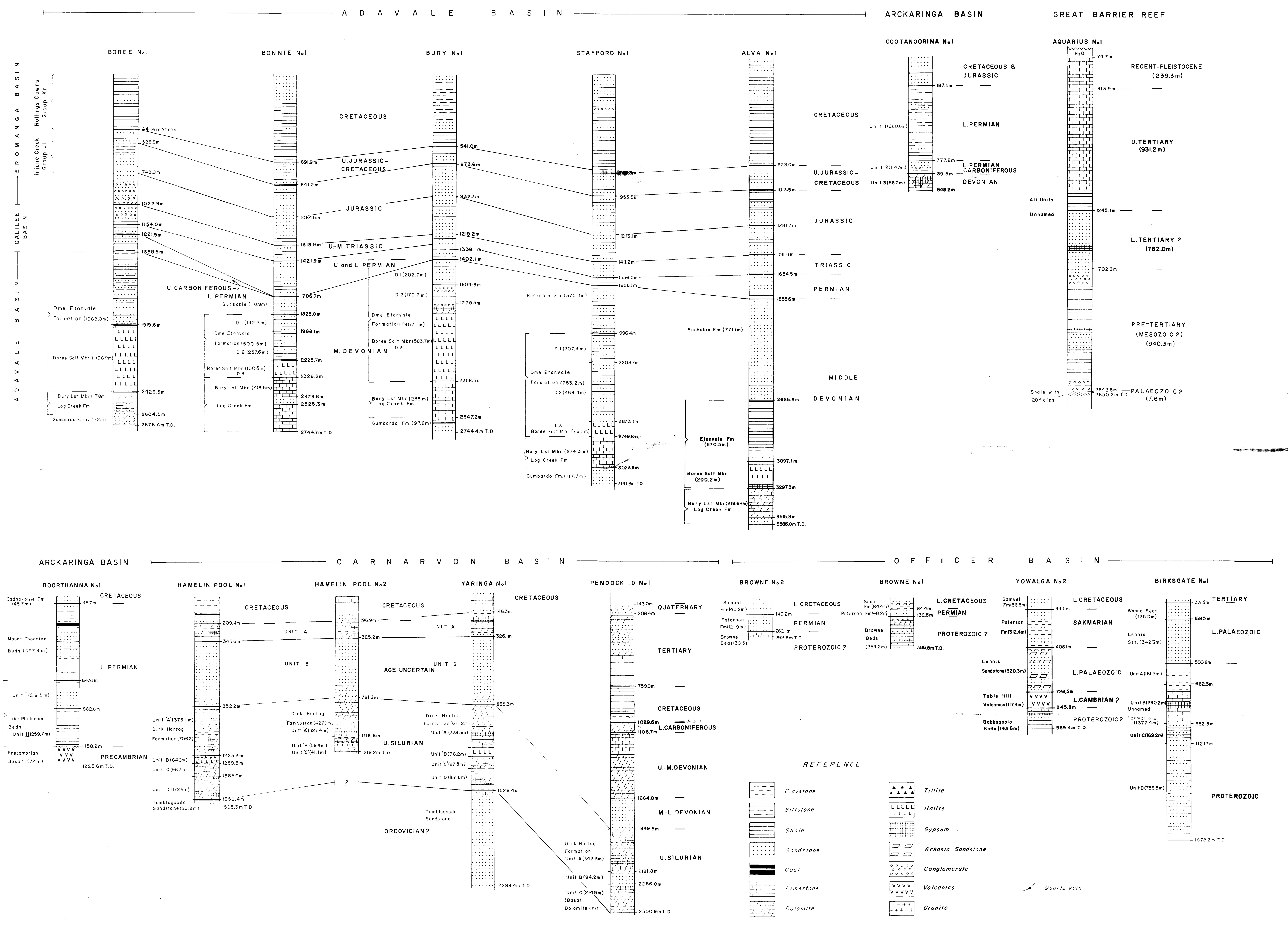
In the Amadeus Basin the salt of the Bitter Springs Formation can easily be proved by gravimetric surveying and shallow drilling. The same holds for the

Chandler Salt which could be defined more closely by facies investigation in the field. The continuation of exploration in these areas where water for solution mining would be extremely rare, seems to be, at least for the present, of little use.

2. <u>Potash</u>

The only known potash indications are in the Adavale Basin. Three wells show that in this basin the concentration point for the sedimentation of KCl has been reached several times. But no commercially interesting bed has been found up to date. The other basins can be judged neither positively nor negatively.

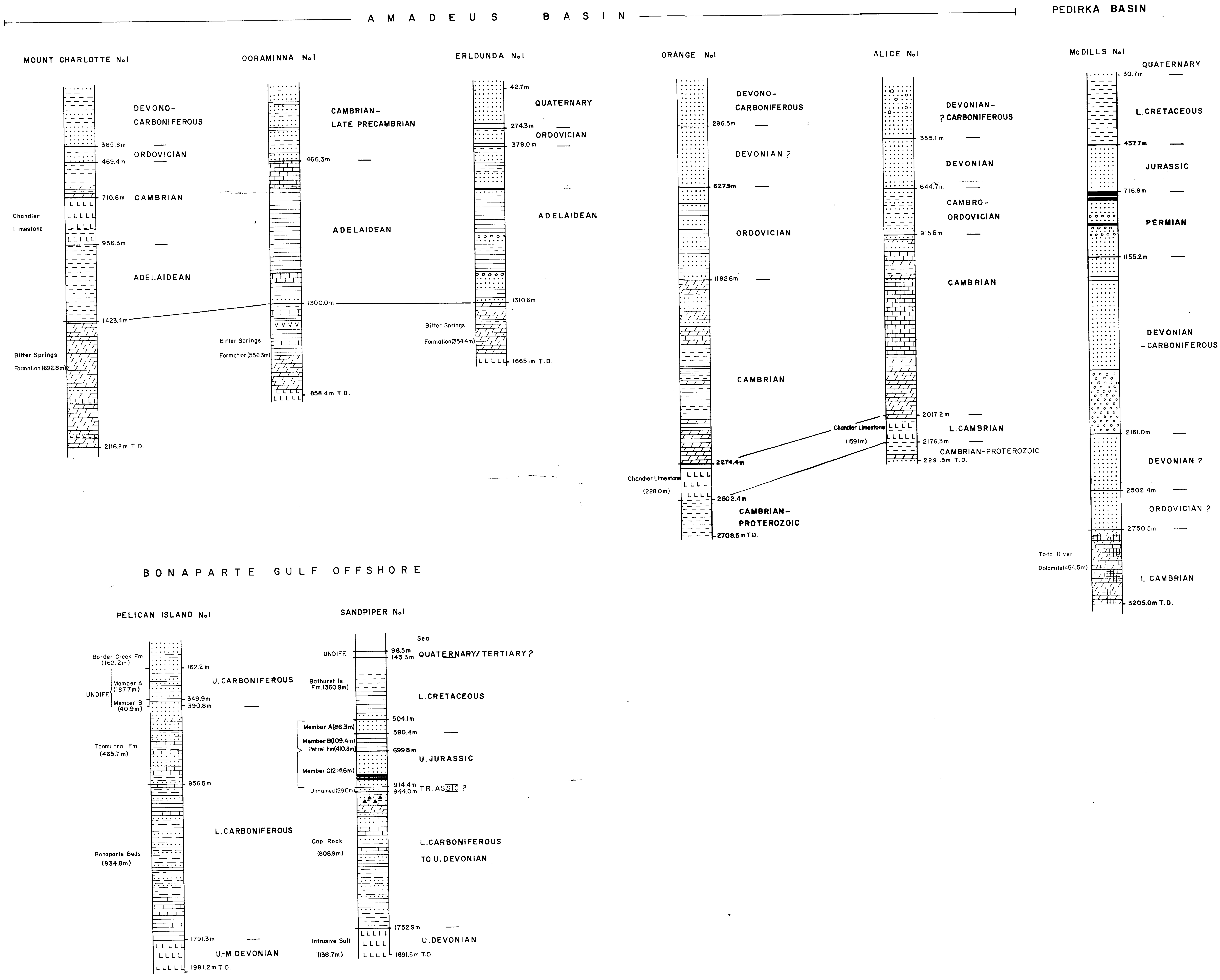
PLATE I-GRAPHIC SECTIONS OF WELLS SHOWING EVAPORITES



To accompany Record 1973/170

M(G)278

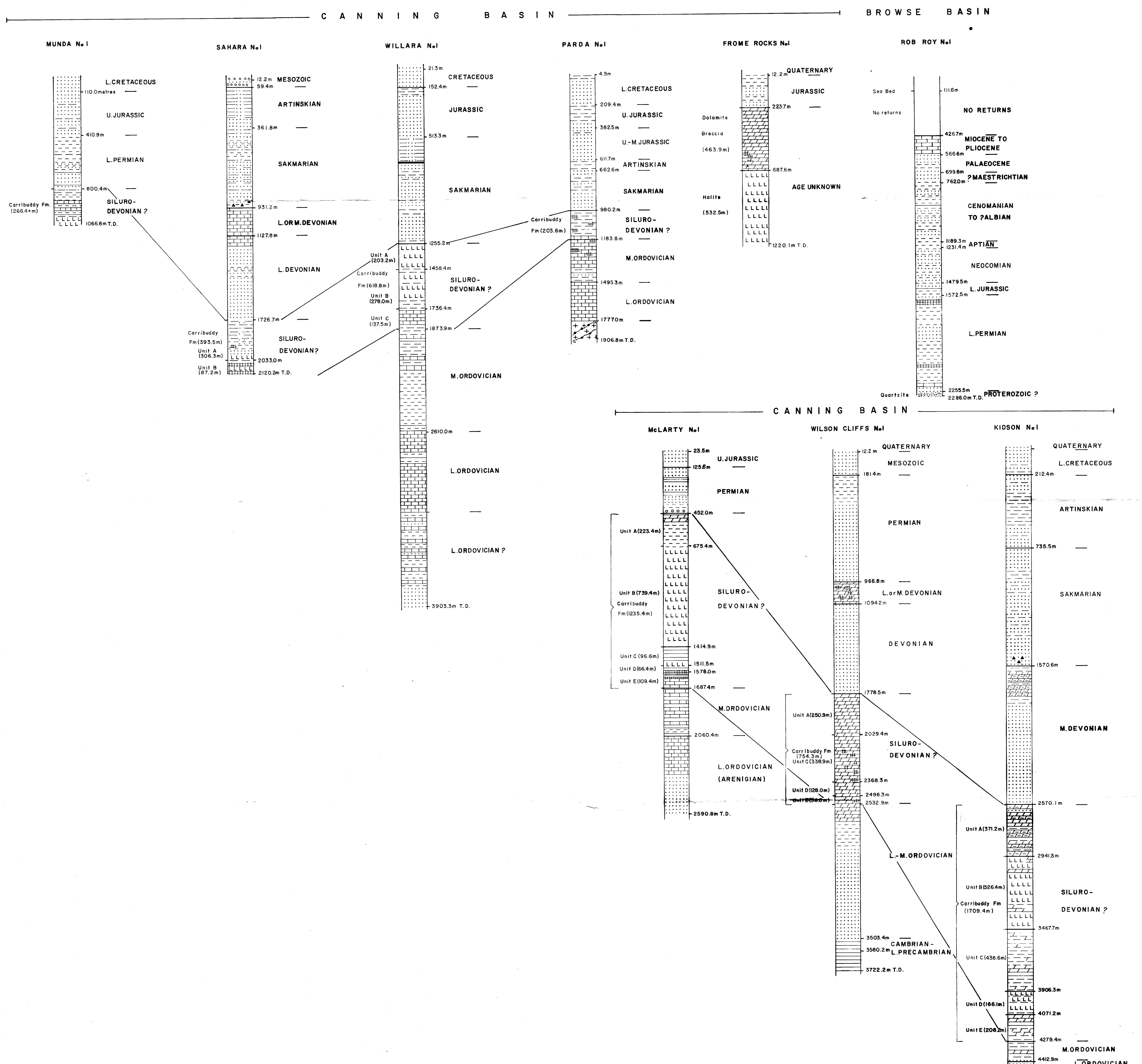
PLATE II—GRAPHIC SECTIONS OF WELLS SHOWING EVAPORITES



To accompany Record 1973/170

M(G) 279

PLATE III-GRAPHIC SECTIONS OF WELLS SHOWING EVAPORITES



To accompany Record 1973/170

M(G) 280

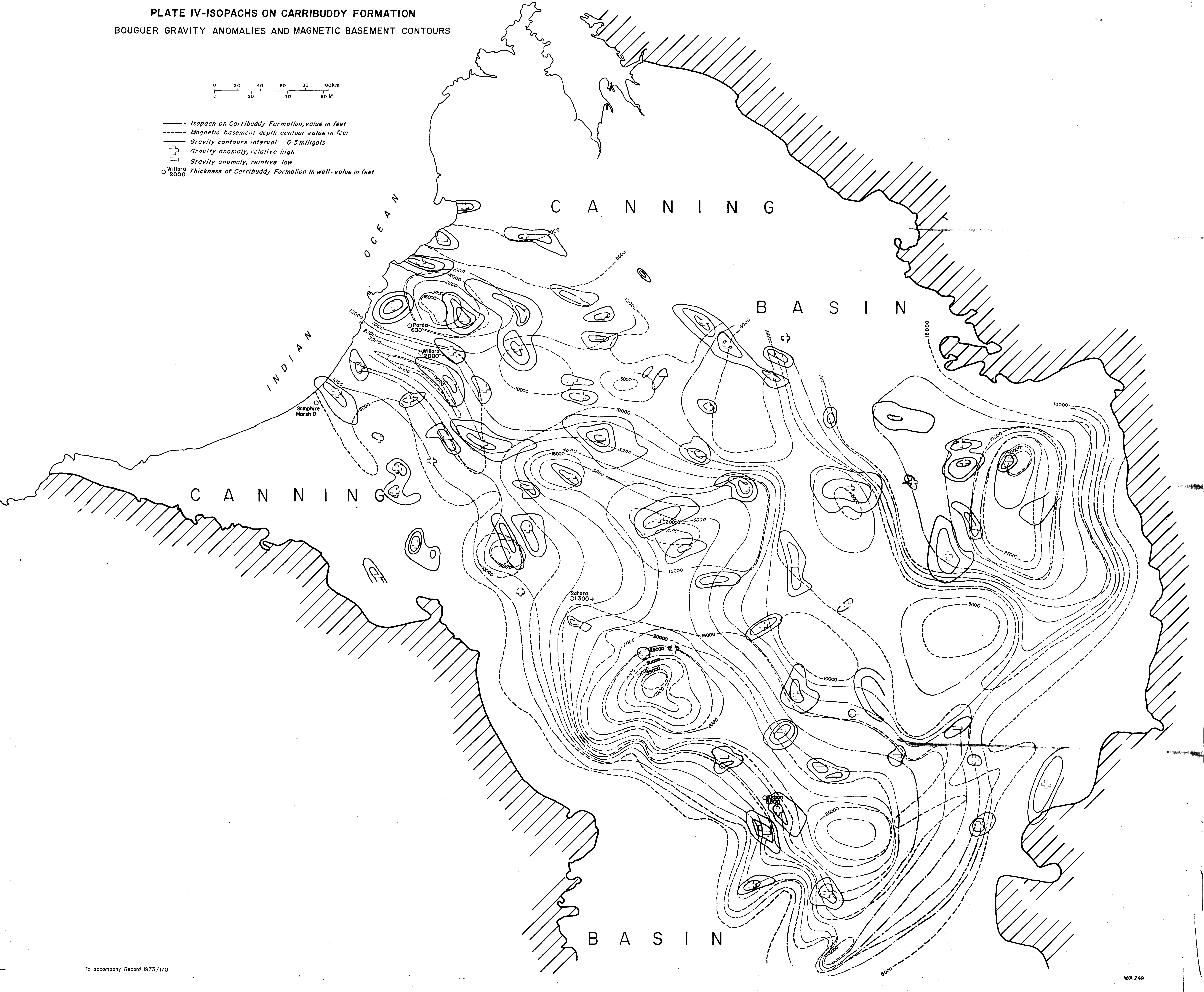


PLATE IV-ISOPACHS ON CARRIBUDDY FORMATION
BOUGUER GRAVITY ANOMALIES AND MAGNETIC BASEMENT CONTOURS
0 20 40 60 80 100km
0 20 40 60 M
Isopach on Carribuddy Formation, value in feet
Magnetic basement depth contour value in feet
Gravity contours interval 0·5 miligals
Gravity anomaly, relative high
Gravity anomaly, relative low
Willara 2000 Thickness of Carribuddy Formation in well-value in feet
INDIAN OCEAN
CANNING BASIN
CANNING BASIN
Parda 600
Willara 2000
Samphire Marsh
Sahara 1,300+
Kidson 5,500
To accompany Record 1973/170
WA 249

PLATE V-CROSS SECTION OF KIDSON SUB-BASIN

To accompany Record 1973/170

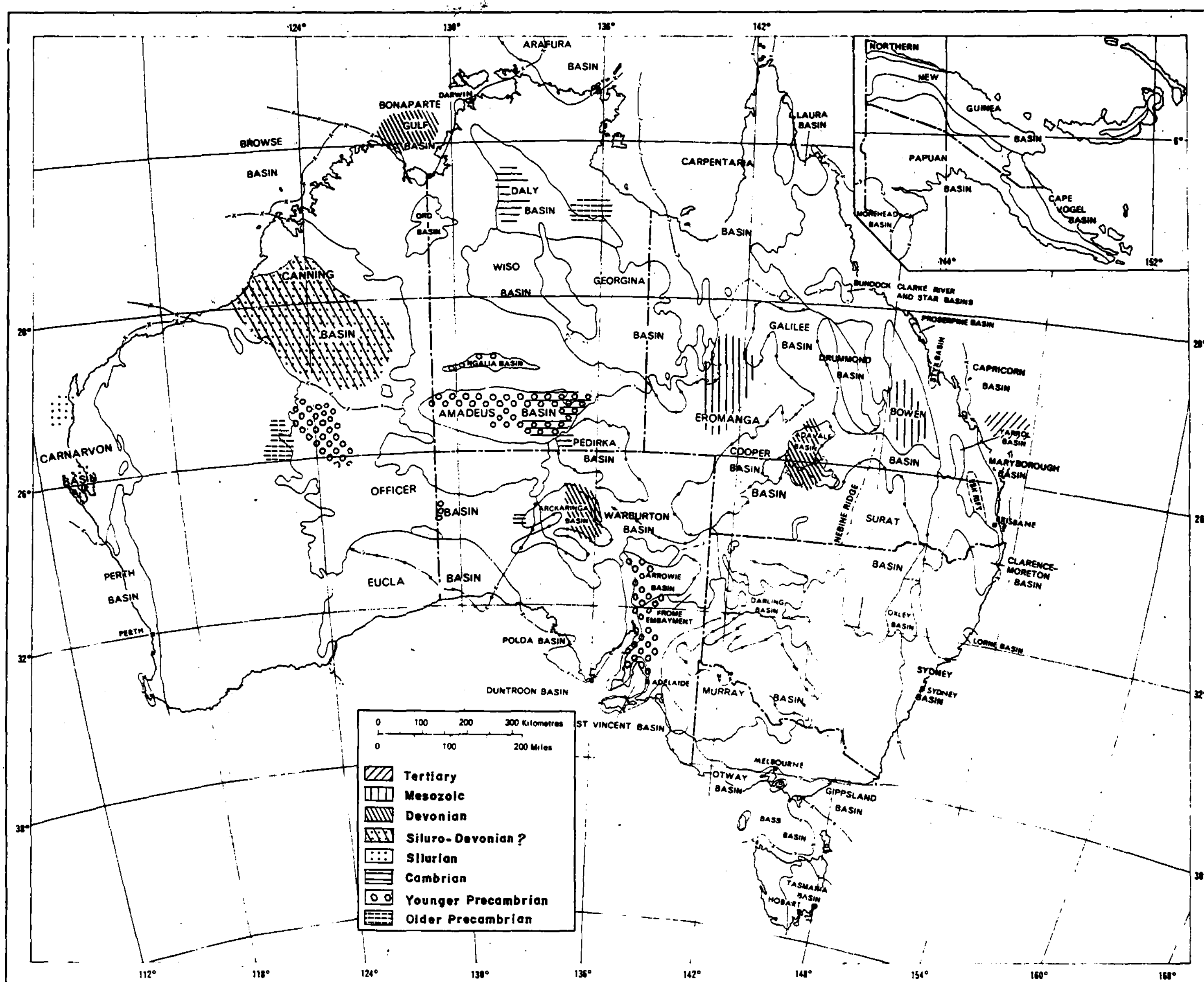
W/A 250

PLATE VI-LOCATION OF SUBSIDISED WELLS IN WHICH EVAPORITES HAVE BEEN ENCOUNTERED-and other wells mentioned in text of report

To accompany Record 1973/170

AUS 2/303

PLATE VII- PROBABLE SUBSURFACE EXTENT OF EVAPORITES OR EVAPORITE FORMATIONS



To accompany Record 1973/170

Aus I/223