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Front cover:

A thin section of chert, *circa* 3500 m.y. old, from the North Pole barite mine near Marble Bar, WA. The rock was originally a fine-grained carbonate in which rosettes of gypsum grew during diagenesis. The former presence of gypsum confirms the occurrence of sulphate evaporites early in the Archaean.

Photograph (x8): R. Buick, Department of Geology, University of Western Australia, Nedlands, WA, 6009.

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Calibration of gravity meters with a quartz-mechanism

D. A. Coutts, P. Wellman & B. C. Barlow

Gravity meters with a quartz mechanism can be calibrated on tilt tables, on hillside calibration ranges with stations at different altitude, or on level calibration ranges with stations at the same altitude. Twenty Worden, Sharpe, and Scintrex gravity meters have been calibrated in Canberra on a PEG-1 tilt table borrowed from the Soviet Academy of Sciences. These calibrations agree, to within experimental error, with tilt calibrations by the manufacturers in North America, and calibrations based on sea-level stations along the Australian Calibration Line. Calibrations on hillside calibration ranges differ systematically from other calibrations, and indicate a mean altitude effect of (2.5 ± 0.5) × 10^{-3} μm s^{-2} m^{-1}. This altitude effect is higher than the mean of (1.5 ± 0.3) × 10^{-3} μm s^{-2} m^{-1} found by pressure-chamber studies in North America and Europe. If quartz-mechanism gravity meters are used either in base station gravity networks, or for field stations in areas with over 500 m of relief, then a correction should be made for this altitude effect, particularly if the anomalies are to be used for geodetic purposes.

Introduction

Most gravity surveys in Australia have been carried out using gravity meters with a quartz-mechanism. This is because instruments of this type were the most satisfactory instrument available in the 1960's, when most of the gravity work was undertaken; they are still the most widely available type of gravity meter. In Australia the major problem, that of calibration, was essentially solved in 1960-61 when the Bureau of Mineral Resources (BMR) set up hillside calibration ranges throughout Australia (Barlow, 1967).

At the time the calibration ranges were established it was known that calibrations measured on hillside calibration ranges differed systematically from calibrations obtained by the manufacturer by the tilt method (Barlow, 1967). Observations on the Australian Calibration Line in 1970 showed that there was a large discrepancy between gravity intervals measured by LaCoste & Romberg gravity meters and quartz-mechanism gravity meters when the stations differed greatly in altitude (Cooke, 1970). In addition one gravity meter on the 1970 survey gave a distinctly non-linear response between dial-reading and gravity. Overseas work prior to 1963 had shown that gravity meters with a quartz-mechanism are affected by ambient pressure, and that the instrument scale factor is related to the average daily ambient temperature and the pressure in the vacuum chamber of the instrument (Gantar & Morelli, 1963).

In 1973 the Soviet Academy of Sciences offered to lend BMR a tilt table and train an operator in its use, so that some of these known problems could be investigated experimentally. Coutts was trained in Moscow during four weeks of 1974, and later calibrated gravity meters intermittently in Canberra from 1975 to 1977.

It was decided to calibrate as many Australian gravity meters as possible on the tilt table, both to obtain as much information as possible on the relative magnitude of tilt and hillside calibration factors, and to investigate the linearity of as many as possible of the gravity meters that had been used to obtain the reconnaissance gravity coverage of Australia. A circular was sent to all known owners of gravity meters with quartz mechanism in Australia, requesting the loan of their meters for one to two weeks. There was an excellent response to this circular, and twenty gravity meters were investigated.

This paper compares tilt table calibrations by BMR in Canberra, tilt table calibration by the manufacturer in North America, calibration on the hillside calibration range in Canberra and Melbourne, and calibration along the sea-level stations of the Australian Calibration Line. It also discusses the pressure effect, and the non-linearity of calibration of some gravity meters.

Comparison of the two methods of calibrating gravity meters with a quartz-mechanism

Calibration range

A calibration consists of making alternate gravity meter readings at two stations which differ in gravity by a known amount. The gravity meter calibration constant is calculated by dividing the gravity interval by the average difference between the two sets of readings. In Australia calibration ranges are often on hill-sides, the two gravity stations differing in altitude by about 250 m. Instrumental drift and earth tide are corrected using the assumption that they are linear between successive observations at one station.

The disadvantages of this method of calibration are:

(a) If a single calibration is made without resetting, then only two points on the reading screw are utilised, and the method does not check the non-linearity of the reading screw and spring.

(b) Most calibration ranges have a gravity interval of only about 500 μm s^{-2}, so that meters with this small range can be calibrated (1 μm s^{-2} = 0.1 mGal). Calibration over 2000 μm s^{-2} would be desirable for larger range meters.

(c) If the gravity meter is not completely compensated for changes in atmospheric pressure, then the calibration on a hillside range will not be correct for gravity measurements on level terrain.

(d) There are difficulties in accurately determining the magnitude of the gravity interval.

The advantages of the calibration range method are:

(a) The calibration constant for a particular part of the dial can be checked precisely with no special equipment or skill, and the time required is only two or three hours.

(b) The process of calibrating the gravity meter checks that the meter works under field conditions, and in particular checks its sensitivity to vehicle movement.

Tilt table

A tilt table is a specially designed apparatus for tilting a gravity meter in the direction of the hinge of the gravity meter beam. If the angle of tilt (θ) is small the quartz mechanism should not deform, so if g is the gravitational acceleration at that site, the effective gravitational acceleration on the beam will be g.cos θ. If the gravity meter is read for a range of tilt angles, a least squares relation can be calculated between each reading (R) and the tilt angle

$$g.\cos\theta = a + k_1 R$$

where a is a constant and k_1 is the calibration constant for the meter. Deviations from this relation reflect experimental errors and non-linearity of the reading screw and spring. If the deviations are much greater than experimental error and are systematic, the reading screw or spring is non-linear and a table of corrections to dial reading should be prepared. These corrections should be applied to all readings on this gravity meter.

The disadvantages of the tilt calibration method are:

(a) A trained observer and special equipment are required.

(b) A total calibration takes longer than two hours because, although the tilt measurements take about 75 minutes, the meter must be allowed to settle down when it is initially put on the tilt table.

(c) Tilt calibrations cannot be made on LaCoste & Romberg or North American gravity meters, because they have a hinge system which deforms on tilting.

The advantages are:

(a) The calibrations are absolute if the correct value of gravity at the point is used, and the quartz mechanism does not deform.

(b) The calibrations are made under laboratory conditions, so each one is made at a single temperature, pressure, and vibration regime.

(c) The linearity of the reading screw and spring is checked and calibrations encompass the full range of the meter.

The Soviet tilt table (Fig. 1) differs from American tilt tables in that (a) angles are measured using a theodolite, and (b) the working parts of the meter are removed from their vacuum flask and case and clamped firmly, so that no movement can occur between the working parts and the tilt table. However, with no vacuum flask to damp ambient temperature variations, much more care must be taken to keep such temperature constant, and radiant heat from the observer has a greater effect on the temperature of the mechanism.

Calibrations using a tilt table

The initial tilt table work was carried out at Moscow in the Institute of the Physics of the Earth. Details of the tilt-table procedure are given by Rukavishnikov & Zukov (1969), and they are summarised in English by Csapo & others (1974). Two BMR gravity meters were calibrated, Worden 169 on tilt table PEG-1 No. 17 and Sharpe 145 on tilt table PEG-3 No. 2743. The Moscow tilt calibration site is a room about 7 m square on the ground floor of a multi-storey apartment block adjacent to the Institute. Use of an isolated concrete pier largely eliminated building noise; however, the measurements were affected by traffic on a major

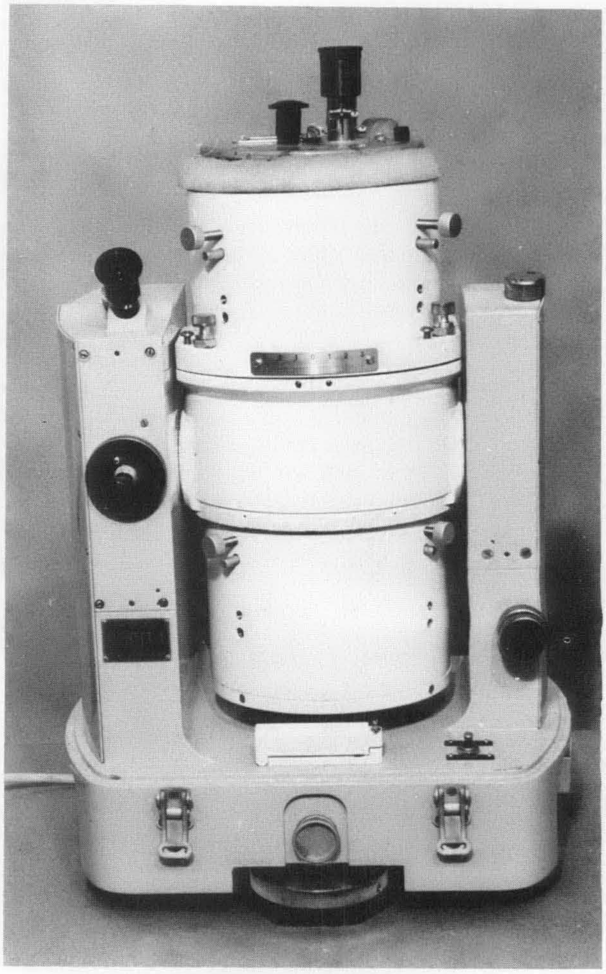

Figure 1. PEG tilt table with a gravity meter inside.

city road about 50 m away. The temperature of the room varied from 15 to 20°C, the acceleration due to gravity at the site is 9 815 610 μm s^{-2}. Both meters were subsequently calibrated on the hillside range of the Moscow Polygon.

The tilt calibrations in Canberra were in a 6 x 6 m basement room of the four-storey (above ground) BMR building. Although there was no isolated pier the site was quieter than that in Moscow. The room temperature varied less than 0.2°C during a calibration, about 1°C during a day, and throughout the year varied from 19 to 23°C. Tilt table PEG-2 No. 1 was used for all Canberra calibrations. For logistic reasons the metal tripod for the tilt meter was not brought to Australia. The tilt table was set up directly on the concrete floor with the operator seated on the floor. The acceleration due to gravity at this site is 9 796 039 μm s^{-2}.

The following is a summary of the procedure that took place on receiving a gravity meter for tilt calibration in Canberra. The meter was first evacuated to 6 mm pressure for Worden, and less for Sharpe and Scintrex meters. The mechanism of the gravity meter, without the Dewar flask and outside case, was then clamped into the tilt table. Sharpe, Scintrex and long Worden gravity meters were clamped at the top and bottom; short Worden gravity meters did not reach the lower clamp so were clamped only at the top.

Level bubble and sensitivity tests were then made, and the bubbles were adjusted if necessary. A series of measurements and adjustments were then carried out

Gravity meter No.	Owner‡	Date of tilt calibr.	Max dial reading used (sc.div.)	2nd degree cal. const. ($\mu m\ s^{-2}/(sc.div.)^2$) x$10^7$	Linear calibration constant from tilt calibration ($\mu m\ s^{-2}$/scale division)[2]	(1)	(2)	(3)	(4)	(5)	(6)	Weighted mean	Hillside calibration after Canberra or Moscow tilt calibration ($\mu m\ s^{-2}$/sc.div.)	Manufacturer's tilt calibration and year ($\mu m\ s^{-2}$/sc.div.)	
W41	U. Syd.	11/74	700	86±38	1.01+	80±2	68±3	76±2	72±2	70±4	64±4	1.0174±2	1.0158±4		
W61	BMR	05/75	700	−192±99	0.90+	71±2	87±3	93±3	85±3	76±3		0.9080±4	0.9053±5		
W70	U. WA	09/75	700	−286±126	1.06+	81±3	84±5	87±4	84±3	86±8		1.0684±1	1.0676±2	1.067	1973
W140	BMR	01/77	2100	11±13	1.02+	13±1	16±1	16±1	15±2	14±1		1.0215±1	1.0200±1	1.0212	1975
W169 I	BMR	09/74	2100	−20±18	1.01+	38±2	36±2	39±2	40±2			1.0139±1	1.0118±9*	1.0123	1973
II		04/75	2100	−1±11	1.01+	19±1	21±1	18±1	21±1	19±1		1.0120±1	1.0114±1	1.0123	1973
III		04/77	2100	−21±07	1.01+	18±1	20±2	18±2	19±2	17±1	19±2	1.0118±1	1.0113±2	1.0123	1973
W216	Min. Ad.	10/76	700	760±153	1.00+	65±6	64±7	62±9	65±5	52±6	71±3	1.0066±3	1.0056±10		
W260	BMR	06/75	2100	−19±06	1.00+	43±1	48±2	47±1	46±1	48±2	45±1	1.0045±1	1.0034±2	1.0046	1975
W273	U. Tas.	06/75	1900	−7±11	1.00+	80±2	77±1	81±2	81±2	79±1	80±1	1.0079±1	1.0061±2	1.0091	1967
W274	Wongela	06/75	2100	6±10	0.91+	74±1	74±1	74±1	75±2	75±1	75±1	0.9175±1	0.9166±2	0.9176	1969
W286	XLX Pet.	11/74	700	−1±79	0.93+	38±3	52±2	41±2				0.9344±4	0.9322±3		
MW548	BMR	03/77	2100	−51±08	1.09+	65±2	65±2	60±2	64±1	62±1	66±2	1.0964±1	1.0965±2	1.0967	1975
W592	Wongela	06/75	2100	28±06	0.97+	91±1	92±1	89±1	89±1	95±1	90±1	0.9791±1	0.9778±6	0.9805	1977
W708	Wongela	05/75	1900	31±14	1.01+	06±1	04±1	04±2	04±1	03±1	08±2	1.0104±1	1.0089±2	1.0097	1974
W818	U. Qld	03/76	2100	122±19	0.86+	51±4	49±3	50±2	50±2	47±4	46±3	0.8649±1	0.8646±1	0.8655	1973
S145 I	BMR	09/74	900	48±39	1.01+	04±5	10±3	10±4	14±3	17±3	14±2				
						11±3	16±2	09±3	18±3	15±3	18±3	1.0114±1	1.0117±5*	1.0125	1973
II		10/74	900	373±29	1.01+	12±5	13±4	13±4	17±4	17±3	18±2	1.0116±1	1.0117±2	1.0125	1973
III		04/77	900	245±35	1.01+	16±4	20±3	20±5	21±4	19±3	20±2	1.0120±1	1.0113±2	1.0125	1973
S154	BHP	07/75	900	15±60	1.10+	22±3	27±3	21±3	27±3	23±3	23±3	1.1024±1	1.1007±1		
S201	SA Mines	08/75	900	136±46	1.00+	20±2	16±2	14±3	17±2	16±3	14±2	1.0016±1	1.0018±1	1.0646	1967
S190G	SA Mines	08/75	900	276±49	1.00+	42±4	43±2	48±4	46±4	21±7†	41±4	1.0044±1	1.0012±2		
S255G	U. Melb.	09/76	900	181±54	1.01+	02±3	06±4	99±4	11±3	10±3	13±3	1.0108±2	1.0102±2	1.0107	1969
S308	U. New Eng.	07/75	900	58±34	1.00+	80±3	79±2	81±2				1.0080±1	1.0068±1		

* using Moscow calibration range. † previous measurement rejected. W meters are Worden gravity meters, S meters are Sharpe, except S255G and S308 which are Scintrex. All uncertainties are given as standard deviation of the mean. ‡ full names, see acknowledgements.

Table 1. Results of tilt-table calibrations in Canberra and Moscow.

to position the torsion hinge of the gravity meter as closely as possible perpendicular to the rotation axis of the movable frame of the tilt table. After these preparations the meter was allowed to settle down overnight.

A tilt calibration consists of measuring tilt angle and gravity meter dial reading for equally spaced positions along the gravity meter small dial. The gravity meter is set on each of the required dial positions, it is tilted in one direction until it gives a null reading, then tilted in the other direction until it again gives a null reading; the required angle is one half the angle between the two null readings. Generally dial positions 100 to 200 scale divisions apart are used. Alternate calibrations were made with slightly different sets of dial positions. Instrument drift and earth tides are corrected for by assuming that they vary linearly during each set of measurements.

A set of six tilt-table calibrations was made on each gravity meter, each calibration taking about 75 minutes. Usually one to three calibrations were made in each eight-hour day; a greater number is thought to decrease the calibration accuracy because of increasing strain on the gravity meter mechanism, and because of operator eye-strain and fatigue owing to the long periods of concentration. However, for gravity meters W41, W169, W260, W708 and W818 there was insufficient time available to space the tilt calibrations over two days, and four or five calibrations were completed in one day. Results of Moscow and Canberra tilt calibrations are given in Table 1. (All errors given in this and subsequent tables are standard deviations of the mean.)

The manufacturers in North America carry out tilt calibrations on new gravity meters, and meters sent back to them for a major overhaul. For these calibrations the complete gravity meter stands on a rigid table supported by three points; tilting is by means of slip gauges. These calibrations are called by the manufacturers an 'absolute calibration'. For comparison with the Canberra calibrations they are listed in Tables 1 and 2.

Calibrations using a hillside calibration range

Hillside calibration ranges in Australia have an altitude difference of about 250 m, and a gravity interval of about 500 μm s^{-2}. For each calibration four readings are made at the bottom station; these alternate with three readings at the top station. Until shortly before calibration runs in Canberra and Melbourne the meters were stored in a basement room, the temperature of which varies from 19 to 23°C. The temperature of the gravity meter mechanism does not change substantially through the calibration run of two hours. During the Canberra hillside calibrations the mean outside temperature ranged from 4°C to 23°C, and averaged 7°C cooler than during the tilt calibrations.

Hillside calibrations were made at the end of the Moscow tilt calibrations, and generally a few days after Canberra tilt calibrations. The hillside calibration ranges used were the Moscow Polygon of 523.7 ± 0.2 μm s^{-2}, and the Black Mountain Canberra Calibration Range of 547.72 ± 0.02 μm s^{-2}. Results are given in Table 1.

BMR gravity meters have throughout their life been calibrated on hillside ranges at irregular intervals. Some of these earlier calibration results are used later in this paper. Early calibrations were on the Melbourne Calibration Range of 530.25 ± 0.10 μm s^{-2}, calibrations between 1965 and 1977 on the Black Mountain Canberra Calibration Range, and later calibrations on the Mount Ainslie Canberra Range of 559.82 ± 0.04 μm s^{-2}.

These gravity intervals for hillside calibration ranges were calculated by Wellman & McCracken (1975). The scale determination for the intervals is accurate, because the only observations used are those of LaCoste & Romberg gravity meters that had been accurately calibrated over a gravity interval of at least 20 000 μm s^{-2} within three months of the hillside observations. The minor pressure effect of about 3 10^{-4} μm s^{-2} Pa^{-1} (Boedecker, 1978) for LaCoste & Romberg gravity meters was not corrected for; this effect would lead to errors in the gravity intervals of about 0.06 μm s^{-2}, or an error in scale of about 1 10^{-4}.

Calibration on the Isogal network and Australian Calibration Line

Major surveys in Australia using two or more quartz-mechanism gravity meters include surveys in 1965 and 1967 to set up the Australian National Gravity Base Station Network (Isogal network) (McCracken, 1978) and surveys along the Australian Calibration Line (ACL; Tasmania to Papua New Guinea) in 1970 (Cooke, 1970) and in 1973 (Wellman & others, 1974; unpublished data). During these surveys both LaCoste & Romberg and quartz gravity meters measured gravity intervals on calibration ranges and on north-south lines of stations spanning 20 000 to 30 000 μm s^{-2}.

The LaCoste & Romberg observations have been used to calculate gravity values on the Isogal 74 system for all ACL stations including the stations defining calibration ranges (Wellman & others, 1974; Wellman & McCracken, 1975; McCracken, 1978). These values are thought to be consistent within experimental error with the milligal defined by IGSN71 values outside Australia (Wellman & others, 1974).

Accurate calibrations can be calculated for the quartz gravity meters using the 1967, 1970 and 1973 measurements along north-south lines of the Isogal network and the ACL. Table 3 shows these results and the sillside calibration for these meters during the same year.

Comparison of tilt, ACL, and hillside calibrations

The tilt table results from the Moscow and Canberra work are given in Table 1. Of all the results only one of the six calibrations for meter S190G has been rejected. In the remaining calibrations all but 9 of 138

Gravity meter number	*Year*	*Tilt-table calibration by manufacturer (μm s^{-2}/sc.div.)*	*Hillside calibration immediately after return to Australia (μm s^{-2}/sc.div.)*
WW35	1959	1.1578	1.1558
W61	1959	0.9081	0.9065
W140	1961	1.1167	1.1142
W140	1961	1.1141	1.1128
W140	1975	1.0212	1.0203
W169	1961	1.0607	1.0583
W260	1958	1.0832	1.0818
W260	1975	1.0046	1.0011
MW548	1960	0.9012	0.9002
S145	1963	1.0742	1.0634
S145	1973	1.0125	1.0107
S255G	1969	1.0107	1.0095

Table 2. Comparison of tilt-table calibrations by the manufacturer with hillside calibrations.

results are within two standard deviations of the tilt calibration error from the weighted means. This is close to the ratio expected from random errors, so the individual calibration constants are thought to represent unbiased samples from normal distributions, the weighted mean for each meter adequately summarising the individual calibrations.

The manufacturer's tilt calibration is also listed in Table 1 when it is known. If the large difference of 0.0630 μm s^{-2} sc.div.$^{-1}$ for S201 is ignored, then the remaining meters show little difference in the pairs of tilt calibrations—the ratio Canberra tilt/manufacturer tilt ranging from 0.9986 to 1.009. The mean ratio of 0.9998 ± 0.0002 does not differ significantly from 1.0000.

Gravity meter number	*Year*	*Calibration & method (μm s^{-2}/sc.div.)*		*Mean of hillside calibrations in the same year (μm s^{-2}/sc.div.)*
W140	1967	1.0197±7	Isogal net	1.0201±3
	1970	1.0200±7	ACL	1.0203±2
	1973	1.0208±2	ACL	1.0201±1
	1975	1.0212	Man. tilt	1.0201±2
	1977	1.0215±1	BMR tilt	1.0198±3
W169	1970	1.0116±16	ACL	
	1973	1.0123±1	ACL	1.0115
	1973	1.0123	Man. tilt	1.0115
	1974	1.0139±1	Mos. tilt	
	1975	1.0120±1	BMR tilt	1.0095±2
	1977	1.0118±1	BMR tilt	1.0113
W260	1970	1.0886±1	ACL	1.0879±3
	1973	1.0898±1	ACL	1.0886±1
	major change in calibration factor			
	1975	1.0046	Man. tilt	1.0034
	1975	1.0045±1	BMR tilt	1.0034
MW548	1967	1.0953±10	Isogal net	1.0950±1
	1970	1.0955±12	ACL	1.0956±1
	1973	1.0958±1	ACL	1.0948±5
	1975	1.0967	Man. tilt	
	1977	1.0964±1	BMR tilt	1.0965±2

Table 3. Comparison of Australian Calibration Line calibrations with tilt and hillside calibrations.

Canberra tilt-table calibrations are generally greater than the hillside calibrations made immediately afterwards (Table 1), the mean ratio tilt/hillside being 1.0012 ± 0.0002. The mean ratio of manufacturer's tilt table calibrations to hillside calibrations made immediately afterwards in Canberra and Melbourne (Table 2) is 1.0017 ± 0.0002 and so is slightly higher. It is unlikely that the difference of these ratios from 1.0000 solely reflects temperature differences, because the mean temperature coefficient for calibration constants is 9 × 10^{-5} °C^{-1} (Gantar & Morelli, 1963), so mean temperature differences of 13°C and 19°C would be necessary, and we know that temperature differences were less than these.

Differences between tilt calibrations and calibrations using Isogal stations on the Australian Calibration Line (Table 3) could be caused by experimental errors, a real difference in calibration between the two methods, or a change in calibration constant with time. For calibrations with an uncertainty of 0.0003 μm s^{-2} sc.div.$^{-1}$ or less, the ratio ACL calibration/hillside calibration is 1.0010 ± 0.0001. This ratio is similar to the mean ratio of Canberra tilt calibration/hillside calibration, so calibrations using the Isogal 74 values on the Australian Calibration Line seem to be the same, to within experimental error, as Canberra tilt calibrations.

The pressure effect

The differences between calibrations on hillside ranges and calibrations on either a tilt table or the ACL are attributed to a pressure effect. Table 4 summarises the Australian and overseas measurements of the magnitude of this effect. The values obtained using the manufacturer's tilt table calibration may be slightly too high owing to the temperature effect, as discussed above. Also the effect calculated from ACL stations not at sea level may be too high owing to lower temperatures at higher altitudes decreasing the calibration constant. The Australian measurements suggest that the mean effect for the meters investigated is about (2.5 ± 0.5) × 10^{-3} μm s^{-2} m^{-1}. This is higher than

Method of determining scale	*Method of determining altitude effect*	*Altitude change (m)*	*Data reference*	*Gravity meters used*	*Altitude effect (μm s^{-2}/m)x10^4*
ACL	hillside calibration range	250	Cooke, 1970; McCracken, 1978; BMR, unpubl. data	W140	10±3
				W169	27±4
				W260	14±2
				MW548	10±4
				S145	7±7
				mean	13±8
ACL	ACL stations not near sea level	560 & 1630	as above	W140	27±7
				W169	33±7
				W260	29±8
				MW548	34±8
				mean	31±2
Tilt table at BMR	hillside calibration range	250	Table 1	mean of 20	26±5
Tilt table at manufacturer	hillside calibration range	250	Table 2	mean of 12	38±4
———	pressure chamber	2000	BMR, unpubl. data	W140	27±2
				W260	23±4
———	pressure chamber	2000	Gantar & Morelli, 1963	mean of 15	15±3

Table 4. Estimates of the altitude effect on quartz-mechanism gravity meters.

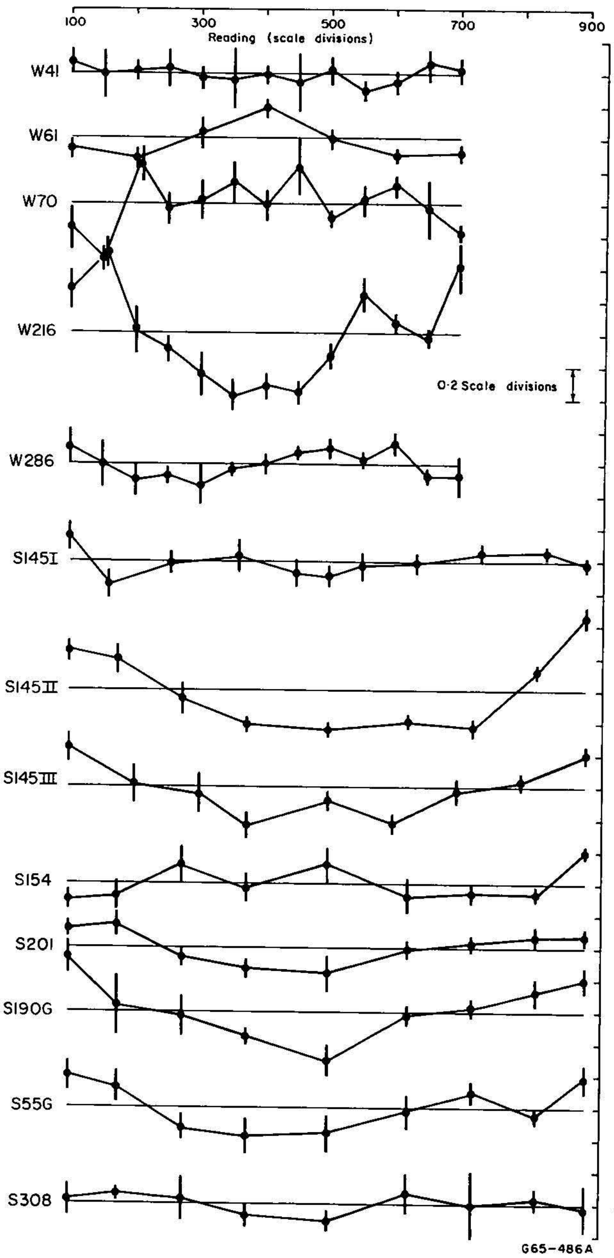

Figure 2. Dial reading corrections.

the mean of the results, $(1.5 \pm 0.3) \times 10^{-3}$ $\mu m\ s^{-2}\ m^{-1}$, summarised by Gantor & Morelli (1963).

The GAG-2 gravity meter is a Soviet quartz-mechanism instrument, operated by tilting instead of using a reading screw and auxiliary spring. In 1973 GAG-2 and LaCoste & Romberg gravity meters were taken together along the whole length of the ACL, including stations at Canberra, Mount Hagen and Laigam that are well above sea level. The difference between the results given by the two types of gravity meter is shown in figure 10 and Table 6 of Wellman & others (1974). The differences suggest that there is no significant pressure effect on GAG-2 gravity meters. This lack of pressure effect is due to the mechanism of this gravity meter being in liquid rather than a vacuum.

Corrections for non-linearity of dial readings

Figures 2 & 3 summarise the mean deviations from a linear correlation between dial reading and gravity. In these figures some mean deviations are averages for adjacent dial readings—such averaging standardises the number of individual measurements used to form the averages. For most gravity meters the mean deviations are small and not significantly different from zero; however, for W216, S145 set II, and W818 the deviations are significantly different.

The second-degree calibration coefficients given in Table 1 have been calculated by least squares using the mean deviations of Figures 2 & 3. Using a second-degree term the relation between gravity (g.cosθ) and dial reading (R) has the form

$$g.\cos\theta = a + k_1 R + k_2\ (R - b)^2$$

where a is a constant, k_1 is the weighted mean linear calibration constant of Table 1, k_2 is the second-degree calibration constant of Table 1, and b is related to 'M', the maximum dial reading used (Table 1) by $b = (M - 100)/2$.

The second-degree calibration constants were determined three times for meters W169 and S145. For W169 the three determinations agree to within experimental error. For S145 the last two determinations agree to within experimental error, but do not agree with the first determination in Moscow. The reason for this lack of agreement is not known. The reproducibility of the Canberra results suggests that they are real, and that a second-degree calibration constant term should be applied where it is significantly different from zero. Of the twenty meters investigated ten had second-

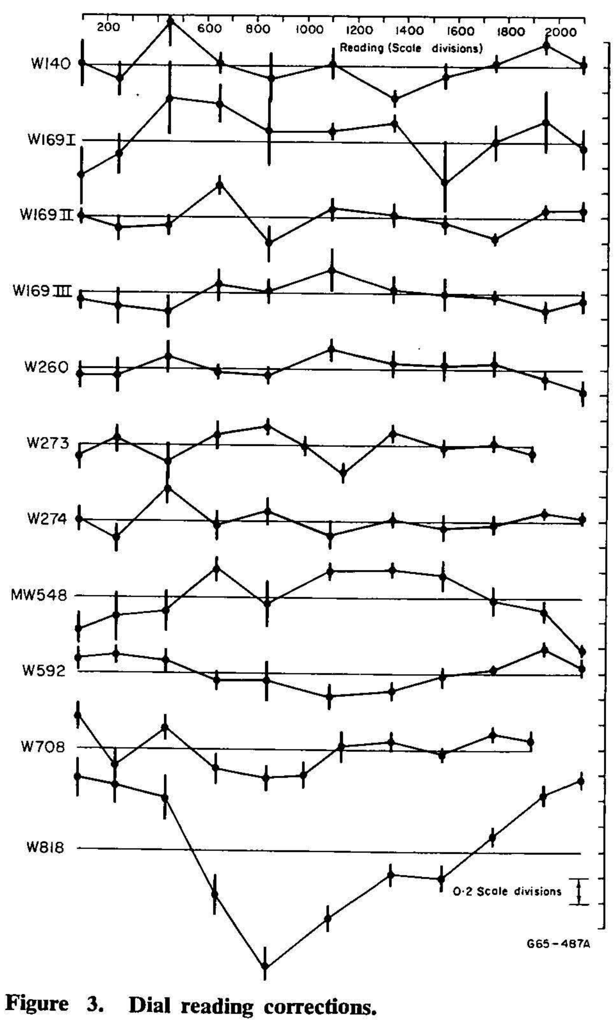

Figure 3. Dial reading corrections.

degree calibration constants that differed significantly from zero at the time of the tilt calibration because they were over three standard deviations from the mean.

Conclusions

Tilt calibrations of quartz-mechanism meters using a Soviet tilt table in Canberra give the same result to within experimental error as the tilt calibrations by the manufacturers in North America, and the same result as calibrations using observations at sea-level gravity stations along the Australian Calibration Line.

Calibrations of quartz-mechanism gravity meters using hillside calibration ranges give results that are too low, owing to an altitude effect which decreases the gravity meter reading with decreasing pressure. On a 250-m calibration range the decrease in calibration constant is 1.2 10^{-4} to 1.7 10^{-4}. Australian laboratory and field measurements give an estimate for the mean of this effect of $(2.5 \pm 0.5) \times 10^{-3}$ $\mu m\ s^{-2}\ m^{-1}$. Laboratory data in North America and Europe gives a mean effect of $(1.5 \pm 0.3) \times 10^{-3}$ $\mu m\ s^{-2}\ m^{-1}$. Both means are from a wide range of values, but the means appear to be significantly different.

Deviations from a linear relation between dial reading and gravity are found by tilt-table measurements to be as great as 0.5 $\mu m\ s^{-2}$. Second-degree calibration constants are significantly different from zero for ten of the twenty meters investigated.

Acknowledgements

We are extremely grateful to Prof. Yu D. Boulanger who offered to lend BMR the tilt table, and who arranged for the loan and the training in its use, and to Prof. R. B. Rukavishnikov who carried out the training in tilt procedure in Moscow. We are also grateful to Mr R. Grigg and Mr D. O. Stevens who carried out evacuations and any necessary adjustments on twenty gravity meters, to Mr I. Hartig who drafted the figures and Mr W. I. Reilly who commented on the draft paper. The paper would not be possible without the generous offer of loans of gravity meters from Broken Hill Pty Ltd, Mines Administration Pty Ltd, Wongela Geophysical, XLX Petroleum, SA Department of Mines and Energy, and the Universities of Sydney, Western Australia, Tasmania, Queensland, Melbourne, and New England.

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The Great Artesian Basin, Australia

M. A. Habermehl

The Great Artesian Basin occupies 1.7 × 10^6 km^2, or about one-fifth of Australia, extending across parts of Queensland, New South Wales, South Australia, and the Northern Territory. It underlies arid and semi-arid regions where surface water is sparse and unreliable. The discovery of the basin's groundwater resources around 1880, and their subsequent development, have allowed an important pastoral industry to be established. Pastoral activity and town water supplies are to a very large extent dependent on artesian groundwater. The groundwater basin consist of a multi-layered confined aquifer system, with aquifers occurring in continental quartzose sandstones of Triassic, Jurassic and Cretaceous age. The intervening confining beds consist of siltstone and mudstone; a thick argillaceous sequence of sediments of marine origin and Cretaceous age forms the main confining unit. The basin is, in places, 3000 m thick, and forms a large synclinal structure, uplifted and exposed along its eastern margin and tilted southwest. Recharge occurs mainly in the eastern marginal zone, and large-scale groundwater movement is generally towards the southwestern, western and southern margins. Natural discharge occurs from spring in these areas; most springs are connected with structural features. Minor recharge occurs in the western margin.

The potentiometric surfaces of the Triassic, Jurassic and Early Cretaceous aquifers are still above groundlevel in most areas of the basin. Considerable lowering occurred in heavily developed areas; from about 1880 to 1970, regional differences of up to 80 m were recorded, and in some areas waterwells ceased to flow. Waterlevels of some Cretaceous aquifers are below the groundsurface throughout most of the basin area. Hydraulic gradients of the main aquifers in the Lower Cretaceous-Jurassic sequence are about 1:2000, and of aquifers in the Cretaceous sequence 1:1800. Transmissivity values of the main aquifers in the Lower Cretaceous-Jurassic sequence, from which most flowing artesian wells obtain their water, usually are several tens to several hundreds m^2/day. Hydraulic conductivities range from 0.1 to 10 m/day, with a predominance in the lower part of the range. Storage coefficients, as interpreted from wire-line logs, average about 10^{-5}. Aquifer thicknesses range from several metres to several hundred metres. Average groundwater velocity in the eastern marginal parts is from 1 to 5 m/year. Environmental isotope analysis shows that the artesian water is of meteoric origin. About 4700 flowing artesian wells have been drilled to depths of up to 2000 m, but average 500 m. Individual flows exceeding 10 000 m^3/day have been recorded. About 3100 wells remained flowing during the early 1970s, when the accumulated artificial discharge was about 1.5 × 10^6 m^3/day, as compared to the maximum flow from the basin of about 2 × 10^6 m^3/day from about 1500 artesian wells around 1918. The high initial discharge in the early years of exploitation, which was caused by the release of pressure in the aquifers, gradually levelled off, and has now approached a steady-state condition, in which total basin discharge is roughly balanced by recharge. Non-flowing artesian water-wells mainly in the higher Cretaceous aquifers number about 20 000, and are generally shallow, up to several hundred metres deep, and are usually equipped with windmill-operated pumps, supplying on average about 10 m^3/day each. Most flowing wells occur in the marginal areas of the basin, as the main aquifers in the Lower Cretaceous-Jurassic sequence which they tap are too deep for economical abstraction in the central part of the basin. In the central part mainly non-flowing shallow wells are found.

Groundwater in the most widely exploited pressure aquifers in the Lower Cretaceous-Jurassic sequence generally contains about 500 to 1000 mg/l total dissolved solids, dominated by sodium bicarbonate. Water quality improves with increasing depth of aquifers in the sequence. Groundwater from the aquifers in the Lower Cretaceous-Jurassic sequence is of good quality and suitable for domestic and stock use, though it is generally unsuitable for irrigation because in much of the basin area it is chemically incompatible with the soil. Water from the upper, Cretaceous, aquifers has a higher salinity. More than 90 percent of the water from flowing artesian wells is wasted owing to seepage, transpiration and evaporation associated with the distribution of the water by open earth drains, many of which are tens of kilometres long.

Introduction

The Great Artesian Basin is a confined groundwater basin comprising aquifers in continental quartzose sandstones and confining beds of partly marine mudstone and siltstone of Triassic, Jurassic and Cretaceous age.

The Great Artesian Basin underlies 1.7 x 10^6 km^2, about 22 percent of the Australian continent and is one of the largest artesian basins in the world. It underlies parts of Queensland, New South Wales, South Australia and the Northern Territory (Fig. 1). The part described here lies south of latitude 20°S, an area of about 1.3 x 10^6 km^2.

Most of the groundwater basin area consists of low-lying interior plains, bounded in the east by tablelands and uplands of the Great Dividing Range. The

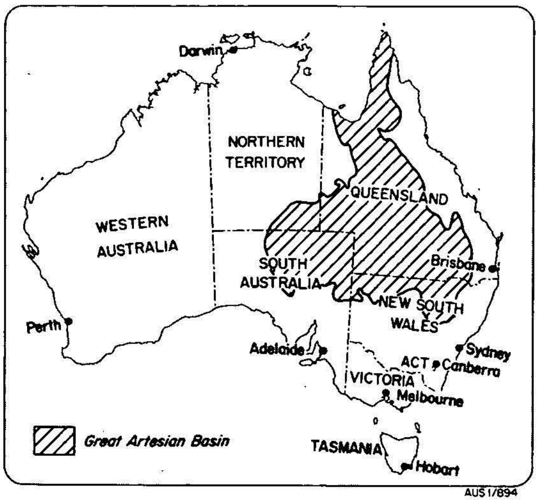


Figure 1. Location and extent of the Great Artesian Basin, Australia.

surface generally slopes towards the main depression near Lake Eyre in the southwest, an interior drainage feature up to 16 m below sea level. The summits of the Great Dividing Range vary from 600 to 900 m in Queensland, to 1200 to 1500 m in New South Wales. Ephemeral rivers, draining the Range flow generally southwestward through stretches of plains, most of which lie below 150 m, and show very low relief of less than 30 m.

Bordering the main eastern divide, are "rolling downs", which consist of stony lowlands, erosional landscapes with mesas and tablelands capped by duricrust. The inner, low-lying parts of the interior lowlands are flood plains of anastomosing rivers, forming depositional landforms and dune fields of aeolian sand of the Simpson Desert.

The Great Artesian Basin is largely located in the arid and semi-arid parts of Australia. Very dry hot to warm climates predominate; a more temperate climate is present in the most eastern areas.

Average annual rainfall ranges from a minimum of about 100 mm in the Simpson Desert in the western part to maximum values of about 600 mm near the eastern marginal areas of the basin in the Great Dividing Range (Fig. 2). Rainfall variability follows this zonal distribution, with the more reliable rainfall coinciding with higher rainfall areas. Seasonal distribution is marked by a relative dry winter and wet summer.

Average annual temperatures throughout most of the basin range from 18° to 24°C; the highest average annual temperatures are in the north. An annual temperature range between highest monthly average maximum and lowest monthly average minimum temperature of more than 30° is common in most parts; extreme maximum air temperatures exceed 50°C in the central and western parts.

Evaporation throughout most of the basin area is very high and average annual tank evaporation reaches a maximum of about 3500 mm in the north of South Australia (Fig. 2).

Surface water

All streams in the basin area (Fig. 3) are characterised by extreme variation in discharge and flow duration. Very variable seasonal and annual streamflow patterns are caused by tropical cyclonic and summer monsoonal rainfall, and in most areas

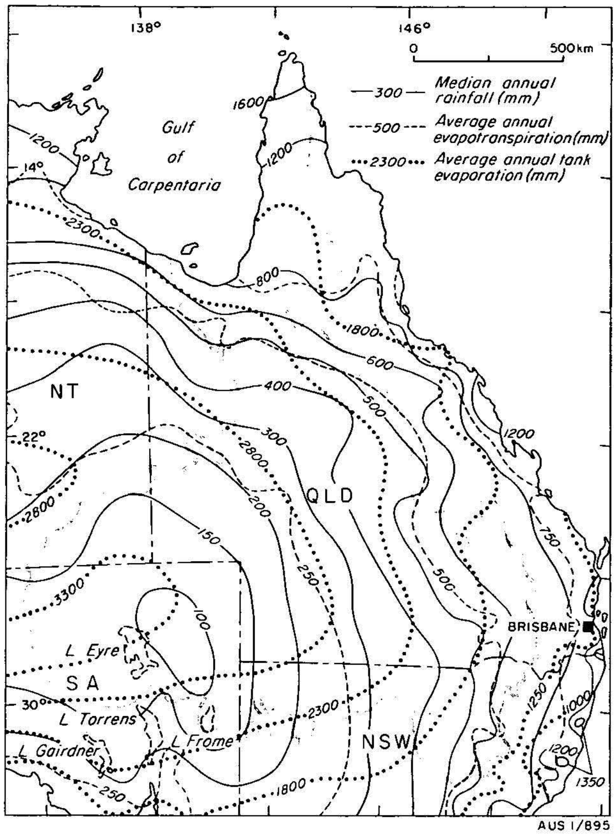


Figure 2. Median annual rainfall (mm), average annual evapotranspiration (mm) and tank evaporation (mm) (after Atlas of Australian Resources).

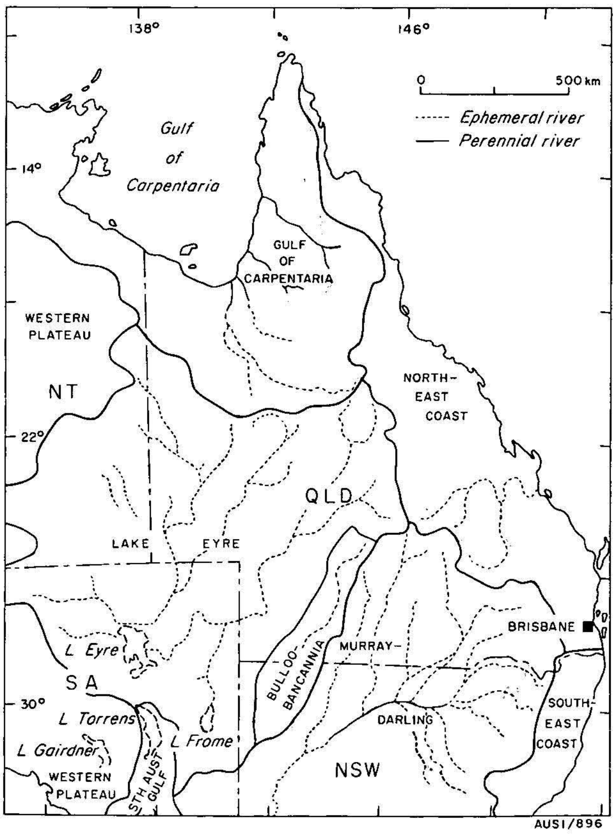


Figure 3. Surface water and drainage divisions (after Atlas of Australian Resources, and Australian Water Resources Council, 1976).

extended periods of droughts, some lasting for many years, alternate with major, long-lasting floods.

Little rainfall occurs in the interior of the basin west of the main eastern divide. Heavy summer rain, usually restricted to the north results only in streamflow in the headwaters and middle reaches of the river-systems. Flows usually do not reach Lake Eyre because of the great distance, low gradient and high seepage, and evaporation losses. Generally this, and other lakes in the southwestern part of the basin, occur as flat, dry, salt-encrusted depressions.

In the southeast of the basin rivers discharge through the Murray-Darling system into the Southern Ocean. A few streams in the eastern marginal area flow out towards the Pacific Ocean (Fig. 3).

Average annual run-off in the basin area is much less than 10 mm and generally less than 5 mm.

Large natural waterholes are present in the channels of the network of ephemeral rivers which flow very infrequently, sometimes at intervals of several years. These waterholes provide permanent supplies in some locations.

No major surface water diversions or storage dams are present in the Great Artesian Basin area. Local farm dams and excavated earth tanks occur in large numbers, but most of these surface storages are of recent origin, and early development of the area was dependent mainly on artesian groundwater resources.

Vegetation

Natural vegetation shows a close interdependence with the zonal distribution pattern of climate and soil types. It is dominated by tussock grassland on grey and brown soils of heavy texture and red earth soils in the northeastern and central parts, low open-woodland with widely spaced hummock grasses in the northwestern and northeastern areas on skeletal and sandy soils. Woodland with trees and shrubs and hummock and tussock grasses occur in the eastern and southeastern parts. Generally dry creeks and rivers in the eastern recharge areas are commonly heavily lined by large phreatophytes. The central part of the basin area is surrounded by low open-woodland with tussock grasses, and the centre consist of open herbfields and some open grassland. Tall open-shrubland with hummock grass characterises the western parts, and low and tall open-shrubland with tussock grass occurs in the southwestern parts.

Large parts in the centre and southwest are covered by stony desert tablelands, with a continuous surface of wind-polished siliceous stones. The western and southwestern parts are covered by red sandhill deserts and ephemeral salt lakes.

Low soil moisture rather than low soil fertility is the production restraint in these arid and semi-arid regions. Low to very low carrying capacity in pastoral activity is probably all that can be expected, as in most areas no arable agriculture or sown pasture production is possible. Xerophytic tussock grass grazing lands (Mitchell Grass Downs) in the northern and central parts of the basin area are the most productive grazing lands in the arid regions. Introduced plants and fertilizers are only applied in small parts of the southeastern area.

Land use and economy

Almost all the non-desert parts of the Great Artesian Basin area are used for low intensity livestock grazing of sheep for wool and beef cattle (Fig. 4).

Physical conditions favourable for more intensive land use, including combined wheat-sheep farming, cereal production, and cotton, fruit and vegetables, only occur in the most eastern and southeastern parts. In the western part, the Simpson Desert is too dry and infertile for any productive use.

The early years of occupation were characterised by overestimation of the grazing capacity of the land, and rapid extension in stock numbers also occurred as watering points increased. Severe droughts in these arid and semi-arid parts caused declines in carrying capacity, as well as deterioration of the native pastures and soil erosion. Rabbit plagues and economic depressions were other contributing factors. Ultimately stable stocking rates were established after reassessment of the fact that droughts were the rule rather than the exception in this country, and of economic considerations.

The very variable rainfall forms the most important factor for provision of feed, and so adverse rather than favourable seasons significantly determine stocking rates. However, grazing capacity is also directly related to the distribution of watering points and with little surface water available, stock is mostly dependent on artesian wells and excavated tanks.

Changes in land use occurred from sheep to beef-cattle grazing in some areas, and to crop growing in the southeastern area. Irrigation water for the latter is obtained from surface water and from shallow groundwater in alluvial aquifers. Little irrigation development is expected as a result of artesian groundwater availability, mainly because of restrictions concerning chemical compatibility of the groundwater and the dominant soils, and of the quantities required.

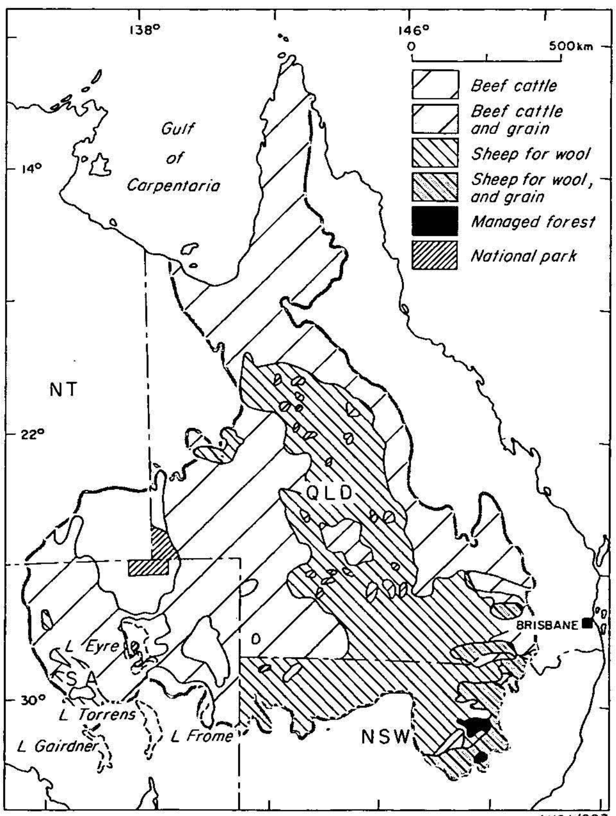


Figure 4. Dominant land use (after Atlas of Australian Resources).

The total population of the Great Artesian Basin area is probably not more than 100 000. This low density population is very unevenly distributed, with most of the twenty-five major centres being located in the eastern and southeastern areas of the basin in Queensland and New South Wales. About half of these urban centres are in Queensland and have on average a population of less than 2 500, the other half in New South Wales have a population of more than 5 000, and up to 10 000.

Access to most of the area is good, with bitumen roads leading into the basin area in the northern and eastern parts. Unsurfaced gravel roads serve the central, southern and marginal western areas. Many roads in the basin area quickly become impassable after rain, especially in the northern and central areas during summer. East-west railway lines penetrate the basin area as far as the east-central parts, and connect these areas and the southwestern margin with the coastal towns.

Investigations of the geology and hydrology of the basin

Early work around 1880 suggested that meteoric water infiltrated the western slopes of the Great Dividing Range, and that artesian springs near Lake Eyre indicated artesian water could be found across most of central and eastern inland Australia (Rawlinson, 1878; Russell, 1880, 1889; Tate, 1879, 1882). Geological investigations led Jack to conclude in 1881 and 1885 (Jack, 1895a, b; 1898), that a large synclinal trough existed in western Queensland, in which pervious beds occurred with artesian water.

Geological mapping of the intake beds along the Great Dividing Range in Queensland and New South Wales and along the northern, northwestern and southern margins by Brown, Cameron, David, Jack, Maitland, Pittman and Wilkinson (references in Pittman, 1914, Interstate Conference on Artesian Water, 1913), and waterwell information helped to outline the shape and size of the basin, so that by the end of the nineteenth century the basin was accepted by many as a classic artesian basin. Pressure data from field surveys confirmed the theory, though controversy remained as to whether the pressure head was hydraulic or hydrostatic. The difference in hydrodynamic conditions of the basin was important, as it would assist in predicting the effects of the already occuring decrease in flow and pressure of artesian wells. The interpretations of origin and movement of artesian water were attacked by Gregory (1901, 1906, 1911, 1914, 1923), who attributed the water in the Great Artesian Basin to connate and plutonic origins, and the movement as the result of heat, gas and rock pressure in the earth's crust, rather than a meteoric origin and movement under hydraulic conditions. Gregory's theories were supported by Symmonds (1912) and Du Toit (1917), but were skillfully refuted by defendants of the meteoric and hydraulic theory, notably Knibbs (1903), Pittman & David (1903) and Pittman (1907, 1914, 1915, 1917). The latter theory gained ground and became generally accepted; the controversy, however, inspired increased research in the basin.

Diminishing flows and pressures in artesian wells increasingly alarmed well owners, and ultimately State Governments became involved, whose attention had already been drawn to the wastage of water from many of the privately drilled wells. Once legislation was passed in the early 1900s to control the use of subsurface water, wells had to be licensed, detailed information provided and wells completed according to prescribed standards. State Water Authorities commenced systematic and periodical measurements which replaced the earlier intermittent data collection; information on wells has been collected since that time, and extensive surveys carried out.

Systematic investigations of the groundwater conditions in the basin increased markedly as a result of the five Interstate Conferences on Artesian Water, held between 1912 and 1928 (Interstate Conference on Artesian Water, 1913, 1914, 1922, 1925, 1929).

The conferences were originally called to study the serious reduction in pressure and diminution or cessation of flows, the extent of the basin, the origin and movement of artesian water, the corrosion problems of well casing and to inquire into a better utilisation of the groundwater.

The reports of the first and second conferences are mainly concerned with the collection of information and the verbal presentations by the (State) delegates and pastoralists, well owners, drillers, engineers, chemists and administrators. The reports of the third, fourth and fifth conferences record submissions by the State representatives (geologists and hydraulic engineers), who presented detailed data about the basin, the wells, and progress in local (State) investigations. The accompanying geological and potentiometric maps, cross-sections, tables with well data, water temperatures, chemical analyses results and other information, show the improvement of knowledge of the basin during the years.

Bibliographies relating to groundwater in Australia during and prior to the period, are included, as well as a detailed description of the deepest waterwell (QWRC Reg. No. 3489) in the basin, completed in 1921 at a total depth of 2136 m (7009 ft) in Queensland.

No further meetings were held until 1939, when an Interstate Conference on Water Conservation and Irrigation met in Sydney, which was concerned with most aspects of ground and surface water, and not confined to artesian water. Discussion concentrated on the diminution and control of flow from wells and the improvement in distribution. It was recognised that the wastage of water from flowing wells was the main problem.

Systematic surveys of the geology and of investigations of hydraulic characteristics continued to be carried out on a State basis. In New South Wales Kenny (references in Packham, 1969; Kenny, 1934, 1964), and Tandy (1939, 1940) completed several surveys during the 1920s and 1930s. The reports by Tandy concentrated on the southeastern parts of the Great Artesian Basin and contain maps, sections, potentiometric maps, graphs and diagrams and calculations and interpretations on well discharges, aquifer permeability, recharge and groundwater flowrates. Newer theories, including elastic storage, were applied. Recommendations were made on water conservation by the partially closing of wells and improved distribution methods. Dulhunty, Mulholland and Rade reported on the geology and groundwater aspects during the 1940s, 1950s and 1960s, (references *in* Packham, 1969; Dulhunty, 1973), whereas more recent studies and reviews occur in Williamson & Hind (1962), Griffin (1963), Williamson (1966), Hind & Helby (1969) and Water Conservation and Irrigation

Commission (1971). Hind & Helby (1969) described the geology and hydrology of the New South Wales part of the basin. Water movement is said to vary between 1.6 and 10 m/year in the Coonamble Embayment. It was reported that some 3000 wells obtain water from the basin in New South Wales, and that in 1968 682 were flowing artesian wells with a combined flow rate of 289 x 10^3 m^3/day. The remainder yield pumping supplies ranging from several tens m^3/day to 3.8 x 10^3 m^3/day.

In South Australia Jack (1915, 1923, 1925, 1930) studied the geology, groundwater hydrology and chemical characteristics, and Ward (1946), Chugg (1957), and Ker (1966) reported data on the Great Artesian Basin; a recent review is included in Sheperd (1977).

In Queensland a committee of geologists and hydraulic engineers was set up in 1939 to investigate the nature and structure of the Great Artesian Basin. A First Interim Report was presented by the committee in 1945 (Queensland Government, 1945), which mainly dealt with the geology, hydrology, use of water and diminution of flows and pressures. It emphasised the principles of recharge, elastic storage, the resulting diminution of flows and pressures and the gradual decrease in diminution, and the importance of water conservation by the control of wells. Another report by the Artesian Water Investigations Committee was produced in 1954, and formed the most comprehensive description of detailed investigation on the hydrogeology of the Queensland part of the basin (Queensland Government, 1954). Appendixes, which were published separately, provide detailed descriptions of the geology (Whitehouse, 1954) and hydrology (Ogilvie, 1954). The report described the nature and structure of the Queensland portion of the Great Artesian Basin, with emphasis on the quantity of water and its aquifer system, and the study of geological, physical and chemical aspects of the problem of diminishing supply. Recommendations concerned the proper use, regulation and control of water from wells, and the suggestion not to enter in the strict conservation of flows from existing wells.

In the Explanatory Notes to the 1:2 500 000 map of the Groundwater Resources of Queensland (Geological Survey of Queensland and Irrigation and Water Supply Commission, 1973) some new figures related to the 1954 report were published. In 1954 it was estimated that the increase in recharge which tended to offset the pressure losses, would reach a steady state in the year 2010, when the total discharge would equal the recharge. The general trends of the earlier (1954) work were confirmed in the 1973 publication, but it was estimated that the ultimate steady output of the wells in 2010 would be 590 x 10^3 m^3/day, underflow to other states at 90 x 10^3 m^3/day, and recharge at 680 x 10^3 m^3/day. The 1973 report further states that the pressure gradients steepened from an initial 1:2933 to about 1:1760, and that the computed total withdrawal from the basin up to 1973 was 35.1 x 10^9 m^3, 70 percent of which had come from elastic storage. The 1973 Queensland report reiterated that the most economical long-term policy to conserve the resource was not to undertake expensive reconditiong of old flowing wells and maintain the existing area of flowing wells, but rather to aim at an ultimate total withdrawal rate for flowing and pumped wells commensurate with natural recharge rates under equilibrium. Randal (1978) described the hydrogeology, including hydraulics and groundwater chemistry, of a small area near the northwestern margin of the basin.

A review of the Great Artesian Basin as a whole is given in David (1950), and more recent information, though on a State basis in — Groundwater resources of Australia (Australian Water Resources Council, 1975). In this publication discharge from the basin was reported to be about 540 x 10^6 m^3/year, subdivided into Queensland — 330 x 10^6 m^3/year, New South Wales — 130 x 10^6 m^3/year, South Australia — 75 x 10^6 m^3/year, and the Northern Territory — 1 x 10^6 m^3/year. Further information on the Great Artesian Basin is shown in the Review of Australia's Water Resources 1975 (Australian Water Resources Council, 1976), where the abstraction during 1974 is listed as 526 x 10^6 m^3, the estimated annual recharge 410 x 10^6 m^3, the estimated number of wells in 1974 at 22 770, and the range of common individual well yields from 0.4 m^3/day to 5.2 x 10^3 m^3/day.

From 1971 to 1979 a basin-wide hydrogeological study of the Great Artesian Basin was carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR) at the request of the Australian Water Resources Council's Technical Committee on Underground Water. Objectives of this hydrogeological study were to review the geological and hydrological data of the multi-layered confined aquifer system of the Great Artesian Basin and to develop and apply a mathematical, computer-based model to simulate the groundwater hydrodynamics.

An outline of the hydrogeology of the basin is given in this paper, and the digital model GABHYD based on the finite difference approach is described by Seidel (1980). Results of the digital computer simulation model predictions of the future hydraulic behaviour of the basin following management interventions can be used for assessment, planning and management purposes on a regional scale of the basin's artesian groundwater resources (Habermehl & Seidel, 1979). The model calibration and application are given in Seidel (1978a, b).

A joint study of the isotype hydrology of the Great Artesian Basin has been carried out with the Nuclear Hydrology Group of the Isotype Division of the Australian Atomic Energy Commission since 1974.

Data sources and data collection

Basic data for the present hydrogeological and model study included the results of geological surface mapping by BMR and State Geological Surveys obtained during the 1950s to early 1970s. Geological maps at scale 1:250 000 and their accompanying notes cover most of the Great Artesian Basin; geological maps at scale 1:1 000 000 cover the entire area except South Australia. Subsurface information was obtained from several hundred petroleum exploration wells. Stratigraphic drill-holes, both shallow and deep, drilled by BMR and the State Geological Surveys provided additional data, as did drillers logs of waterwells, which are available for most flowing artesian waterwells and for some non-flowing artesian waterwells.

Identification and correlation of hydrogeological units was further possible from wire-line logs of waterwells in the Great Artesian Basin. BMR logged about 1250 waterwells in the basin during the period 1960 to 1975; in the New South Wales part of the basin about 235 waterwells and in the South Australia part 17 waterwells were logged by the Geological Survey of those States. As almost all existing waterwells are lined with metal (steel) casing, the types of wire-line logs which can be run in the wells are restricted.

Hydrological data were obtained from the files and records of the Irrigation and Water Supply Commission (IWSC) (now Water Resources Commission) in Queensland, the Water Conservation and Irrigation Commission (WCIC) (now Water Resources Commission) in New South Wales and the Geological Survey of the Department of Mines in South Australia. Records on flowing artesian wells contain the bulk of the available hydrogeological data; these wells represent the most significant artificial discharge points in the basin, and periodic measurements on discharge, pressure, temperature and chemistry have been carried out since the early development of the basin. Non-flowing artesian (generally called sub-artesian) waterwells produce much smaller discharges, and information on these wells is generally restricted to basic data obtained at completion.

An automatic data-processing, storage and retrieval system was designed to contain the basic waterwell data from the Great Artesian Basin. The fixed format of the data base, consisting of thirteen data type cards, is described in Ungemach & Habermehl (1973). Data on nearly all 4700 flowing artesian waterwells was collected and listed on the Master, Well casing and screen, Aquifer description cards which contain fixed information, and further on the Well discharge, Head and temperature, Hydrodynamics, Pump or flow test, and Total dissolved solids cards with contain time variable data. These data form the basis of the GAB-ADP data bank, from which hydrogeological analysis and most input data for the digital simulation model was prepared.

The data were sorted according to location (State and 1:250 000 map sheet), identification (well number), and type of data (type of cards) and subsequently checked, as described by Krebs (1973). Manipulation of the basic data was carried out by a large set of processing programs, some of which were reported in Krebs (1974). The storage and retrieval system of the data was described by Seidel (1973).

Groundwater exploration and development

Early exploration of the basin

Artesian water in the Great Artesian Basin in a shallow, flowing waterwell was first discovered southwest of Bourke (NSW) in 1878. Many shallow and deep wells were soon drilled, first near springs at the margin of the basin, as in New South Wales and in

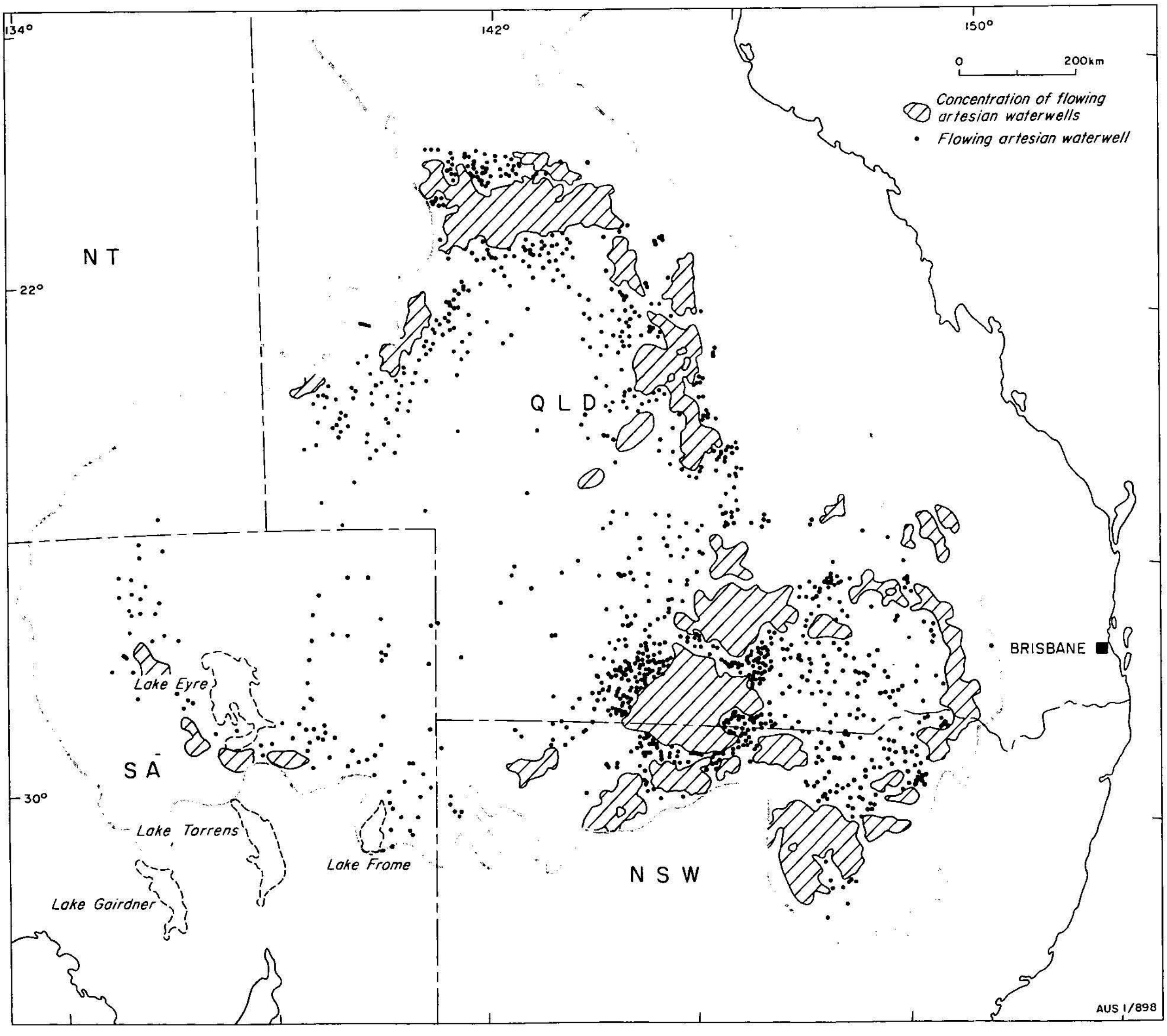


Figure 5. Location of flowing artesian waterwells.

South Australia west of Lake Eyre, but later further basinwards. Droughts and poor water supplies led to the drilling of the first deep artesian wells near the central Queensland towns of Cunnamulla and Barcaldine in 1887, and was followed by many others drilled for stock, domestic, and town water supplies. Drilling and geological investigations led to the discovery of artesian water nearly everywhere in the arid interior of the basin, and the extent of the artesian conditions was defined before the end of the nineteenth century.

Demand and utilisation of artesian groundwater

Flowing supplies of sufficient quantity and of good quality can be obtained from aquifers in most areas of the basin to support low density grazing. This pastoral activity requires relatively small amounts of water of acceptable quality for sheep and cattle from widely spaced watering points distributed over a large area.

Flowing artesian waterwells occur mainly in the northern, eastern and southern marginal areas of the basin, and in most of the south-central parts (Fig. 5). The economical drilling depths to the main artesian aquifers account for the relatively high well densities in these areas. Flowing artesian waterwells are almost absent in the central part of the basin, where the main aquifers occur at great depth. In these parts of the basin groundwater is obtained from shallower aquifers, though these aquifers produce more saline water under non-flowing conditions. In the eastern marginal parts there are many non-flowing artesian wells.

Most of the water derived from flowing artesian wells is distributed by open-earth drains or ditches, which in most areas run for many tens of kilometres through the flat countryside. The amount of the water distributed that is used by livestock is very low, much less than ten percent (Tandy, 1939, 1940); Queensland Government, 1954; Water Conservation and Irrigation Commission, 1971), or 1 to 2 percent (Ker, 1963).

Seepage and evaporation losses in these drains are considerable, and regular maintenance is required. The requirement in recent times to use polyethylene pipes for the distribution of water from new wells, in many cases in combination with metal tanks, automatic valves and windmill operated pumps, will probably assist in the wider distribution of water in a more efficient manner. Many government-operated wells and some privately owned wells are already equipped in this way.

Individual homesteads rely mostly on rainwater stored in metal tanks as a source for drinking water. If a waterwell tapping the main artesian aquifers is present near the homestead, then that water usually constitutes the main alternative supply for domestic purposes, with, in addition, possible storage in earth-tanks and permanent waterholes.

Nearly all towns in the Great Artesian Basin area are dependent for their water supplies on groundwater from the deeper aquifers in the basin. Although the flowing supplies are acceptable in quantity and quality, a minor inconvenience is the high water temperature, which needs to be reduced.

Pastoral, domestic and town water supplies are the main users of artesian water, and little if any other, including industrial applications, are found.

Groundwater from the Great Artesian Basin is generally chemically unacceptable for prolonged use for irrigation purposes on the soils in most areas, and State water authorities considered that stock and domestic requirements should have priority in water use, and that no artesian water should be used for irrigation.

Effects of development

The high initial discharge from individual wells — and from the basin as a whole — during the early years of exploitation, was mainly the result of the release at high pressure of water from elastic storage in the groundwater reservoir. This high flow rate gradually levelled off and diminished to a more steady artificial discharge rate, which approaches a steady-state condition (Fig. 6).

Approximately 4700 artesian waterwells in the basin originally flowed (about 3300 in Queensland, 1200 in New South Wales and 150 in South Australia). Many of these wells ceased flowing as the potentiometric surface fell below ground surface. At present about 2300 wells in Queensland, 650 in New South Wales and 150 in South Australia are still flowing. Most of the wells which ceased flowing are still in use, and being pumped (usually by windmill-operated pumps), as are most of the 20 000 original non-flowing artesian waterwells in the basin.

The potentiometric surface of the aquifers in the Lower Cretaceous and the Jurassic sequence was above the ground surface over the whole of the basin before exploitation began around 1880. Since then the regional potentiometric surface of the exploited aquifers in the Lower Cretaceous and Jurassic sequence has dropped by several tens of metres in many heavily developed areas (Fig. 7). Individual wells show falls of over 100 m. The heavy draw on the aquifers by the large number of freely or mainly freely flowing wells caused a marked lowering of the potentiometric surface in the immediate areas surrounding these wells. This process has been aggravated by the interference effect of relatively closely spaced wells, resulting in overlapping and accumulation of pressure drawdown cones and the resultant lowering of the regional waterlevels.

The potentiometric surface fell below the ground-surface in some highly developed areas near the margins and in the southeast-central part of the basin. As a result, flows from some flowing artesian wells ceased in those areas. However, in all areas where artesian waterlevels have been lowered below ground level, artesian water is well within economical pumping depths.

The significant change is that free-flowing wells ceased flowing, and that mechanically operated pumps had to be installed in these wells. The yield from pumped wells is usually very much less than from free-

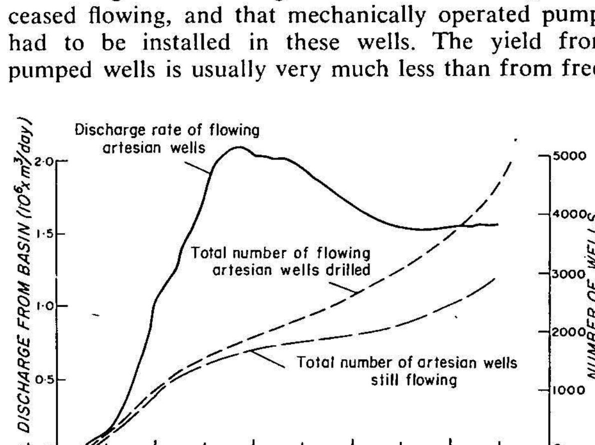


Figure 6. Discharge rate of flowing artesian wells, total number of initial flowing artesian wells drilled and total number of wells still flowing.

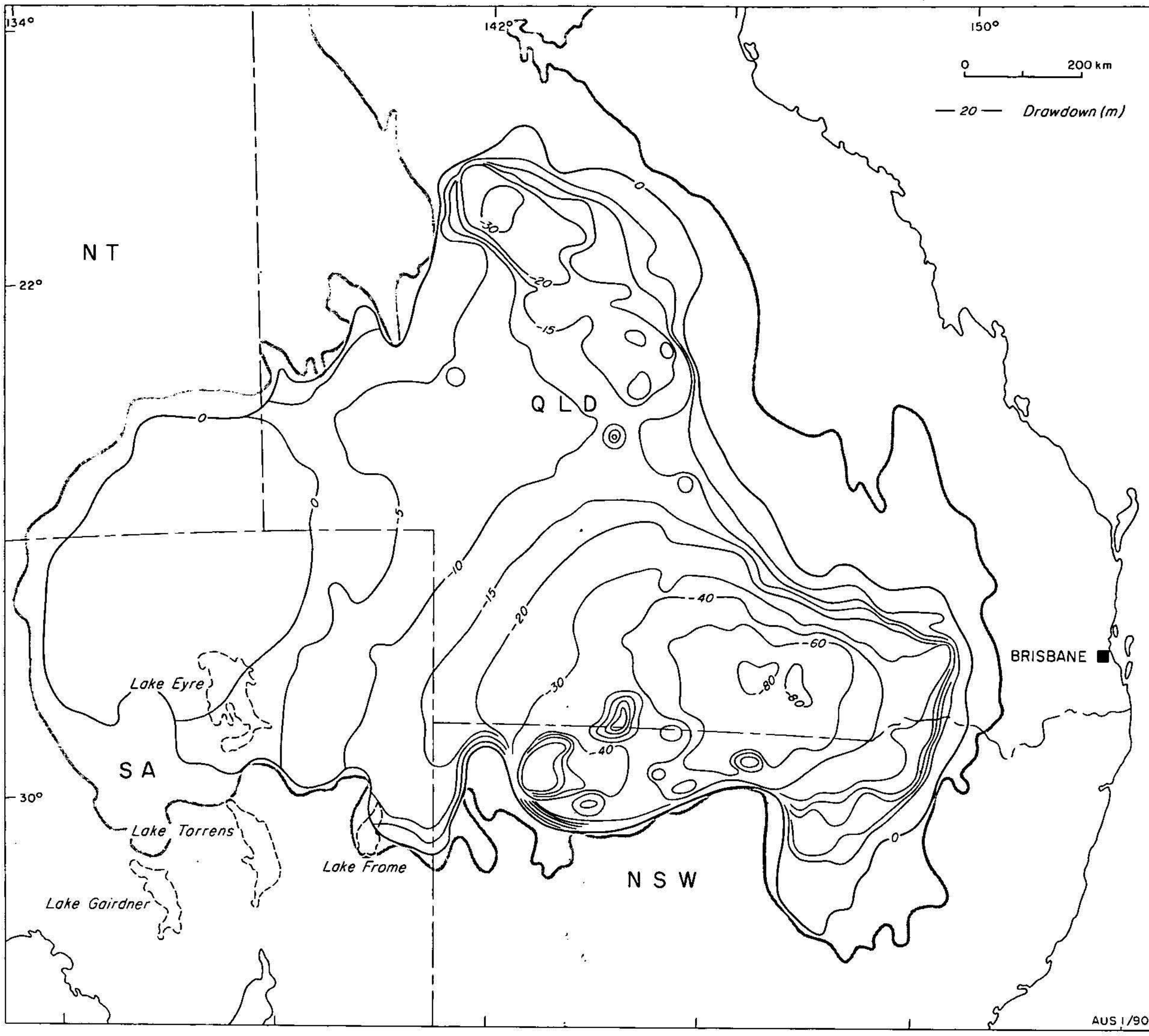


Figure 7. Regional drawdown (in metres) of the potentiometric surface of the main artesian aquifers in the Lower Cretaceous-Jurassic sequence following development during the period 1880 to 1970.

flowing wells, and no large-scale distribution system can be maintained by such wells.

The potentiometric surface of the aquifers in the upper part of the Cretaceous sequence has always been below the ground surface, consequently wells tapping these aquifers are non-flowing artesian, and have to be pumped. Because of their relative small discharge as compared with the high discharge from free-flowing artesian waterwells, the lowering of waterlevels in pumped wells is generally very much less . Regional drawdown in these aquifers is accordingly also much smaller. Data on waterlevels and exploitation rates of original non-flowing wells are sparse, in contrast to the amount of periodic measurements carried out on flowing artesian wells by State water authorities.

Exploitation of the basin's aquifers has caused significant changes in the rate of the various discharges in time (Fig. 6; Habermehl & Seidel, 1979, Seidel, 1980). Prior to development, the basin was in a natural steady-state condition, with an equilibrium between recharge and natural discharge, the latter by springs, vertical leakage and some lateral outflow. Following development, artificial discharge by wells became very prominent and vertical leakage and spring discharge diminished. A visible effect has been the diminution in flow from springs in the south-central and southwestern parts of the basin. Abstraction by wells caused a steepening of the hydraulic gradient and allowed more recharge water to enter the system.

At present a new steady-state condition has been reached in which total recharge and discharge are approaching equilibrium again (Fig. 6; Habermehl & Seidel, 1979; Seidel, 1980). Provided no new, major developments occur which will affect this equilibrium situation, discharge and potentials will not change significantly.

Geology

The Great Artesian Basin comprises the sedimentary Eromanga, Surat, and Carpentaria Basins and small upper parts of the Bowen and Galilee Basins (Fig. 8). Confined aquifers within the basin consist mainly of Triassic, Jurassic and Cretaceous continental sandstones. The aquifers alternate with low to very low permeability, confining beds consisting of siltstone and mudstone of continental or shallow-marine origin. The basins are mainly very broad synclinal structures trending northeast (Eromanga) or north (Surat and Carpentaria). They are contiguous across shallow ridges

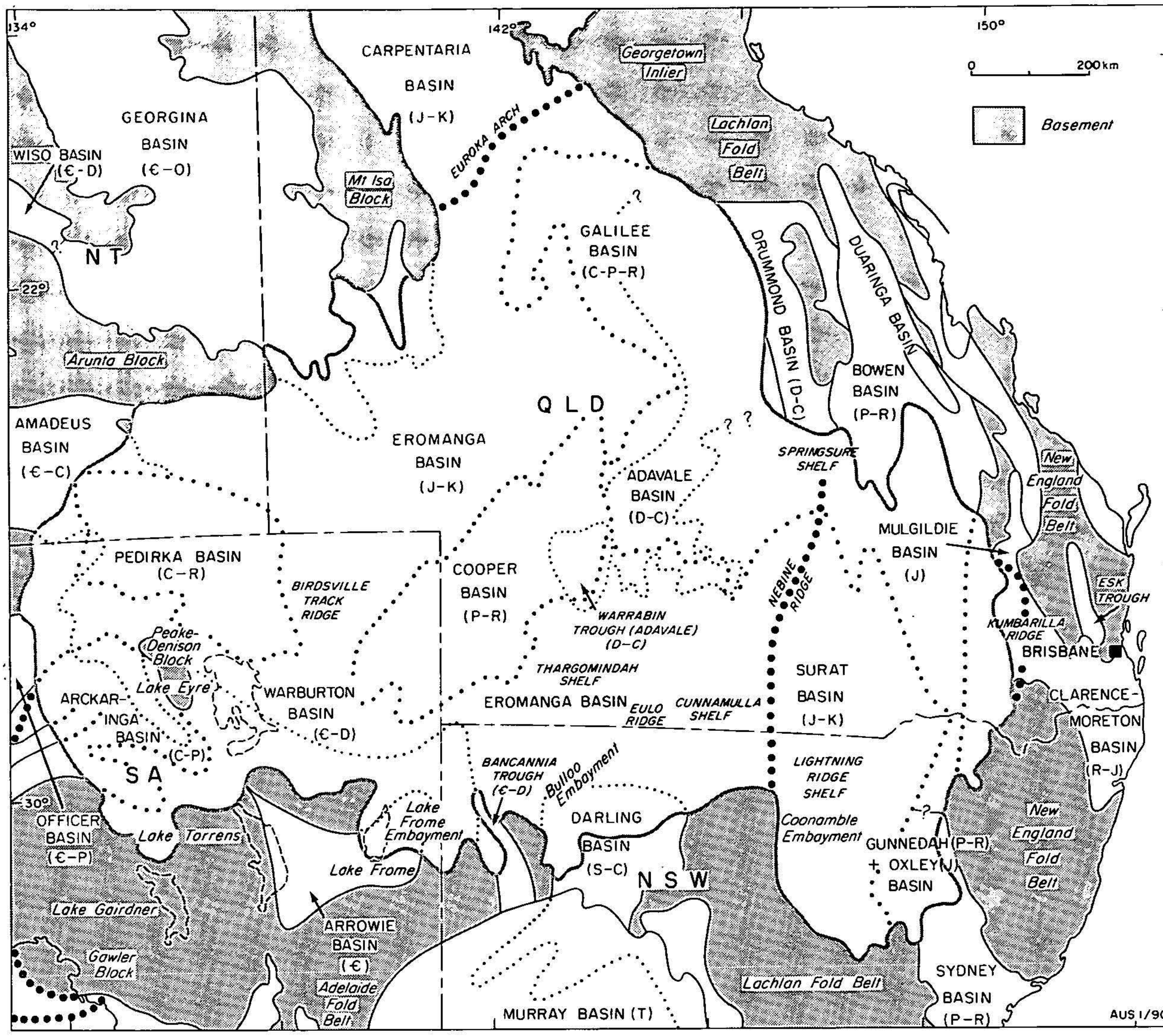


Figure 8. Constituent sedimentary basins, intermediate ridges and outlines of pre-Jurassic basins and their ages.

and platforms of older sedimentary, metamorphic or igneous rocks (Fig. 8). Similar rocks of pre-Jurassic age underlie the constituent sedimentary basins, and represent the impervious hydrogeological basement.

The Mesozoic sedimentary sequence present in the Great Artesian Basin reaches a maximum total thickness of about 3000 m in the central part of the Eromanga Basin. Marginal parts of the constituent geological basins have been partly eroded, particularly along the eastern rim which was uplifted during Cainozoic times. Sheet-like rock bodies are characteristic of the sedimentary basins, and persist relatively unchanged for hundreds of kilometres.

Notes on the constituent geological basins are given below:

Eromanga Basin. The Eromanga Basin (Fig. 8), which occupies about 1 x 10^6 km^2, consists of a conformable, almost horizontal sequence of Lower Jurassic to Upper Cretaceous sedimentary rocks (Parkin, 1969; Wopfner & others, 1970; Exon & Senior, 1976; Vine, 1976; Senior & others, 1978). The Jurassic sequence comprises continental quartzose sandstone, with lesser siltstone and mudstone. Siltstone, mudstone and lithic sandstone were laid down in shallow-marine environments during Early Cretaceous times. During the Late Cretaceous more sandy sediments were deposited in lacustrine and fluviatile environments. Most units crop out in the eroded eastern margin of the basin. Cretaceous outcrops in the central part are markedly weathered.

The Eromanga Basin is deepest where it overlies Palaeozoic and older Mesozoic sedimentary basins. The thinner sequences are present near the Nebine Ridge and Cunnamulla Shelf, where the Eromanga Basin connects with the Surat Basin, and across the Euroka Arch, where it connects to the Carpentaria Basin (Fig. 8). The Jurassic rock sequence thins and in places wedges out against these relatively shallow, buried basement structures near the southern part of the Eromanga, and also in the northern part.

Surat Basin. The southeastern part of the Great Artesian Basin is the sedimentary Surat Basin (Power & Devine, 1970; Exon, 1974, 1976; Allen, 1976; Exon & Senior, 1976) and occupies about 300 000 km^2 (Fig. 8). It consists of 2500 m of nearly horizontal sedimentary rocks of Jurrassic and Cretaceous age. The Jurassic sequence is an alternation of continental sandstone, siltstone and mudstone and some coal. The Cretaceous sediments consist of some continental, but mainly shallow-marine lithic sandstone and mudstone. Aquifers occur in many of the sandstone units; intake beds of these aquifers are present in exposures in the northern and eastern margins of the basin. The northern marginal area of the basin forms an erosional edge where Jurassic rocks unconformably overlie Triassic sediments of the Bowen Basin. Mesozoic sediments which connect the Surat and Eromanga Basins across the Nebine Ridge and Cunnamulla Shelf rest unconformably on Triassic sediments of the Bowen Basin and on the Palaeozoic sedimentary and igneous rocks of the Lachlan Fold Belt.

The Surat Basin intertongues with the Clarence-Moreton Basin across the Kumbarilla Ridge; this basin contains Triassic and Jurassic continental clastic sediments. Part of the eastern Surat Basin margin is controlled by a north-trending fault, but most of the northeastern, eastern and southwestern margins are bounded by Palaeozoic folded and faulted sedimentary and igneous rocks.

The Coonamble Embayment (Hind & Helby, 1969; Bourke & others, 1974; Hawke & others, 1975; Bembrick, 1976) forms the southern part of the Surat Basin, and is separated from the main part of the basin by the Lightning Ridge Shelf. The Jurassic rocks overlying the Gunnedah Basin in the most southeastern part of the Great Artesian Basin are referred to as the Oxley Basin (Bembrick & others, 1973; Bourke & others, 1974; Bourke & Hawke, 1977).

Carpentaria Basin. The northern extension of the Great Artesian Basin is the Carpentaria Basin (Doutch, 1976; Smart & others, in press), which occupies about 125 000 km^2 onshore and about 375 000 km^2 offshore in Queensland and the Northern Territory. It consists of continental rocks of Jurassic age, and mainly marine sedimentary rocks of Cretaceous age. The sequence is up to 1200 m thick and occupies a large north-trending syncline. Late Jurassic and Early Cretaceous rocks conceal the Euroka Arch, which is underlain by Proterozoic rocks (Smart, 1976).

Bowen and Galilee Basins. The uppermost sandstones in the Triassic sedimentary sequences of the Bowen and Galilee Basins contain aquifers which form part of the Great Artesian Basin; they are partly overlain by the Eromanga and Surat Basins. The Bowen Basin (Exon, 1974; Jensen, 1975; Paten & McDonagh, 1976) contains Permian and Triassic sedimentary rocks and forms an elongate, northerly trending basin. The main part is exposed in

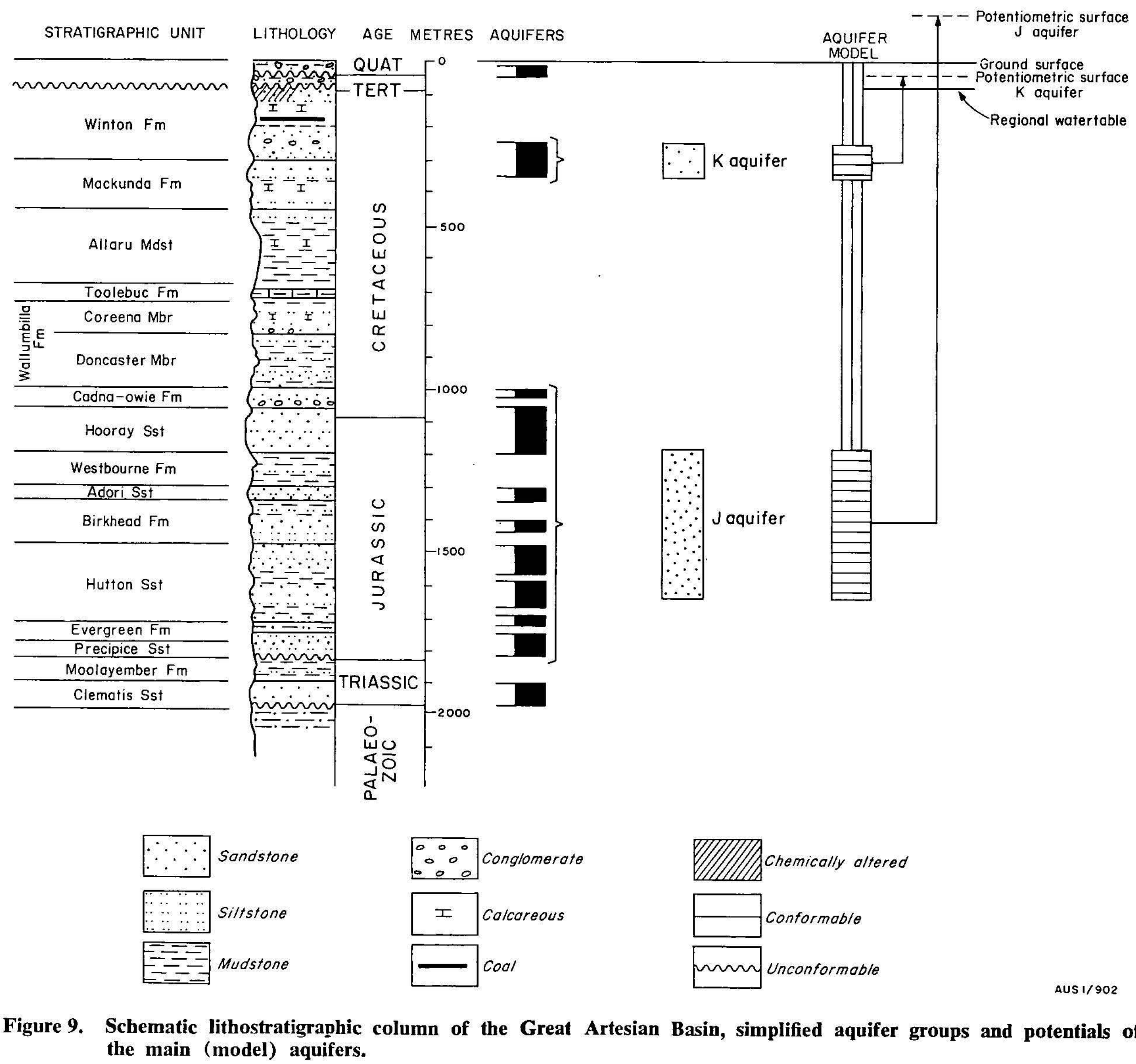


Figure 9. Schematic lithostratigraphic column of the Great Artesian Basin, simplified aquifer groups and potentials of the main (model) aquifers.

the north, the southern part is concealed beneath the Surat Basin. The Permian sediments consist of shallow-marine and continental deposits, and some volcanics; the Triassic sediments are continental. The Bowen Basin is bounded by older Palaeozoic rocks. The Narrabri Structural High separates the Bowen Basin from the Gunnedah Basin; the latter forms the transition to the Sydney Basin. The Bowen Basin intertongues with the Galilee Basin across the Springsure Shelf and the Nebine Bridge (Senior, 1971).

The Galilee Basin (Vine, 1976) contains up to 3000 m mainly of continental sediments of Late Carboniferous to Triassic age, which overlie older Palaeozoic sedimentary basins (Drummond, Adavale Basins) and Proterozoic rocks. Rocks are exposed along the eastern margin, but the main part of the Galilee Basin is concealed by the Eromanga Basin.

Cainozoic rocks. The Great Artesian Basin is partly concealed by Cainozoic continental sedimentary rocks as much as 150 m thick. These deposits mainly occur in the northeastern and southwestern parts of the Eromanga Basin, and cover almost the whole of the Surat and Carpentaria Basins (Wopfner & Twidale, 1967; Wopfner & others, 1974; Wopfner, 1974).

In the northeastern part of the Eromanga Basin, the northern part of the Surat Basin and in the eastern part of the Coonamble Embayment, Tertiary basalts cover some areas of Mesozoic rocks.

Stratigraphy

The stratigraphic succession present in the hydrogeologic Great Artesian Basin is given in summary form, excluding local marginal facies equivalents and minor units, in Figure 9 and Table 1. The distribution and correlation of these rock units of Middle or Early Triassic to Late Cretaceous ages in the sedimentary Bowen, Galilee, Eromanga, Surat and Carpentaria Basins, which constitute the hydrogeologic Great Artesian Basin are given in Figure 10.

Detailed descriptions of the lithostratigraphic units, their nomenclature and associated information is given in Hind & Helby (1969), Wopfner (1969), Wopfner & others (1970), Hawke & others (1975), Senior & others (1975), Exon (1976), Exon & Senior (1976), Smart (1976), Senior & others (1978) and Smart & others (in press).

Generally thin Cainozoic sediments (several tens of metres thick) overlie parts of the Great Artesian

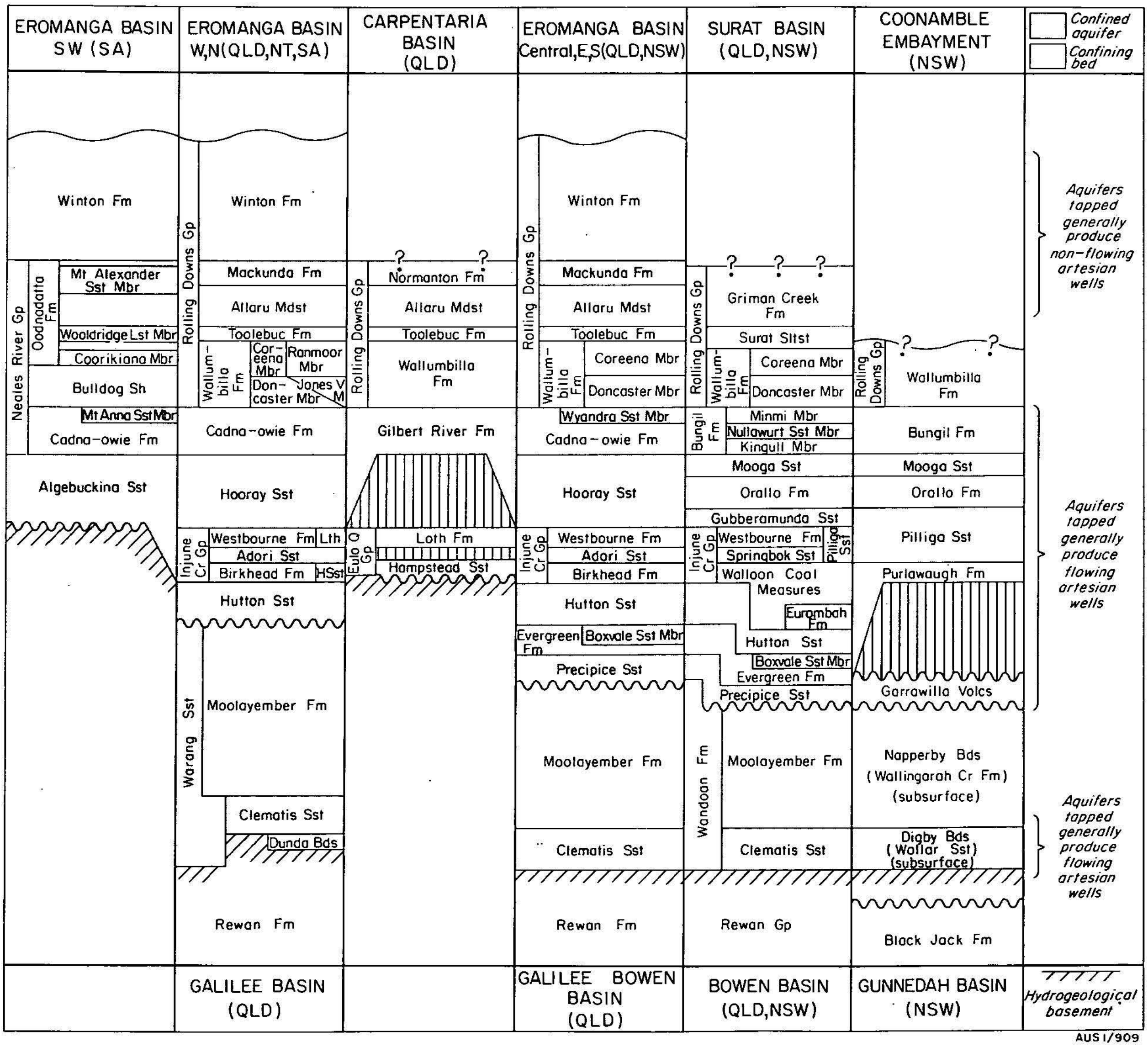


Figure 10. Correlation of hydrogeological units in the Great Artesian Basin.

Basin, and form shallow basins as much as 150 m deep. They rest on the deeply weathered erosional surface of the Cretaceous sediments; the older, Tertiary, sediments are also partly weathered and silicified, Quaternary sediments are mostly unconsolidated.

Structure

The Great Artesian Basin is an asymmetrical basin, elongated northeast-southwest, and tilted towards the southwest. The southern and northeast margins have slopes of about 2°, but in the west and southwest the regional dip increases to about 5°.

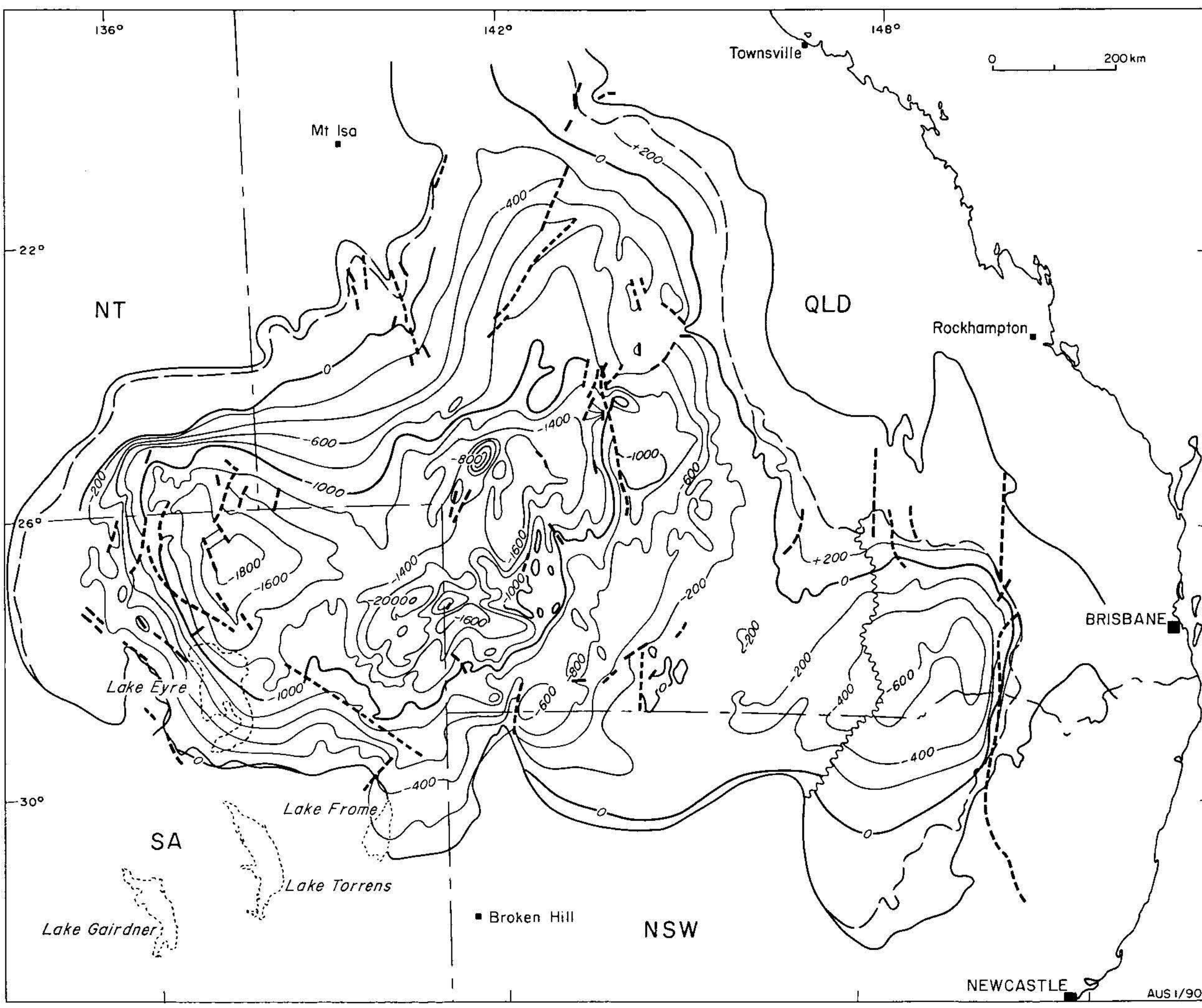
Tertiary uplift along the eastern margin, and subsidence in the central and southwestern parts, led to the basin's asymmetry and the present dominant southwesterly groundwater flow.

The broad structures in the basin are shown in Figure 11, a structure contour map of the top of the upper main aquifer producing flowing artesian wells (the base of the Rolling Downs Group, see Fig. 10) in the Jurassic-Cretaceous sequence in the Eromanga and Surat Basins.

Subsurface basement rises separating the Triassic and Jurassic-Cretaceous sedimentary basins are shown in Figure 8.

Many of the near-surface folds, particularly monoclinal features, grade downwards into faults and are the product of draping and differential compaction of the sediments over basement faults and fault-bounded basement blocks. Major fault and fold systems extend across the basin, sometimes forming in en echelon structures. Throws along major faults, affecting major aquifers, are as much as 300 m in the Eromanga Basin, and up to 150 m in the Surat Basin. Displacement of Jurassic-Cretaceous sediments along normal faults is usually much less, but considerable in some Permo-Triassic (1000-2000 m in the Bowen Basin) and older sediments.

Hydrodynamic conditions in the Great Artesian Basin, if considered on a basin-wide scale, will generally not be greatly influenced by the fold displacement of the sedimentary sequence. The faults are locally significant, in that they not only disconnect aquifers, and also give rise to hydraulic connection between different aquifers, but also act as preferential pervious or impervious structures, either to horizontal or vertical groundwater movement. However they do not significantly affect the broad regional flow patterns.



Boundary between Cadna-owie Formation/Hooray Sandstone and Mooga Sandstone — *Fault* — *-200 Contours (m), datum M S L, contour interval 200 m*

Figure 11. Structure contour map of the base of the Rolling Downs Group (Table 1 and 2) and top of the upper main aquifer producing flowing artesian wells in the Lower Cretaceous-Jurassic sequence.

Lithostratigraphic unit *Age*	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
WINTON FORMATION Late Cretaceous Cenomanian	500 200-1200	Lithic sandstone, siltstone, mudstone. (Continental, fluviatile and lacustrine.) Upper part erosional surface, weathered and silicified	Confined aquifer, lenticular. Upper aquifer in Great Artesian Basin. Recharge in extensive outcrop areas; natural discharge from eroded anticlinal structures. Many shallow non-flowing artesian wells in central part of basin, wells pumped, low to moderate yield, water quality poor
MACKUNDA FORMATION Early Cretaceous Late Albian	60 30-250	Lithic sandstone, siltstone, mudstone. (Shallow marine to paralic.)	Confined aquifer, lenticular. Recharge in outcrop, no natural discharge. Many shallow non-flowing artesian wells in central part of basin, wells pumped, low yield, water quality poor
ALLARU MUDSTONE Early Cretaceous Late Albian	200 30-370	Mudstone, siltstone. (Shallow marine)	Confining bed. Thick uniform mudstone sequence. Extends across most of Eromanga Basin
TOOLEBUC FORMATION Early Cretaceous Late Albian	15 5-75	Bituminous and calcareous shale. (Shallow marine)	Confining bed. Excellent marker-bed because of organic-rich argillaceous sediments (in lithological logs and strong positive gamma-ray anomaly in gamma-ray logs). Outcrops near western, northern and southern margins of Eromanga Basin; extends across most of Eromanga Basin, and southern part Carpentaria Basin
GRIMAN CREEK FORMATION Early Cretaceous Middle to Late Albian	300 480	Lithic sandstone, siltstone, mudstone. (Shallow marine, grading from beach to fluviatile)	Confined aquifer, interbedded with confining layers. Sandstone aquifer small proportion of thickness. Recharge in northern margin of Surat Basin, in central part covered by Quaternary sediments, which form in part confining bed. No connection with pervious beds in Eromanga Basin. Shallow non-flowing artesian wells, pumped, low yield, water quality poor
SURAT SILTSTONE Early Cretaceous Early to Middle Albian	100 150	Siltstone, mudstone. (Shallow marine)	Confining bed, insignificant aquifer. Restricted to Surat Basin
OODNADATTA FORMATION Early Cretaceous Albian	150-600	Siltstone, mudstone. (Marine)	Confining bed, minor aquifers (Mt Alexander Sandstone Member). Restricted to southwestern part of Eromanga Basin
COREENA MEMBER (Wallumbilla Formation) Early Cretaceous Early to Middle Albian	100 25-200	Siltstone, mudstone. (Shallow marine and paralic)	Confining bed, minor aquifers. Recharge in outcrop in eastern margin of Eromanga Basin and Surat Basin. Shallow non-flowing artesian wells in eastern and southeastern Eromanga Basin and western Surat Basin; wells pumped, low yield, water quality poor
DONCASTER MEMBER (Wallumbilla Formation) Early Cretaceous Late Aptian	150 120-270	Mudstone, siltstone. (Shallow marine)	Confining bed, minor aquifers. Permeable sandstone beds at base. Recharge in outcrop in eastern margin Eromanga Basin and Surat Basin. Shallow non-flowing artesian wells in eastern and southeastern Eromanga Basin and western Surat Basin; wells pumped, low yield, water quality poor
BULLDOG SHALE Early Cretaceous Aptian/Albian	200-500	Mudstone, shale. (Marine)	Confining bed. Southwestern part of Eromanga Basin
CADNA-OWIE FORMATION Early Cretaceous Neocomian to Early Aptian	60 15-80	Quartzose and lithic sandstone, siltstone. (Paralic to shallow marine)	Upper part good confined aquifer, lower part poor aquifer or confining bed. Recharge in subsurface from aquifers in connecting Hooray Sandstone. Cadna-owie Formation restricted to subsurface in Eromanga Basin, except for outcrops in southwestern margins, where spring discharge occurs. Many shallow and deep flowing artesian wells, high yield, water quality good
WYANDRA SANDSTONE MEMBER (Cadna-owie Formation) Early Cretaceous Late Neocomian to Early Aptian	15 3-20	Quartzose sandstone with quartz pebbles. (Shallow marine, beach)	Good confined aquifer. Restricted to subsurface of central and eastern Eromanga Basin. Recharge in subsurface through lateral conection with Hooray Sandstone. Usually first aquifer in Eromanga Basin producing flowing artesian wells. Majority of flowing wells tap this aquifer; except in centre, because of depth. High yield, water quality good
BUNGIL FORMATION Early Cretaceous Neocomian to Early Aptian	150 100-300	Lithic and quartzose sandstone, siltstone, mudstone. (Paralic)	Confined aquifers and confining beds. Recharge in northern and eastern margins of Surat Basin. Many flowing artesian wells obtain water from these aquifers in northern Surat Basin. Moderate to good yields, water quality good
MINMI MEMBER (Bungil Formation) Early Cretaceous Early Aptian	20-70	Quartzose and lithic sandstone, siltstone, mudstone. (Paralic)	Confining bed, minor aquifers. Some flowing artesian wells
NULLAWURT SANDSTONE MEMBER (Bungil Formation) Early Cretaceous Early Aptian	20-30	Quartzose and lithic sandstone, siltstone. (Paralic)	Confined aquifer. Flowing artesian wells

Table 1. Main lithostratigraphic and hydrogeologic units in the Great Artesian Basin.

Lithostratigraphic unit Age	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
KINGULL MEMBER (Bungil Formation) Early Cretaceous Neocomian	30-50	Lithic and quartzose sandstone, clayey. (Paralic)	Confining bed
GILBERT RIVER FORMATION Early Cretaceous Late Jurassic Neocomian	45 30-140	Quartzose and lithic sandstone. (Continental and shallow marine)	Confined aquifer. Recharge in eastern margins of the northern Eromanga Basin and Carpentaria Basin. Springs present in southeastern Carpentaria Basin. Flowing artesian wells, good yields and good water quality in northern Eromanga Basin, and (most wells) in southern Carpentaria Basin
HOORAY SANDSTONE Early Cretaceous Late Jurassic	150 45-400	Quartzose and lithic sandstone, siltstone, conglomerate, mudstone, coal. (Fluviatile, paralic, littoral)	Good, confined aquifer. Permeable throughout. Good permeability (intrinsic permeability several 100-several 1000 md) and porosity (average 25 percent). Transmissivity several 10 to several 100 (up to 1000) m^2/day, hydraulic conductivity 0.1 to 10 m/day. Recharge mainly in outcrop in eastern margin and small area of western margin of Eromanga Basin, northwestern Surat Basin. Discharge from springs in western margin and south-central part of Eromanga Basin. Most flowing artesian wells in Eromanga Basin obtain water from this aquifer. Good, to very good, yield (exceeding flows of 10 000 m^3/day), water quality good (500-1000 mg/l total dissolved solids, better quality than water from aquifers in Cadna-owie Formation. Wells tapping this aquifer throughout the basin; however, few in centre because of depth of aquifer
MOOGA SANDSTONE Early Cretaceous Neocomian	100 30-300	Quartzose and lithic sandstone, siltstone. (Fluviatile)	Confined aquifer. Recharge in outcrop in northern and eastern margins Surat Basin. Many flowing artesian wells obtain water from this aquifer in Surat Basin. Moderate to good yield. Water quality good
ORALLO FORMATION Late Jurassic	200 140-270	Lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Confined aquifer in sandstone beds, more than half of total thickness is confining bed. Recharge in northern and eastern margins Surat Basin. Few wells in Surat Basin.
GUBBERAMUNDA SANDSTONE Late Jurassic	100 45-300	Quartzose to lithic sandstone, siltstone, mudstone. (Fluviatile)	Confined aquifer; aquifers more than half of total thickness. Recharge in northern and eastern margins Surat Basin. Many flowing artesian wells in Surat Basin obtain water from this aquifer. Good yield and water quality good
ALGEBUCKINA SANDSTONE Late Jurassic	25 20-350	Quartzose sandstone, conglomerate. (Fluviatile)	Good, confined aquifer. Generally permeable throughout. Good permeability and porosity. Restricted to southwestern part of Eromanga Basin. Recharge in western margin but main recharge by lateral connection with Hooray Sandstone in subsurface. Many mound springs in southwestern marginal area provide natural discharge. Most flowing artesian wells in southwestern part obtain water from this aquifer. Good, to very good yield (flow exceeding 5000 m^3/day), water quality good to very good
WESTBOURNE FORMATION Late Jurassic	100 60-200	Siltstone, mudstone. (Fluviatile, lacustrine, shallow marine)	Confining bed; minor confined aquifers in part of Surat Basin
ADORI SANDSTONE Middle to Late Jurassic	50 25-70	Lithic to quartzose sandstone. (Fluviatile)	Confined aquifer. Recharge in aquifer outcrop in eastern margin Eromanga Basin and northwestern Surat Basin. Some flowing artesian wells in eastern part of Eromanga Basin. Good supplies and water quality good
LOTH FORMATION Late Jurassic	60 50-100	Quartzose sandstone, siltstone. (Fluviatile)	Confining bed, minor aquifers. Few wells in northern Eromanga Basin and southern Carpentarian Basin
SPRINGBOK SANDSTONE Middle to Late Jurassic	60-250	Lithic sandstone, siltstone, mudstone. (Fluviatile, deltaic)	Interbedding of minor aquifers and confining layers. Recharge in northern and eastern margins Surat Basin. Few flowing artesian wells northern and central parts Surat Basin
BIRKHEAD FORMATION Middle Jurassic	100 30-130	Lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Confining bed, some minor aquifers

Table 1 (cont.).

Lithostratigraphic unit Age	*Thickness Average min.-max. (m)*	*Major lithology (environment of deposition)*	*Hydrogeologic characteristics, recharge, discharge, wells, yield and quality*
PILLIGA SANDSTONE Middle to Late Jurassic	-300	Quartzose sandstone, conglomerate. (Fluviatile)	Good, confined aquifer. Permeable throughout. Good to very good permeability (intrinsic permeability 100-several 1000 md), good porosity (25 percent). Transmissivity several 10 to several 100, up to 1000 m^2/day, hydraulic conductivity 0.1 to 10 m/day. Recharge in outcrop of aquifers in eastern margin of Surat Basin. Very few springs in the western part of the Coonamble Embayment. Many flowing artesian wells (most wells in Coonamble Embayment) obtain water from this aquifer. Good to very good yield (exceeding 5000 m^3/day). Water quality good (500-1000 mg/l total dissolved solids), better quality than water from aquifers in higher aquifers
HAMPSTEAD SANDSTONE Late Jurassic	40 30-60	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer. Recharge northeastern margin Eromanga Basin, southeastern Carpentaria Basin. Flowing artesian wells in northern Eromanga Basin and southern Carpentaria Basin
WALLOON COAL MEASURES Middle Jurassic	-650	Lithic sandstone, siltstone, mudstone. (Lacustrine, fluviatile)	Confining bed
PURLAWAUGH FORMATION Early to Middle Jurassic	10-120	Mudstone, sandstone, siltstone. (Fluviatile, lacustrine)	Confining bed
HUTTON SANDSTONE Early to Middle Jurassic	150 120-250	Quartzose and lithic sandstone, siltstone, mudstone. (Fluviatile, lacustrine)	Good, to very good confined aquifer. Most of formation is permeable. Moderate to good permeability (intrinsic permeability several 10-several 1000 md), good porosity (25 percent). Recharge eastern margins of Eromanga Basin, and northern and eastern margins Surat Basin (partly east of surface water divide). Some flowing artesian wells mainly near northern, northeastern and eastern basin margins, restricted elsewhere by depth. Good yield (flows 5000 m^3/day) and good quality. Water quality better than for water from higher (Jurassic and Cretaceous) aquifers (lower total dissolved solids values)
EVERGREEN FORMATION Early Jurassic	10-260	Siltstone, mudstone. (Fluviatile, lacustrine, deltaic, shallow marine)	Confining bed. Northern and central Surat Basin, eastern Eromanga Basin
BOXVALE SANDSTONE MEMBER (Evergreen Formation) Early Jurassic	45-90	Quartzose sandstone, siltstone. (Fluviatile, lacustrine)	Confined aquifer. Recharge in eastern margin Eromanga Basin, northern margin Surat Basin. Some flowing artesian wells and artesian wells near basin margins. Good yield and good quality
PRECIPICE SANDSTONE Early Jurassic	45-150	Quartzose sandstone, siltstone. (Fluviatile, lacustrine)	Good, confined aquifer, especially lower, coarser sandstone. Good to very good permeability (intrinsic permeability several 10-20 000 md), good porosity (20 percent). Recharge in outcrop in eastern margin Eromanga Basin, northern margin Surat Basin. Some springs 'overflow' in margin of northern Surat Basin. Flowing artesian and artesian wells near basin margins. Good yield and water quality good
GARRAWILLA VOLCANICS Late Triassic to Early Jurassic	-180	Trachyte and trachy-basalt lavas, tuff. (Interbedded lavas, sills)	Confining bed
MOOLAYEMBER FORMATION Middle Triassic	200-1500	Siltstone, mudstone. (Fluviatile, lacustrine, deltaic, shallow marine)	Confining bed
NAPPERBY BEDS Middle Triassic	15-200	Siltstone, mudstone. (Fluviatile)	Confining bed
CLEMATIS SANDSTONE Middle to Early Triassic	20-300	Quartzose to lithic sandstone. (Fluviatile)	Good, confined aquifer. Lowest aquifer in the Great Artesian Basin. Permeable throughout. Moderate to good permeability (intrinsic permeability 5-3000 md), moderate to good porosity (20 percent). Recharge in aquifer outcrop eastern margin Galilee Basin and northern margin Bowen Basin (east of topographic watershed). Flowing artesian and artesian wells near eastern margins of the basin. Good yield and water quality good
DIGBY BEDS Early Triassic	200	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer. Few wells
WARANG SANDSTONE Middle to Early Triassic	-700	Quartzose sandstone, siltstone. (Fluviatile)	Confined aquifer
REWAN FORMATION/GROUP (Middle to) Early Triassic	-3500	Mudstone, siltstone, lithic sandstone. (Fluviatile, lacustrine, aeolian)	Confining bed

Table 1 (cont.).

Groundwater hydrology

Hydrogeological units

The Great Artesian Basin consist of confined aquifers and confining beds throughout the Middle Triassic to Late Cretaceous sedimentary sequence in the constituent sedimentary Bowen, Galilee, Eromanga, Surat and Carpentaria Basins. Confined aquifers are present within a rock sequence, which, where complete, is bounded by the Rewan Group at the bottom, and the Winton Formation at the top (Table 1; Figs. 9, 10).

Aquifers are present in the Clematis, Precipice, Boxvale, Hutton, Adori and Hooray Sandstones, and in the Cadna-owie Formation and their equivalents, as well as in the Mackunda and Winton Formations (Table 1; Figs. 9 and 10). Most of the aquifers are continuous and hydraulically connected across the constituent geological basins. Aquifers in Tertiary and Quaternary sedimentary rocks and sediments, which are partly confined, but mostly unconfined, with a discontinuous distribution, are not considered part of the Great Artesian Basin.

The major confining beds consist of the Rewan Group, Moolayember, Evergreen, Birkhead, Westbourne, Wallumbilla and Toolebuc Formations, and their equivalents, as well as the Allaru Mudstone, and parts of the Mackunda and Winton Formations (Table 1; Figs. 9, 10).

Hydrogeological basement comprises impervious sedimentary, metamorphic or igneous rock, and this basement forms in part an aquiclude or aquifuge.

The aquifers of the Great Artesian Basin are generally well separated from high salinity water in Permian and older units, except in the southwestern part, where Permo-Triassic strata are in direct contact with Jurassic aquifers (Youngs, 1975a, b). Confining beds further north separate aquifers in the Hooray Sandstone from higher salinity water in Cambrian and Ordovician carbonate sediments of the Georgina Basin (Randal, 1978). In part of the Galilee Basin, the Clematis Sandstone extends further westward than the overlying and confining Moolayember Formation, resulting in a hydraulic connection between the aquifer in the Clematis Sandstone and the aquifers in the Hutton or Precipice Sandstones. As a result of the onlapping nature of the Jurassic and Lower Cretaceous sedimentary sequence, migration of water occurs from aquifers in the lower part to aquifers higher in the sequence, where these units subcrop against impervious basement, as along the northern margin of the Thargomindah and Cunnamulla Shelves.

Most sandstones in the Triassic, Jurassic, and Cretaceous sedimentary sequence in the Great Artesian Basin are aquifers. Separate aquifers within individual sandstone units, though distinguished in drillers and geophysical well logs, were not studied in this regional hydrogeological study. Instead groups of aquifers were considered, which correspond broadly to aggregates of individual aquifers occurring in lithostratigraphic units (Table 1; Figs. 9, 10). Most of the lithostratigraphic units which contain a significant component of sandstone, represent the major aquifers of the Great Artesian Basin. Confining beds are represented by rocks with relatively low permeabilities and consist of mudstone and siltstone.

Most of the lithostratigraphic units have a rather uniform geometry, lithology, structure, texture, and depositional origin throughout the basin. Similar generalities apply to the hydraulic characteristics of the aquifers and the confining beds; in detail, however, the hydraulic properties, including the permeability and porosity of the rocks, show marked differences laterally and vertically.

Hydraulic characteristics of the aquifers and the confining beds

Transmissivity values determined from test data generally range from 1 to 2000 m^2/day: low values, usually less than 10-20 m^2/day, predominate in the south-central and most eastern parts of the basin. Higher values, in the order of 10s and 100s m^2/day, are present in the northern and southern parts.

Transmissivity values were calculated from data derived from periodical systematic tests carried out by the State water authorities since the early development of the basin, on flowing artesian waterwells in the Queensland and New South Wales parts of the basin. Hydraulic tests include recovery (static pressure) tests for wells which were found flowing, and constant drawdown (flow recession) tests for wells which were found with the headwork valves completely or partially closed. Step drawdown (dynamic) tests, being either an opening dynamic test for a closed well or a closing dynamic test on a flowing well were also carried out by these organisations. Transmissivity values include results from approximately 200 step drawdown tests on flowing artesian wells in Queensland which were analysed by R. N. Eden and C. P. Hazel of IWSC (now QWRC), unsing a modified version of the Sternberg method (Kruseman & De Ridder, 1970, Eden & Hazel, 1973).

Field data from recovery and drawdown tests in New South Wales were transcribed and transmissivity values determined using the modified Jacob method (Kruseman & De Ridder, 1970). Hydraulic conductivity values generally range from 0.1 to 10 m/day, the majority being in the lower part of that range; some higher values occur. No particular pattern or preferred distribution is apparent, though such a distinction is difficult to establish with the distribution and amount of data available (about 350 wells with hydraulic conductivity values). Almost all wells are completed in aquifers in the Cadna-owie Formation, Hooray Sandstone (and their equivalents) and the Pilliga Sandstone, and therefore almost all the available transmissivity and hydraulic conductivity values come from these aquifers.

Storage coefficient values of the aquifers tapped could not be determined from the data obtained by the tests carried out without observation wells. An empirical method, using the relationship between aquifer porosity and the storage coefficient was used to derive the latter. In most petroleum exploration wells drilled through the basin sequence, sonic or acoustic logs were run, though these logs (as most other geophysical logs in these wells) do not cover the upper parts of the Cretaceous sequence. Porosities of permeable layers in the Cretaceous-Jurassic sequence were calculated (Keys & McCary, 1971, Schlumberger, 1972), as the lithology was known from the lithological log and from other geophysical logs run in the boreholes and converted into storage coefficient values. For aquifers where no logs were available Lohman's (1972) approximation was used, where $S = 3.3 \times 10^{-6} \times$ thickness of the aquifer (m). Storage coefficient values obtained by either of the two methods result in values averaging about 10^{-5} (range from 10^{-4} to 9×10^{-5}).

Intrinsic permeability, average effective porosity (percentage of bulk volume) and average density (dry bulk and apparent grain) values were determined by the Petroleum Technology Laboratory of BMR from many core samples of the aquifers sequences encountered in petroleum exploration wells and stratigraphic drillholes, as well as outcrop samples. Some results are reported in Petroleum Search Subsidy Acts publications, in Gray (1972), and well completion reports of stratigraphic holes drilled by the Geological Surveys of New South Wales and Queensland. Intrinsic permeability and porosity values range from several tens to several thousands of millidarcys, and from about 10 to 30 percent respectively; they decrease with depth.

The vertical flow from one aquifer to another is restrained by the very low permeability of the confining beds which are assured to be leaky. Hydraulic parameters of the confining beds could not be determined from the available data. An approximate vertical hydraulic conductivity value of the confining beds was calculated (Audibert, 1976). Confining beds in petroleum exploration wells were defined from geophysical logs and subdivided into four rock types according to their dominant lithology. Each rock type was assigned a value (Todd, 1959; Castany, 1967): sandstone—10^{-1} m/day; sandstone, siltstone, shale—10^{-2} m/day; shale, siltstone, sandstone—10^{-3} m/day; shale—10^{-4} m/day. The conductivity values were distributed according to the thickness of each layer, and produced an average value for the total thickness of the confining unit. Average vertical hydraulic conductivity values were obtained from

$$K_{av} = \frac{D}{\frac{d_1}{K_1} + \frac{d_2}{K_2} + \dots \frac{d_n}{K_n}}$$

in which D = total thickness confining unit, d_1 = thickness layer 1, K_1 = vertical hydraulic conductivity of layer 1 (International Institute for Land Reclamation and Improvement, 1972; Bouwer, 1978). The resultant average vertical hydraulic conductivities of confining beds in some parts of the sequence intersected by petroleum exploration wells in the basin range from 10^{-1} to 10^{-4} m/day.

Recharge

Outcrop areas of aquifers, most of which provide the opportunity for recharge to the aquifer units, occur mainly along the eastern margins of the basin (Fig. 12).

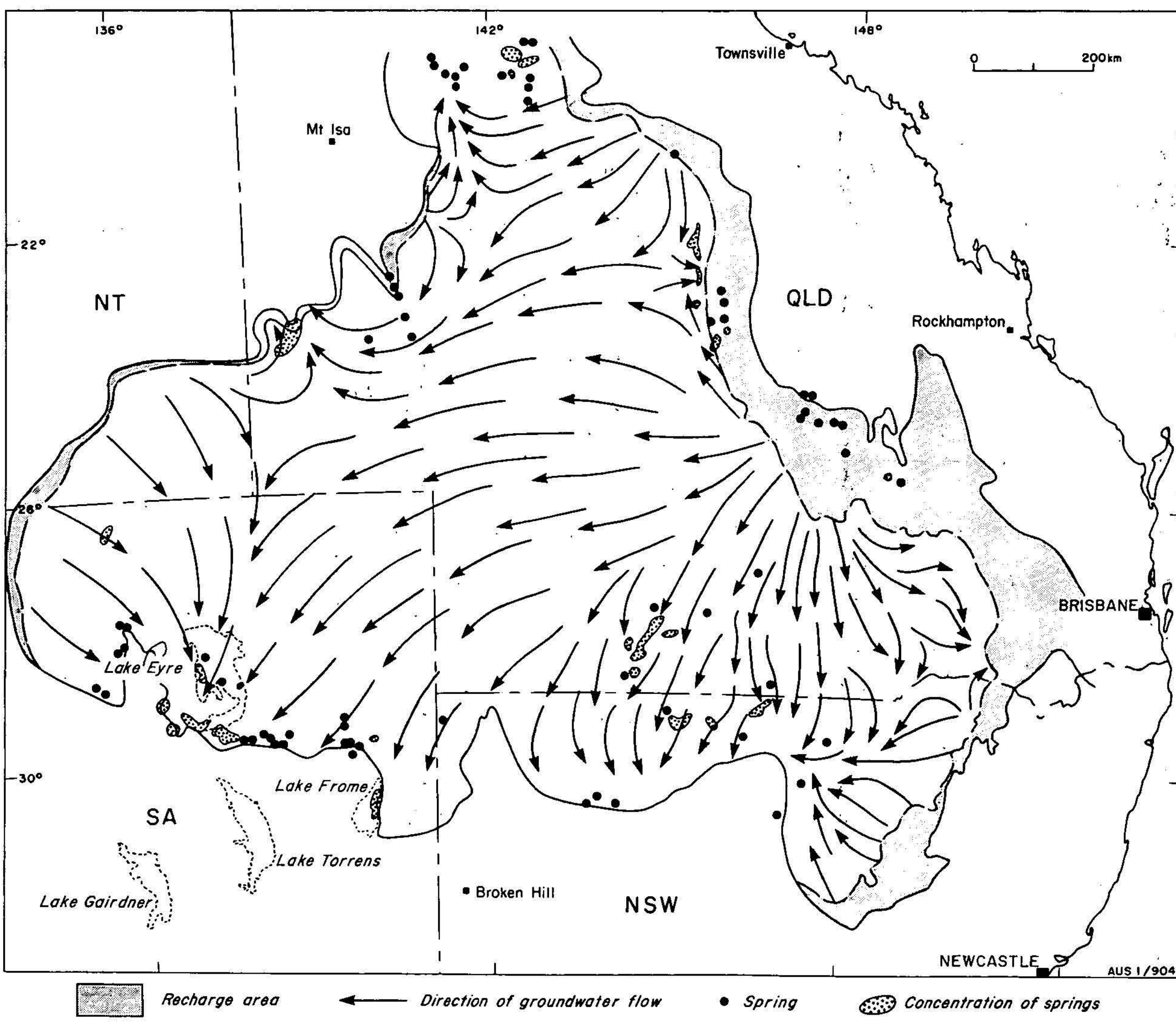


Figure 12. Recharge and natural discharge (springs) areas and directions of regional groundwater flow in the Great Artesian Basin.

Most recharge areas are on the western slope of the Great Dividing Range (though some aquifers in rocks of Triassic age outcrop on the eastern side of the surface watershed), and vary from scarp-bounded plateaus and cuestas to alluvial or rolling country, traversed by creeks and rivers. Some recharge takes place through Cainozoic sandy sediments overlying sandstone units, as in the eastern part of the Surat Basin.

Outcrops of aquifers and subcrops of aquifers in the Jurassic-Cretaceous sequence overlain by sandy sediments along the western margins of the Great Artesian Basin provide the possibility of recharge in those areas (Fig. 12). Randal (1978) also inferred recharge in the northwestern area.

Gradients of the potentiometric surfaces of confined groundwater in the aquifers of the Cretaceous and Jurassic rock sequence indicate the flow of the groundwater, and the occurrence of surface recharge has been interpreted from the distribution of well potentials (Fig. 15). Studies of environmental isotopes from water of wells in areas basinwards of the recharge areas support the assumption of continuing recharge from geological to modern times (Airey & others, 1979; Calf, in prep.). Stable-isotope (D/H and $^{18}O/^{16}O$) results show unequivocally that the artesian water is of meteoric origin. Observed systematic variations in chloride levels of water samples with distance from the recharge area probably reflect variations in the mean annual rainfall and the rate of infiltration of recycled salt throughout the Late Quaternary; the minimum and maximum of the chloride curve correlate with the last glacial and interglacial period respectively (Airey & others, 1979).

Discharge

Discharge from the Great Artesian Basin takes place as natural discharge in the form of concentrated outflow from springs, vertical leakage towards the regional watertable, subsurface outflow into neighbouring basins, and as artificial discharge by means of free artesian flow and pumped abstraction from wells drilled into the aquifers.

Springs occur in groups, mainly in the marginal areas of the basin (Fig. 12); many appear to be fault-controlled, others occur where aquifers abut impervious basement rocks or where only thin confining beds are present.

Discharges from individual springs range up to 85 l/sec; the total discharge of all known springs (*c*350), which form eleven groups, is estimated at about 1500 l/sec. Many are only seepages or are no longer flowing; spring discharges generally have declined since the early development of the wells in the basin. The largest concentrations of springs are in the southern, south-central and southwestern parts of the basin; the area southwest and northwest of Lake Eyre contains the largest and most active springs. Williams (1979) stated that 95 percent of the natural discharge in South Australia occurred from the group of springs at Dalhousie (Williams & Holmes, 1978), northwest of Lake Eyre, near the State border. Springs are commonly characterised by conical mounds of sand and silt-size sediment and carbonate, which range in height and diameter from a few metres to tens of metres (Fig. 13). Some of the larger mounds have waterfilled craters. Springs near Lake Eyre were described by Williams (1974, 1979), and Cobb (1975); some data on mound springs in Lake Frome is given in Draper & Jensen (1976). Springs in eastern areas are described by Ball (1918), Jensen (1926), and Rade (1954b, 1955).

The discharge of some springs is sufficient to maintain small creeks for hundreds of metres or some kilometres in this arid region, in which evaporation and evapotranspiration is very high. Vegetation lines some of these streams and surrounds many of the springs, whereas usually swampy areas and large, bare salt plains are present away from many of the springs.

Few historical records exist on springs in the basin, but diminishing spring discharge in the northwestern area, following well development, is shown by figures in Interstate Conference on Artesian Water (1913), David (1950), Queensland Government (1954), Whitehouse (1954) and Randal (1978).

Some springs in the eastern marginal part of the basin owe their flows to 'overfilling' of aquifers in nearby recharge areas (rejected recharge).

Southwest of Lake Eyre several ancient non-active mound-springs occur more than 40 m above the surface of the surrounding plain. The present, lower landsurface in this area is partly the result of tectonic movement and dissection, but mainly from deflation (Wopfner & Twidale, 1967; Bowler, 1976). Lowering of the spring outlet levels has resulted from the combined action of a series of step-wise stages of lowering of the landsurface by erosion and denudation, and the breakthrough of water at a lower level. The latter caused a reduced flow from higher springs. Clogging of the upper outlet of springs by sediments and (carbonate) cement, and the resulting lower-level breakthrough and discharge of water, has a similar effect.

Vertical leakage from the confined aquifers upwards through the confining beds, which are considered semi-pervious, probably occurs over extensive areas of the basin, and despite the low percolation rate, involves a considerable volume of water. High evaporation rates and a deep phreatic surface (generally several tens of metres below the ground surface), disguise vertical leakage. Areas most likely to be influenced by concentrated leakage from aquifers, as inferred from the potentiometric maps of the aquifers in the Jurassic and Cretaceous sequences, are the western part of the Coonamble Embayment, and parts of the southern and western margins of the Eromanga Basin. Contributions from upward groundwater movement could be obliterated by the surface water inflow in some of these areas (Fig. 3). Intermittent river systems, large swamps and lakes are present in these possible discharge areas. The relative high groundwater table in the Lake Eyre region during long dry periods suggest upwards leakage

Figure 13. Moundspring in the area near Lake Eyre.

from the underlying confined aquifers in the Cretaceous and Jurassic sequence.

Geological evidence suggests that subsurface outflow into any of the surrounding or underlying basins is negligible. Though connections exist with the Moreton and Sydney Basins, effective groundwater divides are present, preventing subsurface outflow. Inflow is possible through aquifers in the Hutton Sandstone across the Kumbarilla Ridge. Hydraulic continuity is present across the Euroka Arch, and outflow directed northwards occurs into the southern part of the Carpentaria Basin through the aquifers in the Jurassic-Cretaceous sequence, as shown by potentiometric maps (Fig. 12, 15). Some of this water may eventually emerge through sub-sea springs in the Gulf of Carpentaria.

Most groundwater from the Great Artesian Basin is exploited from flowing artesian waterwells (Figs. 5, 6), which are up to 2000 m deep, but average about 500 m. Flows from individual wells exceeded 10 000 m^3/day (more than 100 l/sec), but the majority have much smaller flows. About 3100 of the original 4700 flowing artesian wells drilled remained flowing during the early 1970s. The accumulated discharge rate of these wells at the time was about 1.5 x 10^6 m^3/day, compared to the maximum flow rate of about 2 x 10^6 m^3/day from about 1500 flowing artesian wells around 1918 (Fig. 6).

Flowing artesian waterwells (Fig. 14) obtain their water from aquifers in the Lower Cretaceous and the Jurassic sequence (mainly the upper aquifers), and the original non-flowing artesian waterwells generally tap the aquifers in the Winton and Mackunda Formations (Figs. 9, 10; Table 1). These non-flowing wells are generally shallow, and several tens to hundreds of metres deep. It is estimated that these generally windmill-operated pumped wells supply on average 10 m^3/day. Most wells drilled to aquifers in the Lower Cretaceous, Jurassic or Triassic sequence encountered Upper Cretaceous aquifers higher in the hole; the latter aquifers are usually cased off, as the water is of poor quality. A proportion of wells drilled into aquifers in the pre-Rolling Downs Group part of the sequence obtain their supplies from more than one aquifer unit (or formation). Most wells produce from perforated or slotted casing intervals opposite aquifers, or from an interval of open hole in the aquifer below the casing. Almost all existing waterwells are lined with metal (steel) casing in the form of a single telescopic string or several strings of different diameter (usual diameter about 300, 250, 200, or 150 mm).

Flow rates and potential data of individual wells, when plotted against time, show curves with high initial flow rates and pressures. Most curves flatten out with time, and ultimately approach asymptotic shapes similar to the curve of accumulated discharge rate in Figure 6 for the period 1918 to about 1960.

The areal distribution of high (initial) flowrates is fairly uniform in the areas of development, and the accumulated discharge taken from specific areas (usually from the highest aquifer in the Lower Cretaceous-Jurassic sequence) relates mainly to the density of wells in the area and the prevailing net pressure—the head or waterlevel elevation above groundlevel to which the free-flowing discharge is directly related. Most of the flowing artesian wells tap aquifers in the Cadna-owie Formation, the Hooray Sandstone and the Pilliga Sandstone. A few wells obtain water from aquifers below the Hooray Sandstone; in such cases they usually tap aquifers in the Hutton and Clematis Sandstones. Only a small number of flowing artesian wells originate from aquifers in the upper part of the Cretaceous sequence.

Groundwater levels

Potentiometric maps showing the conditions during the early years of development and around 1970 for the main aquifers in the Lower Cretaceous-Jurassic sequence—which produce flowing artesian wells—are given in Figure 15a and b respectively. These maps were prepared with the GABHYD simulation model (Seidel, 1980); all available potential data were used and some manual adjustments made.

First waterlevel readings in newly drilled, widely spaced wells during the early years of development represent data for almost undisturbed aquifer conditions, approximating the natural steady-state condition of the groundwater basin.

Measurement of water levels in the Great Artesian Basin commenced with the drilling of the first waterwells, and were repeated until the present on a periodical basis on most flowing artesian wells. Potentiometric surface maps, covering only parts of the basin, are included in Gregory (1906), Pittman (1914), Interstate Conference on Artesian Water (1913, 1914, 1922, 1925, 1929), Ward (1922), Tandy (1939, 1940) and Ogilvie (1954) and Randal (1978). Ward (1946) only showed a map with the general direction of groundwater movement.

Enough pressure data are now available for wells tapping specific aquifers, and ground elevation data of wells, to prepare reliable potentiometric contour maps of large parts of the basin for certain time intervals.

State water authorities systematically measured pressure heads of existing flowing artesian wells, usually by reading pressure gauges as the flowing well was closed and pressure built up. Water levels of original non-flowing artesian wells are usually only measured at the time of completion of the well.

Pressure-head values recorded in the GAB-ADP system during the present study, were recalculated using a standard equivalent of pure water at 15°C, and the potentials determined. Corrections caused significant changes for temperature effects, but because of the low salinity of the groundwater, only a negligible effect for the latter. Most pressure-head values relate to wells tapping aquifers in the Hooray Sandstone and its equivalents (including the Pilliga Sandstone, which is the main aquifer tapped by wells in the southeastern

Figure 14. Flowing artesian waterwell in the Great Artesian Basin (WRC-NSW Reg. No. 4263—Four Posts-2; depth 1174 m, flow 35 l/sec, wellhead temperature 57°C; aquifer Pilliga Sandstone).

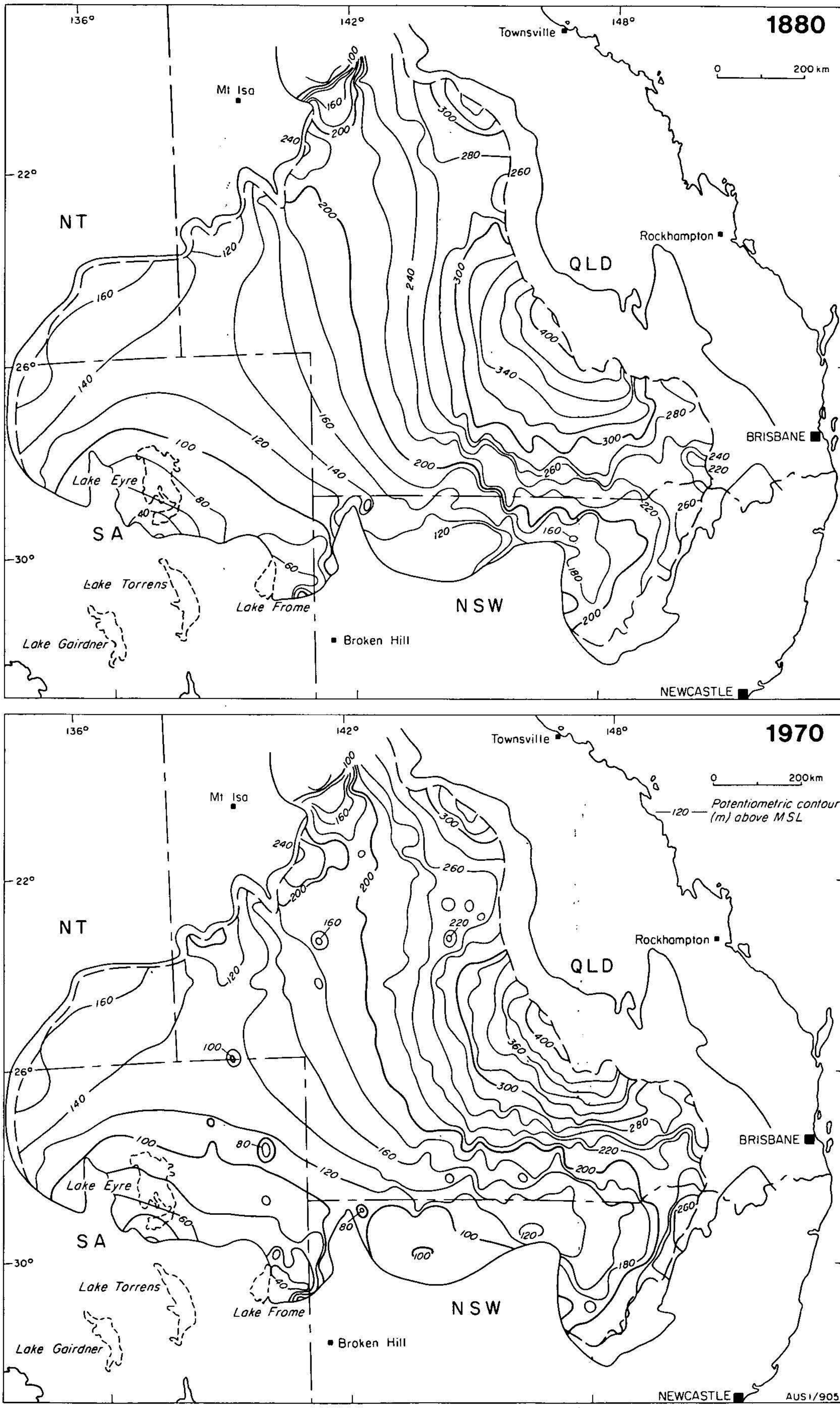


Figure 15. Potentiometric maps of the main aquifers in the Lower Cretaceous-Jurassic sequence during 1880 and 1970, modified from GABHYD simulation model results, using all available potential data. Datum is mean sea level, and potentials relate to pure water at 15°C.

part of the basin) and few data are available for other aquifers.

Waterlevels recorded during drilling of wells include those encountered in the upper confining beds of the sequence, which are regarded as the upper boundary of the saturated zone, and as such the regional watertable (Fig. 16). It is the uppermost expression of the (leaky) artesian system of the Jurassic and Cretaceous aquifers (Fig. 9). The generalised contour map of the regional watertable has a marked resemblance to the topographic contour map; this proven affinity between the regional watertable and the topography in areas with dense data coverage has been used to extrapolate contours to those parts of the regional watertable map, where few data points are available. Local confined and unconfined aquifers, usually as perched aquifers in Cainozoic sediments overlying the Great Artesian Basin sequence, have been ignored.

The change in waterlevels as a result of development is shown in Figure 7. The concentration of development in some of the marginal areas (Fig. 5) led to considerable changes in the patterns of isopotential contours (Fig. 15). Hydraulic gradients of aquifers in the Lower Cretaceous and Jurassic sequence (Fig. 15) changed in some areas from 1:2150 to 1:1750, and from 1:2300 to 1:1600. Hydraulic gradients of aquifers in the upper part of the Cretaceous sequence are about 1:1800. Changes to potentials of the aquifers in the upper part of the Cretaceous are much smaller during the period of development because of the small rate of withdrawals. Furthermore, a relatively large part of these Cretaceous aquifers is unconfined; in these areas, relatively few changes are expected in the regional watertable which represent the waterlevel of this aquifer.

Groundwater movement

Regional groundwater movement in the basin, as determined from the potentiometric surface maps of the aquifers in the Jurassic and Cretaceous sequences (Fig. 15), is shown in Figure 12.

Convergence of flow and steepening of the hydraulic gradient coincides with the occurrence of springs near the Eulo Ridge, and the lowering of transmissivities reflects thinning of aquifers. Similar preferential drainage patterns are also present in the southeastern part of the basin. Along the northwest margin of the basin an area of outflow is bordered by two areas of inflow.

In some areas faults locally displace or disconnect aquifers, and obstruct part or all of the groundwater flow in the main Early Cretaceous and Jurassic aquifers, which is normally directed to these structures. Little is known about the hydraulic character of these faults, which could act as impermeable barriers or as preferential permeable zones.

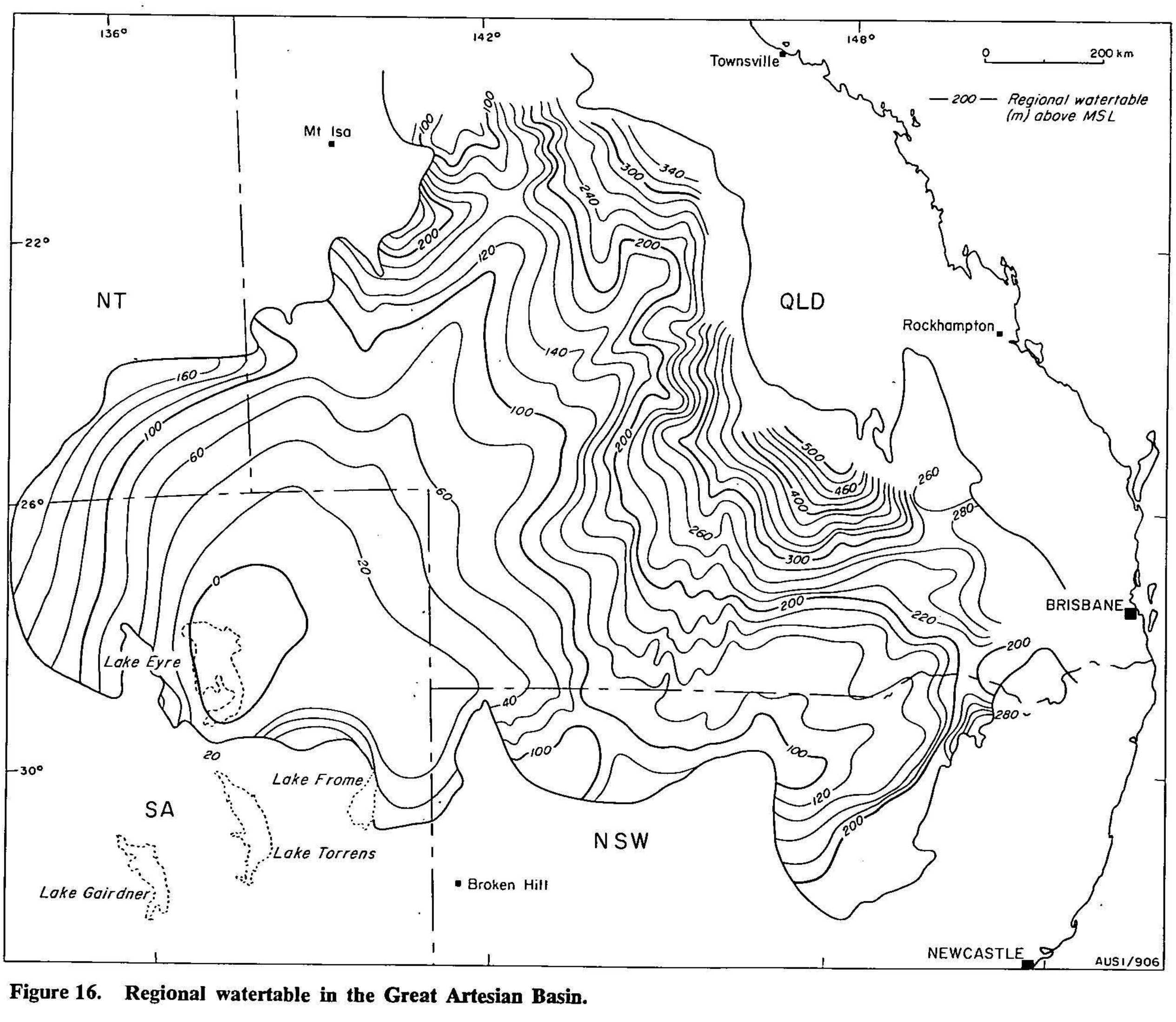


Figure 16. Regional watertable in the Great Artesian Basin.

Where they act as barriers, flow directions will have changed, and salinity of semi-stagnant water could increase. Hydrocarbons, from either the marginally mature or mature Eromanga Basin sequence or the underlying Cooper, Galilee or Adavale Basins, and transported by the groundwater flow, could accumulate and be trapped near such faults in stagnant or semi-stagnant zones (Senior & Habermehl, 1980). Upward migration of warm artesian water through permeable zones near the Canaway Fault, is indicated by the geothermal gradient (Polak & Horsfall, 1979; Senior & Habermehl, 1980).

Estimate of the average groundwater velocity can be made with the equation $\bar{v} = \frac{Ki}{p}$ where $\bar{v}$ = average velocity, K = (horizontal) hydraulic conductivity; i = hydraulic gradient, p = porosity (decimal fraction). Groundwater movement in the main aquifer in the Lower Cretaceous-Jurassic sequence in the eastern marginal areas of the basin have average velocities ranging from about 1 to 5 m/year. These values for the rate of flow of artesian groundwater severely restricts the application of ^{14}C dating (Airey & others, 1979). Residence time determinations with this naturally occurring isotope are limited to relative short distances from the recharge areas of the aquifers, as ^{14}C has a half-life time of 5730 years and the method can be used only for water with ages up to about 30 000 to 40 000 years. Application of ^{36}Cl, which has a half-life time of about 308 000 years would be more suitable for the dating of very old groundwater (Elmore & others, 1979), such as in the Great Artesian Basin, i.e., where it has moved over considerable distances.

Groundwater chemistry

Groundwater in the most widely exploited aquifers in the Lower Cretaceous and Jurassic sequence is generally of good quality, containing usually about 500 to 1000 mg/1 total dissolved solids, mainly sodium bicarbonate with some chloride and minor sulphate. A higher chloride and sulphate content is present in the most western parts of the basin (Fig. 17). The salinity values tend to increase near discharge areas. Some results of chemical analyses carried out from 1968 to 1978 by the Government Chemical Laboratories of Queensland, and the Chemical Laboratories of Department of Mines, New South Wales; Department of Mines, South Australia; Water Resources Branch, Northern Territory Administration; and Australian Atomic Energy Commission, on groundwater samples from the main aquifers in the Lower Cretaceous-Jurassic sequence in different parts of the basin are

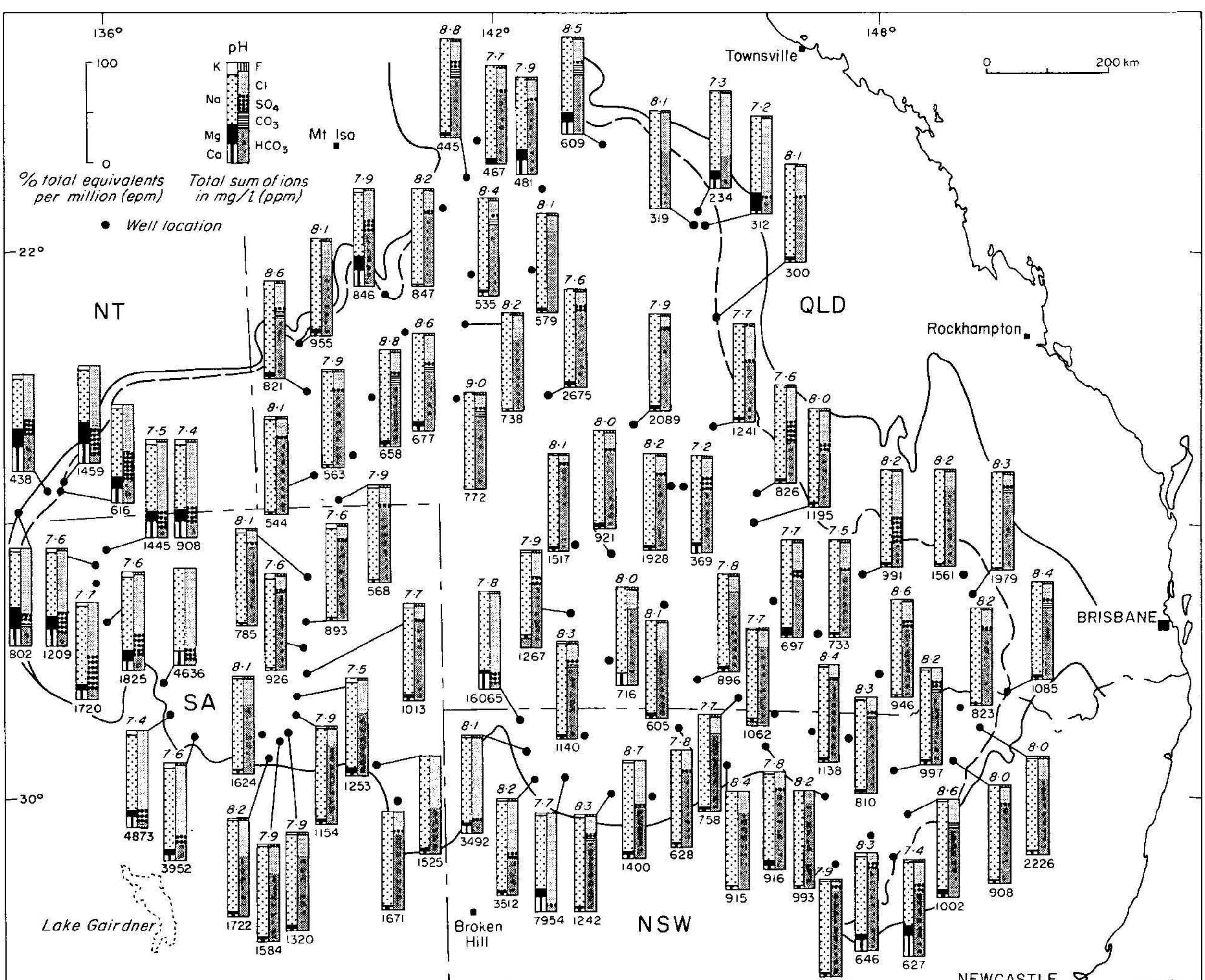


Figure 17. Chemical compositions of groundwater from selected flowing artesian wells tapping aquifers in the Lower Cretaceous-Jurassic sequence.

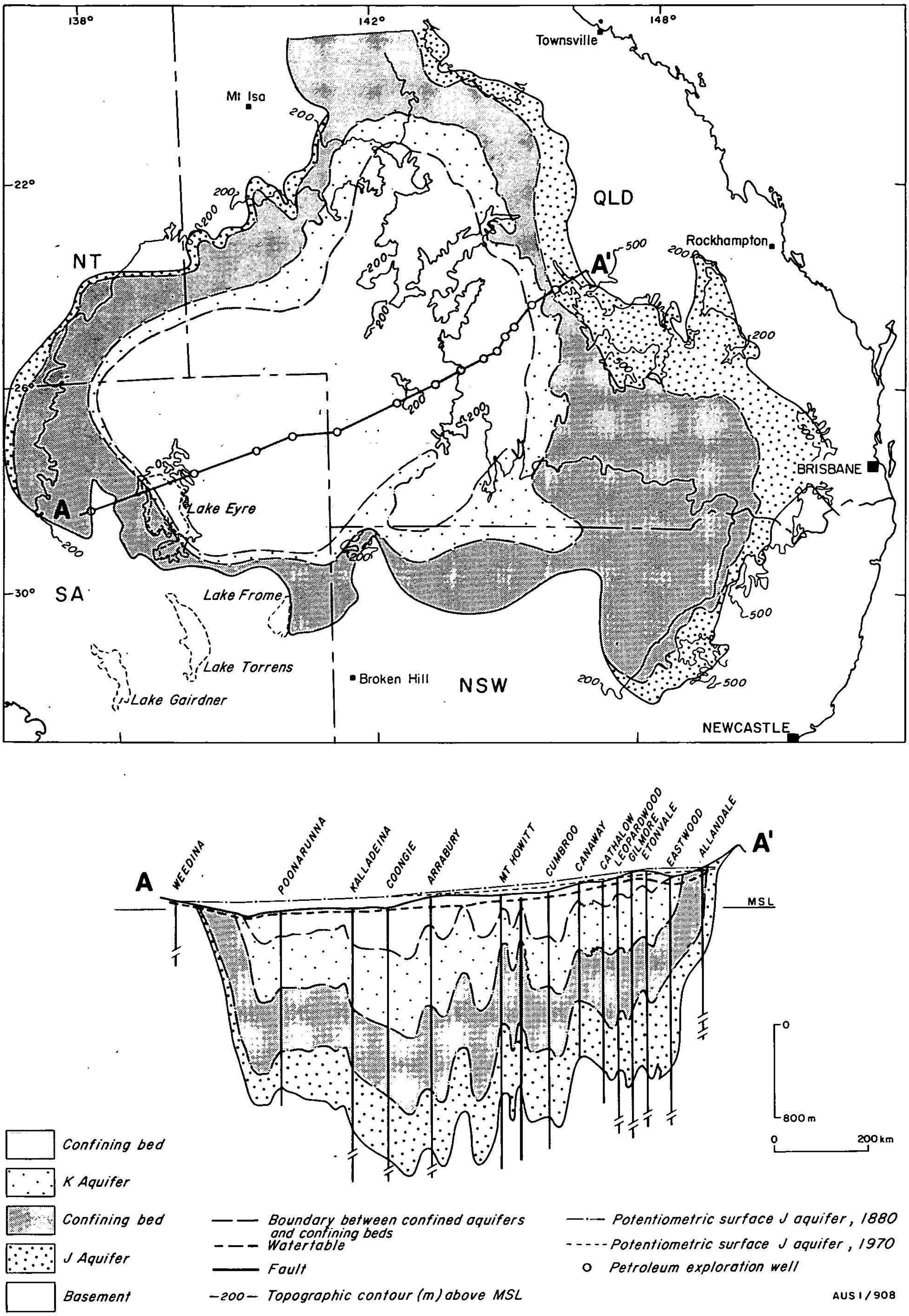


Figure 18. Lateral extent of simplified hydrogeological (model) units and cross-section.

shown in Figure 17. Other examples of groundwater chemistry occur in Australian Water Resources Council (1975) and Randal (1978).

Aquifers lower in the Jurassic sequence generally contain water of better quality than the aquifers higher in the Lower Cretaceous-Jurassic part of the sequence, though the proportion of chemical constituents is similar. Poor quality water of much higher salinity than the main, lower aquifers, occurs in aquifers in the Winton and Mackunda Formations. From detailed analyses the State water authorities usually indicate the suitability of the water in each well for drinking, domestic, stock and irrigation purposes.

The water quality generally prohibits use for irrigation, because of high sodium content and high residual alkalinity. The quantity of groundwater required for large irrigation projects would probably represent a further restriction. The chemistry of the groundwater indicates a high to very high sodium hazard, and a medium to high salinity hazard.

Hydrochemical indications of groundwater flow directions were provided by Jack (1923), who determined the southwest and southeast directed flow near Lake Eyre from a potentiometric map, and discovered that westward-moving water, originating from the eastern margin, is characterised by carbonate ions, and eastward-moving water from the western recharge areas, by sulphate (the latter causing rapid corrosion of well casings—Stanley, 1971). The eastward-moving water was shown to have a much higher salinity and a higher chloride content than the good-quality westward-moving water.

Several areas in the northeastern and southeastern parts of the basin contain water that corrodes well casings, mainly because of dissolved carbon dioxide.

In the southeastern part of the basin, results by Andrews (1976) show that some hydrochemical trends are consistent with flow patterns determined from potentiometric maps. Hydrochemical and environmental isotope studies confirm the groundwater movement basinwards of the recharge areas near the eastern margins (Airey & others, 1979; Calf, in prep.).

Groundwater temperatures

The temperatures of water in wells tapping aquifers in the Early Cretaceous and Jurassic generally range from about 30° to 50°C, but in many areas of the basin temperatures at the wellhead are as much as 100°C. Spring temperatures range from about 20° to 40°C.

Geothermal gradients in the Great Artesian Basin range from 15.4°C/km to 102.6°C/km, with a mean of 48°C/km (Polak & Horsfall, 1979). Seventy-five percent of these values exceed the world average of 33°C/km. Temperature data (Polak & Horsfall, 1979; Senior & Habermehl, 1980) were obtained from continuous temperature logs run in flowing and non-flowing artesian wells during BMR's wireline logging program in the Basin from 1960 to 1975, and from petroleum exploration wells (Senior & Habermehl, 1980). Geothermal gradients in the basin are also given in Thomas (1960), Heyl & Thomas (1964), and Hind & Helby (1969).

High gradients occur where shallow basement rocks are present, adjacent to some major faults, and near some discharge areas.

Modelling the groundwater system

A model to simulate the hydrodynamics of the Great Artesian Basin has been developed (Seidel, 1980); this digital computer model (GABHYD), based on finite difference approximation, replaced an earlier version (GABSIM; Ungemach, 1975). After calibration (Seidel, 1978a) it has been applied to predict the hydraulic behaviour of the groundwater basin following management interventions (Seidel, 1980; Habermehl & Seidel, 1979). The results are satisfactory for broad, regional assessment purposes, planning and management decisions, and preparation of recommendations for future exploitation in the basin.

Input data and model prototype

To model the multi-layered real system, a simplified aquifer model was proposed (Fig. 9), which consists of a confined aquifer (K or Cretaceous aquifer, corresponding to the aquifers in the Winton and Mackunda Formations), and a lower aquifer (J or Jurassic aquifer, corresponding to the aquifers in the Lower Cretaceous-Jurassic part of the sedimentary sequence; in parts of the eastern areas the J aquifer includes Triassic aquifers). The aquifers in a simplistic conception of the complex groundwater system, are overlain by confining beds which correspond to the confining beds in the Cretaceous sequence above the aquifers in the Winton Formation, and the confining beds (the main confining unit in the Great Artesian Basin) between aquifers in the Mackunda and Cadna-owie Formations (Fig. 10). The components of this simplified model or prototype, are represented in Figures 9 and 18, and form the link between the real-life system and the digital computer simulation model, which consist of a set of mathematical equations.

Grouping of aquifers in the Jurassic aquifer was necessary because of the complexity of the many aquifers and the paucity of hydraulic data from individual aquifer groups. Most waterwells tap aquifers in the Cadna-owie Formation, and the Hooray and Pilliga Sandstones and their equivalents, resulting in a disproportionate amount of hydraulic data for these aquifers, and a paucity of data for other aquifers. Although pressures are higher in the deeper aquifers in the sequence, the differences are relatively small. Hydraulic heads from individual aquifers in the Cretaceous-Jurassic part of the sequence in neighbouring wells, and heads measured from different aquifers in individual wells, do not show significant differences, and justify the model simplification.

The geometry of the aquifer model or prototype is shown in Figure 18. The boundaries of the units broadly correspond with the boundaries of the lithostratigraphic units which made up the original hydrogeological units. An exception to this is the boundary of the model Cretaceous aquifer, which was mainly determined from the occurrence of non-flowing artesian wells tapping the Winton and Mackunda Formations (Audibert, 1976).

Hydraulic characteristics of the prototype include simplifications based on assumptions derived from the hydrogeological analysis. Flow in the model aquifers is considered to be in the plane of the aquifers only, and the vertical components of flow within the aquifers are neglected. In the confining beds the horizontal flow component is neglected and only the vertical component is taken into account. These assumptions allow the application of Hantush's leaky artesian aquifer scheme (Hantush, 1960; Bredehoeft & Pinder, 1970). Hydraulically the acquifer model is thus characterised by two confined aquifers, consisting of two-dimensional layers with lateral aquifer flow, connected by vertical upwards leakage, and upwards directed vertical leakage from the upper aquifer to a constant based boundary, the regional watertable or upper limit of the vertical leakage. Lateral boundaries are of the prescribed head type and of the impermeable type. Recharge is through prescribed head boundaries, natural discharge through lateral boundaries or vertical leakage. Artificial discharge is through free-flowing artesian wells or through pumped wells and applied in the mathematical model as a function of the hydraulic head.

Transmissivity values of the prototype aquifers were obtained by combining the effective permeable thickness (which is the total thickness of the sequence less the thickness of confining beds between aquifers) and the (horizontal) hydraulic conductivity values; the hydraulic conductivity values are mainly restricted to aquifers in the Cadna-owie Formation and Hooray and Pilliga Sandstones, and are irregularly distributed over the basin, but these values were assumed to reflect the general characteristics of the prototype Jurassic aquifer. No values for the Cretaceous aquifers are available, and the hydraulic conductivity for the prototype Cretaceous aquifer was assumed to be 10 m/day.

Storage coefficient values for the latter aquifer were not available, and it was assumed that the specific storage coefficient is 3.3×10^{-6} per metre of aquifer thickness. Determination of storage coefficient values for the prototype Jurassic aquifer and of vertical hydraulic conductivity values for confining beds have already been described.

Potentials and free-flowing well discharges were obtained from measured data in the GAB-ADP system.

All prototype parameters (geometry of the aquifer model, hydraulic characteristics of the aquifer units and confining beds), variables (hydraulic heads and free-flowing discharges), and boundary conditions (prescribed heads and impermeable boundaries) were quantified. For this purpose, a regular square grid with gridlines spaced 25 km, parallel to the X and Y axes of the mathematical model, was applied. The prototype is covered by 67 x 58 gridlines. Because a gridpoint covers 25 x 25 km^2, several original data points (wells) could be covered by a grid square, necessitating averaging; in other areas no data points are available. Initially maps were prepared showing parameters for areas rather than gridpoints.

Further details on the data preparation, GABHYD model calibration and application are given in Seidel (1980).

Assessment of the groundwater resource and its utilisation

Predicting the effects of future exploitation

The digital computer simulation model GABHYD produces quantitative information (potentials and well discharges) about the real hydrogeological system at greatly reduced time scales derived from calculations on a simplified version of the groundwater basin. Predictions of effects of exploitation for regions or small parts of the basin can be determined. Many management options, generally applicable to the free-flow situation, but also for pumped discharges, and variable space and time requirements, can be specified for the model (Seidel, 1978b, 1980). Despite the approximation and simplification inherent in the prototype and model, necessary because of the complexity of the natural system, and the limitations in available data, it appears that the model results are sufficiently complete and precise to allow interpretation and application of regional effects.

Future exploitation patterns resulting from different demands in the Great Artesian Basin, and the location, timing, size and duration of such changes, are difficult to predict. Usage by the principal landusers for grazing purposes and domestic and town water supply will probably not change significantly, and consist of relative small discharges. Even greatly improved economic conditions which could induce the construction of more watering points are probably less important than the carrying capacity of the arid grazing lands. Furthermore, it would probably cost less to construct shallow wells and earthtanks rather than deep flowing artesian wells for pastoral purposes, which would be a continuation of the present trend in economics and State government policy.

Large-scale development for other than the present users, for example mining or industrial applications, would generally occur as medium to long-term (25 years or longer) high discharges, to be obtained from relatively small areas. The model can estimate changes to the potentiometric surface, extent of the drawdown, and the change in discharge of free-flowing artesian wells for such developments (Habermehl & Seidel, 1979; Seidel, 1980). Physical consequences of such large-scale basin development can be predicted by the model; thus allowing for forecasting, planning or alternative recommendations to deal with the effects of lowering of groundwater levels and reduction in discharges from wells in certain areas caused by development in those and other parts of the basin.

Throughout the historical development of the Great Artesian Basin potentials and discharges of wells tapping the basin's aquifer continued to fall, until a new steady-state condition was reached when total recharge and discharge again reached equilibrium. This equilibrium condition developed during the last decade; provided that no further new development takes place in the basin, little change is expected to occur to the recharge and discharge on a basin-wide scale (Habermehl & Seidel, 1979; Seidel, 1980).

Planning and regulation of groundwater use

The large set of data available, and the simulation model, allow for large-scale, regional planning, and could simplify the monitoring of the groundwater basin. Simulation of local, small-scale development and individual well control is not possible with this model, but could be achieved by applying a similar model to a smaller area, using established boundary conditions from the basin-wide model.

Continued or increased development of the Great Artesian Basin by drilling more flowing and non-flowing artesian waterwells, or abstracting more water from existing wells by pumping, will further lower the potentiometric surface, which will in time result in diminishing flows and cause more wells to cease flowing. Detailed planning and management is required for large-scale developments, which could produce significant hydraulic effects and even cause possible changes in water quality in specific areas.

Conservation of groundwater can be achieved by eliminating wastage of free-flowing artesian water by restricting the flow from wells, if only on a seasonal basis. More efficient distribution systems, the changing from earth drains to plastic piping, reconditioning or pressure-cementing of leaking and corroded well casings, and the regulation of uncontrolled flowing wells could all contribute to a more rational water use. These measures, which are generally expensive, are being carried out in most States, with favourable results. The smaller amounts of water required allow a forced reduction in discharge from flowing wells, which results in an increase of the pressure in the aquifer in that area and so improves duration of flows from the well and neighbouring wells. The present policy in most of the basin area, not to carry out expensive conservation measures in order to preserve flowing wells—but to aim at a withdrawal rate commensurate with natural recharge—is acceptable, provided efficient use is made of the water abstracted.

The ultimate in groundwater conservation would occur if the potentiometric surface were lowered to groundlevel in the whole of the basin area. In such a hypothetical situation no more flowing artesian wells would exist; all groundwater would have to be lifted by mechanical means, necessitating strict economical considerations of water use. Withdrawal rates would be very much less, wastage minimal, and drawdown much reduced. However, with the present or any increased future production rate such a condition is unlikely to occur in most areas of the basin. The extent of the flowing artesian conditions and the size of the regional net pressure show that large areas of the basin will have free-flowing artesian conditions available for very long time periods, provided no change to many large-scale heavy developments occurs.

Development of the basin since about 1880 has mainly yielded water from elastic storage, and caused lowering of the hydraulic head—only a small percentage of the withdrawal was obtained from aquifer throughflow. As development progressed, a change in recharge occurred, and a new equilibrium was established between recharge and discharge. This equilibrium condition prevents mining of the aquifers, which would only occur if abstraction of groundwater exceeded the recharge rate of the basin.

Model results and historical data show that in the early part of the period from 1880 to 1970 the artificial discharge increased, but, as the effects of elastic storage of the groundwater reservoir became less later, it diminished. The discharge from springs decreased during the period, as did the vertical upwards leakage. However, as a result of the pressure decline and steepening of the hydraulic gradient, the recharge to the aquifers of the basin increased significantly, from about 26 to 35 m^3/sec (Habermehl & Seidel, 1979; Seidel, 1980). Rainfall data and the areal extent of aquifer outcrops suggest that the discharge from the wells (565 x 10^6 m^3/year in 1970), which presently takes up about 50 percent of the model computed recharge to the basin, equals about 1 percent of the average amount of water available for recharge.

Withdrawal from the basin by free-flowing and pumped artesian waterwells is small compared to the groundwater reserves; hydraulic characteristics indicate that long-term development is feasible with only minor lowering of the potentiometric surface. Mining of the reserves by using up the net pressure and lowering the waterlevels to within economical pumping depths would provide very large amounts of groundwater.

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Application of the GABHYD groundwater model of the Great Artesian Basin, Australia

G. Seidel

The GABHYD model was developed to provide a tool for predicting the effects of groundwater development alternatives for the Great Artesian Basin. Data from flowing artesian wells are averaged and discretised to provide the data base for a finite difference numerical model defined on a regular square grid. A quasi-three-dimensional simplification is employed to represent the different aquifers in the vertical direction. The model was calibrated using a newly developed direct method. The resulting model was found suitable for predicting regional effects of groundwater management for the major artesian aquifers for which adequate data are available.

As an example the model shows that controlled pumping of 900 l/s in one area of South Australia creates drawdowns of 23 m locally, 3 m 100 km away and 1.5 m at a distance of 110 to 170 km. The model also predicts that drawdown for the year 2000 will be little more than these figures.

Introduction

Data on artesian well flows and pressures have been collected by the various state organisations concerned with the administration of the Great Artesian Basin since 1896. In 1972 work commenced at the BMR to enter the data from most artesian wells of the basin into a computer-based data bank and to use these data in a groundwater model of the entire basin. At the same time it was decided that analogue modelling techniques were too inflexible for this case, and that a numerical model using a large digital computer should be used.

BRGM Australia provided contract assistance from 1972 to 1974 and made available a modified version of a model which was named GABSIM (Ungemach, 1975). Experience gained from its use helped greatly in the development of the GABHYD model by the author from 1975 to 1978.

The actual geometry and hydrogeology of the basin had to be drastically simplified so as not to exceed the modelling capacity, even on a large computer. The original data used by the model are described in greater detail elsewhere (Habermehl, 1979).

Finite element methods were not sufficiently well proven for three-dimensional transient groundwater flow when a decision on the model type was made. Therefore a finite difference method was chosen for modelling the basin on a square grid of uniform spacing. This required a substantial effort in restructuring the available data, and a new method of model calibration was developed to satisfy the continuity equation with the model data and parameters.

The GABHYD model was introduced to potential users (mostly from water authorities in Queensland, New South Wales and South Australia) at a workshop held at the BMR in August 1978; the model has been operational since then.

Definition of the model prototype

To arrive at a numerical model it was necessary to first reorganise the data from the Great Artesian Basin into a form suitable for numerical processing. This step is called the prototype development, whereas the next step—the model calibration—deals with the adjustment of these reorganised data. The type of model dictates the form which the data organisation takes.

The numerical model operates by simulating the actual case through a numerical process based on a discrete network of points rather than a continuum. For the finite difference type of numerical solution chosen these discrete points lie on a regularly spaced grid. This applies to every dimension considered, i.e. to three in the case of the Great Artesian Basin.

The task of the prototype development was to find a data set defined on a regularly spaced, three-dimensional lattice, which when used with a suitable numerical model simulates the real artesian groundwater flow of the basin with sufficient accuracy. A major problem was to restrict the number of points of the lattice so that they could be handled with the available computer capacity. The following discretisation was adopted:

— horizontally, a square grid of uniform spacing (25 km) with the gridlines running north-south and east-west. The basin as modelled fitted into a grid of 67 x 58 such lines.

— vertically, one grid layer representing one aquifer, confining beds being modelled by their resistance to flow between layers only.

Although it is possible to distinguish between a large number of aquifers geologically, not enough data were available to model them all separately. Finally only two aquifer groups were modelled, each group represented by one layer of grid nodes in the model. These were: confined aquifer 1, broadly corresponding to aquifers of Cretaceous age; and confined aquifer 2, containing a number of aquifers, most of which belong to the Jurassic sequence. As a convenient abbreviation these two groups are referred to as the Cretaceous and the Jurassic aquifers, respectively, in the model. Figure

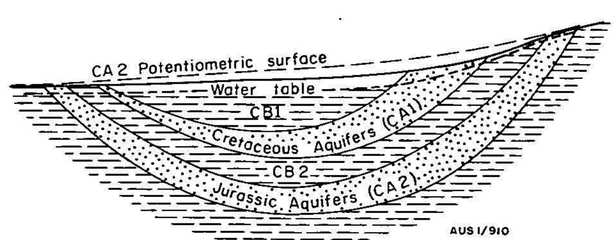

Figure 1. Schematic vertical cross-section of model prototype.

1 is a schematic cross-section through the model prototype, showing these two aquifers.

The discretisation employed is thus quasi-three-dimensional. Within each aquifer the flow direction is along the plane of the aquifer, i.e. horizontal. Leakage flow between aquifers is vertical, and storage within the confining beds is not considered.

After defining a suitable lattice for the model prototype it became necessary to find the data to assign to all points of that lattice. The spacing of actual data from flowing artesian wells is far from regular, in fact in some areas several tens of wells have to be represented by one point on the grid of the prototype, whereas in other areas no data at all are available for several tens of grid points. For some data items, e.g. the aquifer thickness, this problem was overcome by contouring the available data, digitising the contours, and interpolating by computer between the contours to define values on each point of the model grid. For other data, potentials in particular, this approach proved inadequate and a different method was employed which is described with the model calibration.

Data preparation and calibration

For the process of calibration it is convenient to distinguish between system-state variables, which describe the state or condition of the system at any given time, i.e. the head or potentials in the system. The system parameters are the properties determining the response of the system to variations, and the decision variables permit the imposition of variations on the system. Calibration consists mostly of adjustment to parameters until the response of the system agrees with all recorded data of system-state variables. Sometimes the opposite approach may be used, however, when errors in the data or system-state variables are present and system parameters are considered to be more reliable.

For a model of artesian groundwater flow the system-state variables are the potentials (water-pressure head and elevation head with respect to a datum) and the discharges when they are free-flowing. The model parameters are all those data which are required by the model to simulate the flow by calculating state variables starting from a supplied initial state. These are in particular the hydraulic parameters, which for this model are the transmissivities and storativities. Also required are boundary conditions, which include the location of barrier boundaries and recharge boundaries, and the potentials at prescribed head boundaries. Vertical leakage factors between the top aquifer and the constant headwater table determine upper boundary leakage flows and also form boundary conditions in this model.

The available data are from a large number of irregularly distributed artesian wells. They consist of geological and hydrological information obtained at the time of drilling a bore and, for flowing artesian bores, of the measurement of free-flowing discharges and shut-off pressures (usually taken after shutting off the flow for several hours to allow measurement of an aquifer pressure), taken at intervals of months or years. For a number of bores recovery tests were analysed to provide point values of transmissivity, but no other hydraulic parameters were available.

Direct data for hydraulic parameters were hence insufficient, and the data on state variables which could be used to check and correct any estimates of parameters were distributed irregularly. A solution by systematic trial and error for obtaining parameters was tried unsuccessfully. Eventually computer programs were developed which systematically determine corrections to less reliable data items from more reliable data until all internal inconsistencies with respect to the model continuity equation are removed. At the core of this procedure is a program which determines directional transmissivities from the distribution of potential differences and boundary conditions (Seidel, 1978). The data requirements for this procedure were met by recorded potentials calculated directly from bore records, aquifer thicknesses and estimates of vertical leakage factors and transmissivities at permeable boundaries (Krebs, 1973, 1974; Audibert, 1976).

Features and limitations of the model

The quality of the input data set and the degree to which these can be made to agree with each other by calibration are a major factor in the quality of the model results. Another factor is the limitation of the accuracy of results imposed by characteristics of the model itself. Both the accuracy of the results and the ease with which these can be obtained are important in assessing the usefulness of a particular model and its support programs. Only a relatively small number of programs and subroutines are part of the GABHYD model in its narrow sense. This reflects the considerable amount of processing outside the model, to provide the model with the data needed to analyse the results. Within GABHYD there are four groups of programs:

1. GABBRI, a series of programs translating and restructuring data from their original form into the standard data file set for use by the model.
2. CALSYS, a group of programs developed for the model calibration. Using all data available on the standard data-file set the less reliable data items are adjusted to match the more reliable ones until the model reproduces recorded data sufficiently accurately.
3. RUNMOD consists of a model-manipulation program and the model program itself. The manipulation program is provided to assist in the coding of running instructions for the model.
4. OUTSYS, a group of data presentation programs which access the full standard data file set and the model result files and present them in specified forms.

All four groups of programs can be altered independently because they have only the standard data file set in common (Fig. 2).

Logically all programs could be transferred to different large capacity computers and most of the program code is available in ANSI standard FORTRAN. However, job-control statements will require translation for use on a different computer. Also many of the output subroutines access special facilities on CYBERNET (computing network based on CDC CYBER 76 computer operated by CSIRO, Canberra), and it might not be possible to transfer them.

The solution algorithm used by the model has been used successfully in previous models, and is considered well proven. It can be summarised as a point-successive iteration, with provision for over relaxation when appropriate, on a regular square grid, quasi-three-dimensional, employing an implicit equation for

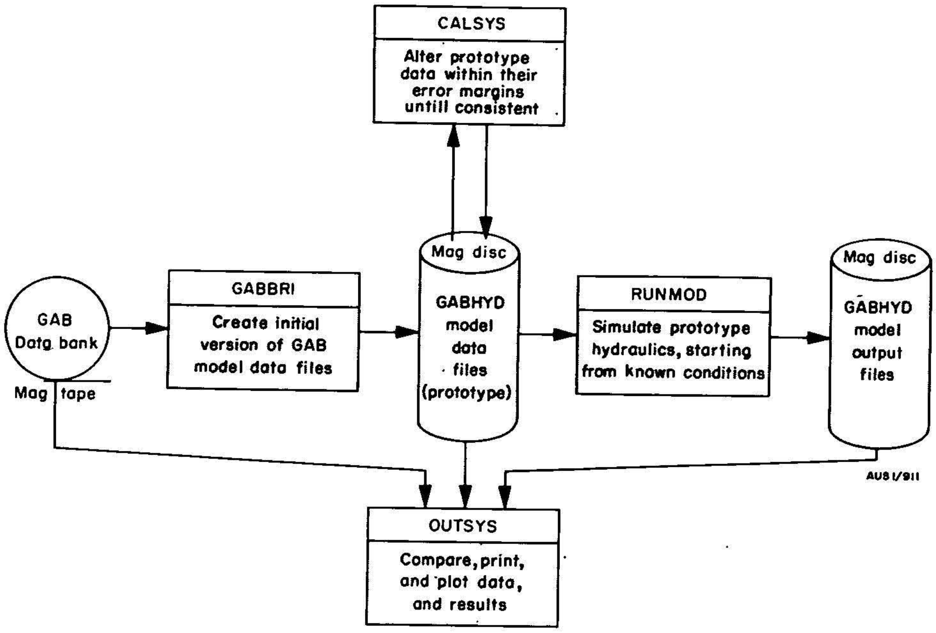

Figure 2. Macro flow chart of GABHYD model.

solution. The calibration method is also considered to be reliable. This leaves as the major sources of uncertainty the errors inherent in the simplification and discretisation of the aquifer system and in the incompleteness of the data available for the model's calibration.

Simplifying the geometry of the aquifer system affects firstly the resolution of the model. To be meaningful it is recommended that model results should be analysed in minimum areas of 50 kilometre squares, i.e. four model elements at a time. This precludes making predictions for individual bores within such an area. The model is to be used for regional predictions.

In the vertical dimension the model is very much simplified by allowing for two aquifers only. In one particular area (Eulo Ridge in Queensland) it became obvious during the calibration that this is not always accurate, yet there is insufficient data to model and calibrate more than two aquifers and thus gain more accurate results. In fact so few data were available for aquifer one (Cretaceous) that although this aquifer was included in the model to provide hydraulic continuity it could not be properly calibrated, and hence the predictions made by the model for this aquifer have not been used.

Operating the model

Ease of operation was one of the major considerations in the design of the model; the first step in achieving it is to minimise the input data required by the model.

For its operation the model requires starting conditions, and running instructions. The starting conditions consist of the system-state variables, i.e. the potentials for the first year of the time interval over which the model is to run. Typically these starting conditions will be available as part of the results of a previous model run which either included that particular year or terminated with it. The model has been designed to operate in such a chain fashion.

The running instructions consist of operating parameters and decision variables. The decision variables are set by the user to simulate the particular groundwater development alternative to be tested. The operating parameters are mainly of concern to the modeller, and are used for the fine tuning of the model's performance. They can be left set at the default values for most applications. It is the decision variables which are of major concern. To be sufficiently flexible the model must allow the user to specify either discharge coefficients determining the free-flowing discharge in response to a pressure head or pumped discharge, or a combination of the two. A practical example of such a combination would be where an artesian well is allowed to flow freely—providing the free flow meets a specified minimum demand—but is supplemented by pumping when required to maintain this minimum supply. The specifications required of the user for such an application would include: the location in grid-node indices, the time in years, the free-flow coefficient, the ground elevation at the well outlet, and the minimum yield to be maintained by pumping if necessary. The model requires detailed data on decision variables for each grid node of the model, and for each year of the time span over which the model is to run. That is much more than merely specifying the data for the grid node and the year with which the model user is specifically concerned. For this reason it was necessary to provide a flexible, and preferably interactive user-access program.

Such an access program was developed to run on CSIRONET computer system in Canberra. It is documented in the operating manual for the model (Seidel, 1978). It allows the routine specification of the decision variables, as a so-called discharge background, to be set automatically based on data from previous runs; the user then overlays his specifications for the locations and for the time span he is interested in by answering prompting questions on an interactive terminal. Many components of the access program cannot be transferred directly to other computer in-

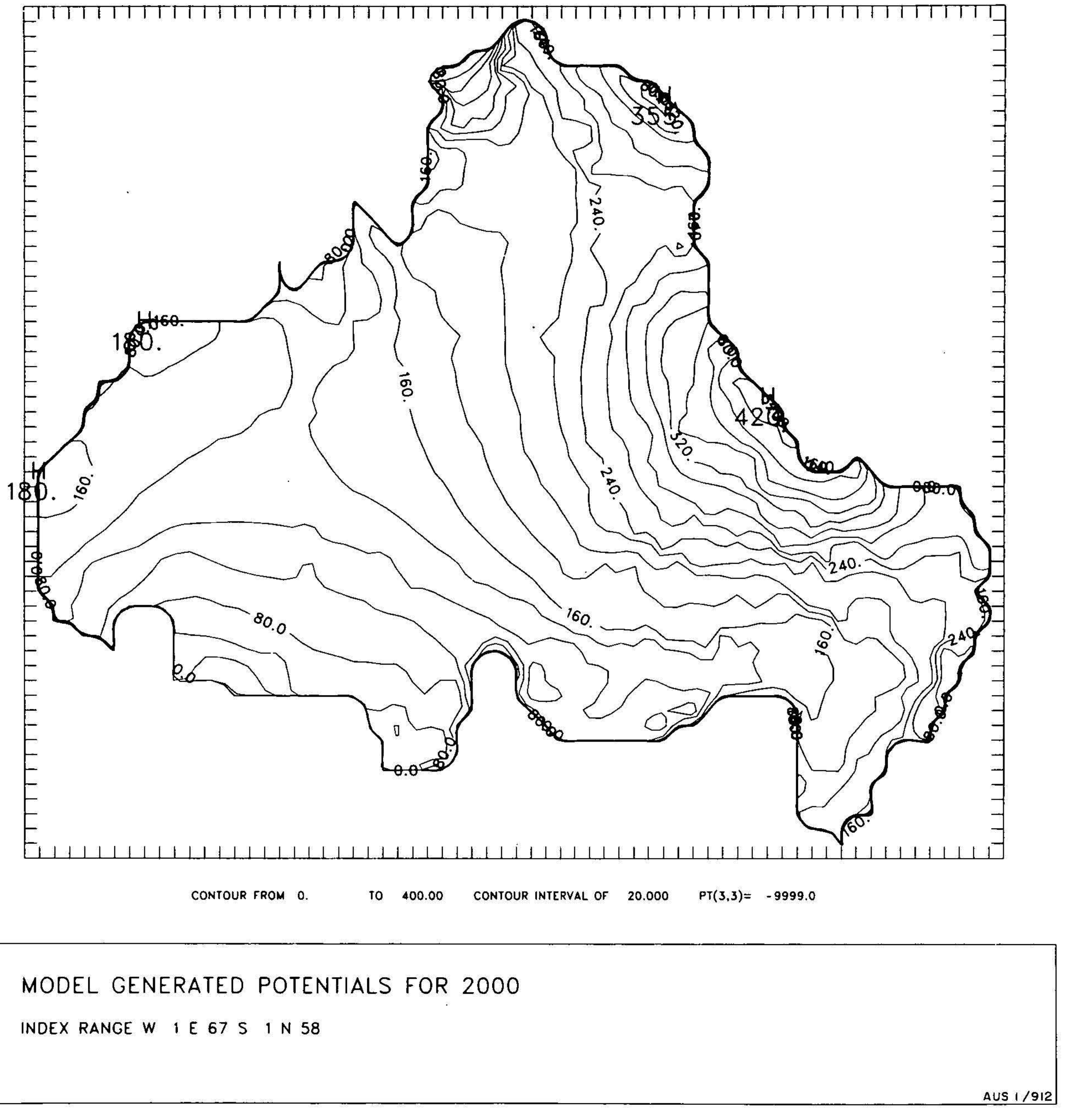

Figure 3. Contour map of predicted potentials for 2000.

stallations. However the logic on which they are based can be translated into a similar program for any large computer with interactive editing facilities.

Sample application

Several applications were carried out as part of the process of verifying the model. One such application closely matched a subsequent request from the South Australian Department of Mines & Energy to investigate the possible effects of withdrawing an additional 900 l/s from the Great Artesian Basin to supply a proposed new development. The sample application was repeated in greater detail and using more precise specification; some of the results are reproduced here.

To properly assess the effect of a new development it has to be compared to what would have happened without it. The first step of the application therefore was to run the model up to the year 2000, assuming that no new development had occurred. Figure 3 shows the potentials predicted by the model for the year

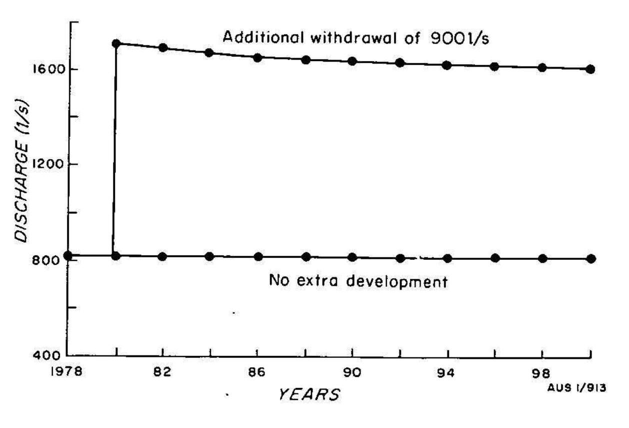

Figure 4. Free-flowing discharge from artesian wells 1978-2000.

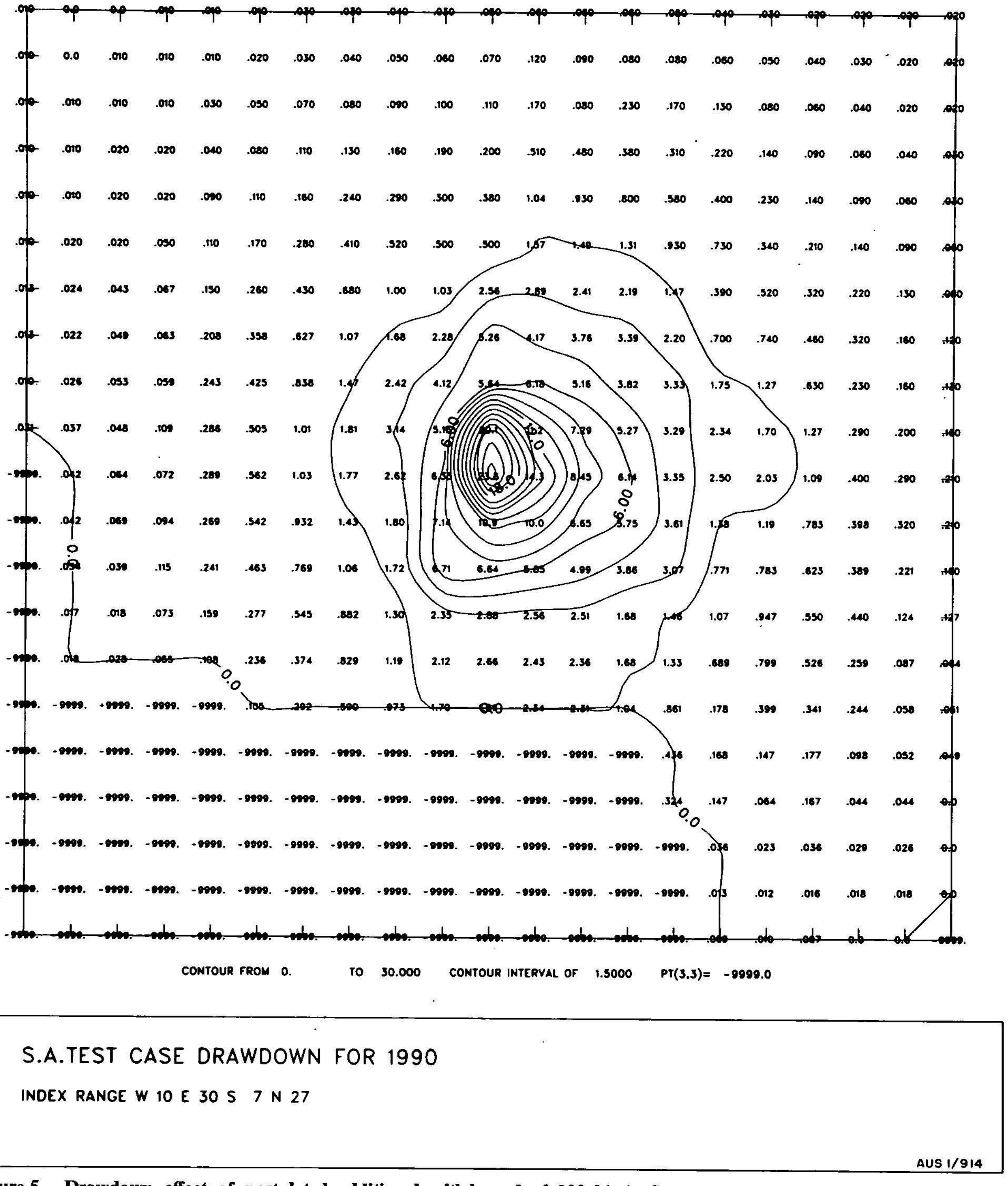

Figure 5. Drawdown effect of postulated additional withdrawal of 900 l/s in South Australia after ten years.

2000. At a glance this is indistinguishable from the corresponding map for 1970, except for its title. The basin is very close to equilibrium conditions and the difference in potentials between 1970 and 2000 can only be seen on a detailed scale. How close the basin is to equilibrium is also demonstrated by the lower trace on Figure 4; which is the projected free-flowing discharge from wells for most of the South Australian portion of the basin, assuming that no further new development occurs.

The second trace of Figure 4 shows the projected total well discharge, including additional withdrawal by controlled pumping of 900 l/s. The most notable aspect of the result is that the overall yield from 1980 to 2000 only drops by 7 percent and appears to approach a new equilibrium. This indicates that the additional withdrawal could be sustained for a long period.

The effect of the proposed development on pressures is illustrated on Figure 5. After ten years the maximum drawdown expressed in pressure heads is 23.6 metres on the newly developed site, with several adjoining grid nodes experiencing drops of 10 metres or more. At a distance of 100 km the pressure drop is typically 3 metres; the 1.5 metre contour at a distance between 110 km and 170 km indicates that the effect is still mostly relatively local. A similar map for the year

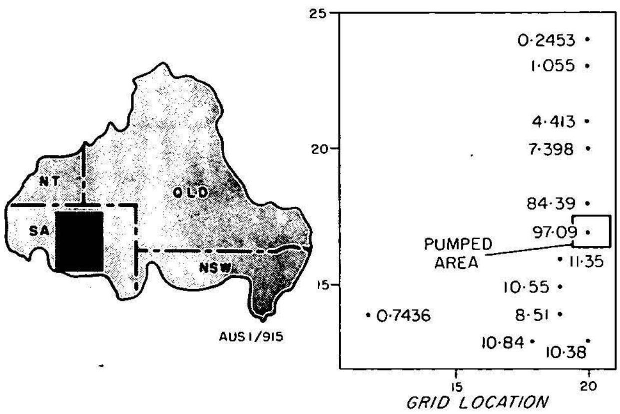

Figure 6. Percentage change in discharge as result of additional withdrawal in South Australia.

2000 (not shown) indicates a similar picture with a small increase in drawdowns, and a greater regional spread of very small drawdowns of less than 0.5 metres.

The model also produces predictions of free-flowing discharge. A map of predicted percentage change of well discharge is reproduced as Figure 6. Hovever, care should be taken when using these discharge predictions. Firstly, it must be remembered that values should only be used from areas larger than those with one node. Secondly, all data within a node are averaged. This is not too serious a simplification when dealing with hydraulic parameters or horizontal potential gradients. However free-flowing discharges are calculated from the difference between the potential and a ground elevation minus temperature correction (the net pressure). Ground elevations averaged over an area of 25 km^2 are not always meaningful when a difference of a few metres in the result is the difference between a large artesian flow and no flow at all. A better approach predicting well flows in such an area

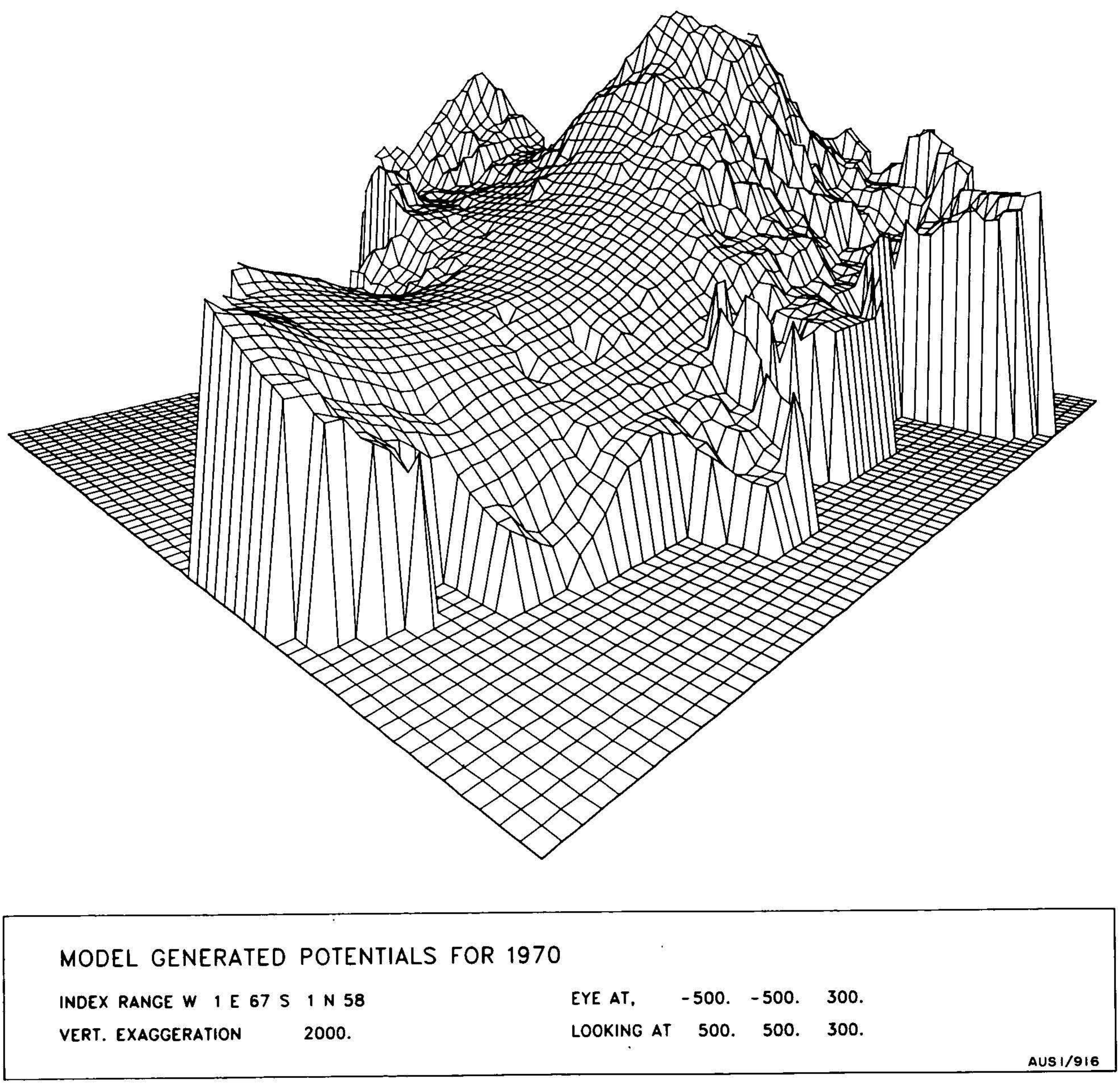

Figure 7. Perspective view of potentiometric surface for 'Jurassic' aquifer in 1970.

is to use the prediction for the drop in pressure, and apply this directly to individual wells in the area for analysis.

Then the user has to assess the results of the model run and determine how significant the predicted effects would be. For example a drop of 30 percent in the yield from an area might be of little consequence if most of the free-flowing discharge flows to waste at present, or it might require compensation to current users if current yields are already fully utilised.

The model output system provides that the results can be presented in a variety of ways. A form suitable for illustrating potentiometric surfaces is the perspective view of Figure 7. It does not provide accurate information, as a contour plot does, but it can easily be appreciated and is a useful public relations tool.

As this sample application shows, the model is capable of predicting the regional effects of proposed new groundwater developments, and allows the systematic trial of alternative methods to make the best use of the artesian groundwater resources of the Great Artesian Basin.

Acknowledgement

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Structure, hydrodynamics and hydrocarbon potential, central Eromanga Basin, Queensland, Australia

B. R. Senior & M. A. Habermehl

Possible economic hydrocarbon accumulations could exist in the Eromanga Basin sequence in southwest Queensland, particularly adjacent to faults transverse to groundwater flow. Interpretation of LANDSAT imagery and air-photographs indicates the probable presence of many faults hitherto unsuspected from field observations and seismic surveys. Most Jurassic and probably some of the more deeply buried Cretaceous rocks have generated hydrocarbons from relatively abundant source rocks, and under a variety of geothermal gradients. Hydrocarbons could also have migrated into the Eromanga Basin sequence from underlying basins whose equivalents elsewhere contain commercial accumulations.

Introduction

The hydrocarbon potential of the Jurassic-Cretaceous Eromanga Basin sequence in southwest Queensland is outlined, and theoretical conditions which could give rise to petroleum entrapment have been determined. Some intersecting faults normal to regional groundwater flow are considered to produce groundwater stagnation zones where hydrocarbons could accumulate. In the central part of the Eromanga Basin, the sedimentary sequence is up to 3000 m thick, but little attention has been paid to the hydrocarbon potential. There are few deep water bores and the existing petroleum exploration wells were drilled mainly to investigate targets in pre-Eromanga Basin rocks (the Permo-Triassic Cooper and Devonian-Carboniferous Adavale Basins). The Eromanga Basin, a major part of the hydrogeological Great Artesian Basin, has generally been regarded as having been flushed by basin-wide groundwater movement, but recent commercial and sub-commercial discoveries of oil (Strezelecki-3, Poolowanna-1, Dullingari North-1) and gas (Namur-1, Wackett-1) in northeast South Australia and within the region studied, demonstrate that flushing has not been as efficient as formerly assumed.

Stratigraphy

The Eromanga Basin sequence ranges from Early Jurassic to Late Cretaceous (Exon & Senior, 1976; Senior & others, 1978). In the area studied (Fig. 1) it conceals parts of the Middle Devonian to Early Carboniferous sequence of the Adavale Basin and the Early Permian to Middle Triassic sequence of the Cooper Basin. The Jurassic sequence is 500 to 1200 m thick and consists mainly of continental deposits, comprising quartzose arenites interbedded with carbonaceous siltstones and mudstones and minor coal. The preserved Cretaceous sequence is 500 to 1800 m thick in the central Eromanga Basin region, the thickest accumulations are in the Thomson and Cooper Synclines and Wilson Depression (Fig. 1). The mainly marine Early Cretaceous sequence consists of labile arenites, interbedded with montmorillonite-rich siltstones, mudstones and claystones. Similar rocks occur in the Late Cretaceous sequence but were deposited in paralic, lacustrine and fluvial environments. Individual units vary little in lithology and thickness over much of the basin; the succession shown in Figure 2 is typical for the area described.

Structure

Regional features

The Eromanga Basin sequence is characterised by broad, generally low-amplitude folds and linear faults with throws of up to 300 m (Figs. 1, 3). The folds, many of which apparently originated as drapes over basement blocks and horsts (Senior & others, 1978), have a variety of trends; but most are northerly. Dips on their flanks are commonly 1°-2° at surface, increasing gradually with depth.

Structures indicated by remote sensing

Most known folds and some faults were identified during reconnaissance geological investigations using sparse field data, standard photo-interpretation techniques, and information from seismic surveys (Senior & others, 1978). During later studies (Senior, 1977) further linear features were identified, using 1:80 000 scale aerial photographs for the northwest part of the area and LANDSAT imagery over the entire area (Fig. 3). It was found that in general all but the thickly alluviated tracts, commonly coincident with synclines, contain linear features and that several coincide with faults delineated by seismic surveys (Fig. 3). In places lineations 'extend' seismically determined faults for considerable distances. Lineations close to and parallel to the north-northwesterly trending Windorah and Harkaway Anticlines indicate the probable presence of parallel faults there. The Curalle Dome and the Morney and Mount Howitt Anticlines are intersected by numerous northwest-trending lineations, presumably faults, hitherto unsuspected.

Evolution of structures

Major structuring of the basin sequence probably began in the Early Tertiary when, following a period of intense weathering, fluvial deposits accumulated in slowly subsiding synclines (Senior & others, 1978). Faulting, particularly along the Curalle-Morney fold belt, probably took place at the same time.

A second phase of generally gentle warping occurred in mid-Tertiary or later time, as shown by the presence of gently sloping duricrusts which formed in Late Oligocene to Early Miocene time (Idnurm & Senior, 1978). Locally the deformation was relatively intense as, for instance, dips of up to 50° are present along the western limb of the Curalle Dome. Some faulting probably postdated the warping, as is shown by the presence of lineaments in the sloping weathered profiles.

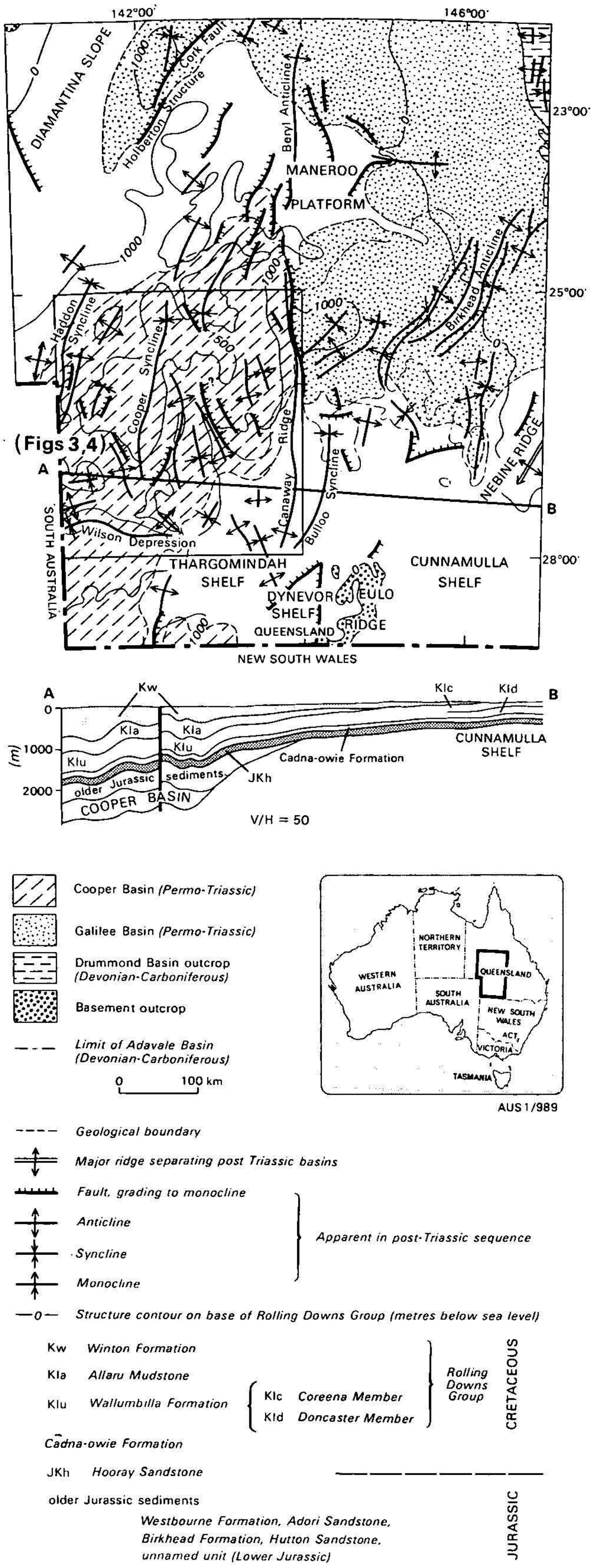

Figure 1. Location map showing regional geology and major structures in the Eromanga Basin sequence.

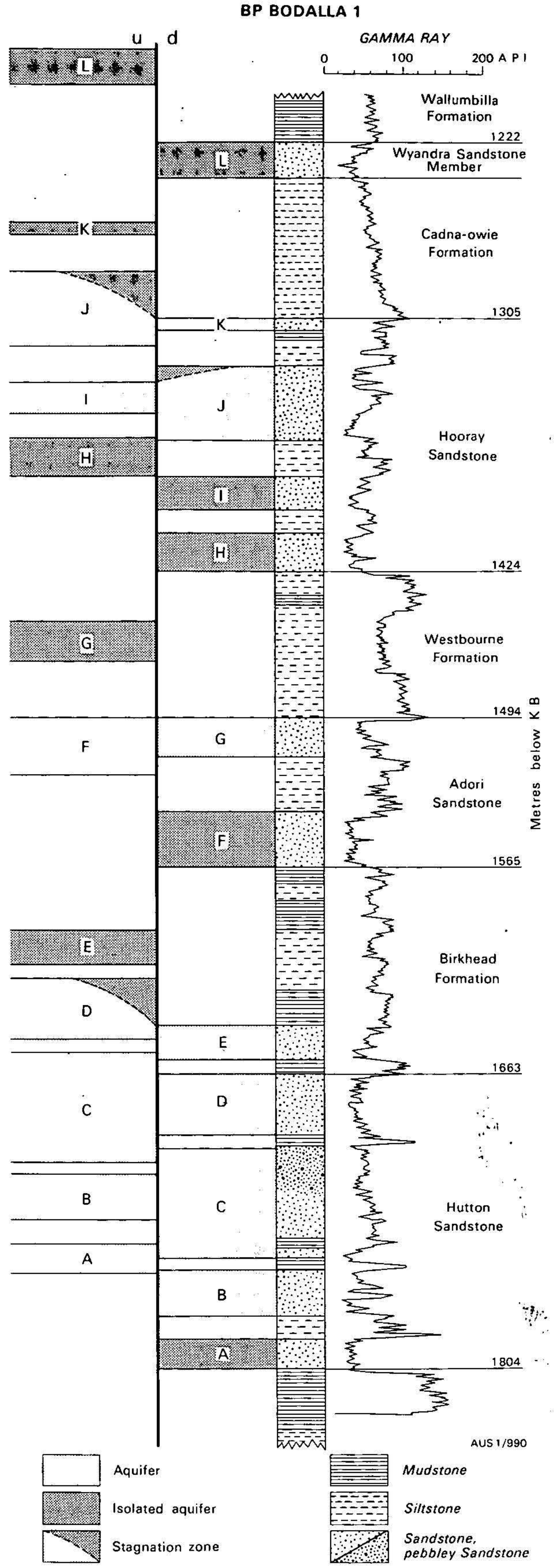

Figure 2. Stratigraphic succession, aquifers and confining beds in BP Bodalla-1 petroleum exploration well; the theoretical fault displacement is 45 m.

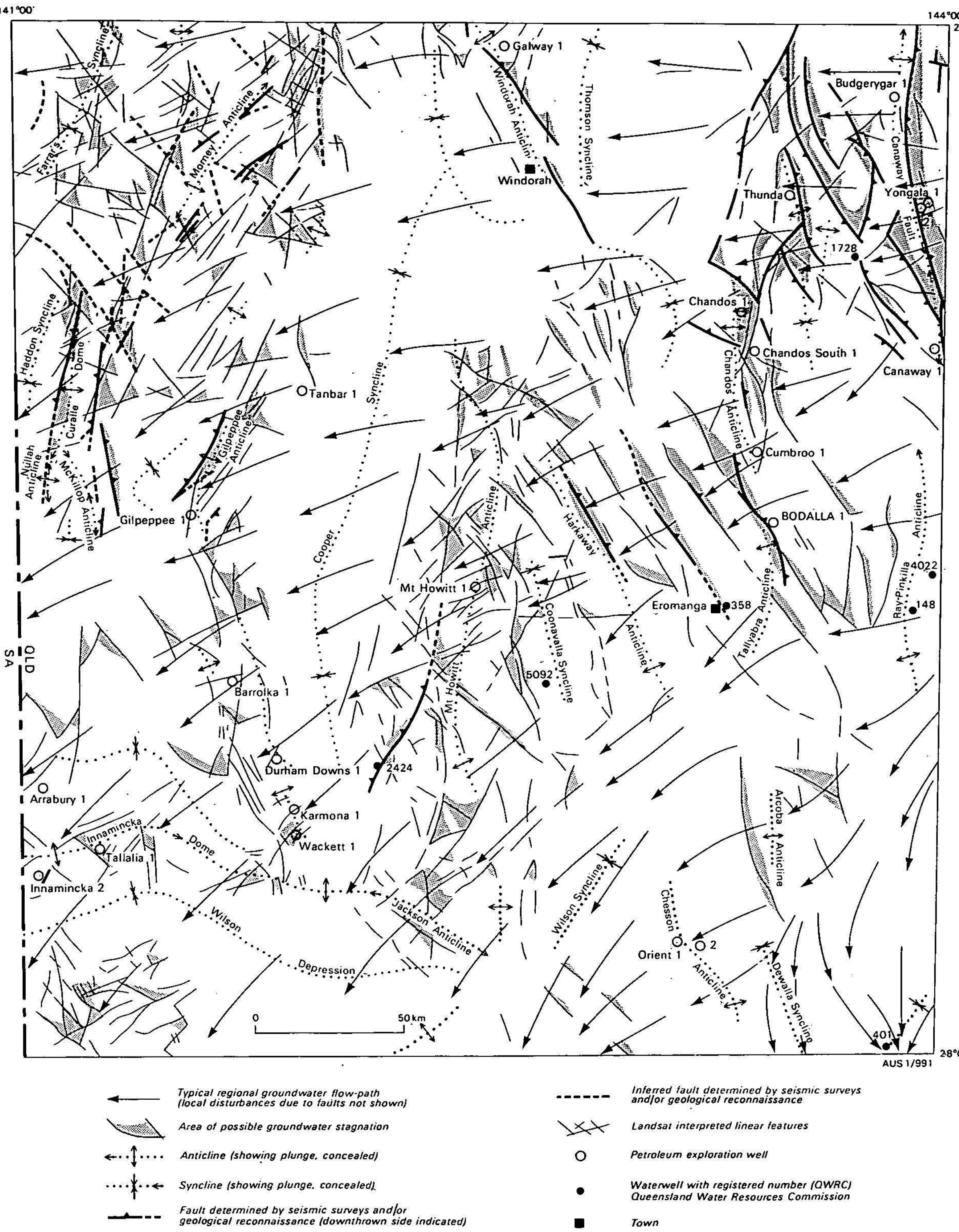

Figure 3. Regional groundwater flow directions in aquifers in the Lower Cretaceous-Jurassic sequence, geological structures and areas of possible groundwater stagnation.

Hydrogeology

The Eromanga Basin forms part of the Great Artesian Basin, a multi-aquifer confined groundwater basin (Habermehl, 1980) in which, in the study area, flow directions are west to southwest (Fig. 3; Habermehl, 1980) in the main Early Cretaceous-Jurassic aquifers (Fig. 2).

The potentiometric surfaces of aquifers in the Jurassic and Early Cretaceous units in the study area are generally above ground level, whereas those in the upper part of the Cretaceous sequence are mostly below the groundsurface.

Hydraulic data, supported by studies of naturally occurring isotopes in the groundwater and some of the

Petroleum exploration well name and number	*Hydrocarbons*	*References*
DSVAT Wackett 1	Gas at 2 200 MCFD from Hutton Sst and 100 MCFD from Injune Creek Group	BMR data
AOD Budgerygar 1	Minor gas shows in Hutton Sst	Cadart, 1969
AOD Chandos 1	3.8 barrels 53 gravity oil in DST from the Triassic	Laing & Benedek, 1966
AOD Cumbroo 1	Trace of oil in Permian	Campe, 1969
DS Mount Howitt 1	Minor shows in Jurassic and in Nappamerri Formation	Delhi-Santos, 1966
†SOE Scout 2 (Canaway Downs)	Grease, methane and nitrogen from Winton Formation	GSQ, 1960
†SOE Scout 3 (Gumbla)	Grease and numerous gas shows of hydrogen, methane and inerts within Winton Formation	GSQ, 1960
†SOE Harkaway Scout 1	Numerous gas shows/hydrogen and methane in Winton Formation	GSQ, 1960
SOE Orient Scout 1	Numerous gas shows (hydrogen, inerts and methane) mainly from Hooray Sst	GSQ, 1960
SOE Orient Scout 2	Gas show in Allaru Mudstone?	GSQ, 1960
DFS Betoota 1	Yellow fluorescence, oil stain and gas from Injune Creek Group and Hutton Sst	Harrison & others, 1961
Water well		
*7311 (Tallyabra)	Oil of vaseline-like consistency and inflammable gas in Winton Formation	Cameron (undated)
*357 (Eromanga Town)	Methane and inert gas probably from Winton Formation	GSQ, 1960
*358 (Eromanga Town)	Carbon dioxide and methane from Winton Formation and Hooray Sandstone	GSQ, 1960
*3950 (Lynfield)	Methane in Winton Formation	GSQ, 1960
*1728 (Bulgroo)	Inflammable gas at 800 psi from Allaru mudstone and wax in Injune Creek Group	GSQ, 1960

† Percussion drill holes which failed to penetrate the entire Eromanga Basin sequence. * Water well number refers to Registered Number of Queensland Water Resources Commission. These water wells were completed in aquifers no older than the Hooray Sandstone.

Table 1. Hydrocarbon occurrences within, or in hydraulic continuity with, the Eromanga Basin sequence.

chemical data, show that lateral rates of groundwater flow near the northeast basin margin are of the order of 1 to 5 m/year (Airey & others, 1979; Habermehl, 1980). Hydraulic conductivity values of the most widely explored and utilised flowing aquifers (Cadna-owie Formation and Hooray Sandstone, Fig. 2) range from 0.1 to 10 m/day, with a predominance in the lower part of the range. Porosity values of most Jurassic and Early Cretaceous aquifers range from 10 to 30 percent, diminishing with increasing depth, intrinsic permeability ranges from about 100 to 4000 md. Hydraulic gradients in the area studied range from 1:2000 to 1:3000.

The groundwater in the Jurassic and Early Cretaceous aquifers contains about 500 to 1000 mg/1 total dissolved solids, dominated by sodium and bicarbonate, with minor chloride and sulphate (Habermehl, 1980). Salinity values do not significantly change across the basin though some slight increases occur near discharge areas. However, higher salinities with chloride water occur locally, such as in waterwell QWRC 7311 and in Yongala-1 petroleum exploration well (Laing, 1966). Well-head temperatures usually range between 30° to 50°, and some approach 100°C.

Hydrocarbon generation

Source rocks

Source rocks occur throughout the Jurassic and Early Cretaceous sequence (Table 2) and comprise numerous coal seams and disseminated carbonaceous matter present in most rock types. Fine-grained rocks in the Birkhead, Westbourne and Cadna-owie Formations, and an unnamed local Early Jurassic unit encountered below the Hutton Sandstone in Galway-1, contain the bulk of the potential source rocks in the central Eromanga Basin. With the exception of the unnamed Early Jurassic unit and the Cadna-owie Formation, which show brackish water or have shallow-marine affinities, all potential source rocks were deposited mainly in lakes and swamps. The Early Cretaceous sequence contains abundant source rocks comprising shallow-marine, fossiliferous, lithic and feldspathic arenites and lutites.

Reservoir rocks

Porous and permeable quartzose sandstones mainly occur in the unnamed Early Jurassic unit, Hutton, Adori and Hooray Sandstones and the Wyandra Sandstone Member of the Cadna-owie Formation (Fig. 2). Hydrocarbon occurrences in Eromanga Basin rocks within the region studied are listed in Table 1. In the area studied gas in economic quantities has been discovered in the Hooray Sandstone of Namur-1 in South Australia, and in subeconomic quantities within the Adori Sandstone of Wackett-1 (Table 1). Significant quantities of oil were discovered within the unnamed Lower Jurassic unit of Poolowanna-1, within the Injune Creek Group of Strzelecki-1 and in the Hooray Sandstone at Dullingari North-1.

Thermal maturation

Vitrinite reflectance studies on twenty-six core samples from the Eromanga Basin sequence (Table 2) indicate that it is marginally mature or mature, and that the carbonaceous argillaceous rocks in the Jurassic are poor, fair, or in rare instances very good source rocks for oil. The Cretaceous sequence appears to be immature. However in areas of deep burial such as towards the middle of the Cooper Syncline and the Wilson Depression, part of this sequence might be sufficiently mature to generate hydrocarbons.

Rocks below 1283 m in Betoota-1 (Westbourne Formation) located west of the area studied, and below

Lab. No.	Well	Core	Depth (m)	Age	Formation	Total extract (ppm)	Alphatic fraction (ppm)	Aromatic fraction (ppm)	Polar fraction (ppm)	Organic C (%)	Reflectance (%)*	Interpretation Maturity index	Hydrocarbon potential
61392	Betoota 1	10	1283	Jurassic	Westbourne Fm	1892	555	625	210	2.00	0.63(85)	M	Very good oil source
61393	Betoota 1	12	1460	Jurassic	Adori Sst	533	41	33	20	0.20	0.76(20)	M	Poor oil source
61394	Betoota 1	13	1591	Jurassic	Birkhead Fm	3281	330	1404	266	4.30	0.95(80)	M	Good oil source
61395	Betoota 1	14	1746	Jurassic	Hutton Sst	105	24	10	43	0.15	0.99(25)	M	Poor oil source
61396	Canaway 1	2	334	Cretaceous	Winton Fm	5357	316	338	654	20.44	0.47(70)	EM	Good gas source
61397	Canaway 1	3	500	Cretaceous	Allaru Mdst	212	57	26	88	1.45	0.46(70)	EM	Fair oil source
61398	Canaway 1	6	921	Cretaceous	Cadna-owie Fm	142	18	12	82	0.25	0.50(68)	EM	Poor oil source
61885	Canaway 1	7	1091	Cretaceous	Hooray Sst	190	22	6	31	0.65	0.69(68)	M	Poor oil source
61400	Canaway 1	8	1212	Jurassic	Adori Sst	1058	69	125	276	1.15	0.49(69)	EM	Fair oil source
61401	Canaway 1	9	1330	Jurassic	Hutton Sst	429	60	49	153	0.45	0.48(66)	EM	Fair oil source
61402	Canaway 1	10	1416	Jurassic	Hutton Sst	6118	118	1645	1700	6.15	0.52(70)	EM	Good-very good oil source
61403	Yongala 1	1	1355	Cretaceous	Cadna-owie Fm	591	47	12	306	0.50	0.58(68)	EM	Fair-good oil source
61404	Yongala 1	4	1723	Jurassic	Birkhead Fm	414	61	96	122	0.50	0.56(70)	EM	Fair oil source
61405	Yongala 1	8	2022	Triassic	?	369	10	14	110	0.10	0.59(5)	EM	Poor oil source
61437	Chandos 1	1	1427	Cretaceous	Hooray Sst	505	166	137	183	1.15	0.54(70)	EM	Good oil source
61439	Chandos 1	7	2171	Triassic	Nappamerri Fm	402	8	19	732	0.15	0.56(10)	EM	Poor oil source
61442	Chandos 1	10	2369	Triassic	Nappamerri Fm	627	148	66	265	0.35	0.70(30)	M	Good oil source (low C)
61441	Chandos 1	14	2431	Permian	Gidgealpa Fm	26597	203	560	398	21.11	0.83(70)	M	Gas source

Analyses by Dr J. D. Saxby and Mrs L. Bruen, CSIRO Fuel Research Unit. Hydrocarbon potential interpreted by Dr K. S. Jackson, Petroleum Technology Section, BMR, Canberra.

Lab. No.	Well	Core	Depth (m)	Age	Formation	Total extract (ppm)	Hydro-carbons ppm of rock	Hydro-carbons mg/g O.C.	Hydro-carbons % of extract	Organic C (%)	Reflectance (%)*	Interpretation Maturity index	Hydrocarbon potential
01	Galway 1	1	2246	Jurassic	pre-Hutton Sst	3170	215	8	7	2.74	0.72(20)	M	Fair oil source
02	Mount Howitt	1	1284	Jurassic	Westbourne Fm	1200	55	14	5	0.39	0.45(21)	EM	Poor oil source
03	Mount Howitt	2	1420	Jurassic	Birkhead Fm	4173	485	30	12	1.60	0.54(25)	EM	Fair oil source
08	Cumbroo 1	1	1762	Jurassic	Birkhead Fm	1473	60	11	4	0.54	0.45(26)	EM	Poor oil source
09	Cumbroo 1	1	1767	Jurassic	Birkhead Fm	4230	790	3	19	25.29	0.65(17)	M	Good gas source Fair oil source
10	Cumbroo 1	2	1935	Jurassic	Hutton Sst	6673	190	6	3	3.13	0.64(15)	M	Fair oil source
11	Cumbroo 1	3	2025	Triassic	Nappamerri Fm	2820	60	4	2	1.42	0.67(14)	M	Poor oil source
12	Cumbroo 1	3	2029	Triassic	Nappamerri Fm	10773	560	2	5	22.47	0.72(19)	M	Good gas source Fair oil source
13	Cumbroo 1	4	2156	Permian	Gidgealpa Fm	5350	120	1	2	25.96	?0.76-0.87(24)	M	Good gas source Poor oil source
17	Orientos 1	1	1440	Jurassic	Hooray Sst	?11958	?3415	?1313	29	0.26	?0.51(6)	EM	Poor oil source
18	Orientos 1	3	1584	Jurassic	Westbourne Fm	1623	220	13	14	1.76	?0.56(7)	EM	Fair oil source
19	Orientos 1	4	1659	Triassic	Nappamerri Fm	430	75	24	17	0.31	?0.57(4)	EM	Poor oil source
20	Thunda 1	1	1879	Jurassic	Injune Creek Group	1753	165	14	9	1.15	0.40(30)	EM	Poor oil source
21	Thunda 1	2	2108	Jurassic	Injune Creek Group	1533	480	5	31	10.40	0.71(25)	M	Good gas source Fair oil source
22	Thunda 1	2	2115	Jurassic	Injune Creek Group	7795	415	13	5	3.24	0.71(28)	M	Fair oil source
23	Thunda 1	3	2291	Triassic	Nappamerri Fm	—	—	—	—	0.09		M	—
25	Chandos 1	4	1806	Jurassic	Hutton Sst	6153	1010	6	16	16.28	0.71(26)	M	Fair oil source

EM = early mature VR 0.4 to 0.6%. M = mature VR 0.6 to 1.2%. * number of readings shown in parentheses. Analyses and interpretation by Robertson Research (Australia) Pty Ltd.

Table 2. Source rock and maturity data for the Eromanga and Cooper Basin sequences in southwest Queensland.

1767 m in Cumbroo-1 (Birkhead Formation) in the eastern part of the area, are mature. Both wells (Fig. 4) were drilled on anticlines which overlie fault-bounded basement blocks; allowing for downdip deepening, there is about 1700 m of mature Eromanga Basin rocks in the west, and up to 500 m within synclines in the east. This is an approximate determination based on few samples, but it indicates an unexpected variation in depth to the immature/mature interface that is difficult to explain either as a variation in depth of burial or loss of section through erosion. Regional geological studies (Senior & others, 1978) indicate that it is unlikely that more than 500 m of rock has been eroded from any part of this region

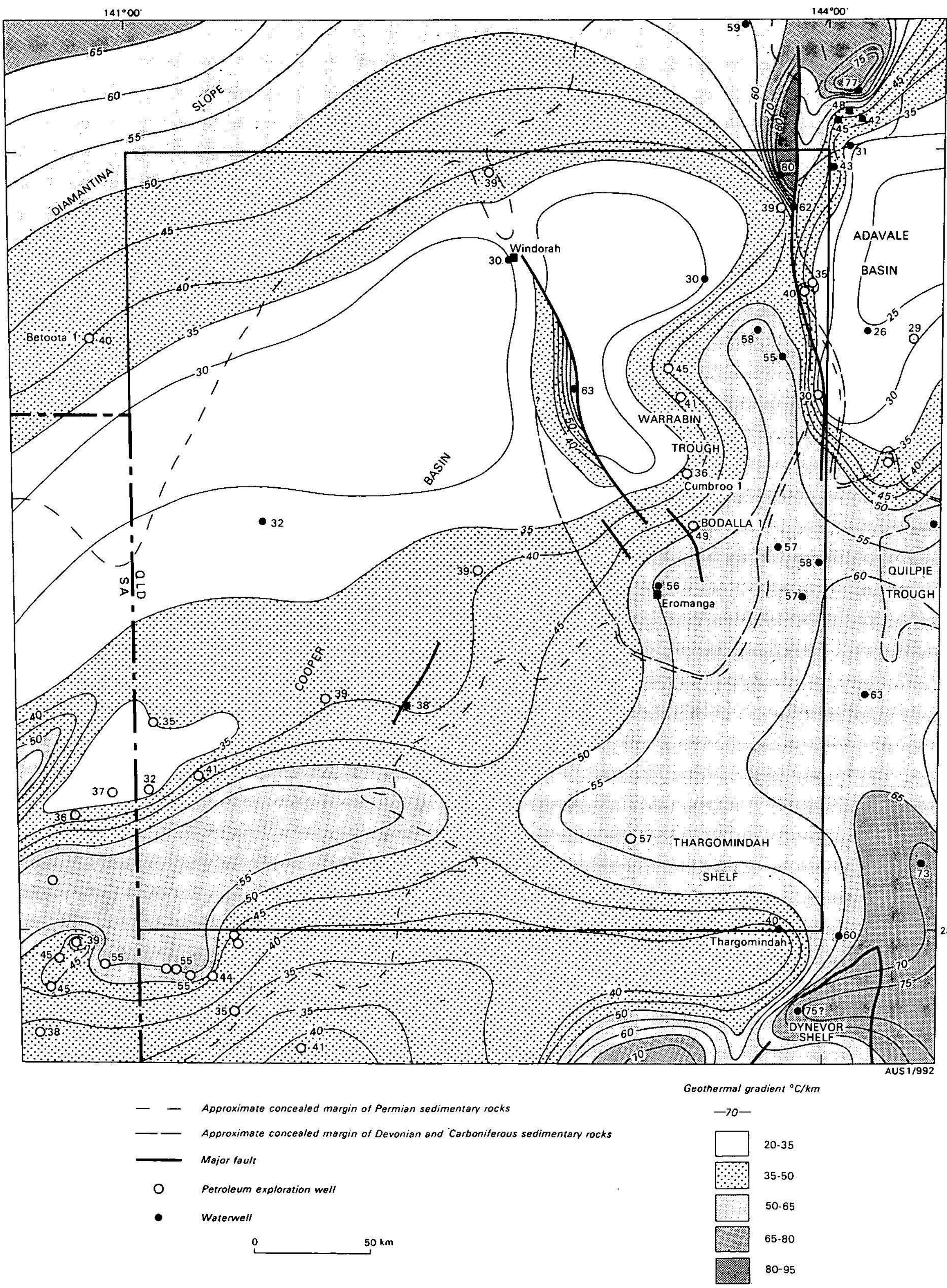

Figure 4. Uncorrected, minimum geothermal gradients.

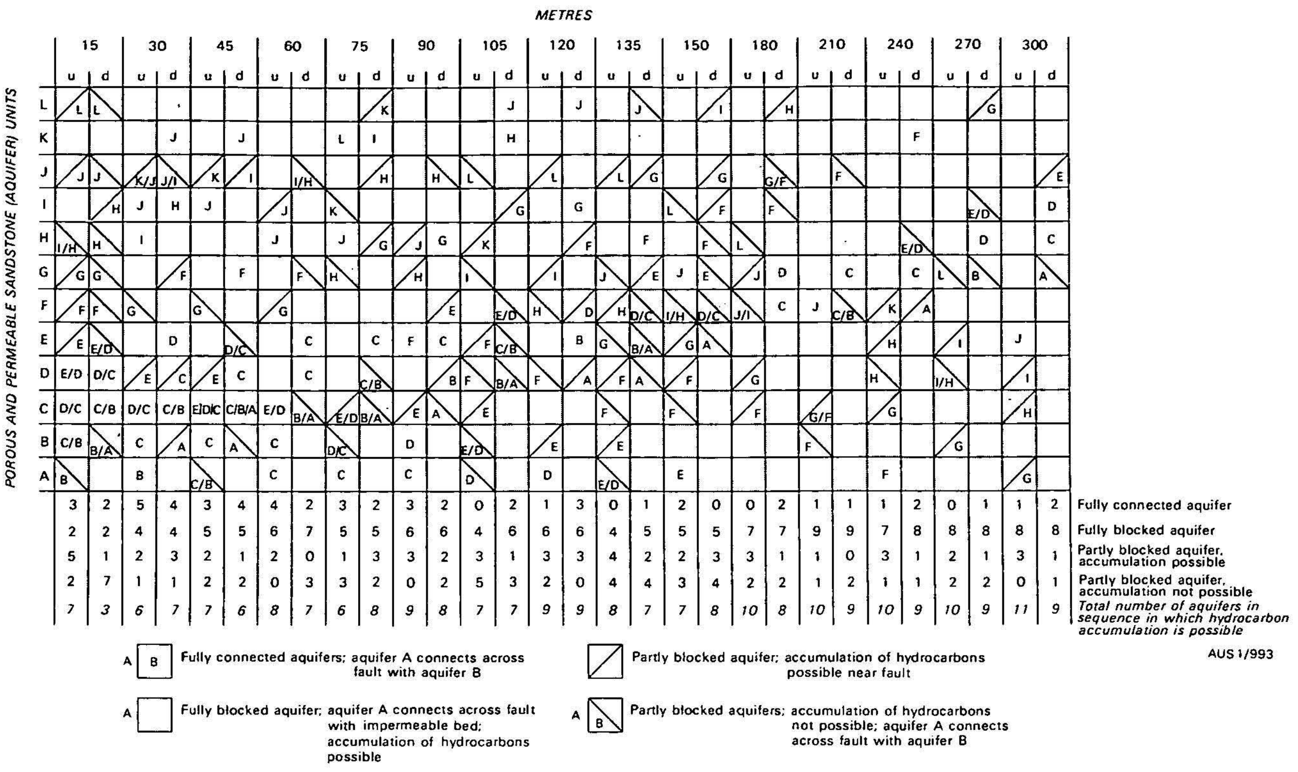

Figure 5. Effect of variable fault displacements on a Bodalla-1 (Fig. 2) stratigraphic sequence. A high-angle displacement of 45 m for example, results in five blocked aquifers on the upthrown side (aquifers E, G, H, K and L) and five blocked aquifers on the downthrown side (aquifers A, F, H, I and L). The blocked aquifers may contain stagnant groundwater and possible associated hydrocarbons, the aquifers fully connected across the fault will contain fresh water. Partially blocked aquifers D and J on upthrown side, and J on downthrown side could also be associated with hydrocarbons.

since deposition of the Eromanga Basin sequence ceased in the Cenomanian. Therefore it appears that other factors, such as the geothermal history of the region, have affected the maturity of these rocks.

Geothermal gradients

About three-quarters of the area has above average geothermal gradient (33°C/km for continental areas), as shown in Figure 4. High values (over 50°C/km) occur above shallow basement rocks (Thargomindah and Dynevor Shelves), and adjacent to major faults. The decrease in thickness of the Eromanga Basin sequence across the Diamantina Slope is marked by a complementary northwesterly increase in geothermal gradient. Anomalously high values along the northern end of the Canaway Fault and in a zone between Eromanga and Windorah (Fig. 3) are attributed by Polak & Ramsay (1977) to the upward migration of hot artesian water along fractures.

Mature rocks occur below 1283 m in Betoota-1, in an area where the present geothermal gradient is approximately 40°C/km (Fig. 4). In Chandos-1 the sequence is mature below 2369 m, where the gradient is comparable (45°C/km). The variation in the depth of mature rocks in these two places appears to indicate that quite different geothermal gradients may have operated in them in the past. A former period of higher subsurface temperatures across the Betoota Dome and perhaps other large folds may well have coincided with the mid-Tertiary tectonic episode. The likelihood that parts of this region have been subjected to a significant increase in geothermal gradients since the Cenomanian was suggested by Kantsler & others (1978), who thought causes could be the development of subcrustal 'hot spots', the injection of intrusives, or renewed tectonic activity.

Hydrocarbon migration and entrapment

Hydrocarbons have been generated in the Jurassic and locally in the lowermost Cretaceous sequence (Table 1). There are abundant porous and permeable units along which they could have migrated with the groundwater, either to natural outlets of the basin or into traps. Faults situated at right or nearly right-angles to flow (grey areas on Fig. 3), and faults which form V-shaped intersections, form possible traps.

In these situations obstruction of groundwater flow will occur as a result of fault displacement and disconnection of aquifers at both the upstream and downstream sides of the fault. Low groundwater flow rates and increased salinities are to be expected in zones adjoining the faults; these will also affect the transport, entrapment and accumulation of hydrocarbons (Tissot & Welte, 1978).

Exploration drilling has demonstrated that broad, low-amplitude anticlines, which are characteristic of the region studied, are flushed of hydrocarbons in their central parts, so that accumulations in folds are likely to be displaced considerably downgradient in anticlinal structures (Hubbert, 1953). Indications of stagnation and reduced circulation (high chloride, low bicarbonate) within Early Jurassic aquifers were found in Yongala-1 petroleum exploration well near the Canaway Fault (Laing, 1969), and in Adavale Town bore, located to the north of the area studied, which flows water too saline for use. Authenticated hydrocarbon shows have been recorded from the Eromanga Basin; those from within the study area are listed in Table 1. Hydrocarbons have not been reported, although specific investigations have not been made in natural groundwater discharge areas of the basin, which occur along the Eulo Ridge and in the Lake Eyre region around the southwest margin of the basin (Habermehl, 1980). It is suggested that hydrocarbons that have been generated are still trapped within the basin.

Relatively small fault displacements will obstruct the flow of several aquifers (Fig. 5). For example a displacement of 45 m will isolate aquifers E, G, H, K, and L on the upthrown side and A, F, H, I and L on the downthrown side in a Bodalla-1 (Figs. 2, 5) L-type stratigraphic sequence. Large displacements of about 300 m block an additional seven aquifers, but a possibly resultant broad fracture zone consisting of many small faults may not form an effective seal, thus permitting substantial leakage. As mentioned above the geothermal gradients indicate that vertical leakage occurs along the northern part of the Canaway Fault.

Partial blocking of aquifers could result in the formation of stagnation zones (wedge-shaped in vertical cross-section) in the upper, blocked part of the aquifers. Hydrocarbons could accumulate in such zones, which would be characterised by inclined oil-water contacts. Examples of such stagnation zones could occur in aquifers D and J (upthrown side) and J (downthrown side) in Figures 2 and 5.

Determination of variation in displacement along the strike of an individual fault would be required to select the optimum exploration target. The presence of faults with considerable strike lengths, but small displacements, appear likely—as indicated by the fracture map interpreted from LANDSAT (Fig. 3).

Although faults appear to be the most likely sites for hydrocarbon accumulation in the central part of the Eromanga Basin other stratigraphic, structural or diagenetic factors could be important. Differences in permability owing to changes in grainsize and the effects of compaction and cementation could provide barrier effects. Groundwater movement can displace and trap hydrocarbons in downgradient positions in anticlines (Hubbert, 1953). Some of the anticlines in the area studied are of interest in this respect. For example the axis of the Harkaway Anticline is normal to the regional flow direction and may have a downdip displaced hydrocarbon accumulation, whereas only the northern part of the Mount Howitt Anticline is favourably orientated for possible hydrocarbon traps.

An estimate of the possible volume of hydrocarbons within the upthrown side of the Harkaway Fault (Fig. 3) was made, assuming the westward continuation of Bodalla-1 type stratigraphy. An allowance for thickness variation was made by comparing the sequences in Bodalla-1 and Mount Howitt-1. Seismic data indicates a displacement of about 60 m, which would give six fully blocked and two partly blocked aquifers (Fig. 5). The volume of these aquifers within the zone of groundwater stagnation was calculated. Assuming 10 percent porosity and 20 percent water saturation within the reservoirs, an indicated 1500 x 10^6 m^3 hydrocarbons could be trapped within this structure.

Conclusions

Some intersecting faults and those normal to groundwater flow are thought to produce zones of groundwater stagnation in which petroleum could accumulate. Most Jurassic and some Early Cretaceous units in southwest Queensland are mature or marginally mature and hydrocarbon source rocks are plentiful. LANDSAT data indicate that faults could be much more abundant than indicated by field and seismic evidence. The development of broad drape structures and widespread faults began at least as early as the Early Tertiary and some movements postdate a Late Oligocene to Early Miocene weathering episode, indicating that potential fault-traps for petroleum came into existence or were rejuvenated at or following the Late Miocene. Increasing geothermal heat, perhaps associated with this structural activity probably resulted in an increase in maturity of potential source rocks.

Hydrocarbons which may have migrated from pre-Eromanga Basin systems (Cooper, Galilee, Adavale Basins) are more likely to occur in fault traps situated at the southwestern proximity of flow-paths of groundwater which has traversed the longest distances across these concealed basins.

Detailed geophysical work and drilling are recommended to delineate and detail some of the seismically determined faults and fractures interpreted from LANDSAT which, with hydrodynamic, structural and geothermal conditions, create the theoretical conditions for possible hydrocarbon reservoirs.

Acknowledgements

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BMR Journal of Australian Geology & Geophysics, 5, 1980, 57-61

Rusophycus (Early Ordovician ichnofossil) from the Mithaka Formation, Georgina Basin

*J. J. Draper**

Large trilobite resting traces *(Rusophycus)* from the Mithaka Formation are up to 30 cm or more in length, and are found in association with asaphid trilobites of similar length. The portion of the Mithaka Formation in which the *Rusophycus* occur contains a rich fauna and ichnofauna, and is considered to have been deposited in very shallow-water marginal to wide intertidal barrier flats behind a sand barrier.

Introduction

The Mithaka Formation (Casey *in* Smith, 1963), of Ordovician (Arenig to Llanvirn) age, forms part of the Toko Group of the Georgina Basin (Fig. 1). In discussing the depositional environment of the Carlo Sandstone, Draper (1977) described the lowermost portion of the Mithaka Formation, and proposed a lagoonal origin for the unit. Among the various biogenic sedimentary structures in the Mithaka Formation are large trilobite resting traces (*Rusophycus*).

The size of the traces (over 30 cm), and their association with trilobites of similar size, are of particular importance.

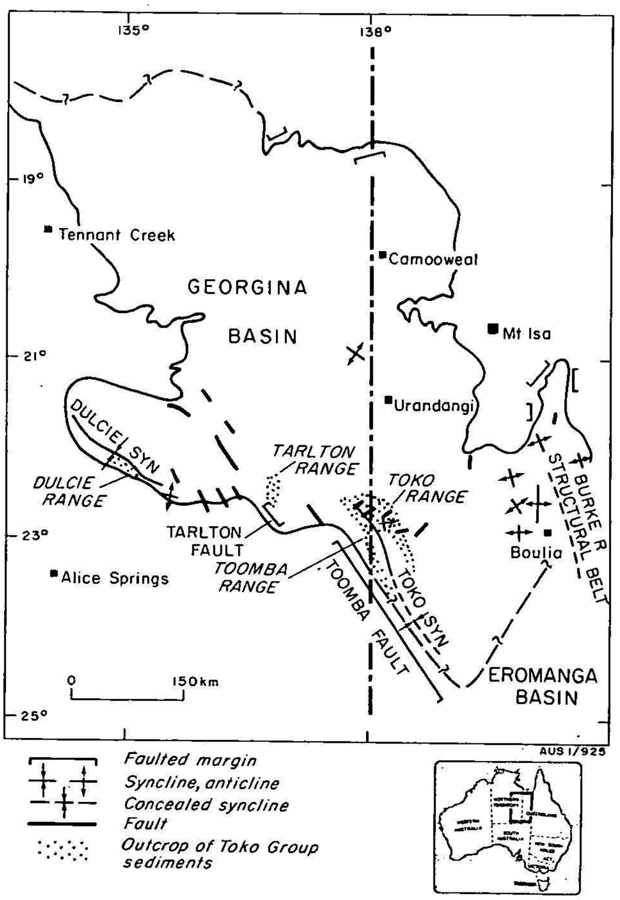


Figure 1. Locality, general geography and general structure of the Georgina Basin; and distribution of the Toko Group.

The Mithaka Formation

A composite section of the Mithaka Formation is given in Figure 3. Medium-bedded, bioturbated, fine-grained quartzose sandstones with shale and siltstone interbeds comprise the lower 5 metres. Mudstone, with numerous thin lensoid beds of fine-grained sandstone, constitutes the remainder of the unit, which has a maximum thickness of 127 m in Ethabuka No. 1 (Alliance, 1975). Finely disseminated pyrite is present throughout as replacements after shell fragments, or rarely, as framboids about 1 cm in diameter. Ironstone ooids are present in the lower 5 m. Lamination is common throughout in both mudstone and sandstone, but is often disrupted by bioturbation.

The Mithaka Formation conformably and transitionally overlies Subunit C of the Carlo Sandstone (Draper, 1977), and is overlain in a similar manner by

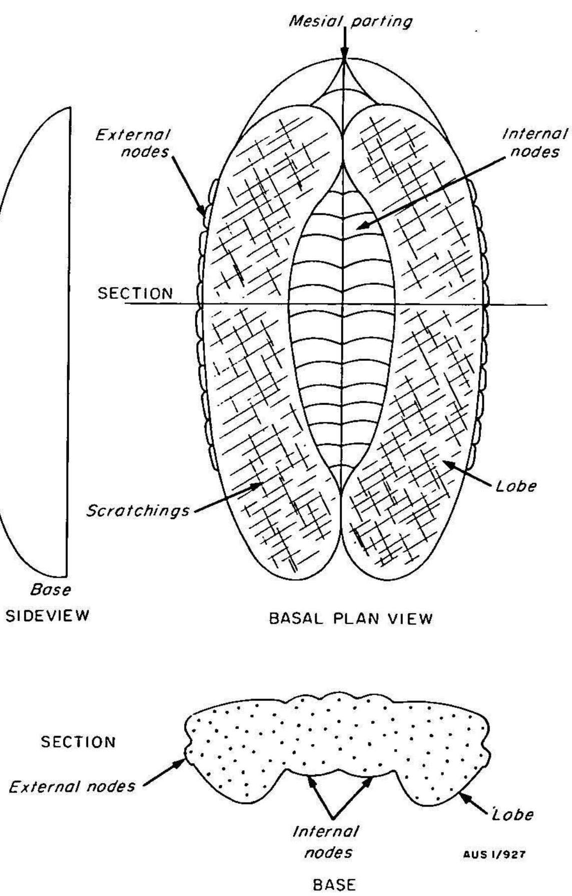


Figure 2. Major features of *Rusophycus* in the Mithaka Formation. Nomenclature modified from Osgood (1970).

* Geological Survey of Queensland, Mineral House, 41 George Street, Brisbane, Qld 4000.

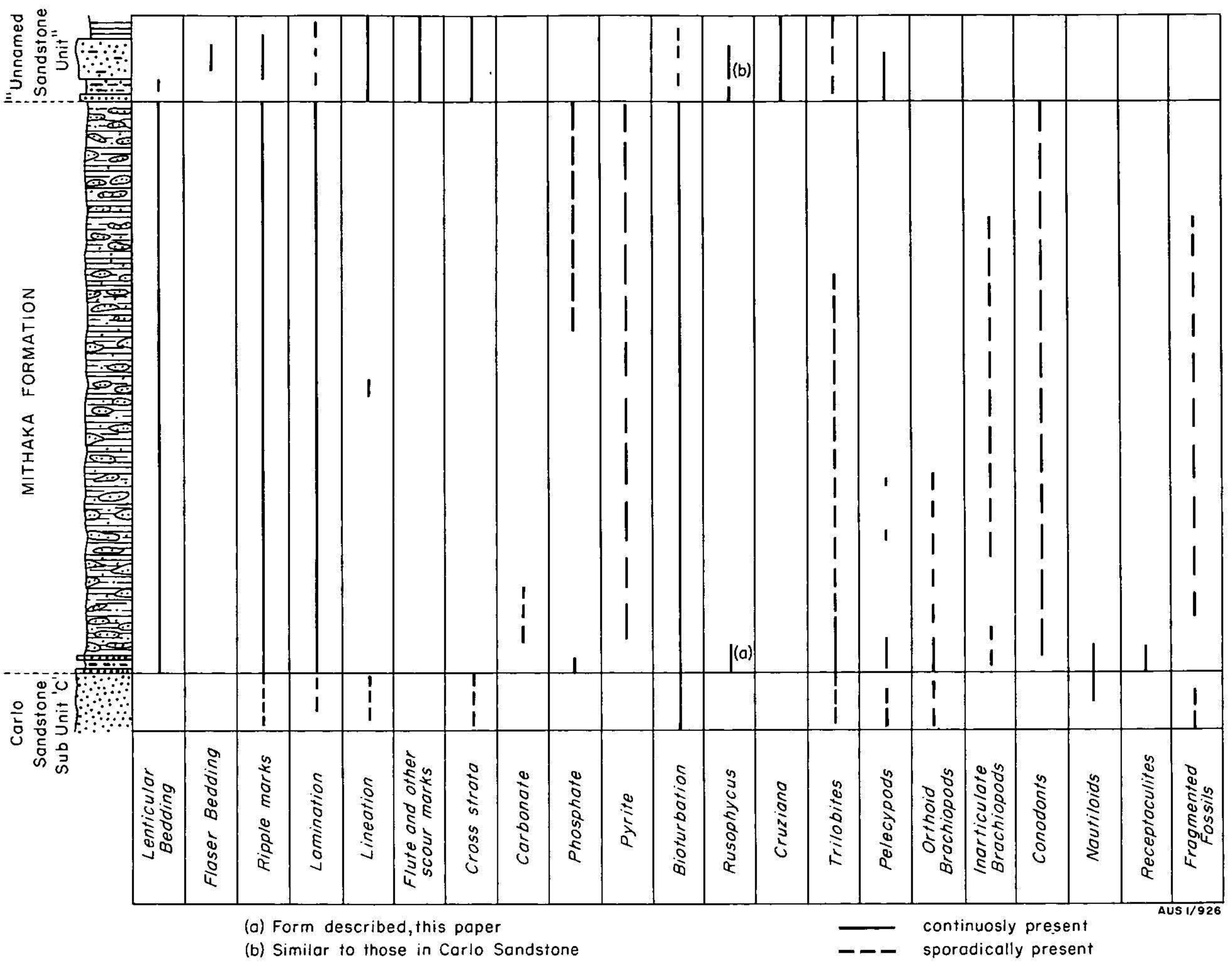


Figure 3. Vertical distribution of various components of the Mithaka Formation.

an 'unnamed sandstone unit' (Shergold & others, 1976). Draper (1977) proposed a barrier-lagoonal model for the Carlo Sandstone and Mithaka Formation, with the Carlo Sandstone representing the barrier and the Mithaka Formation the lagoon. More specifically, the Mithaka Formation was considered to represent shallow bay deposits associated with a wide barrier flat and central bay deposits; the sandy lower portion of the Mithaka Formation representing the shallow bay facies. The formation contains littoral and sublittoral deposits, becoming progressively deeper upwards.

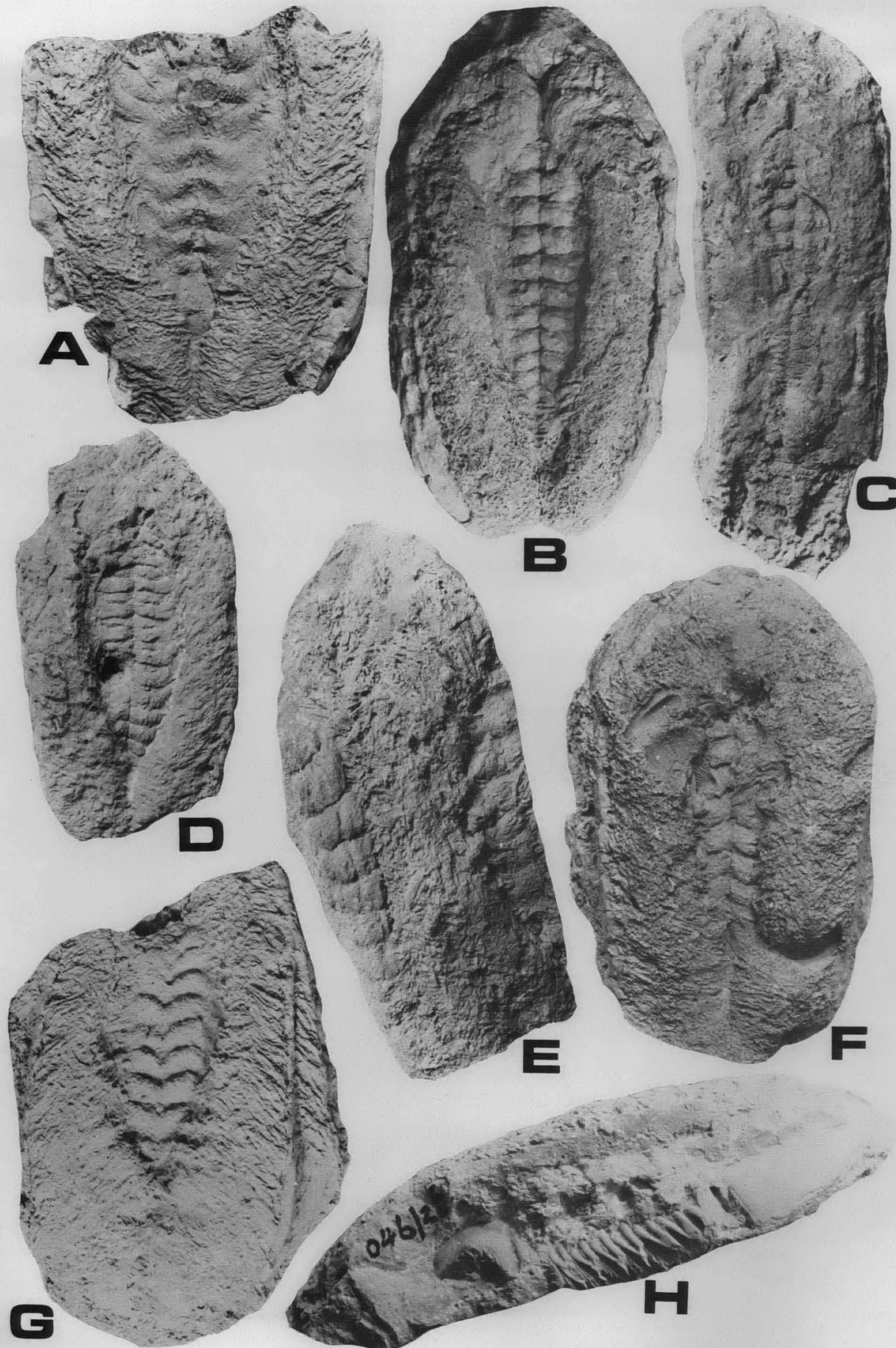
A prolific and diverse fauna is present, particularly in the lower part of the Mithaka Formation, but, to date, none of it has been described, although the trilobites, conodonts, and pelecypods are currently being studied. Large asaphid trilobites (over 30 cm in length), large nautiloid cephalopods, pelecypods, gastropods, articulate and inarticulate brachiopods, bryozoans, sponge spicules, ostracods, *Receptaculites*, and fish remains are present. A chitinozoan, *Desmochitina complanata*, has been identified from this formation in Bedourie Scout Hole (French Petroleum Company, 1964). The distribution of some of the fossil groups within the vertical sequence is shown in Figure 3.

Biogenic sedimentary structures are abundant in the lower part of the unit: particularly *Diplocraterion, Monocraterion, Arenicolites* and numerous irregular burrows (Fig. 5, A-C). Scratch marks are preserved as sole markings. Thin sandstone beds contain numerous surface markings and trails, as well as burrows, including *Chondrites*-like burrows, and the large *Rusophycus*. The upper, lenticular bedded, mudstone-sandstone sequence is bioturbated throughout. Vertical, horizontal and random burrows are present, although the sediment often has a churned appearance.

The *Rusophycus* are generally associated with thinner bedded sandstones, whereas the numerous burrows occur in slightly thicker sandstone beds; but both sandstones are closely related. The types of burrows in the thicker sandstone (Fig. 5) are very similar to those described from the intertidal zone of the Wash in England (Evans, 1965). The biogenic sedimentary structures of this interval in the Mithaka Formation fit within the *Glossifungites* and *Skolithos* facies of

Figure 4.

A. *Rusophycus* with internal nodes and possibly proximal portion of articulated walking leg. Scratches well developed on lobes, x0.5, CPC 19794; **B.** Complete *Rusophycus* showing internal and external nodes, scratches on lobes and striae on external nodes, x0.3, CPC 19795; **C.** Cruziform trace which passes into more definite *Rusophycus*, x0.2, CPC 19796; **D.** Complete *Rusophycus*, weathered surface, x0.3, CPC 19797; **E.** Partial *Rusophycus*, showing internal and external nodes, and scratches on lobe, x0.4, CPC 19798; **F.** Complete *Rusophycus*, internal nodes and lobe well developed, x0.4, CPC 19799; **G.** Partial *Rusophycus* showing well developed internal nodes and scratches on lobes. Portion of earlier *Rusophycus* visible on edge, x0.3, CPC 19800; **H.** Side view of asaphid trilobite and of *Rusophycus*. The trilobite is lying on its back with respect to correct orientation of trace, x0.4, CPC 19801.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Seilacher (1964), and as such are considered to represent littoral environments. The *Rusophycus* would normally be considered to belong to the *Cruziana* Facies (Seilacher, 1964) and hence to represent shallow subtidal deposition. The presence of thinner sandstone beds, pelletal phosphates and the fact that the traces were formed in mud would seem to support this. The *Rusophycus* probably formed in very shallow water marginal to wide intertidal barrier flats, inside a sand barrier.

Description of *Rusophycus*

The *Rusophycus* is a large, bilobate resting trace, which separates mesially to reveal two longitudinal series of nodes (Figs. 2, 4, 5). *Rusophycus* is normally attributed to trilobites (Bergström, 1973), but rarely is the trace-forming trilobite found associated with the trace. In the Mithaka Formation, however, a trilobite of suitable size and shape is found associated with the traces. The large asaphid trilobite (Fig. 4H) is currently being studied by Dr J. H. Shergold (BMR) and Dr R. A. Fortey (British Museum of Natural History), as part of a study of Ordovician trilobites of the Georgina Basin. Osgood (1970) considered *Isotellus* sp., a form similar to those in the Mithaka Formation, to be the trilobite responsible for *Rusophycus carleyi.*

Seilacher (1970, p. 474 & fig. 2) included a rusiform *Cruziana* (*Cruziana dilatata*) from the Tol.o Group with the *Carleyi* Group of his *Cruziana* ichnogenus. Although some forms from the Mithaka Formation are similar to *C. dilatata,* most resemble *C. carleyi* more closely; however, intermediate forms are present. All traces appears to have been made by similar trilobites, and differences therefore appear to reflect sedimentological factors.

The traces are preserved as sandstone casts, and are, in effect, sole markings. Considerable variations exist between traces, but the essential features are as shown in Figure 2. The plan shape is nearly elliptical, but tends to be thinner towards the posterior end. Overall the *Rusophycus* are approximately twice as long as wide and may be up to 10 cm in depth. The largest complete samples are 31 cm in length, but several incomplete specimens have extrapolated lengths which exceed that by 5 cm or more.

The lobes may or may not be separated at each end, and are covered in a series of fine ridges—which may be random and chaotic, or show a preferred angle of orientation. On the outer lateral portions of the lobes are a series of striated nodes (external nodes) which may number up to 11; but these are present in only a few specimens. In most examples the internal nodes are clearly visible, numbering 9 to 11 in complete samples.

The internal nodes are the impressions of coxae or coxal gnathoblastic extensions of the walking leg (Osgood, 1970). The external nodes preserved on the

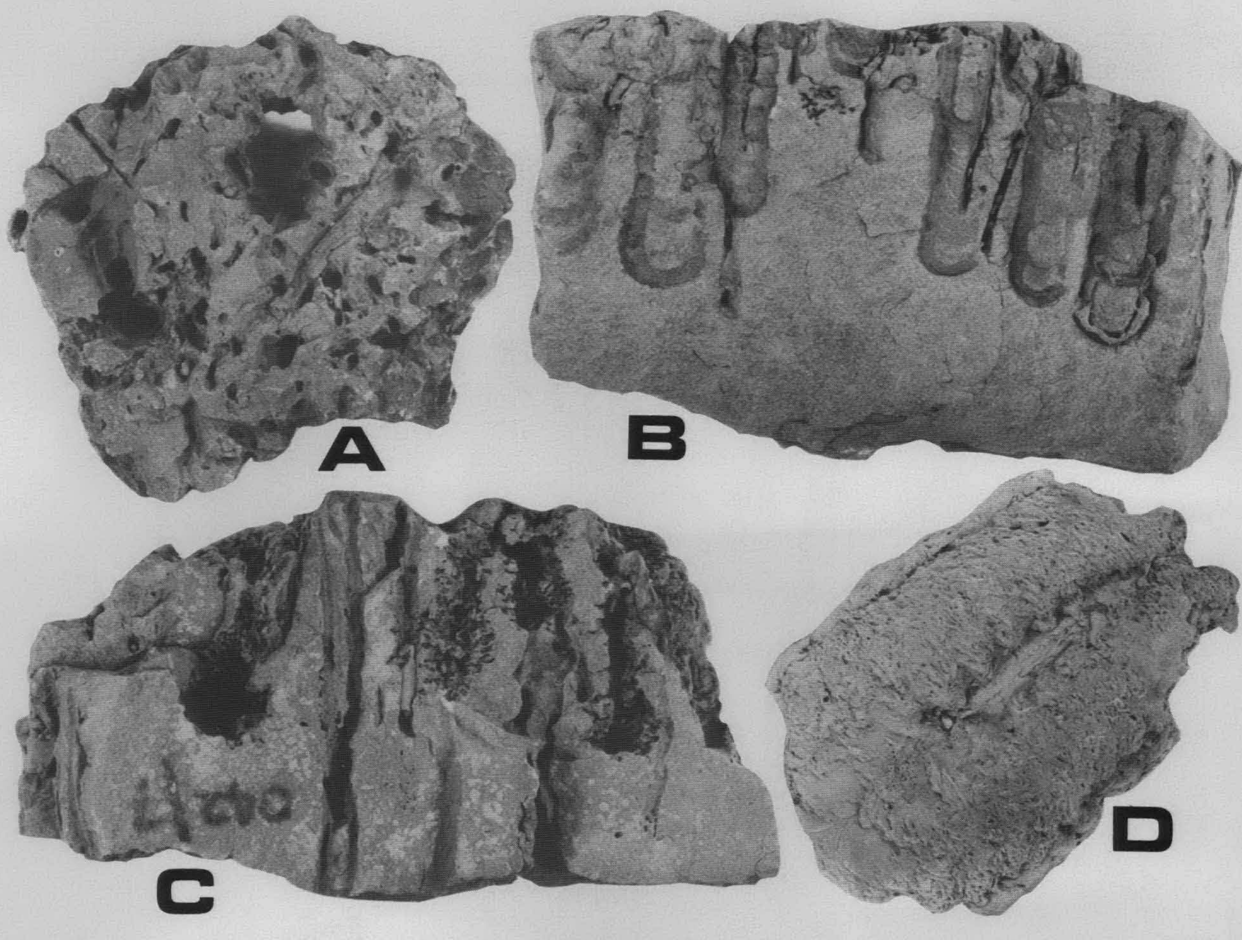

Figure 5. **A.** View of upper surface of rock showing numerous burrows, lower Mithaka Formation, x0.5, CPC 19802; **B.** U-shaped burrows, lower Mithaka Formation, x0.5, CPC 19803; **C.** Irregular burrows, lower Mithaka Formation, x0.4, CPC 19804; **D.** Poorly developed *Rusophycus,* x0.4, CPC 19805.

perimeter of the trace probably result from movement of the distal portion of the walking legs, the striae being formed by small claws at the extremity of the walking legs. Osgood (1970) suggested that the trace may have been excavated by a broad sweeping motion of the appendages in manner similar to a swimmer doing the breaststroke. The length of the external nodes indicate limited movement of the walking legs; this, and the presence of the numerous scratches, indicate that the major excavating tool was the pre-epipodite, which is the outer and upper branch of the biramous post-antennal appendages, the walking legs (or endopodites) forming the lower inner branch. The scratches on the lobe would be formed by gill filaments on the pre-epipodite.

A backward and forward motion of the pre-epipodite could form the lobes by turbulent water flow, by direct digging, or, most likely, a combination of these processes. The gill filaments were probably comb-like and stiff.

Variations in the traces are related to a number of factors. Crimes (1975) suggested that there are three stages in the preservation of trilobite traces: production of the trace; preservation between the time of formation and deposition of casting sand; and preservation during the casting process. A fourth factor should be added to these three, namely, that the trace must survive diagenetic, deformational and weathering processes. Trace formation is dependent on the nature of the underlying sediments and the behaviour of the trace-forming animal. The animal may excavate to varying depths and may also excavate at various speeds; these factors influence the shape and morphology of the trace. The preservation of the trace prior to casting depends not only on the nature of the sediment, but also on the manner in which the trilobite leaves the trace—the mode of departure from the trace gives it its final form. The preservation during casting depends on the nature of sediment in which the trace formed, the velocity of the depositing current, and the grain size of the casting medium. The sediment in which the traces formed is not preserved in outcrop, but the casting medium varies from very fine or fine sand to sandy pelletal phosphorite, or fine sands containing ironstone ooids. The traces from the Mithaka Formation have not undergone excessive diagenetic and deformational process, but do show varying degrees of weathering.

The purpose of the traces is not altogether clear, but Bergström (1973) postulated that the smooth exterior and wide rhachis of asaphids is an adaptation to a burrowing habit. Burrows may be for hunting or feeding purposes, passive resting, or a means of escaping predators.

Acknowledgements

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BMR Journal of Australian Geology & Geophysics, 5, 1980, 63-67

Earthquake accelerograms and attenuation of seismic waves at Oolong, New South Wales

Ron S. Smith & A. J. McEwin

The first Australian earthquake accelerograms were obtained from an accelerograph situated in the Dalton-Gunning region of New South Wales. Preliminary results were obtained for earthquakes on 23 November 1976 (maximum resultant acceleration 0.66 m/s^2), 30 June 1977 (0.21 m/s^2), 4 July 1977 (0.95 m/s^2) and 3 February 1979 (1.3 m/s^2). Maximum ground velocities were calculated for these earthquakes, and isoseismal maps drawn for the earthquakes at Bowning on 30 June 1977 and 4 July 1977.

These data were used to test the validity of the relation $Y \equiv ae^{bM}R^{-C}$ for assessing ground motion, and hence determining seismic risk. Because of the uncertainties in the derivation of analytical expressions for ground motions, the fit to observed values of acceleration, velocity and intensity is considered to be good. The relation recommended for use by the Seismic Sub-Committee of the Australian National Committee on Earthquake Engineering included a depth-adjusting factor Co, where ($R^2 = D^2 + h^2 + Co^2$). When Co was omitted a better fit to the observed accelerations was obtained, but a poorer fit to observed velocities.

The isoseismal pattern for the 4 July 1977 earthquake supports the radiation pattern expected from the faulting suggested by the focal mechanism and distribution of aftershocks. The isoseismals for the 30 June 1977 earthquake show a different radiation pattern; this suggests a different focal mechanism.

Introduction

On 17 October 1974 BMR installed an accelerograph at "Hillcrest", about 1 km northwest of Oolong railway station in the Dalton-Gunning region of New South Wales (Fig. 1).

The instrument is a Kinemetrics SMA-1 triaxial strong-motion accelerograph mounted on a concrete slab above a firm veneer of soil overlying granite. The trigger threshold is 50 mm/s^2, and the accelerograph operates for as long as the trigger detects ground motion, plus 10 seconds.

The accelerograph was triggered by four earthquakes: on 23 November 1976, 30 June 1977, 4 July 1977 and 3 February 1979—the resulting accelerograms are the first obtained in Australia. In each earthquake the instrument was triggered by the S-wave, and the largest trace amplitudes were recorded on the horizontal components. The accelerograms are shown in Figure 2.

The traces were digitised manually after photographic enlargement (x3) at intervals equivalent to 20 ms. Parallax between traces was allowed for by measuring the alignment of the sharply defined trace endings.

The first three accelerograms were analysed digitally by the methods described by Denham & Small (1971). However, for this study the 1979 accelerogram has only been hand-scaled. The vector resultant maximum accelerations and velocities are given in Table 1. Durations of ground accelerations in excess of 0.2 m/s^2 were less than 0.5s for the three smallest earthquakes, and about 1s for the largest.

Results and discussion

The Kanai scaling rule is of the form $Y = ae^{bM}R^{-C}$; Y represents the maximum ground acceleration, velocity or Modified Mercalli intensity (for MM intensity $Y_i = \ln Y$) and $R^2 = D^2 + h^2 + Co^2$, D = epicentral distance (km), h = depth to focus (km), Co = depth adjusting constant, M = Richter magnitude (ML). The values of the constants a, b, c, used for the Earthquake Risk Maps of Australia were those obtained by Esteva & Rosenblueth (1964) for the Western United States of America (McEwin & others, 1976). The scaling rule was adopted by the Standards Association of Australia for assessing ground motion and hence determining seismic risk for the Seismic Zone Map of Australia (Standards Association of Australia).

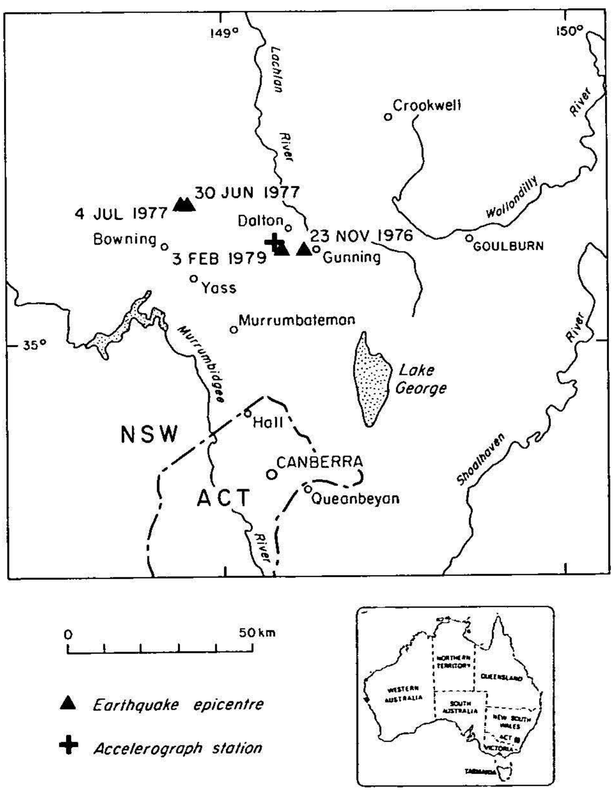

Figure 1. Map of southern NSW showing earthquake epicentres and accelerograph location.

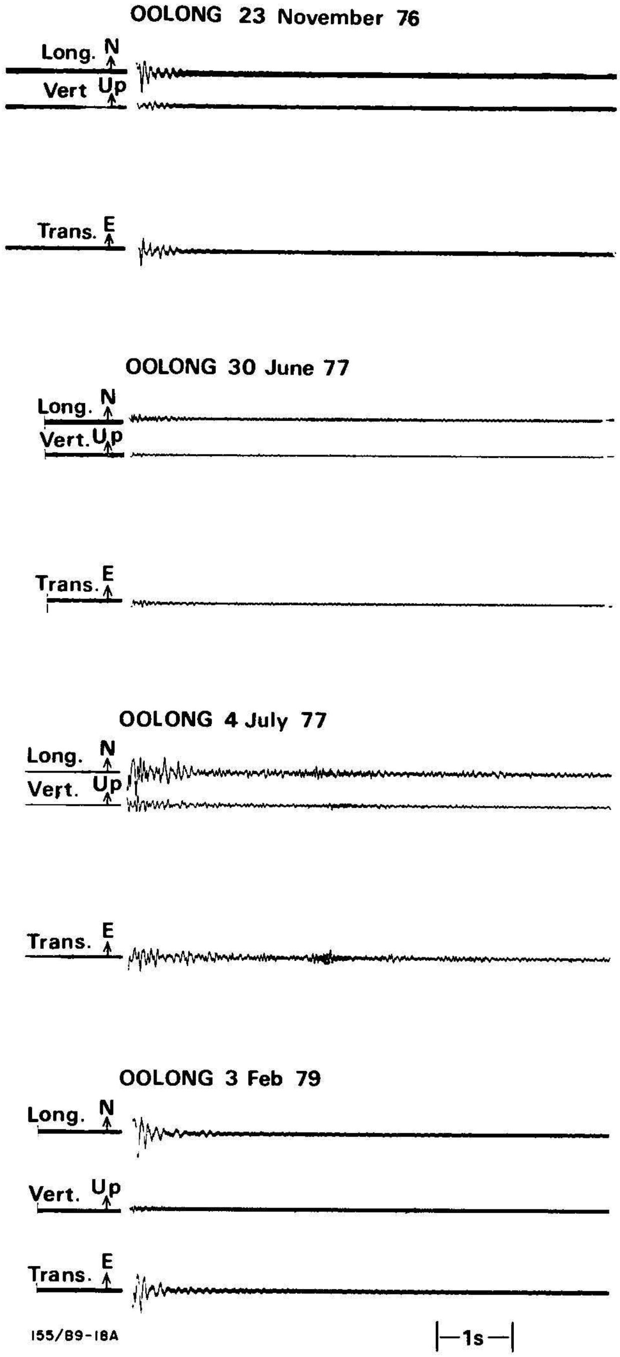

Figure 2. Oolong accelerograms.
Prints of original accelerograms recorded on 70 mm film. The time scale is 1 cm/s and sensitivities about 0.3 m/s²/mm.

Data on the earthquakes and accelerograms are listed in Table 1; results for acceleration are shown in Figure 3, and for velocity in Figure 4.

Spectral analyses have not been made, but periods of maximum accelerations were measured from the accelerograms and converted to frequencies. For these earthquakes the frequencies increase markedly with increasing epicentral distance, but we consider the data inadequate to draw any conclusions.

For three of the four results the calculated acceleration, without the depth-adjusting constant, closely matches the measured acceleration. The exception is the result for 30 June 1977, where the measured acceleration is much less than the calculated acceleration. It is possible that the maximum ground movements occurred before the accelerograph began recording. The nominal delay between triggering and full operation (quoted by manufacturers) is 50ms, which may have been lengthened by low battery voltage. The small gap in traces between the end of one record and the beginning of the next is normally consistent, e.g. for the earthquakes on 23 November 1976 and 4 July 1977 the gaps correspond to about 60-70 ms. However, for the earthquake on 30 June 1977, it corresponds to about 90-120 ms.

For the three earthquakes of 23 November 1976, 4 July 1977, and 3 February 1979, an attempt was made to derive new values for the constants a, b, c in the Kanai scaling rule for accelerations without Co. However, the results depend critically on the acceleration values. The values obtained, $a = 8.36 \times 10^7$, $b = 4.25$, $c = 9.82$ differ from those previously in use, in particular values for 'a' and 'c' are unreasonably high; realistic constants can only be obtained from more recordings.

Maximum resultant velocities were obtained from the digitised accelerograms by integration of the acceleration values, and from measurements of the acceleration and period of ground motion recorded on the undigitised 1979 accelerogram.

These velocities (again with the exception of the result for 30 June 1977 when the velocity measured was very low) are only a fair fit to the velocities given by the Kanai scaling rule; the discrepancies are worse if the depth-adjusting constant (Co) is not applied.

About 500 Earthquake Report questionnaires were distributed promptly after the two Bowning earthquakes of 30 June and 4 July 1977. From the analysis of 257 reports returned, and interviews of 16 residents in the epicentral area, isoseismal maps showing intensities (MM) were drawn (Figs. 5 & 6). The observed isoseismal radii are each the mean of eight measurements at equally spaced azimuths around the epicentre, and are compared with those calculated using the Kanai relation in Table 2 and Figure 7. The calculated radii are a good fit to those observed for the lower

Date	23 Nov 76	30 Jun 77	04 July 77	03 Feb 79
Time (UTC)	06 19 47.6	12 48 23.0	20 05 21.9	16 33 59.7
Latitude (S)	34°47′	34°40′	34°40′	34°47′
Longitude (E)	149°14′	148°54′	148°53′	149°10′
Magnitude (ML)	3.1	4.5	5.0	3.0
Depth (h, km)	14.8	15.8	19.7	14.3
Distances (km)	$S^2 = D^2 + h^2$, $R^2 = D^2 + h^2 + Co^2$			
Epicentral (D)	6	27	29	1
Hypocentral (S)	16	32	35	14
Adjusted R	26	38	40	25
Accelerations (m/s)	$Y = 20.e^{0.8ML}.R^{-2}$			
Measured	0.66	0.21	0.95	(1.30)
Y (with Co)	0.36	0.52	0.67	0.36
Y (without Co)	0.93	0.73	0.89	1.08
Velocities (mm/s)	$Y = 160.e^{ML}.R^{-1.7}$			
Measured	6	3	17	(19)
Y (with Co)	14	30	44	14
Y (without Co)	32	40	56	35
Dominant frequencies				
f(Hz)	17	25	25	11

Accelerograph co-ordinates: 34°46.4′S 149°09.8′E

Table 1. Earthquakes and accelerogram data.

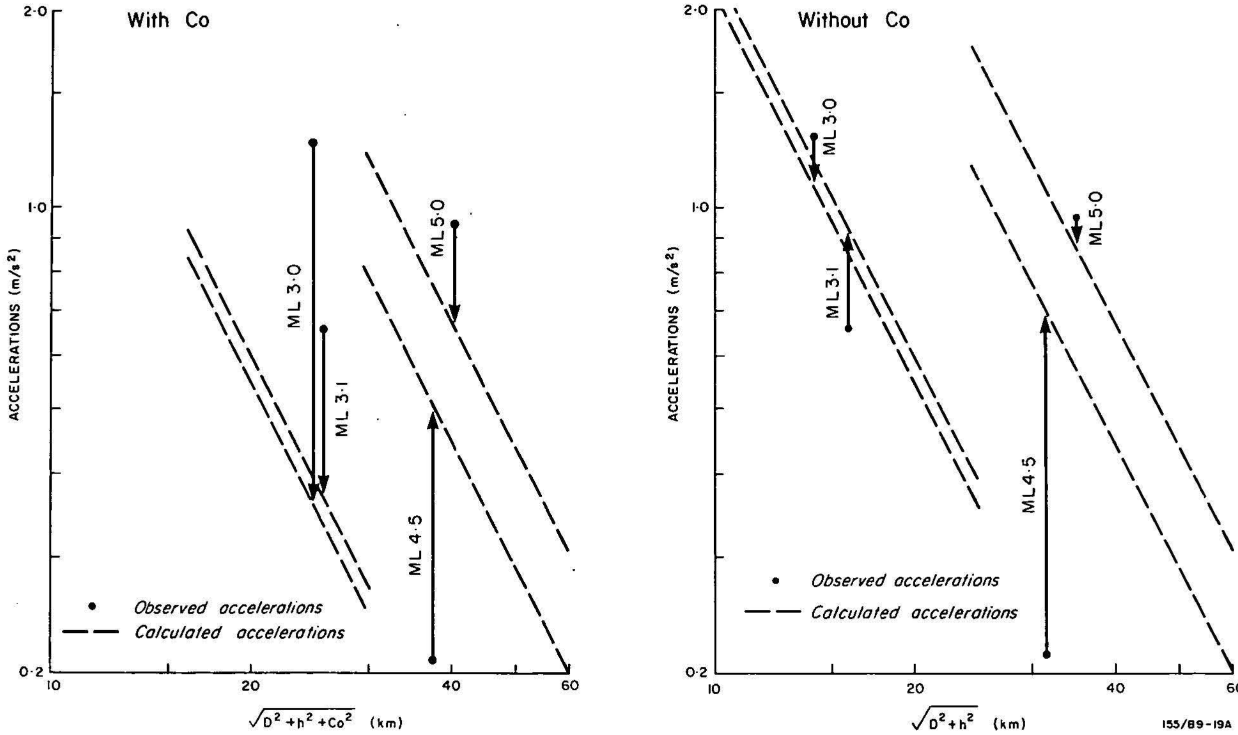

Figure 3. **Observed and calculated accelerations—Oolong, NSW.**
Plot of the relation between observed and calculated accelerations, both with and without the depth correction factor 'Co'. Data are listed in Table 1.

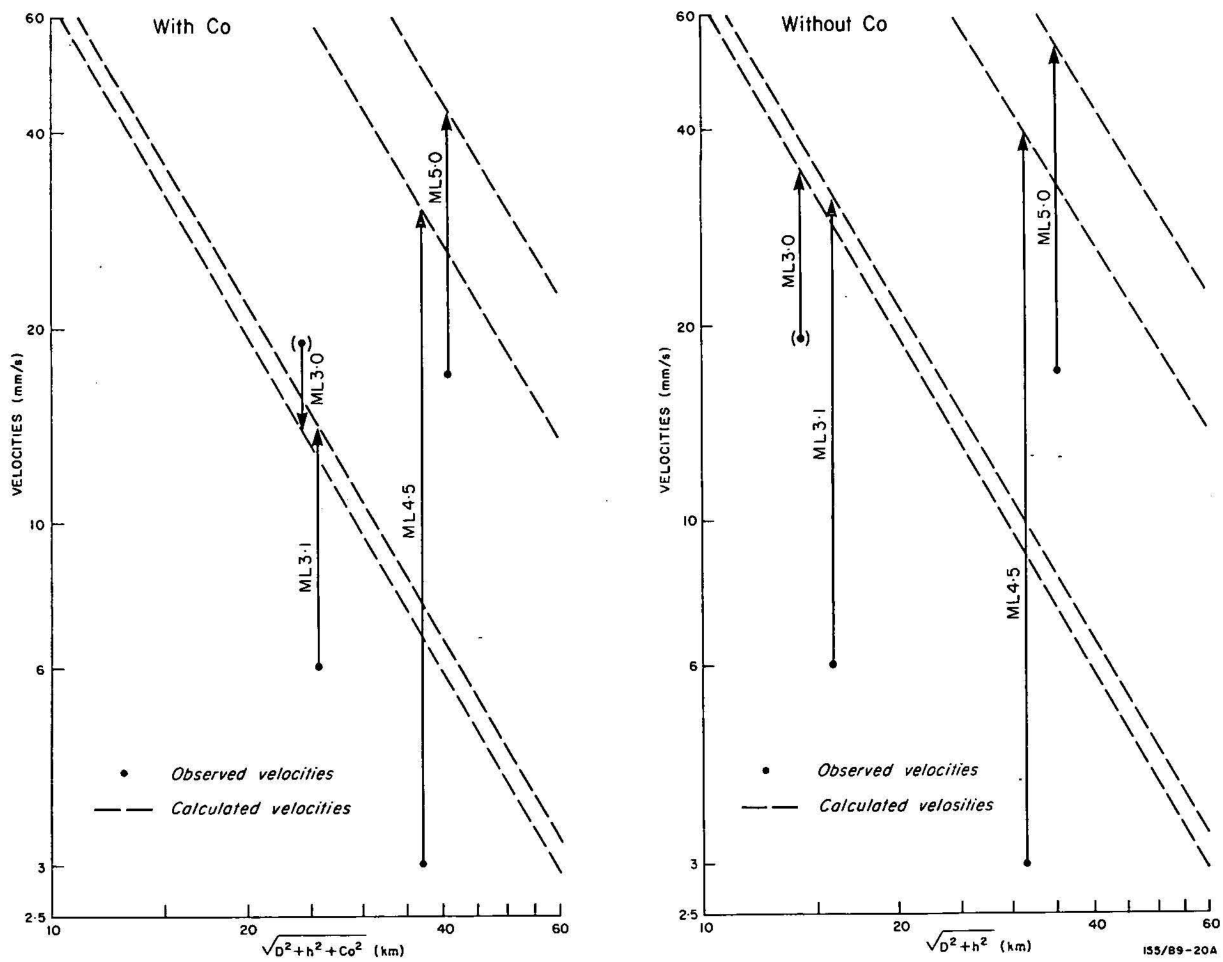

Figure 4. **Observed and calculated velocities—Oolong, NSW.**
Plot of the relation between observed and calculated velocities, both with and without the depth correction factor 'Co'. Data are listed in the table.

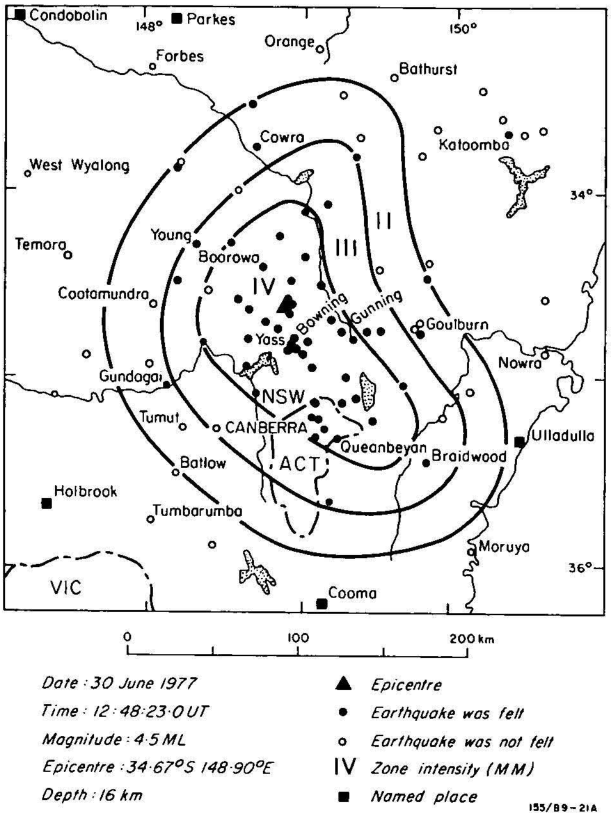

Figure 5. Isoseismal map—Bowning earthquake, 30 June 1979.
Felt intensities determined from the replies to questionnaires distributed. Isoseismals shown delineate the boundaries between zones marked.

Distances (km)	*30 June 1977 Isoseismals (MM)* II	III	IV	V	*4 July 1977 Isoseismals (MM)* II	III	IV	V
D observed	120	87	57	—	228	173	116	11
R observed	123	91	62	—	230	175	119	30
R calc.	164	110	74	49	221	148	99	67

$R^2 = D^2 + h^2 + Co^2$
R calc. derived from $e^{MM} = 2989.\ e^{1.5ML}.\ R^{-2.5}$

Table 2. Mean isoseismal radii—Bowning earthquakes.

intensities at larger distances, but the maximum intensities observed nearer the epicentres are lower than calculated.

The maximum intensity zone for the 4 July 1977 earthquake is elongated along a north-northeasterly axis parallel to the direction of the fault strike of the earthquake (Everingham & Smith, 1979), whereas that for 30 June 1977 is elongated to the southeast. The difference in radiation patterns suggest different focal mechanisms, but too few P-wave first arrivals were recorded for the 30 June 1977 earthquake for a fault-plane solution to be obtained.

Conclusions

Maximum accelerations recorded were 0.66 m/s^2 (.067g) on 23 November 76, 0.95 m/s^2 (.097g) on 4 July 77, and about 1.30 m/s^2 (0.13g) on 3 February 79.

The maximum acceleration of the earthquake on 30 June 1977 was probably not recorded, because of an instrumental malfunction.

The Kanai scaling rule can be used to determine maximum ground motions expected in the Dalton-Gunning region of NSW for earthquakes at mid-crustal depths.

The constants adopted (Esteva & Rosenblueth, 1964) give realistic estimates of ground acceleration, velocity, and intensity.

It is not possible to redetermine reliable constants for the Kanai relation with so few data; more recordings are necessary.

Estimates for acceleration are improved, but estimates for velocity worsened, if the depth-adjusting constant is not used.

The radiation pattern of maximum intensities observed for the 4 July 1977 earthquake confirms the faulting suggested by the fault-plane solution.

The radiation pattern for the 30 June 1977 earthquake suggests a different focal mechanism, but no fault-plane determination has been possible.

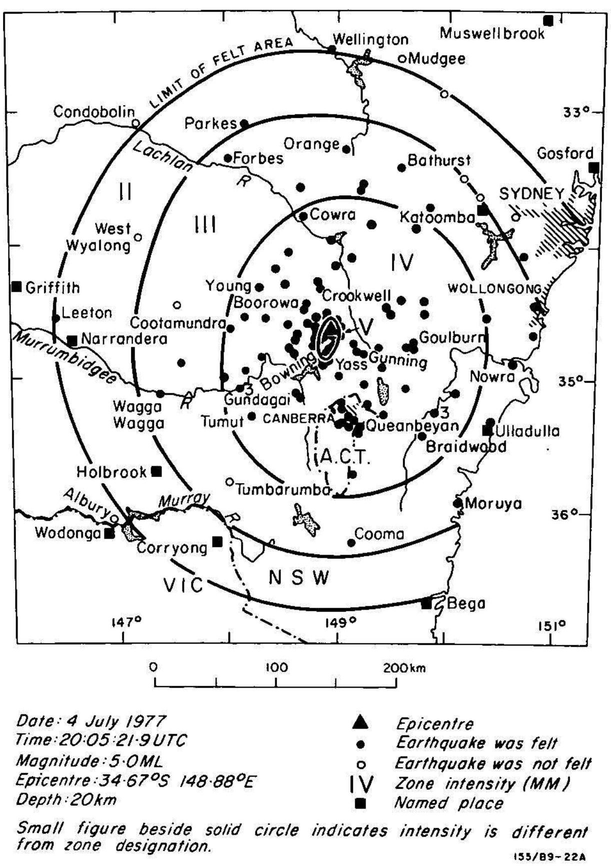

Figure 6. Isoseismal map—Bowning earthquake, 4 July 1979.
Felt intensities determined from the replies to questionnaires distributed and interviews of residents in the near epicentral region. Isoseismals shown delineate the boundaries between zones marked.

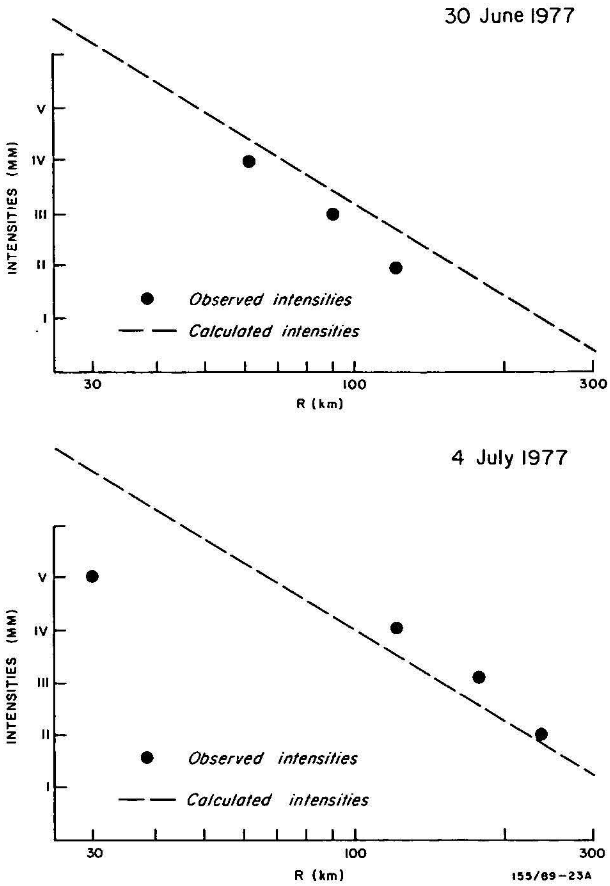

Figure 7. Observed and calculated intensities—Bowning earthquakes.
Plot of intensities showing the relation between calculated and observed radii of isoseismals.

Acknowledgement

The figures were drawn by S. Royle.

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Manganese nodules from the Tasman Sea off Sydney

N. F. Exon, D. Moreton[1], G. Hicks[1]

Two manganese nodules were recently recovered by HMAS *Kimbla* from a water depth of 4300 m, in a northeast-trending trough about 250 nautical miles southeast of Sydney (155°35'E. 36°15'S). They were associated with greenish gray calcareous mud laid down below the lysocline, but above the carbonate compensation depth. The nodules are subspherical and about 10 cm in diameter, and have a high clay content, a low Mn:Fe ratio, and low contents of Ni (0.25%), Cu (0.17%) and Co (0.06%).

During a short geological cruise in May 1979 by HMAS *Kimbla*, to whose captain and crew we are most grateful, two manganese nodules were recovered from the deep sea about 250 nautical miles southeast of Sydney (Exon, 1979). Sampling was carried out using two Benthos free-fall grabs at each station; they sample a bottom area of about 40 x 40 cm, and trap material in a net with 6 mm mesh. Station 5, at which the nodules were recovered, was at 155°35'E, 36°15'S, 40 miles northwest of Gascoyne Seamount, and the estimated water depth was 4300 m. The samplers recovered 1-2 kg of greenish gray calcareous mud, and two large manganese nodules.

The mud is 17 percent sand, 4 percent coarse silt (40-63 microns) and 79 percent fine silt and clay, and contains 28.6 percent $CaCO_3$ by weight. The coarser fractions are dominated by mainly whole, but corroded,

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planktonic foraminifera, with some calcareous benthonic foraminifera, and siliceous sponge spicules and nets. Fresh angular quartz and feldspar make up about 25 percent of the silt fraction. Other minor components are brown glass, volcanic rock fragments, biotite, manganese micronodules, radiolaria and echinoid spines. The fine fraction consists mainly of clay minerals.

The sediments were obtained from a trough trending northeastward, and were deposited below the lysocline but above the carbonate compensation depth. The fresh angular silt-sized quartz and feldspar in the sediments suggest derivation from acid or intermediate volcanics, perhaps by turbidity currents stemming from the Lord Howe Rise or Gascoyne Seamount.

The manganese nodules are subspherical with a rather irregular and rough surface, and are about 10 cm in diameter. They consist of numerous concentric shells, many less than 0.1 mm thick, of brown and black metal oxides, and pale yellowish clay, in roughly equal proportions. The shells enclose pumice fragments up to 1 cm long, which are very altered to clay and silica. The cores of the nodules consist of a number of smaller nodules (1-2 cm ϕ) formed around pumice fragments. A few radial cracks about a millimetre thick are filled with metal oxides.

The metal contents of the nodules (dried at 105°C) were determined at BMR using the atomic absorption method for Mn, Ni, Cu and Co, and a volumetric method for Fe. The results are compared, in Table 1, with results from crusts recovered at *Galathea* Station 574 (Ahrens & others, 1967) to the southeast (159°39′E, 39°45′S), with results from 24 nodules in the Australian region between 135°E and 170°E (Noakes & Jones, 1976), and with average values from the northeast Pacific (Cronan, 1972).

This is only the second record of seafloor manganese nodules from the central Tasman Sea, the first being at an *Eltanin* station 500 km to the south. The low values of Mn, Ni, Cu and Co are comparable to those of nodules from southern waters off southeastern Australia. The *Galathea* analyses were carried out on encrustations, and are most unlikely to reflect accurately the bulk composition of the material.

Station/region	*Weight % (dry basis)*						
	Fe	*Mn*	*Ni*	*Cu*	*Co*	*Ni+ Cu*	*Ni+ Cu+Co*
Kimbla 5B/1	16.0	6.7	0.29	0.21	0.07	0.50	0.57
Kimbla 5B/2	15.6	5.0	0.22	0.14	0.05	0.36	0.41
Eastern Australia	14.7	8.3	0.18	0.10	0.09	0.28	0.37
Galathea 574	8.19	26.2	1.25	0.60	0.19	1.85	2.04
Galathea 574	7.33	27.3	1.30	0.60	0.18	1.90	2.08
Northeast Pacific	9.44	22.33	1.08	0.63	0.19	1.71	1.90

Table 1. Analyses of manganese nodules.

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BMR Journal of Australian Geology & Geophysics, 5, 1980, 68-69

New microform publications

The reports whose titles and abstracts appear below have recently been issued as microfiche.

Report 191
Microform MF69

Officer Basin seismic, gravity, magnetic, and radiometric survey, Western Australia, 1972.

by *P. L. Harrison & I. Zadoroznyj*

ISBN 0 642 04014 1

67 pp., 45 pls., 1978. 4 fiche, **$2.00**

The Bureau of Mineral Resources made a seismic, gravity, magnetic and radiometric survey in the Western Australian part of the Officer Basin in 1972, on a northeast traverse between the Yilgarn and Musgrave Blocks. The survey comprised a series of depth probes using refraction and single to twelve-fold CDP reflection recording. The other geophysical measurements were taken at 1-km intervals mainly along the seismic traverse.

A model of the geology and structure between the Yilgarn and Musgrave Blocks was obtained from the integrated interpretation of the BMR and earlier surveys. The model shows that there are three main rock sequences: Phanerozoic sediments up to 1300 m thick, Proterozoic sediments up to 5700 m thick, and an underlying layered sequence in the southwest, of unknown nature, but which probably consists of igneous and metamorphic rocks up to 12 000 m thick and may be distinct from basement of the Yilgarn Block. It is possible that the rocks comprise metasediments intruded by basic rocks.

Report 203
Microform MF93

Mount Turner geophysical survey, Georgetown area, Queensland, 1976.

by *J. A. Major*

ISBN 0 642 04447 3 — 26 pp., 8 figs., 2 appendixes, 1979. 1 fiche, **$0.50**

During 1976, the Bureau of Mineral Resources made a geophysical survey at the Mount Turner porphyry copper prospect, near Georgetown, Queensland. The objectives of the survey were to assist the geological evaluation of the porphyry copper prospect and to study the applications for geophysics in exploration for porphyry copper orebodies. The prospect occurs in an alteration system within a pluton of Proterozoic Forsayth Granite, which contains enclaves of Robertson River Metamorphics. Vertical electrical soundings were made to map the chargeability and resistivity of the unweathered bedrock. Resistivity and chargeability zones are identified and appear to map out areas of different alteration types. Gamma-ray spectrometry, total-count radiometrics, and magnetics did not contribute to the understanding of the porphyry copper prospect.

Report 210
Microform MF95

Geophysical mapping of buried Precambrian rocks in the Cloncurry area, northwest Queensland.

by *A. J. Mutton & R. A. Almond*

ISBN 0 642 04711 1 — 41 pp., 11 figs., 9 pls., 3 appendixes, 1979. 2 fiche, **$1.00**

In 1975 the Bureau of Mineral Resources carried out a program of geophysical mapping—based on the analyses of existing geophysical, geological, and drilling information, supported by ground geophysical and geological fieldwork—in the eastern part of the Cloncurry 1:250 000 Sheet area, northwest Queensland. The aim of the mapping was to determine the lithology, structure, and depth of burial of the Precambrian Cloncurry Complex beneath a thin cover of alluvium and Mesozoic Carpentaria Basin sediments.

The results of the mapping indicate that Precambrian basement extends at shallow depths—<100 m over most of the survey area, <50 m over half of it—beneath the cover sediments for about 40 km east of the eastern limit of outcrop. The contact between shallow-buried basement and sediments of the Carpentaria Basin is marked by a major fault dipping steeply eastwards. Interpretation suggests that the Cloncurry Complex does not continue beneath the Carpentaria Basin, but gives way to less dense granitic basement east of the fault.

Within the basement complex, the Naraku Granite is interpreted as intruding both the Corella Formation, in which a complex geophysical response suggests contact metamorphism, and the less magnetic rocks of the Soldiers Cap Group with no noticeable contact effect. Dense meta-basalts and amphibolites of the Soldiers Cap Group form a distinct zone of Bouguer anomaly highs, which enables them to be mapped in areas of no known outcrop. Localised intense magnetic and gravity anomalies appear to indicate magnetite and hematite-rich rocks in the interpreted contact aureole in the Corella Formation. Fold patterns are complex, and several interpreted major magnetic lineaments appear to be related to granite emplacement.

Report 213
Microform MF97

Geophysical Branch summary of activities, 1978.

ISBN 0 642 04392 2 — 200 pp., 65 figs., 1979. 3 fiche, **$1.50**

Report 215
Microform MF100

Preliminary report on the Cadoux earthquake, Western Australia, 2 June 1979.

by *P. J. Gregson & E. P. Paull*

ISBN 0 642 04520 8 — 12 pp., 18 figs., 1979. 1 fiche (14 figs. as hard-copy postcards), **$2.00**

An earthquake occurred on 2 June 1979 near the small town of Cadoux, Western Australia. Only one person was injured, but the cost of damage in the town and surrounding district could exceed $1.5m. Preliminary results show that the earthquake had a Richter magnitude of 6.2 and occurred at 09h 48m 01s UT at latitude 30.83°S, longitude 117.15°E, and at a depth of 15 km. It is the third earthquake of magnitude 6 or greater to occur in the southwest seismic zone in eleven years. The maximum Modified Mercalli intensity observed was IX. The surface of the Earth fractured in a zone 14 km long. Three scarps were formed, the largest was 8 km long and ran northerly with overthrusting up to 1.1 m from the west, and vertical uplift up to 0.6 m. Some right-hand strike-slip occurred. The general direction of movement (70°-80°) conformed roughly with the direction of the axis of maximum stress measured in the area in 1976. The two smaller faults (2 km and 5 km long) ran about southeast; the area between them was raised by up to 0.5 m and left-lateral motion reached 0.6 m.

Report 216
Microform MR104

Stratigraphic definitions of named units in the Arunta Block, Northern Territory.

by *A. J. Stewart & others*

ISBN 0 642 04738 3 — 70 pp., 1980. 1 fiche, **$0.50**

This report presents stratigraphic definitions of named rock units in the Arunta Block, Northern Territory, mapped between 1970 and 1977. Most of the units are of crystalline rocks, but definitions of the Tertiary Hale Formation and four new members of the Upper Proterozoic Heavitree Quartzite are also included.

Report 217
Microform MF105

Abstracts of 8th BMR Symposium, Canberra, 1-2 May 1979.

ISBN 0 642 04511 9 — 22 pp., 1979. 1 fiche. **$0.50**

BMR Journal of Australian Geology & Geophysics, 5, 1980, 70-72

Evidence of an exhalative origin for deposits of the Cobar district, New South Wales

D. P. H. O'Connor[1]

Dr Sangster's contribution on the ore deposits of the Cobar district (Sangster, 1979) is of interest in that it views from a different perspective a group of distinctive and economically important deposits whose origin is enigmatic. Despite the advances in ore genesis theory which have seen many of the former 'hydrothermal replacement' deposits described in terms of volcanic processes operating at or near the ocean—ocean floor interface, workers familiar with Cobar geology have been circumspect in assigning to the Cobar deposits a similar mode of origin. The lead-zinc/copper zonation at the CSA and several of the idle mines which so impressed Dr Sangster had not gone un-noticed by local geologists (e.g. Robertson 1974, p. 180). That they have not taken the next, apparently simple step of considering this zonation in terms of the sedimentary-exhalative orebody model is for the good reason that the comparison does not survive detailed examination.

In offering comment on Dr Sangster's paper it is appropriate to note firstly several areas where the bases for his interpretation in the CSA Mine area are wrong in fact:

1. While there exist no useful marker horizons between the Eastern and Western ore systems the sequence is, nevertheless, well bedded, and the bedding trends have been firmly established by underground mapping. If a syncline is proposed connecting the two ore systems, then, of course, the closure must be defined by bedding. However inspection of Figure 7D shows the syncline to have been drawn without regard to established bedding trends, which are completely at variance to such a closure.
2. Dr Sangster's interpretation requires a reversal of sedimentary facings between the Eastern and Western ore systems. Although alteration and shearing have locally broken down and obliterated bedding in the immediate hangingwall* of the Western ore system (the only ore-host sequence contact available for examination by Dr Sangster at the time of his visit), there is abundant evidence from sedimentary structures observed in drill core (principally graded bedding and cut-and-fill structures) that the parts of the sequence hosting both the Western and Eastern ore systems are unequivocably west-facing. Indeed this consistency of facing is known for several hundred metres to the west and east of the ore systems.
3. That the Western ore system zonation is predominantly footwall copper and hangingwall lead-zinc is a matter of disputation. Figure 7D shows the opposite, as would Figure 7E if the information had been available at the time of its compilation to extend it on the north side. The lowest opened level in the Mine (630 m level) shows the same distribution. In any event the impossibility of the reversal suggested by Dr Sangster obviates the need for such a zonation.
4. The two-favourable-horizons concept is tenuous at best in that Figure 7A-E would seem to show that it is more honoured in the breach than the observance. More specifically, it is entirely unconvincing when it is known that the Western Orebody depicted as horizon 2 in Figures 7B and 7C is the same continuously stopeable orebody represented as horizon 1 in Figure 7D.

Although the unequivocal west-facing nature of the sequence effectively disposes of fold-repetition of the ore system, it is of interest to note that while exploration to the west of the Western ore system has not been exhaustive and an unknown ore position could conceivably be present there, exploration has disclosed a promising new ore zone in quite the opposite direction—to the east of the Eastern ore system—across a portion of the sequence where sedimentary facings are again consistently to the west.

Four comments are relevant to Dr Sangster's proposition that the lead-zinc/copper zonation observed in the CSA Mine (and elsewhere) might reflect transposition into the cleavage of an originally sedimentary-exhalative derived ore deposit:

1. The concept fails to recognise the role of fracturing and shearing in ore localisation. The most obvious controls of the ore systems at the CSA Mine are zones which are manifested by magnesium alteration (talc and magnesian chlorite development) and silicification in areas of weakened rock competence. Robertson (1974) considered fluids effecting alteration and mineralisation to have migrated upwards through narrow, but vertically extensive planes of weakness. Such movement would explain the lack of a broader alteration zone—as might be expected if lateral migration were an important mechanism, and the explanation of base-metal zonation might be sought in fluid dynamics and fractionation rather than the sea floor interface-time sequence mechanism.

1. **Mines Exploration Pty. Ltd., P.O. Box 57, St. Marys, South Australia 5042.**

*** Footwall and hangingwall are used in the long-accepted mining sense of the under and over-surfaces of a dipping lode or fault. Thus a footwall lead-zinc/hangingwall copper zonation means, in the example of the CSA Mine, that the lead-zinc occurs along the western side of the easterly dipping ore zone. This explanation is desirable in view of the vogue usage of the terms "structural" and "stratigraphic" footwall and hangingwall. By the former is presumably meant no more than the normal mining term. The latter has never been satisfactorily explained to the writer; in the case of a bedded lode it might have some meaning. but where a lode cuts across bedding the term is a source of puzzlement. If the purpose is to discriminate between the host sequence on either side of the lode, then the descriptions footwall sequence and hangingwall sequence are unambiguous and do not involve the distortion of a useful and long-standing terminology.**

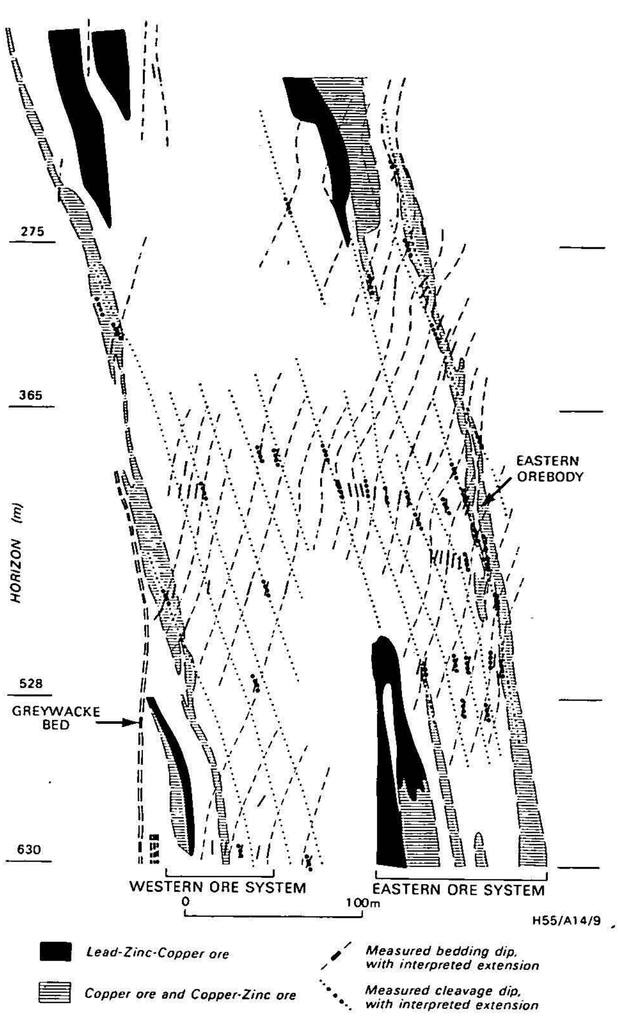

Figure 1. CSA Mine, cross-section 1523 708N, showing orebody-bedding-cleavage geometry. Section looks north.

2. The distribution of chert-like rock in and on the immediate hangingwall of the ore zones follows the elongation of the ore zones. Robertson (1974) described the progressive alteration of siltstone host rock culminating in the cherty rock type which in isolation resembles the characteristic accompaniment of the sedimentary-exhalative type of deposit. The observation of Kappelle (1970) that mineralisation in this rock type is conformably controlled by bedding is an interpretation that takes no account of the wider distribution of the 'chert'. Possible alternative interpretations are that the rock type represents silicification of siltstone carrying bedded sulphide, or that the sulphide layering parallels the bulk of the ore layering which is sympathetic to cleavage rather than bedding (Robertson, 1974, p. 189).
3. The present orebody geometry could not have been produced by local re-alignment in the cleavage, such that an original lead-zinc/copper zonation was more or less preserved. If this had occurred the enveloping surfaces of the two ore systems would be extended approximately along bedding. The relationships in the Figure 7 plans are not entirely clear, because of the relatively limited strike length of the ore systems, and extension along bedding could perhaps be claimed through viewing these plans in isolation. However consideration on cross-section (see accompanying figure) of the vertical interval over which the systems have been delineated discloses no mere local discordance but a grossly transgressive relationship as the divergence between the easterly dipping ore systems and predominantly westerly dipping host sequence becomes more accentuated. Down to the lowest current mine level (630 m below surface) the well defined Eastern Orebody of the Eastern ore system progresses some 180 m through the stratigraphy. If the sequence continues its expected westerly dip down to the lowest horizon to which the ore systems have been proved by drilling (950 m below surface) the progression will necessarily be even greater. The transgression of the sequence is thus a real and major feature and cannot be lightly dismissed in any consideration of the genesis.
4. The known east-west horizontal extent of the ore zones, including the recently discovered far-eastern zone, is some 600 m representing a total distribution within the sequence of some 700 m down to the 630 m horizon. Again the amount of the sequence so occupied can be expected to increase with depth as the ore systems continue their transgression. This distribution is in stark contrast to Dr Sangster's proposal of two 'stacked' horizons at a more or less unique stratigraphic level.

In considering the possible mode of origin of the Cobar deposits due recognition must be accorded to the sedimentary flavour of at least some of the mineralisation in the Cobar Group (Russell & Lewis, 1965) host sequence. Russell & Lewis made the broad observation of metal zonation sympathetic with the stratigraphy. Brooke (1975, fig. 6) produced evidence of iron and base metal sulphides distributed along bedding in CSA Siltstone. He added the reservation, however, that the alternative interpretation of mobilised sulphides invading bedding planes could not be discounted. In any case the frequency of such observations should be kept in perspective: in the writer's experience they are something of a rarity in that portion of the sequence hosting the CSA ore systems. With regard to possible volcanic activity contemporaneous with sedimentation, although tuffs and lavas have been identified as minor components of the Cobar Group at locations generally distant from the sites of the deposits (the Queen Bee Mine is a possible exception), conclusive evidence for such activity in the deposits of The Peak to CSA group is elusive. Kappelle (1970) referred to quartz particles with shard-like shapes in slate lamellae at the CSA Mine. Robertson (1974) stated that there is an ash-fall tuff near the top of the CSA Siltstone, but provided no supporting evidence.

Given that volcanic processes might have been the source of syngenetic sulphides in the Cobar Group sediments, it is still a long step to explain the present CSA orebody geometry and distribution in terms of these processes. It is certain that the evidence does not support the immediate sedimentary-exhalative model proposed by Dr Sangster, or even perhaps the more generalised concept of Brooke (1974) of mobilisation of sulphides deposited syngenetically close to the current orebody positions. The proposal of Robertson (1974) that the mineralisation was introduced from depth by hydrothermal solutions feeding into a vertically extensive shear and fracture system is in closer accord with the available evidence and not necessarily exclusive of an ultimate volcanic-related origin for the sulphides now comprising the orebodies.

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BMR Journal of Australian Geology & Geophysics, 5, 1980, 72-73

Evidence of an exhalative origin for deposits of the Cobar district, New South Wales

*D. F. Sangster**

O'Connor's comments regarding a proposed sedimentary-exhalative model for the CSA deposit are welcomed as additional contributions to discussions of the genesis of deposits in the Cobar district. His points with regard to 'errors of fact' are answered below:

1. The discordancy between bedding in the host rocks and mineralisation is a point covered at some length in the original paper (Sangster, 1979) so O'Connor's observation that bedding trends in Figure 7D are at variance to an isoclinal fold closure defined by ore zoning is not regarded as an original observation. Although the fold was shown to close to the south, suggesting a north-plunging fold, there is no evidence that it does so. The proposed fold could just as well have a south, vertical, or horizontal plunge.
2. The assertion of unequivocal west-facing structures in host rocks to both the Eastern and Western ore systems is, by far, O'Connor's best point. If, indeed, good west-facing evidence has been noted immediately adjacent to both sides of the Western System, and furthermore, has been observed continuously to the west such that the tight isoclinal fold proposed in my model is absolutely precluded then, of course, I must concede the point. If this were the case, the proposed fold at CSA would not exist and the described zoning would have to be explained by other means. As shown in my Figure, 7A-E, however, a reversal in facing could take place within a hundred metres west of the Western System so that O'Connor must document west-facing structures immediately west of the Western System in order to invalidate the proposed fold in the CSA mine. It is rather interesting that O'Connor's Figure does not record any facing evidence whatsoever.
3. The apparent 'reversal' of the proposed zoning in the Western ore system noted by O'Connor in Figure 7D leaves unexplained the remarkably well-developed 'normal' zoning on the other levels in the mine (e.g. Fig. 7B, C). Neverthless, in answering this comment, I must point out that the proposed zonation pattern was based mainly on published figures in Brooke (1975; 1976) and Kappelle (1970) showing the distribution of ore types.. Experience has shown that zoning in exhalative deposits is best demonstrated by Cu-Pb-Zn assay data and/or mineralogical studies. Distribution of 'ore' is very likely to be less continuous and definitive than a portrayal of the mineralogical features of the same zone. Witness the differences shown in Figure 7C ('ore' distribution) and Figure 8 (mineralogy) for the 365 m level. To further compound the problem, diagrams in Brooke (1975) are labelled 'copper ore' and 'copper ore with zinc'. In the text, however (Brooke, 1975, p. 691), the copper-zinc ore is described as composed of pyrite, sphalerite, and galena with only 'minor' chalcopyrite, leading one to wonder why it is referred to as 'copper-zinc' ore. Nevertheless, in spite of these difficulties, a zoning pattern is still discernible in the CSA deposit and defines two parallel mineralised horizons. In situations where severe transposition of 'stacked' orebories has occurred, as proposed in the CSA mine, it is not difficult to present an arbitrary section through them (as in Fig. 7D) such that the feeder zone copper ore of the stratigraphically higher body is juxtaposed against the lead-zinc zone of the underlying body to give the impression of the 'reversed' zoning noted by O'Connor.
4. For the reason noted in the above paragraphs, O'Connor's observance that my horizon 2 in Figure 7B and 7C is the 'continuously stopeable' equivalent of horizon 1 in Figure 7D cannot be considered definitive proof precluding the 'two horizons' concept. The two proposed horizons occur so close together stratigraphically, and transposition has been so marked, that normal mining methods might well begin on one horizon and, with depth, merge into the adjacent horizon with little or no discernible change in direction.

O'Connor's comments on transposition of the orebodies into cleavage, specifically the structural control of magnesian and silicic alteration, are of interest be-

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cause precisely the same arguments were applied for years to, for example, the volcanogenic massive sulphide deposits of Noranda and Flin Flon districts. All were originally regarded as replacement bodies in silicified, talcose, and chloritic 'shear zones'.

The relative timing of alteration and shearing is difficult to establish firmly in most deposits and it is fruitless to argue the point. Suffice to say that, simply because magnesian and silicic alteration occur together with sheared rock, this cannot be taken to indicate that shearing controlled alteration; the opposite could apply equally as well. Instead of alteration affecting a structurally weak or deformed area, the sheared rocks might well have been preferentially developed in a previously altered rock. The argument is an old and familiar one to geologists and, in deciding between the above alternatives, the distribution of the magnesian alteration relative to the orebodies must be carefully observed. In an exhalative deposit, the magnesian alteration will be asymmetrically disposed only (or mainly) on the original stratigraphic footwall. The issue is further compounded by two other properties of exhalative deposits: 1. because chlorite can occur on both footwall and hangingwall of a simple exhalative deposit, it is necessary to determine chlorite composition because chlorite on the footwall will likely be Mg-rich and that on the hangingwall Fe-rich (in effect, silicate-facies iron-formation); 2. in a 'stacked' orebody situation such as proposed for the CSA mine, magnesian alteration could occur on both hangingwall and footwall of the stratigraphically lower ore zone.

Similar arguments apply to the so-called silicification accompanying exhalative deposits. Simply observing or mapping silica content is not enough to demonstrate that 'alteration' is symmetrically disposed around an orebody and that therefore the deposit cannot be of exhalative origin. The nature of the silicification must also be noted; that on the footwall of an exhalative deposit will tend to be discordant, non-bedded, and will replace pre-existing lithologies although that on the original hangingwall will be concordant and bedded, representing chert chemically precipitated at the same time as detrital deposition of the host rock (i.e., siltstone in the case of CSA). Distinguishing silicified siltstone from co-deposited chert and siltstone in a now-deformed area may be impossible without very careful mapping and petrography. The main point here is that one must be aware of alternate possibilities for the so-called silicification; apparently symmetrically disposed silica does not, in itself, preclude an exhalative origin for the CSA (or other) deposits.

In his other two comments, O'Connor stresses the 'grossly transgressive relationship' shown by the divergence of ore zones and host sequence; he offers a cross-section of the CSA mine in support of his argument. It is apparent from this diagram that it is the siliceous chalcopyrite-pyrrhotite ores which are 'grossly transgressive', an accepted feature of exhalative deposits. The lead-zinc portion of the ores, however, if of exhalative origin, would originally have been disposed parallel to bedding and might not be expected to show as much transgression relative to bedding as the copper-zinc ores. Examination of O'Connor's figure 1 shows that the lead-zinc lodes are not nearly as continuous as the copper-zinc zones, thereby reducing the thickness of the stratigraphic section they purportedly 'transgress'. Further examination of the diagram shows many instances of measured bedding directions with a vertical or eastward dip. These are particularly evident in bedding measured close to the lead-zinc ores. The oft-quoted statements of west-dipping beds in CSA mine may be true in general but, in detail, is shown to have many important exceptions, as shown in O'Connor's diagram; east-dipping beds are also shown in my Figure 7A and D. It thus would appear that the east-dipping lead-zinc lodes may be concordant, or nearly so, with adjacent bedding and do not transgress as much (if any) stratigraphy as do the copper-zinc zones. Both of these parameters are consistent with an exhalative origin for the deposits.

One further point with regard to O'Connor's diagram: the 'interpreted extensions to bedding should be regarded only as interpretations. In the absence of sufficient marker beds in the sequence, there is no basis for joining an individual measured dip with another (as O'Connor has done) to give the impression of through-going beds. In fact, the only admitted marker bed in his figure 1 (the greywacke) shows vertical or eastward dips and, as shown, is in marked discordance with the concept of westward dips of the host sequence.

In conclusion, I am grateful to BMR for providing this opportunity to reply to O'Connor's comments and, in doing so, perhaps help focus attention on some of the critical issues to be studied in order to better understand this exceedingly interesting mineral district.

Readers should be made aware of an error in the original paper. On page 20, in the caption to Figure 6, the reference to Figure 4B should read 5B.

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Mode of emplacement of the Papuan Ultramafic Belt: a discussion

Emile Rod[1]

Connelly (1979) states: "Geological and geophysical evidence from a number of studies has established that the Papuan Ultramafic Belt is probably an overthrust sheet of oceanic crust and mantle with a thicker crustal section than normal oceanic crust".

This hypothesis was first advanced by Thompson in 1957 (see Davies, 1971), and worked out in more detail by Davies (1968, 1971) and Davies & Smith (1971).

In 1973 I presented an alternate interpretation of the Papuan Ultramafic Belt. I quote here from the ANZAAS (1973) abstract: "The interpretation advanced and illustrated by cross sections explains the Papuan ultramafic belt as a deeply eroded portion of an uplifted, extinct, west to southwest dipping subduction zone which—after subduction activity ceased in Late Eocene to Oligocene time—rose to the surface and was squeezed out along a major pre-existing shear zone. Owing to the rapid rising of at least 20 kilometres and the concomitant strong erosion of the sprouting orogenic belt, fragments of the oceanic crust and upper mantle from the ancestral subduction zone are now exposed at the surface and form the Papuan ultramafic belt . . ."

Connelly reiterates the views of Thompson & Fisher (1965), Davies (1968, 1971), Davies & Smith (1971) without mentioning any alternate interpretation. I had tried to show that there is no direct evidence for a slab consisting of oceanic crust and mantle rocks dipping oceanward at an angle of 25 to 30 degrees. I still hold this opinion. In a paper dealing especially with emplacement it could be expected that Connelly would discuss and explore the mechanism by which such a slab is detached from the upper mantle, what kind of forces move the piston (here apparently represented by the westward-spreading oceanic lithosphere of the Pacific Plate) which pushes the slab up a gentle slope of a few degrees over and onto the continental crust, and the geometry of an overthrust onto continental crust.

Moreover, Connelly's findings that the belt was originally aligned north-south and that the compression was in a west-east direction are neither new nor relevant to the emplacement process. In the paleogeographic reconstruction of Eastern Australia and Papua New Guinea Du Toit (1937) and Rod (1966, 1968, 1974) showed a north-south alignment of the area now occupied by the Papuan Ultramafic Belt. The locality where this emplacement occurred or its polarity has nothing to do with the actual mechanism.

In his paper Connelly tries to prove, by using the results of gravity, magnetic and seismic refraction surveys, that the Papuan Ultramafic Belt of today is an overthrust of oceanic crust and mantle.

I do not question the quality of the surveys. But so many measurements can be interpreted in different ways. Especially rock masses of various densities can be moved from one place to another. Densities can be varied. So many gaps exist were geologists and geophysicists are tempted to make sweeping interpolations. One such critical gap is between the observed surface contact of the ultramafic rocks with the gabbro near the Owen Stanley fault in the Lake Trist profile and the point about 20 km under the Solomon Sea near the coast where this same contact is thought to be represented by the refractor with the velocity of 7.96 km/s (Moho?).

Connelly's three cross-sections through the belt (1977, Fig. 2; 1979, Fig. 4) are gravity models only. Whereas Davies, and Davies & Smith, show the outline of the Moho in their illustrations, Connelly does not reveal the position of the Moho at all in his sections. From the text it appears that the Moho for the standard continental crust is at a depth of 32 km. A line at such a depth is drawn at the bottom of all of Connelly's sections. This line seems to represent the depth of compensation. For the continental crust to the west this should be the Moho, but for the oceanic slab of crust and mantle in the eastern part of the sections the Moho has to be placed at the top of the ultramafic zone of density 3.33 tm^{-3}. Thus Connelly considers that the Moho is outcropping in certain areas of the Papuan Ultramafic Belt.

It is relevant to refer to an earlier paper of Connelly's. In 1977 he advocated a rigorous application of physical constraints; he illustrated this with models along the same three profiles which he illustrates and discusses further in his 1979 paper. Among the physical constraints on the gravity models he mentions: "(a) Extent of main outcrops and location of major faults (Davies, 1971); (b) Seismic refraction interfaces and velocities along the northern edge of the Belt (Finlayson & others, 1976)."

I favour such a rigorous application of physical constraints. However, if these constraints are applied to the Papuan Ultramafic Belt, they are—from a study of the maps and sections of Davies (1968), and Davies & Smith (1971):

1. The Owen Stanley fault, which has the characteristics of a major strike-slip fault, dips at an angle of 70° east to vertical. At only one location was a dip of 25° measured on a secondary fault.
2. The Owen Stanley fault is a 5 to 10 km-wide master fault, consisting of a group of nearly vertical faults separating large fault slices. Shear zones are characterised by 100 to 500 m-thick lenses of crushed rocks.
3. The topographic expression of the Owen Stanley fault confirms its interpretation as a master strike-slip fault (geosuture).
4. The outcrop pattern of the peridotite, gabbro and basalt do not prove that those rocks belong to a slab dipping at an angle of 20° to 30° towards the ocean.

Davies & Smith had shown the Owen Stanley fault as a steeply east-dipping fault to a depth of 1½ km only. Their postulated low-angle overthrust abuts on the Owen Stanley fault at about 1 km under the sur-

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face. This compromise solution is structurally untenable.

I recognise that the interpretation which I proposed earlier (1973, 1974) is only one of severable possible explanations. I emphasise again that to have the Moho under the Solomon Sea join the Moho under the continental crust of Eastern Papua in a continuous and smooth way, as happens in a continental margin, is much more plausible than to suggest that the Moho is continuously rising out of the Solomon Sea and is outcropping in the Papuan Ultramafic Belt.

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Mode of emplacement of the Papuan Ultramafic Belt: reply

J. B. Connelly

Rod's criticisms of my paper can be summarised as (1) I have not come up with any revolutionary new mechanism for the emplacement of the Belt; (2) the position of the Moho in my gravity sections is not clear; and (3) the overthrusting hypothesis does not explain either the steep dips along much of the Owen Stanley Fault system or the fact that parts of it are strike-slip in character. The last criticism is by far the most significant; the character of the Owen Stanley Fault being one of the reasons for my modification of the original Thompson-Davies theory, and I suspect the main impetus behind Rod's theory of emplacement.

I stated in the introduction to my paper that I have adopted the overthrusting mechanism of emplacement. I make no apology for not coming up with a revolutionary new mechanism as I think the thrusting mechanism is by far the most likely. Possible methods of emplacement which I can conceive are (1) intrusion of a large body of basaltic lava high in the crust and its subsequent differentiation to produce the observed layering; (2) uplift by isostatic or some other vertically acting force; (3) thrusting in a horizontally compressive regime. The intrusive mechanism has been ruled out by Davies (1971) on chemical and other evidence. The isostatic uplift mechanism seems unlikely in view of the very high density of the rocks forming the Belt itself and also the probable high density of the Owen Stanley metamorphics. This leaves the horizontal compression mechanism of emplacement.

Rod's (1974) explanation of the emplacement involves an initially compressive regime during which the Belt was underthrust beneath continental crust and a complex series of thrust planes was formed above it. When the compressive regime ceased the Belt rose under the influence of some unspecified vertically acting force at a major pre-existing strike-slip fault system of unexplained origin (Rod's geosuture). This explanation certainly accounts for the character of the Owen Stanley fault, but the vertical forces which led to the emplacement are left vague and unexplained. The model also leads to a very complex distribution of ultramafic rocks (Rod, 1974, fig. 3) in which they interfinger with the continental metamorphic rocks. This interfingering is not reflected in the relatively simple outcrop distribution of the ultramafic rocks.

I attempted to explain the characteristics of the Owen Stanley Fault by simple east-west compression. In theory horizontal compression can result in either vertical strike-slip faults or shallow thrusts depending on the orientation of minimum stress (Anderson, 1951). In reality these two types of fault often develop together and the phenomenon is documented in text books on structural geology. De Sitter (1956, p. 165-169) gives several examples and states "we find the remarkably close connexion and **transition** between overthrusting and wrench faulting here accompanied by an echelon arrangement of the latter" (my stress). Rod himself (Rod, 1979) gives an excellent example of this phenomenon in his discussion of the strike-slip nature of the Insubric Line in the European Alps and its transition into thrust faulting in the Orobic and Ivrea Zones. In a combination of thrust and shears the thrusts are perpendicular to the direction of compression and the shears make an angle with it of 45° or less (Anderson, 1951). For the Owen Stanley fault system the north-south sections where the ultramafic rocks crop out are the thrusts, and the remaining NW-SE sections are the shears. The presence of typical strike-slip structures along the NW-SE sections of the Owen Stanley fault system can thus be simply explained without recourse to Rod's complicated ideas of a geosuture. Further, Rod's geosuture if it existed must be linear, as Rod is at pains to prove in his discussion of the Insubric Line (Rod, 1979). The Owen Stanley fault system is far from linear.

The only remaining objection to the overthrust theory is the steep dip of some of the thrusts. Davies (1971) shows the thrust faults as very shallow, overall but steepening as they approach the surface. Rod describes this as structurally untenable, whereas in fact steep thrust planes are well documented in text books of structural geology. De Sitter (1956, p. 235-7) describes these steeply dipping thrust planes, and remarks that they are characteristic of the borders of the great folded mountain systems. For large regional thrusts such as the Owen Stanley Fault system it is difficult to prove that they become shallower at depth. However, very similar steep thrusts occur on a somewhat smaller scale in areas of detachment tectonics where large blocks of strata have moved along shallow thrust planes under the influence of gravity. These areas are often prospective for oil and have therefore been the subject of detailed stratigraphic studies which include information from drill holes. These studies show conclusively that the steep thrust faults often observed at the surface are continuous at depth with the shallow thrust planes along which the detached blocks moved (see for example Jenkins, 1974).

The second of Rod's criticisms concerns the location of the Moho in my gravity sections. I was mainly concerned to show that the gravity and magnetic anomalies were consistent with a combination of thrusts and shears; the Moho was deliberately omitted from the sections. I adopted a Moho configuration very much like that shown by Davies (1971), and I discussed the general structure of the Moho in the section on isostatic compensation of the Belt. The standard crust at 32 km does not represent any real physical boundary and is simply a convenient datum for gravity modelling. A single layer crust to 32 km of density 2.85 tm^{-3} underlain by mantle of density 3.33 tm^{-3} is very close to a world average crustal density column empirically determined from combined gravity and seismic refraction studies Woollard (1962).

I take this opportunity of pointing out that headings in my paper on pp. 60 and 61 should have read 'Emplacement westwards . . .', i.e. rather than from the west. The same applies on p. 59, second column, second paragraph, last sentence.

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