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RECORD No. 1966/24

GRAVITY TIES TO AUSTRALIAN ANTARCTICA, 1953 - 1963

by

W.J. LANGRON

Bureau of Mineral Resources, Geology and Geophysics,
Record No. 1966/24; "Gravity ties to Australian Antarctica, 1953-1963",
by W. J. Langron

ERRATA

1. Islet A and Lewis Island are, in fact, the same island, but gravity readings have been taken at two different localities on the island, as described in Appendix A under "Islet A" and "Lewis Is."

2. Islet B is now known as Thompson Island.

3. Islet C is now known as Nelly Island.

4. On page 10, under RECOMMENDATIONS, "Geophysical Service Inc. pendulum apparatus" should read "Geographical Survey Institute pendulum apparatus."

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ILLUSTRATIONS

SUMMARY

The results for all intervals measured by gravity meter between Melbourne and bases in Antarctica are discussed. The examination is limited to data collected by personnel of the Bureau of Mineral Resources (BMR), but a comparison is made between the BMR data and that collected by other organisations over the principal intervals.

Gravity values have been established in the first place for six stations at which several measurements were made. These values have then been considered as 'fixed' for the purposes of adjusting data at other stations.

The treatment, however, has not been rigorous, as it is believed that significant errors are present because of uncertainties in the performance of quartz-type gravity meters under Antarctic conditions. It is proposed to re-examine all the Antarctic data when a series of gravity meter performance tests are completed.

Values for large gravity intervals, as measured by the BMR, generally appear to be higher than values obtained by other organisations. It is felt that this is partly due to uncertainties in the drift characteristics of the gravity meters and partly because of errors in the large-dial calibration curves supplied by the manufacturers.

Values for each of the Antarctic bases relative to the National Gravity Base Station, Melbourne, are given. It is estimated that these intervals have a possible error of ± 7 milligals. The measured intervals between Antarctic stations are probably accurate to about ± 2 milligals.

1. INTRODUCTION

Gravity observations have been made in Antarctica by the Bureau of Mineral Resources (BMR) since 1953. Much of the work was done in association with seismic observations as part of ice thickness investigations; this part of the gravity work is discussed in reports by Goodspeed (1958), Goodspeed and Jesson (1959), Jesson (1959), and Walker (in preparation) and the results will not be considered here except for some information concerning the drift of the various gravity meters whilst on the Antarctic continent. This record is a summary of the gravity ties between Australia and the various bases that have been occupied on sub-Antarctic islands and the Antarctic continent.

All the ties were made with gravity meters and all were made in co-operation with the Antarctic Division of the Department of External Affairs, using the relief ships of the Australian National Antarctic Research Expeditions (ANARE) for transport.

Between February 1953 and March 1963, fourteen ties to Antarctic and sub-Antarctic bases were attempted. Three of these ties were made using a Norgaard gravity meter and the remaining ties were made with Worden gravity meters including, on one occasion, a Master Worden gravity meter. No results were obtained during 1961 as the Worden gravity meter was dropped and severely damaged during unloading operations at Wilkes in January of that year.

A summary of the ties and of the gravity meters used for this work is given in Table 1. A list of descriptions of Antarctic and sub-Antarctic gravity stations discussed in this report is given in Appendix A.

For the work between 1953 and 1956, the author has drawn on unpublished summaries by C. A. van der Waal and L. W. Williams. An adjustment for gravity meter calibration factor has been incorporated in these results to make them compatible with later work. Results of the work between 1956 and 1963 have been calculated from the original field sheets, and the author wishes to acknowledge the help of Messrs. J. Shirley and D. Townsend in sorting out and checking much of the data.

2. DISCUSSION OF TECHNICAL ASPECTS OF THE WORK

In the early days of BMR participation in the Antarctic programme, gravity work was limited to the summer 'change-over' period or to the time during visits of other relief trips to the bases. Since the introduction of the ice thickness programme of work in 1957, a gravity meter has been kept in Antarctica for periods varying from one to two years. The usual procedure has been for the relief geophysicist to take a gravity meter with him whilst the geophysicist being relieved brings his gravity meter back with him to Melbourne. On this schedule any one meter could be expected to be in the Antarctic region for a period of about 14 months.

However, variations to this schedule occured. As mentioned above, gravity readings were not made during 1961. Worden gravity meter No. 169 was used through 1958-59 because a replacement meter (i.e. one having a suitable operational range) could not be made available. In the 1962-63 change-over, opportunity was taken to obtain additional gravity readings using a Master Worden gravity meter; this, it was felt, would be an advantage in that a thermostatically-controlled meter, which would be absent from Melbourne for a much shorter period than usual, should assist in clearing up some of the discrepancies in the principal ties.

The gravity ties discussed in this record have been made by several people using different gravity meters under a variety of operational and climatic conditions. From these points alone it would not be expected that the accuracy of the final results will be of a very high order. There are, however, two factors that are paramount to a satisfactory assessment of the results:

(1) an accurate knowledge of the performance (and in particular, the drift characteristics) of the gravity meter concerned;

(2) in particular, a knowledge of the calibration (and possible changes of calibration) of the gravity meter under such extreme climatic conditions and over long periods between drift control checks.

These two factors are, of course, inter-related and an attempt has been made to make some allowance for their variation in arriving at the figures quoted for the various gravity intervals. It is not only that the earlier work was done using older, less reliable gravity meters - the Norgaard meter certainly was a poorer instrument than the Worden meters - but the earlier results with the Worden meters are also less reliable than results obtained during the past few years because of a greater awareness in later years of other factorsthat contribute towards the performance of the gravity meters concerned. For example, until recent years calibration of gravity meters in Melbourne was done at rather infrequent intervals and on a range that was not entirely satisfactory. Since that time, the establishment of gravity calibration ranges in Australia has been put on a firm footing by Barlow (1965). In addition, a particular study of the performance of gravity meters (their change of calibration with time and their drift with variation of temperature, pressure, type of transport, etc.) is being made. It is known from evidence collected so far that the drift of gravity meters is downwards with decreasing temperature, but at a non-uniform rate, and that this effect becomes very marked at the low temperatures experienced in the Antarctic. It is also known, for example, that there is a certain 'recovery time' (which could be of the order of several weeks) in relation to the calibration of the meter when it is brought back to warmer temperatures. The quantitative analysis of these tests has not yet been completed but will, no doubt, have an important bearing on the final results of Antarctic gravity work.

Another question is that of the overall drift (including some estimate of the effects mentioned above) for the particular gravity meter during its absence from Melbourne. In most cases all that can be done is to construct a 'composite' drift curve using a period before leaving Melbourne and one after returning, during which several readings at a particular base are taken, and to use any repeat readings obtained during the course of the Antarctic work to provide an indication of the gravity meter driftduring the period between the Melbourne observations. In the latter regard, some of the ice thickness work has been very useful in helping to estimate the long-term (14 months or so) drift of the gravity meter. Plates 4 and 5 are examples of such composite drift curves.

It is known that quartz-type gravity meters exhibit a long-term upward drift and it may be expected that in the absence of any violent physical and thermal shocks this drift will be more or less linear. However, some of the drift curves plotted as outlined above are far from straight lines - in fact, the attitudes of some of the intermediate drift rates are such that serious doubts are cast on the values given for the large gravity intervals involved. If the history of the particular gravity meter is well known and if details of changes in operating conditions, unusual events that might affect the performance of the gravity meter, etc. are noted by the observer during the course of the work, it might be possible to make some reasonable allowance for such effects. However, in most cases, and especially for the earlier work, there are not sufficient data to hand for this purpose.

The transport of the gravity meter to and from Antarctica was usually in a locked instrument cupboard in the passenger section of the ship. Unfortunately, it was not possible to keep the Master Worden gravity

TABLE 1

Gravity ties between Austrlaia and Antarctica

Tie Number	Duration of survey	Gravity meter	BMR Observers	Principal Antarctic stations occupied
1	Feb. - Mar. 1953	TNK 413	L. Ingall and J. Brooks	Kerguelen Is., Heard Is.
2	Mar. - May 1953	(TNK 413	P. McGregor and P. Tenni	Macquarie Is.
3		W 140)		
4	Dec. 1953	W 140	P. Tenni and C. Robertson	Macquarie Is.
5	Jan. - Apr. 1954	TNK 413	K. Lodwick	Heard Is., Mawson
6	Dec. 1954 - Jan. 1955	W 169	C. Robertson and P. Mann	Macquarie Is.
7	Jan. 1955 - Mar. 1955	W 169	H. Oldham	Mawson, Heard Is., Kerguelen Is., Magnetic Is.
8	Nov. - Dec. 1955	W 169	I. Everingham	Macquarie Is.
9	Jan. - Apr. 1956	W 169	P. McGregor	Mawson, Kerguelen Is., Heard Is.
10	Nov. 1956 - Mar. 1959	W 169	J. Goodspeed and E. Jesson	Mawson, Davis, Mirny.
11	Jan. 1958 - Mar. 1958	W 260	E. Jesson	Mawson, Heard Is., Kerguelen Is.,Davis, Larsemann Hills No. 1, Larsemann Hills No. 2., Lewis Is., Dumont D'Urville, Mirny.
12	Dec. 1960 - Jan. 1961	W 260	F. Jewell	Damaged during unloading operations at Wilkes
13	Dec. 1961 - Jan. 1963	W 140	D. J. Walker	Wilkes, Lewis Is.
14	Nov. 1962 - Mar. 1963	MW 548	D. J. Walker	Macquarie Is., Lewis Is., Chick Is.

Note: W = Worden; MW = Master Worden; TNK 413 is a Norgaard gravity meter

meter heated whilst on board ship, so the advantage of using a thermostatically-controlled gravity meter over a large gravity (and time) interval was lost. Transport of the gravity meter during Antarctic operations was usually by means of a 'Snocat' or similar vehicle and sometimes by means of a light aeroplane, helicopter, or landing craft. Where possible in these operations, the gravity meter was carried in the heated cab of the conveyance and only exposed to the outside elements for the minimum period of time required to obtain a gravity reading. In many instances, however, such heating was either absent or was provided intermittently, so that the gravity meter was subject to a considerable risk of thermal shock.

3. EVALUATION AND DISCUSSION OF RESULTS

The results of the principal ties made during this period are summarised in Table 2. Readings obtained with the Norgaard gravity meter, TNK413, have been omitted in the adjustment of the gravity values as the meter behaviour was considered to be too erratic to enable reliable drift curves to be drawn. However, it is noticeable that some of the intervals as measured by the Norgaard gravity meter agree very closely with values obtained using Worden gravity meters.

The drift curves for the ties using the Worden meters showed some marked irregularities. It is thought that these irregularities are due mainly to temperature effects, though the effect of temperature variations as encountered in Antarctic work is not yet fully understood. Usually it has been assumed that the meter drift was linear for the duration of the tie, but in several instances this drift rate was not the same as that obtained at the National Gravity Base Station (N.G.B.S.), Melbourne, over periods of several months before and after the Antarctic tie. It was also notable that instruments showed a high drift at the commencement of observations at a station at which the ambient temperature differed markedly from the temperature at the previous station.

Some drift curves have been included in this record to illustrate the procedure adopted in arriving at the final drift curve over the interval concerned. Plate 3 shows the drift curve for tie No. 7. This is one of the most regular drift curves obtained, perhaps because the period between the repeat sets of readings at Melbourne is relatively short.

Plate 4 shows the drift curve for tie No, 10. Between the 20th February 1957 and the 13th February 1959, the evaluation of instrument drift is based on repeat readings at Mawson. The form of the drift curve over this period has to be fitted to those portions of the drift curves obtained at N.G.B.S., Melbourne. In this example, the extrapolated curve has been smoothed, and it can be seen that the measured difference between the Melbourne and Mawson drift curves constructed on this basis could vary by up to five milligals.

Plate 5 shows the drift data for tie No. 11. Here the instrument drift as indicated by repeat readings at intermediate stations was contrary to that obtained for the repeat readings at Melbourne. In this case the drift was assumed to be linear and lines of best fit were drawn through points obtained by reoccupation of field stations. The composite curve was drawn (shown dashed in the illustration) to obtain the gravity differences between Melbourne and the field stations. It should be noted that the solid line joining the two sets of readings at Melbourne is only slightly curved and that the composite curve is balanced about this line. Another calculation was made by averaging the linear drift for Melbourne and the drift obtained by reoccupations of the intermediate field stations. The gravity intervals between N.G.B.S., Melbourne, and Mawson obtained by these two methods differ by a maximum of 2.1 milligals and this is far less than the uncertainties due to temperature effects. The gravity intervals as obtained by the first method are given here because it is felt that this method of allowing for instrument drift is probably the better one.

TABLE 2

Details of gravity intervals between N.G.B.S., Melbourne, and principal Antarctic stations

Station	Tie Number	Gravity meter	Observed gravity intervals (mgal)	
Davis	10	W 169	+ 2619	
	11	W 260	+ 2621.2	
Heard Is.	1	TNK 413	+ 1508.4	Three different drift curves
			+ 1510.4	
			+ 1501.4	
	5	TNK 413	+ 1496.4	Two different drift curves
			+ 1498.4	
	7	W 169	+ 1506.7	
	7	W 169	+ 1506.3	
	9	W 169	+ 1505.7	
	11	W 260	+ 1507.0	
Kerguelen Is.	1	TNK 413	+ 1106.4	Three different drift curves
			+ 1105.4	
			+ 1097.4	
	7	W 169	+ 1104.3	
	9	W 169	+ 1104.2	
	11	W 260	+ 1104.0	
Macquarie Is.	2	TNK 413	+ 1728.4	Two different drift curves
			+ 1727.4	
	3	W 140	+ 1708.2	
	4	W 140	+ 1713.2	
	6	W 169	+ 1723	Erratic drift
	8	W 169	+ 1714.3	
	14	MW 548	+ 1706.7	
Mawson	5	TNK 413	(+ 1807.4)	This interval is uncertain as the gravity meter was off-scale
	7	W 169	+ 2514.5	
	9	W 169	+ 2512.2	
	10	W 169	+ 2510	
	11	W 260	+ 2511.6	
Mirny	10	W 169	+ 2432	
	11	W 260	+ 2434.7	

Note: W = Worden; MW = Master Worden; TNK 413 is a Norgaard gravity meter.

An attempt has been made to apply a temperature correction to the readings obtained using Worden 169, as some tests had been carried out on this meter. The tests showed that, if the meter were kept in air at a steady temperature, a steady drift rate is shown, and if the air temperature is suddenly changed, the meter then shows a very high drift rate for about 36 hours before settling down to a steady rate, which is different from the rate at the previous temperature. The temperature coefficient as determined by these tests is approximately 0.2 mgal/°C. No such tests were carried out on Worden 140 or Worden 260, although their drift rates also become erratic following a temperature shock; from the results obtained with these meters it seems that there is some significant difference in behaviour between them and Worden 169.

All data have been adjusted to take into account the revision of values of gravity meter calibration ranges (Barlow, 1965). The results obtained for tie No. 13 and tie No. 14 are suspect because of too few base readings taken at N.G.B.S., Melbourne. However, the data have been considered in the final adjustment because the history of Master Worden 548 is reasonably well documented.

During the two seasons in which Worden 169 was retained at Mawson, ties were made to a number of local stations and other bases. Although considerable variation in the drift of this instrument occurred between November 1956 and March 1959 (see plate 4), it showed no significant tendency to erratic drift during the period of the local ties.

One other point is to be noted. All the gravity readings have been evaluated on the basis of the large-dial curves supplied by Texas Instruments Inc. However, there appears to be some ambiguity in interpreting these curves and this doubt has not been cleared up in correspondence with the makers. The most logical method is to integrate the interval under the particular portion of the curve concerned - this technique has been used to obtain the results in this record. The alternative is to use the point values on the calibration curve corresponding to the large-dial readings at the stations; this procedure has been used by several workers in the past.

A better approach to the evaluation of the data has been recognised by running the gravity meter between stations having a large but known range of gravity. In addition, the large-dial/small-dial ratios over this range of gravity can be compared. Unfortunately this procedure has been carried out only intermittently in the past and only with Worden 169 and Worden 140, but the results for Worden 169 suggest fairly conclusively that at least over the range that was measured (between Cairns and Hobart), the large-dial calibration curve should lie below the curve as supplied by the makers at that time, whereas for Worden 140 the makers' curve is nearly correct between Brisbane and Hobart. Uncertainties in calibration could be part of the reason why the values given in this record are in general slightly higher than those obtained by other workers (see Table 5). As stated previously, the small-dial calibration for each of the BMR gravity meters is known very accurately (Barlow, 1965).

Large-dial/small-dial ratio tests are included in the series of gravity meter performance tests being carried out, and it is anticipated that these results will help to strengthen the ties discussed in this report.

4. ADJUSTMENT OF GRAVITY INTERVALS

The closure diagram for all gravity intervals measured by the BMR during the transfer of personnel between Australia and Antarctic stations is shown in Plate 2.

Some adjustment of the original readings (by the method of least squares) has been made but, because of the uncertainties that are considered to be present in some of the larger gravity intervals, no attempt has been

TABLE 3

Antarctic gravity stations-gravity values based on

N.G.B.S., Melbourne

Station	Observed gravity relative to N.G.B.S. Melbourne (mgal)	Observed gravity (mgal)
N.G.B.S., Melbourne		979,979.0
Bretangen	+ 2513	982,492
Chick Is.	+ 2467	982,446
Davis A	+ 2619	982,598
Davis B	+ 2620	982,599
Douglas Is.	+ 2541	982,520
Dumont D'Urville	+ 2428	982,407
Foldoya	+ 2511	982,490
Heard Is.	+ 1506	981,485
Islet A	+ 2374	982,353
Islet B	+ 2416	982,395
Islet C	+ 2423	982,402
Kerguelen Is.	+ 1104	981,083
King Edward VIII Gulf	+ 2508	982,487
Larsemann Hills	+ 2624	982,603
Larsemann Hills No. 1	+ 2625	982,604
Larsemann Hills No. 2	+ 2630	982,609
Lewis Is.	+ 2373	982,352
Lorton	+ 2630	982,609
Macquarie Is.	+ 1711	981,690
Magnet Bay	+ 2459	982,438
Magnetic Is.	+ 2628	982,607
Mawson	+ 2512	982,491
Mawson C	+ 2513	982,492
Mirny	+ 2434	982,413
Mirny A	+ 2432	982,411
Mount Caroline Mikkelsen	+ 2660	982,639
Oldham Is.	+ 2518	982,497
Wilkes	+ 2422	982,401

made to apply a rigorous treatment at this stage. In the adjustment, the values at six stations, i.e. Melbourne, Kerguelen, Heard Is., Mawson, Davis B, and Macquarie Is., have been based on the average of the several ties between them and Melbourne. For the first five of these stations, the closure (before adjustment) around this loop, which involves such large gravity intervals, was relatively small (1.5 milligals). The value for Macquarie Is. is accepted simply on the basis of the numerous ties between it and Melbourne; the loop closure here is not so strong because the remaining intervals have only been singly read. In all cases, unsatisfactory data have been rejected outright.

It is not claimed that the values assumed for these stations will be the final values. They will almost certainly need adjustment after the series of gravity meter performance tests have been completed. They are, however, considered to be the best (adjusted) values based on present data.

The intervals of the network for the remaining Antarctic stations have been adjusted (though not rigorously) using the values at these six stations as 'fixed' values. No attempt has been made to adjust the closure of the network to near zero because it is felt that the present state of the data does not justify such a procedure. It is obvious from Plate 2 that such a procedure could be carried out to reduce some of the larger misclosures. For example, the Melbourne - Davis B - Mirny - Lewis Is - Melbourne loop, on the basis of the unadjusted readings, had a misclosure of +4.8 milligals; over half this misclosure has been taken out by adjusting the Mirny - Lewis and Lewis - Melbourne intervals, but there is an obvious limit to this procedure because all adjacent loops now have positive misclosures and because of the decision to keep certain intervals fixed (those between the 'fixed' stations).

As mentioned earlier, the error in the measured intervals between N.G.B.S., Melbourne, and the Antarctic stations may be considerable. Considering only the uncertainties inherent in estimating the instrument drift (in which the effect of temperature shocks on the performance of the instrument is of prime importance) it is felt that the values given for some of these intervals could be in error by as much as 7 or 8 milligals. The accuracy of the measured intervals between Antarctic stations is better than this - possibly ± 2 milligals.

Table 3 is a summary showing the gravity value of each station (based on a value of 979,979.0 milligals for N.G.B.S., Melbourne) and the gravity difference between each station and N.G.B.S., Melbourne, using the above method of adjustment.

5. OTHER GRAVITY OBSERVATIONS IN ANTARCTICA

Much gravity information has been obtained by overseas organisations and the results that are pertinent to this record, are listed in Tables 4 and 5

In 1953, P. Stahl (1954) of Expeditions Polaires Francaises occupied BMR stations at Macquarie Island and Kerguelen Island with a Western gravity meter (No. 47).

Observers from the Geophysical and Polar Research Center of the University of Wisconsin and the Woods Hole Oceanographic Institution have made gravity observations using La Coste and Romberg gravity meters and pendulum apparatus (Woollard & Rose, 1963). These results are summarised in Table 4.

Other measurements were made during the course of the International Geophysical Year (Theil et al, 1959). In particular, Sparkman (Theil et al, 1959) using a La Coste & Romberg gravity meter (No. 1a) made measurements at Wilkes and Mirny. This work was tied to a pendulum station at McMurdo, which was in turn tied by geodetic gravity meter to a world first-order station

TABLE 4

Principal results obtained by the University of Wisconsin and the Woods Hole Oceanographic Institution

Station	Observed gravity relative to N.G.B.S., Melbourne (mgal)	Instrument used
Davis	+ 2610.5	gravity meter
Heard Is.	+ 1498.1	gravity meter
Kerguelen Is.	+ 1093.7	gravity meter
Mawson	+ 2502.1	gravity meter
Mawson	+ 2502.7	Gulf pendulums
Mirny *	+ 2425.5	gravity meter
Mirny *	+ 2425.6	Gulf pendulums

(* this is not an exact reoccupation of the BMR station at Mirny but is in the same vicinity).

TABLE 5

Comparison of BMR and other gravity data for Antarctic stations

	Observed gravity relative to N.G.B.S., Melbourne (mgal)			
Station	BMR	Stahl	W & R*	Sparkman**
Davis A	+ 2619		+ 2611	
Heard Is.	+ 1506		+ 1498	
Kerguelen Is.	+ 1104	+ 1096	+ 1094	
Macquarie Is.	+ 1711	+ 1716		
Mawson	+ 2512		+ 2502	
Wilkes	+ 2422			+ 2420.6
Mirny	+ 2434		+ 2426	+ 2428.4

* Woollard & Rose, 1963
** Sparkman, 1959

at Christchurch, New Zealand. In 1959, the Russians obtained a value of 982,413 milligals for Mirny using pendulum apparatus (Boulanger, personal communication); however, this value was not considered reliable because of instrumental short-comings.

The gravity intervals obtained by the BMR and those from other organisations discussed in this chapter are compared in Table 5. It will be noticed that in general the BMR values are slightly higher and this could be due mainly to the makers' large-dial calibration curve being incorrect at the time of the work.

6. CONCLUSIONS

The values listed in Table 4 (page 9) are adopted for the BMR gravity intervals although some may be subject to modification after the study of gravity meter performance tests has been completed.

The intervals in Table 4 have an estimated possible error of ± 7 milligals. The measured intervals between Antarctic stations are probably accuract to about ± 2 milligals.

Uncertainties in the gravity intervals may be due largely to the effects of temperature on the Worden gravity meters, particularly those without thermostatic control, which were used for most of the work. Until a lot more is known about the performance of Worden gravity meters under the conditions prevailing during Antarctic work, it would seem that there will be difficulties in evaluating results obtained with them. However, the field data indicate that Worden gravity meters, if used under more or less constant temperature conditions, are suitable for surveys made in conjunction with seismic ice thickness measurements.

Uncertainties in calibration factors could be resolved by establishing a reliable station, preferably with pendulums, at one of the Antarctic bases. There are reservations about the reliability of measurements made so far, and disagreements between them.

7. RECOMMENDATIONS

It is recommended that stations at the following bases be designated as primary stations: Macquarie Island, Mawson, and Wilkes. They should be marked with permanent markers and each should be tied to N.G.B.S., Melbourne, using the Geophysical Service Inc. pendulum apparatus and La Coste & Romberg gravity meters. This should be done as soon as practicable during one of the summer changeovers of Antarctic personnel.

It would be instructive if a Worden gravity meter accompanied this work so that information on the performance of the Worden meter under well documented gravity control could be obtained.

8. REFERENCES

BARLOW, B. C. 1965 Establishment of gravity meter calibration ranges in Australia, 1960-1961 Bur. Min. Resour. Aust. Rec. 1965/19.

GOODSPEED, M. J. 1958 Preliminary report on measurements of ice thicknesses on the Antarctic ice cap by seismic and gravimetric methods. Bur. Min. Resour. Aust. Rec. 1958/40.

GOODSPEED, M. J. and JESSON, E. E. 1959 Australian ice thickness measurements in Antarctica by seismic and gravity methods, 1957-1959. Bur. Min. Resour. Aust. Rec. 1959/128.

JESSON, E. E. 1959 Preliminary report on ice thickness measurements on the Antarctic ice cap by seismic and gravimetric methods, 1958-1959. Bur. Min. Resour. Aust. Rec. 1959/74.

STAHL, P. 1954 Expeditions Terre Adelie, 1951-53. Extrait des Rapports Preliminaires 24, Gravimetrie, Expeditions Polaires Francaises, Missions Paul-Emile Victor.

THEIL, E., BENTLEY, C. R., OSTENSO, N. A., and BEHRENDT, J. C. 1959 Oversnow traverse program, Byrd and Ellsworth stations, Antarctica 1957-1958: seismology, gravity, and magnetism. IGY Glac. Rep. Series No. 2 - IGY World Data Centre A.

WALKER, D. J. [illegible] Wilkes geophysical surveys, Antarctica, 1962. Bur. Min. Resour. Aust. Rec. (in preparation).

WOOLLARD, G. P. and ROSE, J. C. 1963 INTERNATIONAL GRAVITY MEASUREMENTS. University of Wisconsin, Geophysical and Polar Research Center.

APPENDIX A

Station descriptions

Bretangen	: Lat. 67° 28'S. Long. 61° 10'E. Elevation : 2 feet above M.S.L.
Chick Is.	: Lat. 66° 47' 18"S. Long. 120° 59' 40" E. Elevation : 32 feet above M.S.L. The gravity station is on rock, 3'6" below the floor of the hut and at the north-west corner of the hut. The station is approximately 20 feet from Astrofix NMA/550.
Davis A	: Outside the door of the stores hut.
Davis B	: Lat. 68° 34' 36.4" Long. 77° 57' 36" Elevation : 25 feet above M.S.L. The gravity station is on rock 115 feet south-south-east from the south-west corner of the engine hut. It is considered to be the 'original' station.
Douglas Is.	: Lat. 67° 23'S Long. 63° 23'E. Elevation : 28 feet above M.S.L. The gravity station is on the northern islet and is marked by a prominent red cross.
Dumont D'Urville	: Lat. 66° 40.0'S. Long. 140° 00.7'E. Elevation : 35 feet above M.S.L.
Foldoya	: Lat. 67° 20'S. Long. 59° 23'E. Elevation : 15 feet above M.S.L. The gravity station in in a right-angle bend of rocks behind the old camp. It is marked by a red cross with an arrow (visible from the air) pointing to it.
Heard Is.	: Lat. 53° 01' 11"S. Long. 73° 23' 07"E. Elevation : 10 feet above M.S.L. The gravity station is in a special hut with a concrete floor.
Islet A Wilkes Land	: Lat. 66° 06.3'S. Long. 134° 22.4'E. Elevation : 80 feet above M.S.L. The gravity station is approximately 60 feet north-east of the Astrofix on the islet.
Islet B Wilkes Land	: Lat. 66° 00.9'S. Long. 111° 07.2'E. Elevation : 166 feet above M.S.L. The gravity station is approximately 135 feet south-east of the Astrofix on the largest rise of the islet.
Islet C Wilkes Land	: Lat. 66° 13.2'S. Long. 110° 11.2'E. Elevation : 171 feet above M.S.L. The gravity station is near the eastern end of a practically level ledge below the Astrofix, and approximately 875 feet north-east of the highest peak on the islet.
Kerguelen Is.	: Lat. 49° 21' 08"S. Long. 70° 13' 27"E. Elevation : 10 feet above M.S.L. The gravity station is in the ionospheric hut at the camp at Port-aux-Francais.

King Edward VIII Gulf : Lat. 66° 54'S. Long. 57° 42'E.
Elevation : 2 feet above M.S.L.
The gravity station is at the site of an old depot. It is marked by a red cross on a rock with a prominent arrow indicating its position.

Larsemann Hills : Lat. 69° 23' 27"S. Long. 76° 13' 19" E.
Elevation : 5 feet above M.S.L.
The gravity station is at a cairn marking the Fisher Astrofix.

Larsemann Hills No. 1 : Lat. 69° 22'S. Long. 76° 08' E.
Elevation (estimated) : 20 feet above M.S.L.

Larsemann Hills No. 2 : Lat. 69° 23' S. Long. 76° 03' E.
Elevation (estimated) : 10 feet above M.S.L.

Lewis Is. : Lat. 66° 06' S. Long. 134° 22' E.
Elevation : 60 feet above M.S.L.
The station is marked by an eye-bolt set in rock approximately 225 feet west-north-west of a cairn on the highest point on the islet. (A new site has since been occupied at Astrofix A56-1.
Lat. 66° 06' 06" S. Long. 134° 22' 17" E.
Elevation : 86 feet above M.S.L.)

Lorton : Lat. 69° 21' 37" S. Long. 73° 39' 19" E.
Elevation : 1 foot above M.S.L.
The gravity station is on the low-lying part of the southern shore.

Macquarie Is. : Lat. 54° 29' 59" S. Long. 158° 57' 10" E.
Elevation : 20.8 feet above M.S.L.
The gravity station is in the meteorological stores hut.

Magnet Bay : Lat. 66° 23.0' S. Long. 56° 25.4' E.
Elevation : 15 feet above M.S.L.
The gravity station is on ice beneath a red arrow painted on rock with the inscription "20 ft. beneath".

Magnetic Is. : Lat. 68° 33' S. Long. 77° 55' E.
Elevation : 10 feet (approximately) above M.S.L.
The gravity station is at the absolute magnetic station, which is on bare rock at the western end of the island, and is marked by a small cairn of rocks.

Mawson A : Lat. 67° 36' 11" S. Long. 62° 52' 31" E.
Elevation : 15 feet above M.S.L.
The gravity station is in No. 3 store on a concrete floor originally poured for mounting the emergency power unit.

Mawson B : The gravity station is on a comcrete platform in the seismic hut (heated to about 12°C).
This site is probably the Gulf-Wisconsin pendulum station.

Mawson C : A site near the R.A.A.F. hangar.

Mirny : Lat. 66° 33.2' S. Long. 93° 00.6' E.
Elevation : 62 feet above M.S.L.
The gravity station is at the Absolute Gravity Station.

Mirny A : The gravity station is on rock outside the magnetic hut.

Mt. Caroline Mekkelsen : Lat. 69° 44.1' S. Long. 74° 18' E.
Elevation : 4 feet above M.S.L.
The gravity station is on the east side of a small rock about one mile due north of Mt. Caroline Mikkelsen, and is marked by a silver paint cross.

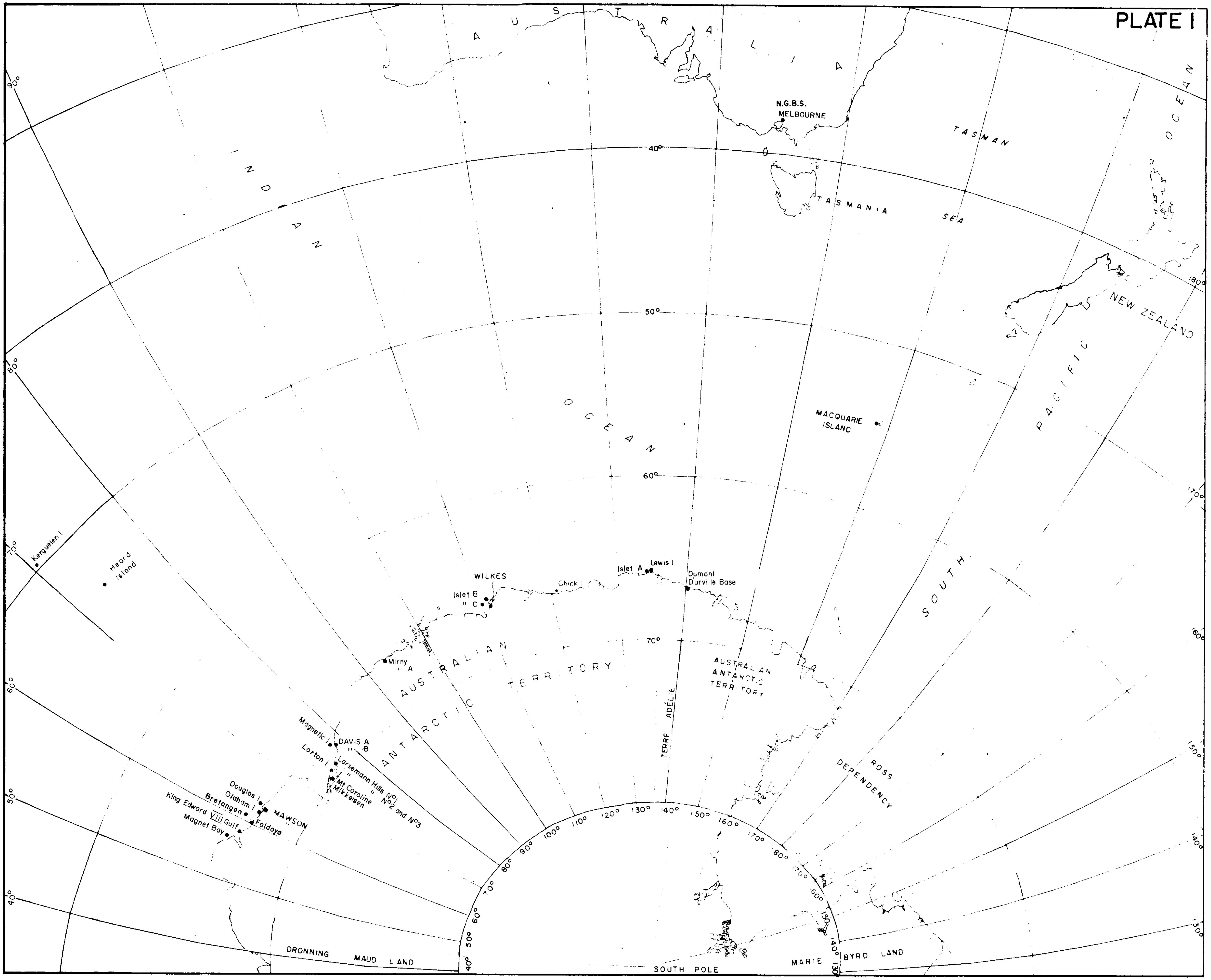
Oldham Is. : Lat. 67° 32' S. Long. 61° 49' S.
Elevation : 13 feet above M.S.L.
The gravity station is on the west side of the island south of the large inlet. It is marked by a red cross painted on the rocks with an arrow on a prominent rock to the east of it and pointing towards it.

Wilkes : Lat. 66° 15' 30" S. Long. 110° 31' 12" E.
Elevation : 31 feet above M.S.L.
The gravity station is on flat rock alongside a brasshexagonal rod fixed firmly in rock approximately 3 feet from the west wall of the old seismograph hut.

Miscellaneous statistical data

Summary of gravity meter calibration and performance

Tie Number	Gravity Meter	Date(s)	Calibration range used	Calibration factor adopted (mgal/div.) SD	LD	Large Dial (LD) / Small Dial (SD)	Remarks
1	Norgaard TNK 413						Makers' tables used for reduction of field data
2	Norgaard TNK 413						Makers' tables used for reduction of field data
3	Worden 140	?	? Brenock Pk. - Kallista	0.08914	6.248(3)		(LD value determined over range Melbourne-Hobart (close agreement with maker's value)
					6.227(2)		(LD value for Macquarie Is. from maker's curve
4	Worden 140	?	"	0.08914	"		
5	Norgaard TNK 413						Maker's tables used for reduction of field data
6	Worden 169	9.11.54	Benock Pk. -Kallista	0.10367	4.980	47.6 (N.G.B.S.,Melb.)	
		12.11.54				47.7 (N.G.B.S.,Melb.)	Drift rate (measured) = 0.332 mgal/day. LD/SD ratios given are the averages of several measurements
		26.11.54				47.6 (N.G.B.S.,Melb.)	
		9.12-16.12.54				47.5	Drift rate (measured) = 0.37 mgal/day.- Melbourne
		27.12-29.12.54			4.930	47.5 (Macquarie Is.)	LD calibration for Macquarie Is. based on maker's curve
7	Worden 169	13.1-25.1.55					
		[illegible].3- 7.3.55		0.10383	4.936	47.71, 47.67, 47.43	Heard Is.
		30.1-31.1.55			4.912		Magnetic Is.
		12.2-28.2.55			4.913	47.53, 47.46	Mawson
		10.3.55			4.946		Kerguelen
		23.3- 9.5.55		0.10383	4.980	(N.G.B.S., Melbourne)	Drift rate (measured) = 0.364 mgal/day - Melbourne
8	Worden 169	22.11-24.11.55	Footscray -Kallista	0.10395	4.980		LD calibration based on maker's curve
		11.12-27.12.55			4.929	47.4, 47.4	LD calibration for Macquarie Is. based on maker's curve
		27.12.55				48.0 (N.G.B.S., Melb.)	
9	Worden 169	24. 2-25.2.56		0.10395	4.912	47.45 (Mawson)	LD/SD ratio given is the average of several measurements
		9.3.56			4.933	(Heard Is.)	LD calibration for Mawson, Heard Is., Kerguelen, and Melbourne based on maker's curve
		11.3.56			4.944	(Kerguelen)	
		26.3-29.3.56			4.978	47.9 (N.G.B.S.,Melb.)	
10	Worden 169	17.11.56	Brenock Pk. -Kallista	0.10614			W 169 returned to maker for adjustment
		25.2-20.3.57					Drift rate approx. 0.312 mgal/day
		7.5.57			4.927	46.44 (Mawson)	(LD calibration based on maker's curve
		8.5.57			4.946	46.62 (Davis)	(
		6.3.59	Branock Pk. -Kallista	0.10609			
		16.4.59	"	0.10604			
11	Worden 260	5.10.56	Brenock Pk. -Kallista	0.10825			
		10.4.58	Brenock Pk. -Kallista	0.10797			
		21.5.59				69.56 (N.G.B.S.,Melb.)	
12	Worden 260	15.12.60	Melbourne	0.10802			
		21.12.60		0.10795			Gravity meter damaged in Antarctica not used for work there.
13	Worden 140	5.12.61	Melbourne	0.1113(0)			
		12.12.61	"	0.11115			
		14.12.61	"	0.11124			
		17. 2.64	"	0.1111(4)			
14	Master Worden 548	24.10.62	Melbourne	0.10965			
		6.11.62	"	0.1099(0)			
		20.12.62	"	0.1096(3)			
		15.1-21.1.62					Performance of MW548 checked against W140 at Wilkes but MW548 subject to severe thermal shock.
		27.3.63	"	0.1097(1)			



BM

LEGEND

• Gravity station

SCALE IN MILES

100 0 100 200 300 400 500 600 700 800

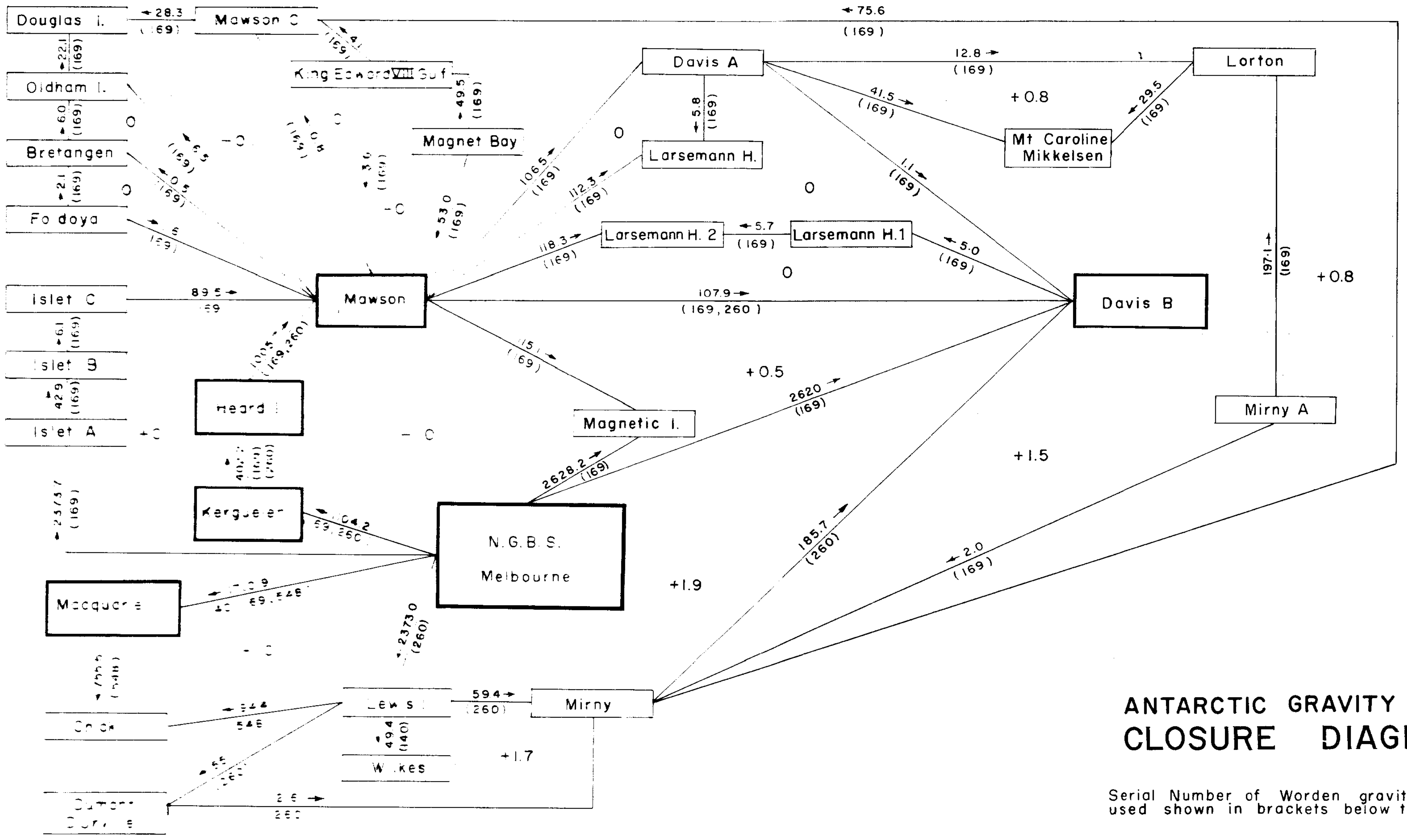
ANTARTIC GRAVITY TIES

TO ACCOMPANY RECORD No. 1966/24

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics

G65-137-1

PLATE 2



ANTARCTIC GRAVITY TIES
CLOSURE DIAGRAM

Serial Number of Worden gravity meter used shown in brackets below tie.

GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS G 265-95

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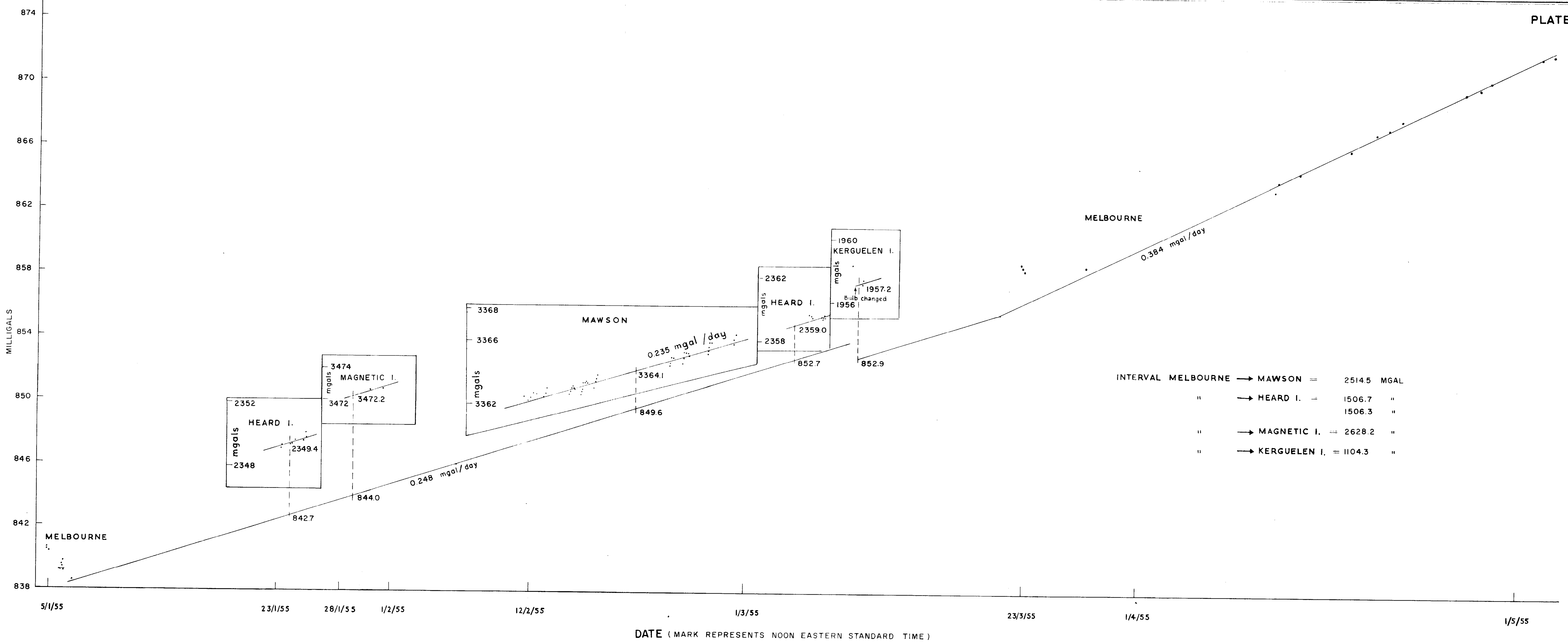


DRIFT CURVE

WORDEN GRAVITY METER No. 169

JANUARY–MAY, 1955

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics. G 265-4

TO ACCOMPANY RECORD NO 1966/24

INTERVAL	MELBOURNE	→ MAWSON (A)	=	2510 MGAL
	MAWSON	→ DAVIS A	=	2620
		→ DAVIS B	=	106·5
		→ MIRNY A	=	79·8
		→ FOLDOYA	=	−1·6
		→ BRETANGEN	=	0·5
		→ KING EDWARD VIII GULF	=	−3·3
		→ OLDHAM I	=	+6·5
		→ LARSEMANN HILLS	=	+111·6
		→ DOUGLAS I	=	28·7
		→ MAGNET BAY	=	−53·0

ANTARCTIC GRAVITY TIES

DRIFT CURVE

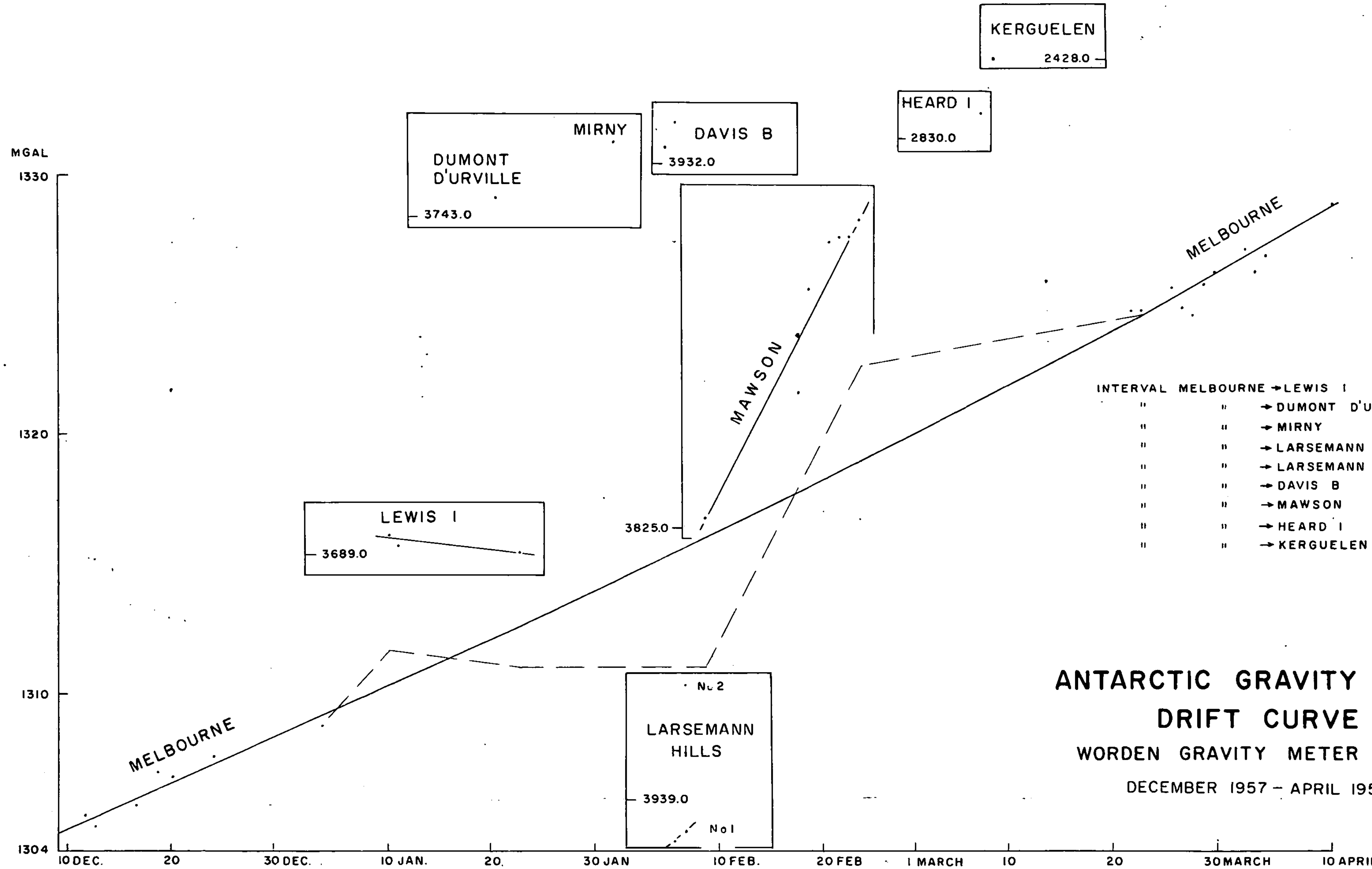
WORDEN GRAVITY METER No.169

MARCH 1956 – JUNE 1959

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics G 265-94

B.M.

PLATE 5



INTERVAL	MELBOURNE	→ LEWIS I	2378.0 MGAL
"	"	→ DUMONT D'URVILLE	2432.6 "
"	"	→ MIRNY	2434.7 "
"	"	→ LARSEMANN HILLS No1	2626.2 "
"	"	→ LARSEMANN HILLS No2	2631.9 "
"	"	→ DAVIS B	2621.2 "
"	"	→ MAWSON	2513.6 "
"	"	→ HEARD I	1507.0 "
"	"	→ KERGUELEN	1104.0 "

ANTARCTIC GRAVITY TIES
DRIFT CURVE
WORDEN GRAVITY METER No 260
DECEMBER 1957 – APRIL 1958

GEOPHYSICAL BRANCH, BUREAU OF MINERAL RESOUCES, GEOLOGY AND GEOPHYSICS G 265-91

TO ACCOMPANY RECORD NO 1966/24