COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

REPORT No. 122

# Gravity Meter Calibration Ranges in Australia



BY

B. C. BARLOW

*Issued under the Authority of the Hon. David Fairbairn*
*Minister for National Development*
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MINISTER: THE HON. DAVID FAIRBAIRN, D.F.C., M.P.

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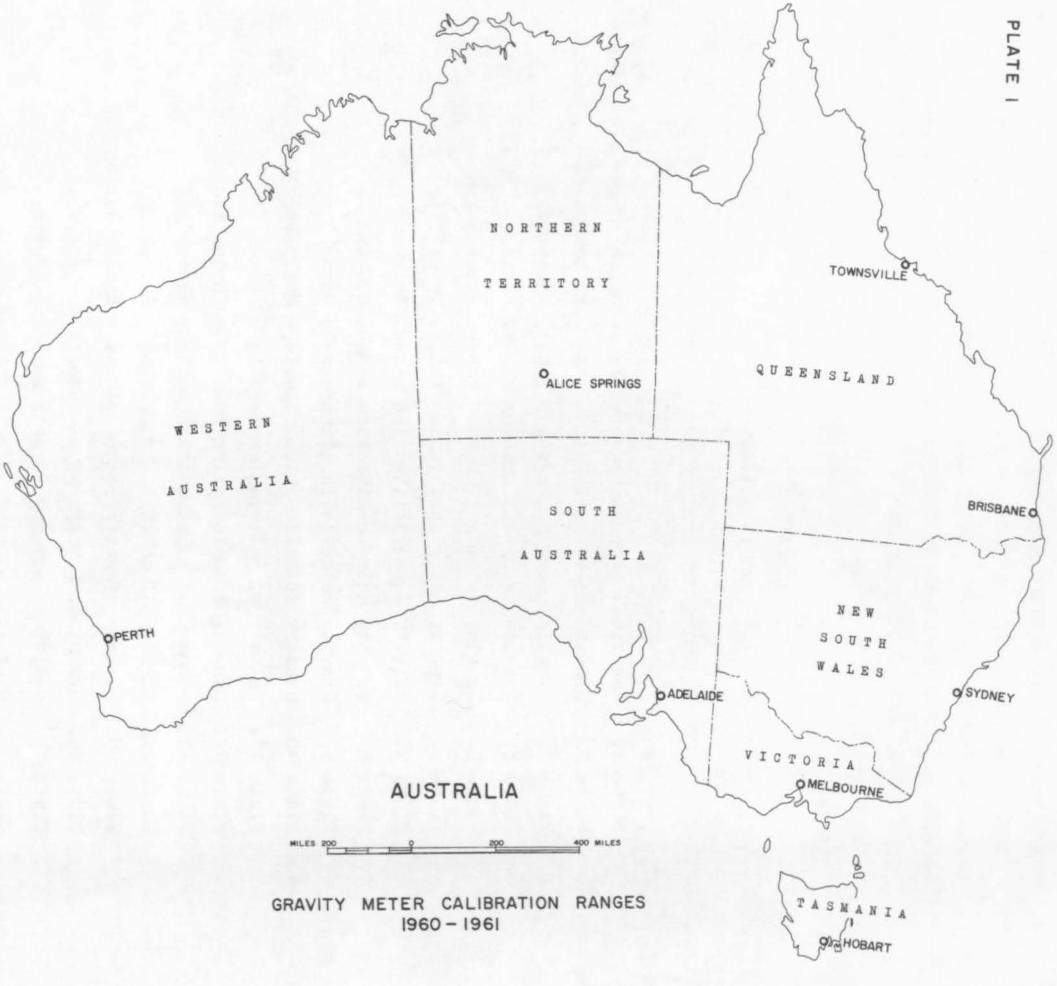


GRAVITY METER CALIBRATION RANGES
1960 - 1961

## SUMMARY

During 1960 and 1961, eight gravity meter calibration ranges were established throughout Australia by the Bureau of Mineral Resources. The gravity intervals of these calibration ranges were determined using groups of gravity meters calibrated between Ferntree Gully and Kallista in Victoria against a gravity interval determined from several pendulum stations observed during 1950 and 1951.

The results of individual determinations have been assessed in terms of the known variation in the calibration factors of the gravity meters and the estimated accuracy of the measurement of the interval. Many inconsistencies are present, but the weighted means of groups of determinations are believed to provide reasonably accurate estimates of the gravity intervals across the ranges.

The Australian calibration system is compared with other calibration standards.

The establishment of gravity meter calibration ranges in all States of Australia permits all users of gravity meters to adopt a common calibration for their meters, and assists in the integration of independent surveys.

# 1. INTRODUCTION

Since 1946, gravity surveys have been conducted by the Bureau of Mineral Resources (BMR) in many parts of Australia. Private companies engaged in the search for oil and other minerals, State Government Mines Departments, Universities, and overseas organisations have also carried out gravity surveys over a period of many years throughout Australia.

The BMR is the Commonwealth authority on gravity investigations in Australia, and is responsible for the provision of basic regional gravity data so that the results of independent gravity surveys can be integrated to form composite gravity maps over extensive areas for use in regional, geodetic, and sedimentary-basin investigations.

A network of 59 gravity base stations was established throughout Australia in 1950 and 1951 using the Cambridge pendulums (Dooley et al., 1961). These base stations are used to reduce the individual gravity meter surveys to a common datum.

To facilitate distribution of closing errors when various gravity meter surveys are tied together, it is also desirable that the meters should be calibrated against a common standard that is consistent with differences in gravity determined from the pendulum observations. Prior to 1960, most gravity meter operators used the calibration factors supplied by the manufacturers, although several local calibration runs were also used. Of these runs, the BMR calibration range between Ferntree Gully and Kallista in Victoria was the only one whose gravity interval had been related to the pendulum observations.

In 1960 the BMR decided to establish gravity meter calibration ranges at capital cities for the convenience of geophysical operators. In addition to the six capital cities (Melbourne, Adelaide, Perth, Brisbane, Sydney, and Hobart), two other centres (Alice Springs and Townsville) were chosen as sites for calibration ranges. Alice Springs was selected because of the oil-search activity in that area, which is about 1000 miles from the nearest capital city, and Townsville was included to serve the northern part of Queensland.

The eight centres at which gravity meter calibration ranges were established are shown in Plate 1.

TABLE 1

GRAVITY METERS USED TO DETERMINE CALIBRATION RANGES

| Calibration range | Gravity meter | Number of determinations | Total number of determinations |
|---|---|---|---|
| Melbourne | World-Wide 35 | 1 | |
| | Worden 61 | 2 | |
| | Worden 169 | 2 | |
| | Master Worden 548 | 1 | 6 |
| Adelaide | Worden 61 | 3 | |
| | Worden 140 | 1 | |
| | Worden 260 | 2 | |
| | Master Worden 548 | 2 | 8 |
| Perth | Worden 61 | 3 | |
| | Worden 140 | 2 | |
| | Worden 260 | 2 | |
| | Master Worden 548 | 2 | 9 |
| Alice Springs | World-Wide 35 | 1 | |
| | Worden 61 | 1 | |
| | Worden 140 | 4 | |
| | Worden 260 | 5 | |
| | Master Worden 548 | 3 | 14 |
| Townsville | World-Wide 35 | 1 | |
| | Worden 61 | 1 | |
| | Worden 140 | 1 | |
| | Worden 260 | 1 | 4 |
| Brisbane | World-Wide 35 | 3 | |
| | Worden 61 | 1 | |
| | Worden 140 | 1 | |
| | Worden 169 | 3 | |
| | Worden 260 | 2 | |
| | Master Worden 548 | 2 | 12 |
| Sydney | World-Wide 35 | 1 | |
| | Worden 61 | 2 | |
| | Worden 140 | 2 | |
| | Worden 169 | 1 | 6 |
| Hobart | Worden 61 | 2 | |
| | Worden 260 | 2 | |
| | Master Worden 548 | 2 | 6 |

## 2. OUTLINE OF SURVEY

The gravity meter calibration ranges in Brisbane, Townsville, Sydney, Adelaide, and Perth were selected and measured in January and February 1960 by the author, who also selected the Melbourne and Alice Springs ranges in July and August 1960. The measurement of the Melbourne calibration range was made by S. Waterlander and G.F. Lonsdale. M.J. Goodspeed made the necessary observations at Alice Springs. The Hobart range was selected and measured by A.J. Flavelle, who also made additional measurements on the Adelaide and Perth ranges. A further determination of the Melbourne calibration range was made by the author in March 1961.

The above measurements were all made using groups of gravity meters, and they form the main basis for the determination of the gravity intervals across the ranges. As described in a later section of this Report, it was possible to compare accurately the Melbourne calibration range with the Ferntree Gully/Kallista range. The groups of gravity meters used to measure the ranges outside Victoria were calibrated against either the Ferntree Gully/Kallista range or the Melbourne calibration range several times, both before and after each measurement.

The results of subsequent calibration runs made on the ranges outside Victoria have also been used in determining the gravity intervals across these ranges, but only in those cases where the calibration factors of the gravity meters were determined on the Ferntree Gully/Kallista range or on the Melbourne calibration range several times within a month of the readings on the other ranges. Gravity meter observations made by various officers of the BMR during the period from January 1960 to June 1962 have been used.

The numbers of determinations made on each range with the various BMR gravity meters are shown in Table 1.

## 3. SELECTION OF CALIBRATION RANGE SITES

The selection of suitable station sites for a gravity meter calibration range should be made in accordance with the following criteria:

(a) The range should be within reasonable driving time of the centre it serves.

(b) The gravity interval between the calibration stations should be between 50 and 60 milligals.

(c) The driving time between stations should be as short as possible.

(d) The station sites should be accessible at all times to officers of private companies or government organisations.

(e) The sites should be permanent.

(f) The sites should be easily located and their exact position obvious to a new observer.

(g) The sites should be free from vibration due to heavy traffic and other causes.

(h) It is desirable that the station sites should be sheltered from gusty winds and preferably also from rain.

Many of the above criteria conflict with each other, and it is not claimed that the station sites of all ranges are ideally located, but all are considered satisfactory for the purpose.

In order to obtain a large enough gravity interval, it was usually necessary to position the range on the side of a hill and to select station sites having a difference in altitude of about 800 feet. Exceptions to this general rule occur at Alice Springs and Perth, where the gravity intervals are the result of steep gravity gradients. It is interesting that the higher of the two calibration stations of the Perth range has the greater observed gravity value.

Brief descriptions of the station sites of the various ranges are given in Appendix B, and location diagrams are given in Plates 2 to 9.

## 4. DETERMINATION OF GRAVITY INTERVALS

The gravity intervals across the various gravity meter calibration ranges have been determined from measurements made with BMR gravity meters calibrated against a standard gravity interval between Ferntree Gully and Kallista in Victoria. This standard interval was originally determined from pendulum observations made on the Australian gravity network and has been adjusted in accordance with the revised values of the pendulum stations (Dooley, 1965). The methods of determining the gravity intervals across the various calibration ranges are described below.

### Ferntree Gully/Kallista

Since 1951, gravity meters used by the BMR have been run between a gravity station at the main gates of Brenock Park (Ferntree Gully) and the BMR pendulum station PS39 (Kallista). These runs were usually made in order to check the instruments for correct operation and for changes in calibration. However, the results can be used to determine the calibration factors of the gravity meters at the time of these earlier runs from the currently adopted value of the Ferntree Gully/Kallista gravity interval.

In 1957, gravity meter ties were made between the pendulum stations located at Melbourne, Kallista, Mildura, Bombala, and Yarram. The gravity interval between PS1 in Melbourne (the National Gravity Base Station) and PS39 at Kallista was determined as 69.9 mgal. A set of gravity meters was used to determine the observed gravity value at the Ferntree Gully station, and the Ferntree Gully/Kallista calibration range was established with a gravity interval provisionally adopted as 55.60 mgal (Dooley, 1959). This calibration range was used to calibrate the BMR gravity meters during the period from 1957 to July 1961, when the Ferntree Gully/Kallista range was replaced by the Melbourne calibration range.

The Australian gravity network was adjusted during 1961, and an essential by-product was the revision of the gravity meter calibration factors used by the BMR. The adjustment of various BMR gravity meter surveys that are tied to more than one pendulum station required that a correction factor of 1.0016 be applied to the calibration factors of the gravity meters. The standard deviation for this correction factor is about 0.0002. The gravity interval across the Ferntree Gully/Kallista range was given a revised value of 55.69 mgal on the basis of this adjustment (Dooley, 1965).

The results of all calibrations made on the Ferntree Gully/Kallista range have been re-computed, using the revised gravity interval, before determining the gravity intervals on the other calibration ranges.

Melbourne calibration range

In 1960 it was decided to replace the Ferntree Gully/Kallista range with the present Melbourne range for the following reasons:

(a) The driving time between the two former calibration stations was unnecessarily long.

(b) Some observers had consistently read at the wrong places, as the stations were not clearly marked.

(c) A quarry had been brought into operation near the Ferntree Gully site, and accurate reading became difficult owing to vibration of the gravity meter.

(d) The station sites were not sheltered from inclement weather.

Two new station sites were selected to form the Melbourne calibration range, which lacks the defects of the Ferntree Gully/Kallista range.

The determination of the Melbourne calibration range in terms of the accepted gravity interval across the Ferntree Gully/Kallista range was not difficult. As shown in Plate 2, the four calibration stations forming these two ranges are near each other and it was possible to take readings on all stations within each drift control loop. The gravity interval across the Melbourne calibration range was then determined from that across the Ferntree Gully/Kallista range using the ratio of the intervals as measured in scale divisions during repeated loops with various gravity meters. The result is not affected by variations in the calibration factors of the gravity meters used in this determination.

From July 1961 the BMR's gravity meters have been calibrated on the Melbourne calibration range.

Calibration ranges outside Victoria

It was originally intended that the gravity interval across every other calibration range should be measured by a set of three gravity meters calibrated in Melbourne before and after the measurements on the other range.

Discrepancies in the results of these measurements indicated that while a gravity meter was in another State its calibration factor was not necessarily the same as that determined in Melbourne immediately before or after the survey. While investigating this problem the results of all calibration runs made in Melbourne were carefully re-assessed. The results of these calibrations (which were made against the same gravity interval) showed that the calibration factor of a gravity meter varies considerably and often changes erratically. These changes are discussed in Appendix A, and are being investigated further.

The gravity intervals across the various calibration ranges outside Victoria were finally determined from the mean results of many separate measurements made with several different gravity meters (see Table 1). An outline of the mathematical treatment of the results of these measurements is given in the next chapter.

## 5. COMPUTATION OF GRAVITY INTERVALS ACROSS RANGES OUTSIDE VICTORIA

The gravity intervals across the various ranges outside Victoria were measured using gravity meters calibrated against either the Ferntree Gully/Kallista or the Melbourne calibration range. Because of the variations in the measurements of these ranges the results must be considered provisional. The mathematical treatment given to the measurements is not rigorous, but the lack of knowledge regarding the factors that affect these measurements does not justify the use of more refined techniques at present.

In the discussion, the results of the Melbourne calibrations of a single gravity meter are considered first, then the result of a single measurement on a range outside Victoria, and finally the determination of mean values for the ranges outside Victoria.

Result of Melbourne calibrations of a single gravity meter

Result of a single calibration. Any single calibration is based on the result of a number of readings made alternately at the two calibration stations. A linear drift was assumed between successive readings at the same station, and the results were plotted as drift curves at the upper and lower stations.

From a total of n readings, n - 2 estimates of the interval in scale divisions* (Di) were obtained from groups of three successive readings. Occasionally a point could not be fitted by any reasonable drift curve, presumably because of a reading error or a temporary 'tare' (instantaneous jump in the reading). The estimate of which this point was the mid-reading was omitted, but those on either side of it were retained. For the remaining estimates a mean value $\overline{D}$ was determined and a maximum probable error $E_D$ was estimated. The calibration factor K was then obtained from:

$$K = G/\overline{D} \quad \text{milligals per scale division*}$$

where G is the accepted gravity interval across the calibration range and is expressed in milligals.

A maximum probable error $E_K$ was also estimated for the calibration factor.

Graphs of calibration results for the gravity meters. The results of all calibrations for each meter have been plotted chronologically on a graph, which also shows the probable error in each determination as a vertical line. The graph also indicates the dates on which the instrument wes evacuated and periods during which it was being repaired by the manufacturer. The graphs showing the calibration results for the various gravity meters used in this work are given in Plates 10 to 15. The results of determinations over ranges outside Victoria are discussed later in this Report but have been anticipated here; they are also included in Plates 10 to 15.

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* "Scale division" in this sense refers to the scale on which the gravity reading is made, not to the eyepiece setting scale possessed by many gravity meters. Some meters, e.g. the LaCoste & Romberg, actually have a mechanical counter instead of a reading scale.

Result of a single measurement of a range outside Victoria

Selection of calibration factor. After examining the graph of the Melbourne calibrations, five expressions were selected to describe the calibration factor of a gravity meter during a measurement on a calibration range outside Victoria. These were:

| | | |
|---|---|---|
| $K_A$ , | the 'maximum possible value' | (maximum calibration factor ever determined in Melbourne). |
| $K_a$ , | the 'maximum probable value' | (maximum calibration factor determined in Melbourne within one or two months of the measurement on the other range). |
| $\overline{K}$ , | the 'most probable value' | (mean of all Melbourne determinations within two or three months of the measurement on the other range). |
| $K_b$ , | the 'minimum probable value' | (similar to $K_a$). |
| $K_B$ , | the 'minimum possible value' | (similar to $K_A$). |

The 'most probable value' of the calibration factor ($\overline{K}$) was used in the next stage of the computations, and the reciprocal of the spread between 'maximum and minimum probable values' ($K_a - K_b$) was used as a factor in deciding what weight should be given to this particular measurement. All five values were used in a graphical analysis of the results, as discussed later.

Measurement of interval in scale divisions. Any single measurement of a range outside Victoria was based on the mean result of many readings made alternately at the two stations. From a total of p readings, p - 2 estimates of the interval in scale divisions (d) were obtained as at Melbourne. Because of the drift of the meter during the measurement, and limitations of reading accuracy, some uncertainty always remained in the estimated interval as measured in scale divisions. Normally, sufficient readings were taken to ensure that this uncertainty was small; in cases where this was not so, the measurement was rejected. The mean value of the interval as measured in scale divisions ($\overline{d}$) was used in the next stage of the computations, and the reciprocal of the 'maximum probable error' $E_d$ was used as a factor in deciding what weight should be given to this particular measurement.

Computation of the interval in milligals. The gravity interval i expressed in milligals is given by:

$$i = dK$$

The 'most probable value' for the interval as a result of the s th measurement (${}_s i^*$) is given by:

$$ {}_s i^* = {}_s\bar{d} \times {}_s\bar{K} $$

This measurement was allotted a weight ${}_s w$ given by:

$$ {}_s w = \frac{{}_s m}{({}_s K_a - {}_s K_b)\ {}_s E_d} $$

where ${}_s m$ is the number of Melbourne calibrations used to determine the 'most probable calibration factor' ${}_s\bar{K}$ and the 'maximum and minimum probable calibration factors' ${}_s K_a$ and ${}_s K_b$ .

Determination of mean values for ranges outside Victoria

Mathematical. From the individual measurements ${}_s i^*$ of any one range, the mean $(\bar{i})$ and weighted mean $(\bar{I})$ were given by:

$$ \bar{i} = \frac{\Sigma\ {}_s i^*}{N} $$

$$ \bar{I} = \frac{\Sigma\ {}_s i^*\ {}_s w}{\Sigma\ {}_s w} $$

where N is the number of measurements of that range.

The error in the weighted mean was taken as the standard error $\sigma$ given by:

$$ \sigma = \left[ \frac{\Sigma\ {}_s w({}_s i^* - \bar{i})^2}{(N - 1)\ \Sigma\ {}_s w} \right]^{\frac{1}{2}} $$

The results for the various ranges outside Victoria are given in Table 2.

TABLE 2

MEAN VALUES FOR RANGES OUTSIDE VICTORIA

| Range | N | $\bar{i}$ | $\bar{I}$ | $\sigma$ |
|---|---|---|---|---|
| Adelaide | 8 | 62.612 | 62.612 | ± 0.007 |
| Perth | 9 | 53.973 | 53.975 | ± 0.009 |
| Alice Springs | 14 | 52.082 | 52.104 | ± 0.014 |
| Townsville | 4 | 60.505 | 60.508 | ± 0.005 |
| Brisbane | 12 | 58.261 | 58.255 | ± 0.011 |
| Sydney | 6 | 58.991 | 58.995 | ± 0.016 |
| Hobart | 6 | 54.715 | 54.712 | ± 0.014 |

As shown in Table 2, the weighted mean is within 0.006 mgal of the mean, for each range except Alice Springs, where the difference is 0.022 mgal. For each range the weighted mean ($\bar{I}$) was accepted as the provisional determination of the gravity interval.

It should be pointed out that the estimate of the standard error itself has an error which is large if the number of measurements is small. This is particularly so in the case of Townsville, where only four measurements have been made; the standard error is probably much greater than that indicated in Table 2.

Graphical. The results of the individual measurements of each range are summarised graphically in Plates 16 to 22.

The s th measurement is represented by a vertical line running between the values ${}_s\bar{d}\,{}_sK_B$ and ${}_s\bar{d}\,{}_sK_A$. The values ${}_s\bar{d}\,{}_sK_b$, ${}_s\bar{d}\,{}_s\bar{K}$, and ${}_s\bar{d}\,{}_sK_a$ are shown as intercepts on this line. The line thus represents the 'most probable value' and the uncertainty due to a lack of precise knowledge of the calibration factor involved.

The uncertainty in the 'most probable value' due to the possible errors in the measurement of the interval in scale divisions is represented graphically alongside the value ${}_s\bar{d}\,{}_s\bar{K}$ by a vertical line extending to $\pm\ {}_s\bar{K}\,{}_sE_d$.

The mean result $\bar{i}$ and the weighted mean $\bar{I}$ are shown as horizontal lines, or levels, on the graph. It was expected that the mean-value level would pass through the various measurements so as to intersect the vertical lines at points between ${}_s\bar{d}K_a$ and ${}_s\bar{d}K_b$, but this was not always so. It was found that the 'most probable values' ${}_s\bar{d}\,{}_s\bar{K}$ were comparatively widely scattered, and for many measurements the mean value for a particular range indicated that the calibration factor lay outside the 'maximum and minimum probable limits' ${}_sK_a$ and ${}_sK_b$.

The spreads in the 'most probable values' ${}_s\bar{d}\,{}_s\bar{K}$ for the Alice Springs and Brisbane ranges are 0.20 and 0.13 mgal respectively. The spreads obtained for the other ranges are all less than 0.10 mgal.

## 6. ACCEPTED VALUES OF GRAVITY INTERVALS ACROSS RANGES

The accepted values of the gravity intervals across the various ranges and the standard errors in these accepted intervals are set out in Table 3. The accepted values are also shown in Plates 2 to 9.

**TABLE 3**

**ACCEPTED VALUES OF GRAVITY INTERVALS AND PROBABLE ERRORS**

| Calibration range | Accepted value of gravity interval | Standard error |
| --- | --- | --- |
| Ferntree Gully/Kallista | 55.69 mgal | - |
| Melbourne | 53.04 | ± 0.01 mgal |
| Adelaide | 62.61 | ± 0.01 |
| Perth | 53.98 | ± 0.01 |
| Alice Springs | 52.10 | ± 0.02 |
| Townsville | 60.51 | ± 0.02 |
| Brisbane | 58.26 | ± 0.02 |
| Sydney | 58.99 | ± 0.02 |
| Hobart | 54.71 | ± 0.02 |

## 7. COMPARISON OF AUSTRALIAN CALIBRATION STANDARD WITH OTHER STANDARDS

The Australian calibration standard agrees fairly well with overseas standards, but as yet there is not very much information on which to base exact comparison.

The calibration figures supplied by the manufacturer of the BMR's Worden gravity meters are generally 0.0 to 0.3 percent higher than those determined by the BMR; the figure supplied with the BMR's World-Wide meter is 0.2 to 0.4 percent higher.

Ties made by various overseas visitors indicate that calibrations made on the Australian system agree fairly well with both the 'Recent American' and the '1957 European' systems described by Morelli (1957).

Table 4 shows a comparison between the gravity intervals as determined by the survey described in this Report and measurements by various observers using the following LaCoste & Romberg geodetic gravity meters:

LaCoste & Romberg No. G20 - Bureau of Mineral Resources
LaCoste & Romberg No. G5 - United States Naval Hydrographic Office
LaCoste & Romberg No. DL1 - Scripps Institute ('Expedition Monsoon')

Close agreement was obtained at the Melbourne, Townsville, and Sydney ranges, and reasonably



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close agreement at Adelaide and Brisbane. The discrepancies at Alice Springs cannot be explained at present.

TABLE 4

ACCEPTED GRAVITY INTERVALS AND INTERVALS MEASURED BY LaCOSTE & ROMBERG GRAVITY METERS

| Calibration range | Accepted value, mgal | LaCoste & Romberg measurements, mgal | | |
|---|---|---|---|---|
| | | G20 | G5 | DL1 |
| Melbourne | 53.04 | 53.03<br>53.03<br>53.03<br>53.02 | 53.01 | |
| Adelaide | 62.61 | 62.58<br>62.55 | | |
| Perth | 53.98 | | | |
| Alice Springs | 52.10 | 52.21<br>52.19<br>52.20<br>52.21 | | 52.06 |
| Townsville | 60.51 | | | 60.51 |
| Brisbane | 58.26 | 58.21<br>58.19 | | |
| Sydney | 58.99 | 59.00 | | |
| Hobart | 54.71 | | | |

## 8. CONCLUSIONS AND RECOMMENDATIONS

Gravity meter calibration ranges have been established at eight centres throughout Australia. The gravity intervals of the various ranges have been determined relative to each other to an estimated accuracy of ± 0.4 percent (± 0.02 mgal). The standard interval against which these ranges were determined is consistent with the adjusted Australian gravity network.

There are some discrepancies between the mean gravity intervals determined for various ranges and estimates of the same intervals measured by geodetic (single-dial) instruments. It is recommended that further determinations be made on these ranges after problems regarding variations in the calibration factors of gravity meters have been clarified.

The station sites at the various calibration ranges are considered permanent, but it is recommended that arrangements be made to erect suitable plaques at the various sites, to facilitate re-occupations.

The establishment of additional calibration ranges, near Darwin, Broome, and Port Moresby would assist operators carrying out gravity surveys near those centres.

It is recommended that all gravity meters used on future gravity surveys in Australia should be calibrated on one or another of the established ranges, to facilitate integration of the results of the various surveys.

## 9. ACKNOWLEDGEMENTS

The assistance given by various Government Departments, Universities, and other organisations is acknowledged. They include:

The University of Queensland, which suggested the establishment of an additional range at Townsville and assisted in the selection of suitable sites at Brisbane.

Mines Administration Pty Ltd, which also assisted in the establishment of the range at Brisbane.

The Mines Department of South Australia, which assisted in the establishment of the range at Adelaide.

The University of Tasmania, which assisted in the establishment of the range at Hobart.

Trans-Australia Airlines and Ansett-ANA, which assisted in the safe transport of the gravity meters.



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## APPENDIX A

## VARIATIONS IN CALIBRATION FACTORS OF GRAVITY METERS

It is known that the calibration factor (or scale value) of a gravity meter is affected by a number of variables, and several overseas organisations have carried out research into this problem.

During the establishment of calibration ranges throughout Australia, the BMR's gravity meters were calibrated frequently. The results of a total of 216 separate determinations of the calibration factors of six gravity meters, over the period from March 1954 to June 1962, were investigated while calculating the gravity intervals over the ranges outside Victoria. Unfortunately the variables that are now known to affect the calibration factor were not precisely determined at the time of the observations, but it has been possible to obtain some data relevant to the problem.

### Temperature effect

Inghilleri (1959) and Gantar et al. (1960) have shown that the calibration factor of a gravity meter increases with temperature. For Worden gravity meters, estimates of the rate of increase range from 0.067 to 0.1 percent per $10^{\circ}C$. This effect has been confirmed by later workers, e.g. Damrel (1960).

Records of the minimum and maximum ambient temperatures before and during some of the BMR calibration runs were obtained from the Bureau of Meteorology. The calibration factors of the gravity meters were apparently unaffected by ambient temperatures differing by more than $20^{\circ}C$, but the effect may have been masked by erratic changes of greater magnitude.

### Ageing effect

Inghilleri (1959) and Saxov (1959) stated that the calibration factor decreases with increasing age of the meter and that, after repairs, the rate of decrease is at first large and then diminishes during the succeeding years. Estimates range from 0.13 to 0.50 percent per year during the first year, diminishing to 0.0 to 0.25 percent per year in succeeding years. Morelli (1957) stated that the rate of decrease was 0.12 percent per year and constant.

Later research indicates that this supposed ageing effect may be due to the gradual increase of pressure within the oscillation chamber of the meter.

Calibration data for six gravity meters have been obtained by the BMR during a period of some years. All these meters have been evacuated regularly, generally at intervals of about six months. Graphs of the results of the various calibration runs are shown in Plates 10 to 15, which also indicate the dates on which the meters were evacuated. Although the calibration results are fairly widely scattered, these graphs provide some evidence that an ageing effect may in fact occur, even if meters are regularly evacuated. The results of some earlier calibrations of the BMR's gravity meters indicate that the change in calibration factor over an extended period does not exceed the random variation (Dooley, 1965).

Pressure effect

Damrel (1960) and Gantar et al. (1960) have shown that the calibration factor decreases with increasing pressure within the oscillation chamber of the gravity meter. The rate of decrease has been estimated as 0.01 to 0.06 percent per 10 mmHg pressure.

The results of the BMR calibration runs cannot be used to provide evidence of a rate of decrease of this magnitude. Calibrations carried out by the BMR several days before and after an evacuation generally showed no significant change in the calibration factor, but some results showed decreases of about 0.15 percent and others increases of the same order (during an evacuation the pressure generally drops from about 30 mmHg down to about 7 mmHg). A group of five calibrations made on Worden 169, at a time when it is believed that the oscillation chamber was full of air owing to a faulty valve, gave results 0.3 percent lower than the normal calibration factor for this instrument.

Transport effect

There is some evidence to suggest that the calibration factor is affected by the mode of transport used to convey the gravity meter. Little is known about this effect, but the gravity interval measured between two stations using a helicopter for transport is generally different from that measured using a ground vehicle.

Erratic effects

Erratic changes have been detected in the calibration factors of all gravity meters used by the BMR. On two particular calibration runs, changes of 0.1 percent and 0.13 percent have been detected in the calibration factors of the meters concerned. On the first occasion the interval across the Melbourne calibration range was measured using Worden 61 and the number of readings was '8 - 7' (i.e. readings were taken alternately at each station giving a total of eight readings at the first station and a total of seven at the second). The results up to 2 p.m. indicate an interval of 588.0 scale divisions obtained from a '3 - 3' run with negligible drift. Results after 2 p.m. indicate an interval of 588.6 scale division obtained from a '4 - 4' run, also with negligible drift.

The separate drift curves based on readings at the two stations diverge at 2 p.m. and the calibration factor apparently decreased by 0.1 percent. On the second occasion, a similar effect was noted with World-Wide gravity meter 35. In this case there were more readings, but the drift of the meter was not quite so steady.

Even larger changes in the results of runs made on near-successive days are common, while over a period of two to three months the calibration factor of an instrument may vary by 0.25 percent. Naturally, the above assessment is based only on calibration runs for which sufficient readings were taken to ensure that the uncertainty in the measured interval due to instrument drift and reading limitations was not more than 0.1 scale divisions. The effect has been detected in all prospecting types of gravity meters used by the BMR.

## APPENDIX B

## BRIEF DESCRIPTIONS OF CALIBRATION RANGE SITES

A brief description of the location of each calibration range and station site is given below. Plans showing the locations of the ranges and the exact positions of the stations are shown in Plates 2 to 9. The new number of each station is followed by the former number in brackets, e.g. 6091.0101 (MCS1).

Melbourne calibration range (Plate 2)

Near Upper Ferntree Gully, 18 miles east of Melbourne.

6091.0101 (MCS1) In picnic shed, National Park, Upper Ferntree Gully.

6091.0201 (MCS2) On verandah of shop near Ferny Creek.

Adelaide calibration range (Plate 3)

Between Kensington Gardens, three miles east of Adelaide, and Norton Summit.

6091.0108 (ACS1) On verandah of Scout Hall, Kensington Gardens Reserve.

6091.0208 (ACS2) On verandah of Bill Brown's Scenic Hotel, Norton Summit.

Perth calibration range (Plate 4)

Between Hazelmere, five miles east of Perth, and Helena Valley.

6091.0117 (PCS1) On concrete footpath in front of shop at Hazelmere.

6091.0217 (PCS2) On terrace of Red Cross Hall, Helena Valley recreation ground.

6091.0317 (PCS2A) At entrance to men's toilets, Helena Valley recreation ground.

Alice Springs calibration range (Plate 5)

On Stuart Highway north of Alice Springs.

6091.0135 (ASCS1) Next to the milepost, 11 miles north of Alice Springs.

6091.0235 (ASCS2) Next to the milepost, 26 miles north of Alice Springs.

Townsville calibration range (Plate 6)

On road to summit of Castle Hill, one mile north of Townsville.

6091.0151 (TCS1) On pathway at the Townsville Central State School.

6091.0251 (TCS2) At memorial to Captain Towns, Castle Hill Lookout.

Brisbane calibration range (Plate 7)

Between Brisbane University (St Lucia) and Mount Coot-tha, four miles west of Brisbane.

6091.0147 (BCS1) Near the rear door of the Geology School, Brisbane University, St Lucia.

6091.0247 (BCS2) At trigonometrical station LD10 at the summit of Mount Coot-tha.

Sydney calibration range (Plate 8)

Near the Pacific Highway, ten miles north of Sydney.

6091.0105 (SCS1) In picnic shed at Lane Cove National Park.

6091.0205 (SCS2) On manhole cover, Illoura Avenue, Wahroonga.

6091.0305 (SCS2A) On concrete path next to water reservoir, Wahroonga.

Hobart calibration range (Plâte 9)

Between the University and the summit of Mount Nelson, three miles south of Hobart.

6091.0160 (HCS1) Near entrance to new Engineering School, Hobart University.

6091.0260 (HCS2) On bottom step of entrance to Marine Board Building, Mount Nelson.

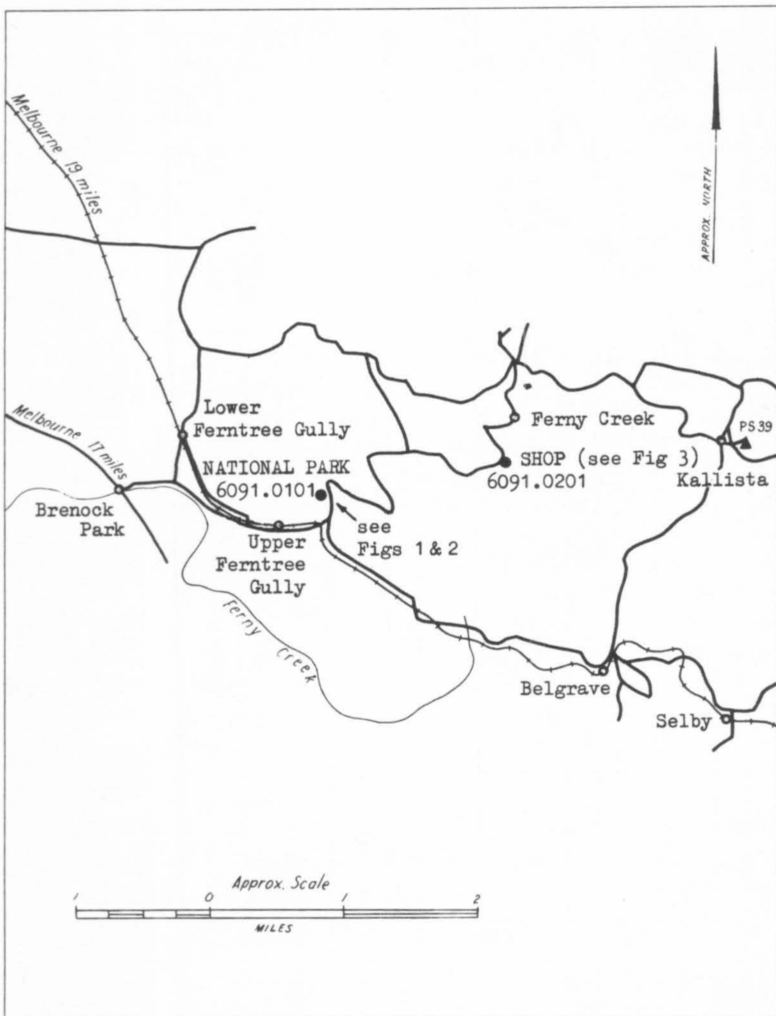



Fig. 1

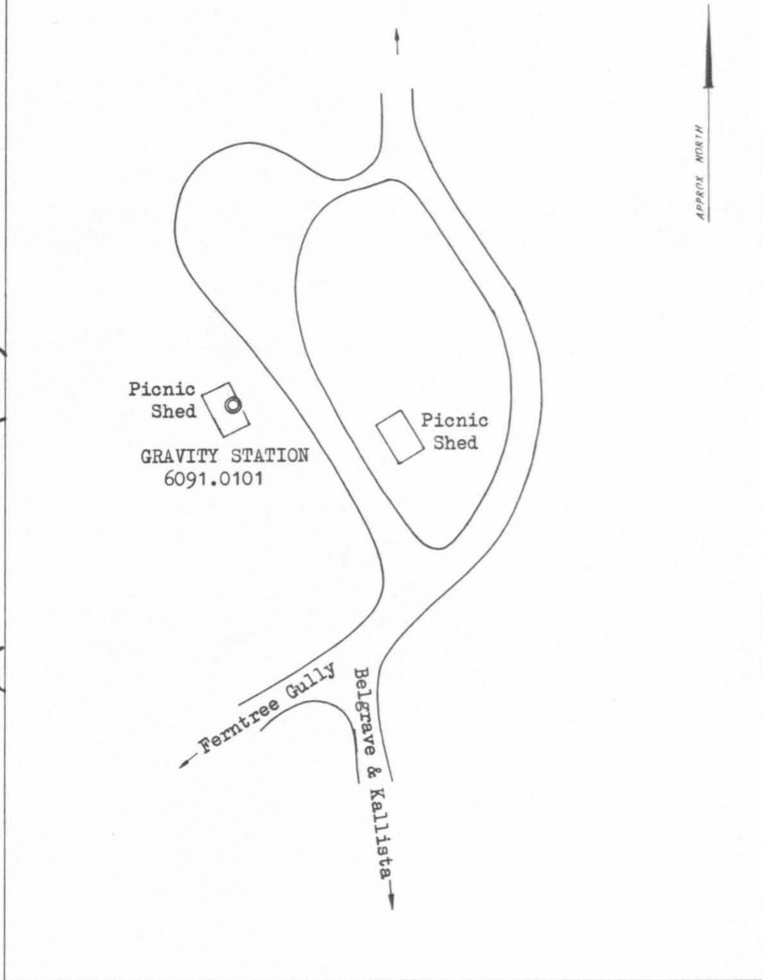



Fig. 2

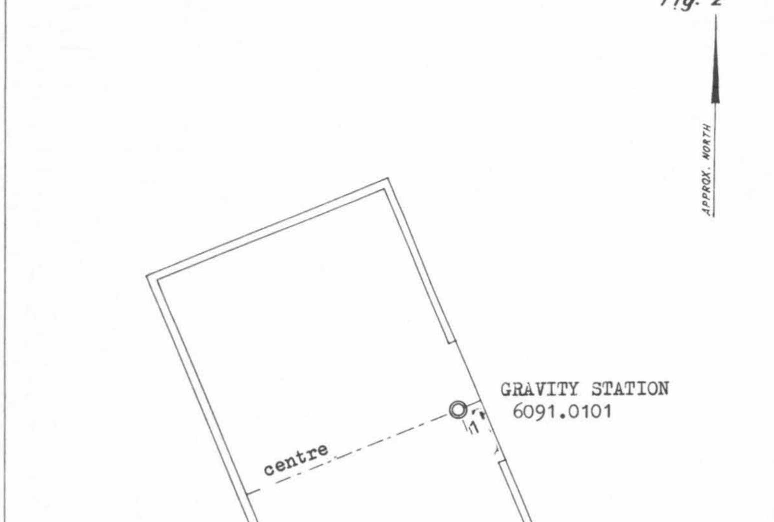
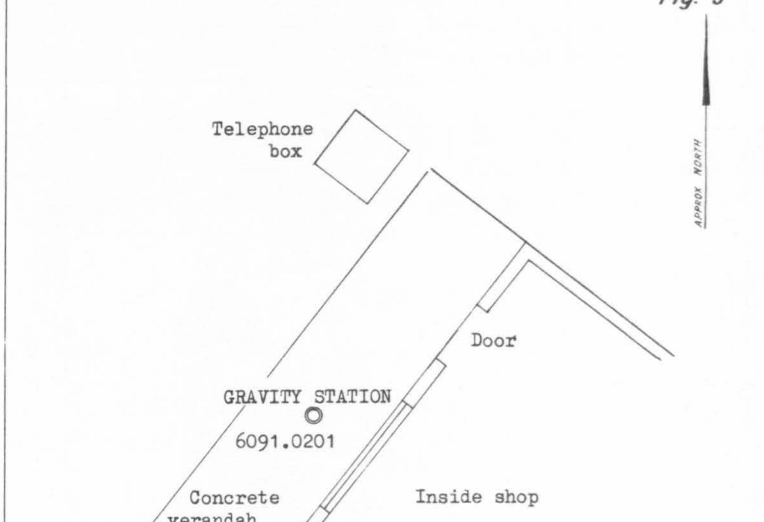



Fig. 3




*Observed gravity interval*
*6091·0101 - 6091·0201 = 53·04 mgal (June 1962)*
*53·04 mgal (Feb. 1963)*

*Station 6091·0101 previously referred to as MCS1*
*" 6091·0201 " " " MCS2*

GRAVITY METER CALIBRATION RANGE

MELBOURNE

PLATE 2

G24-2

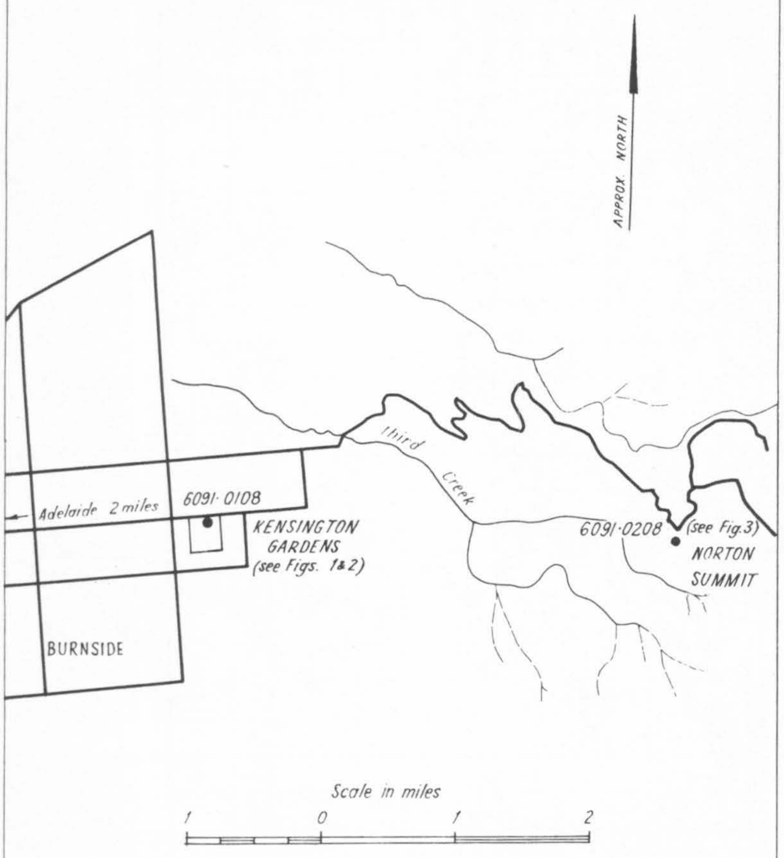



Fig. 1

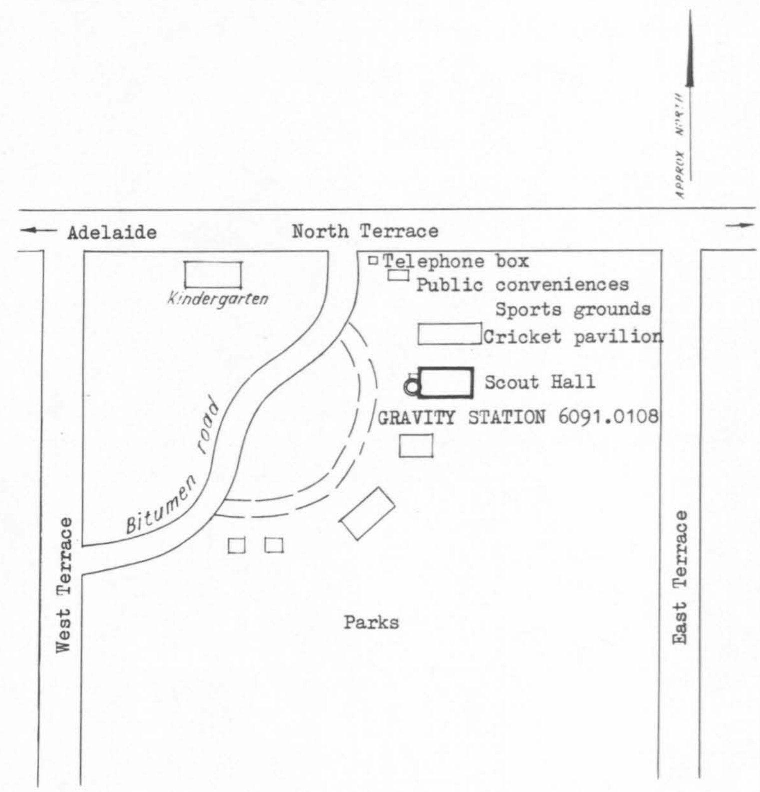



Fig. 2

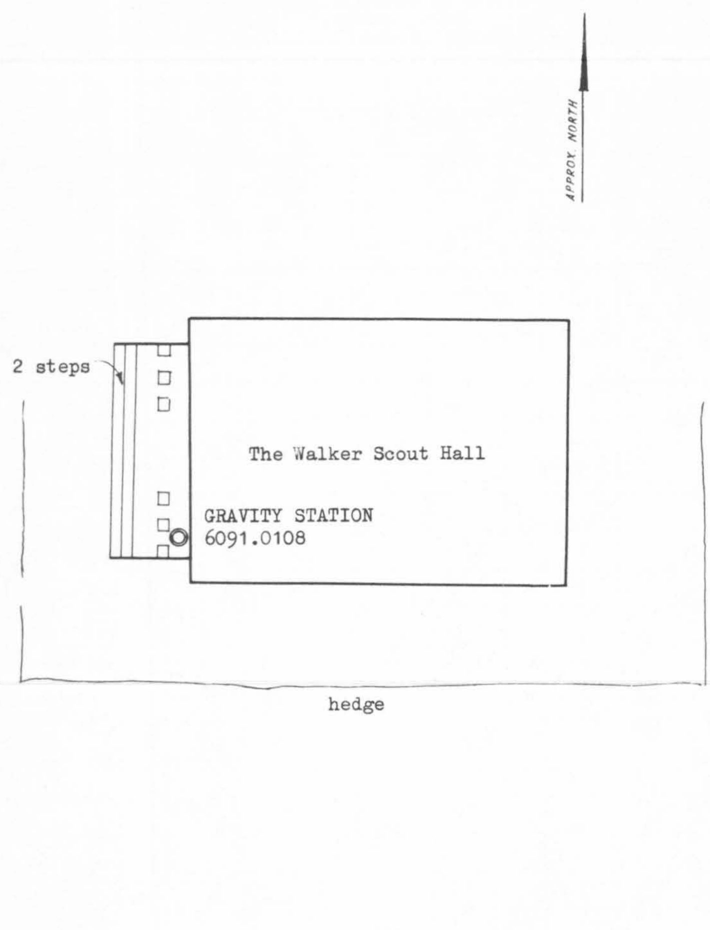
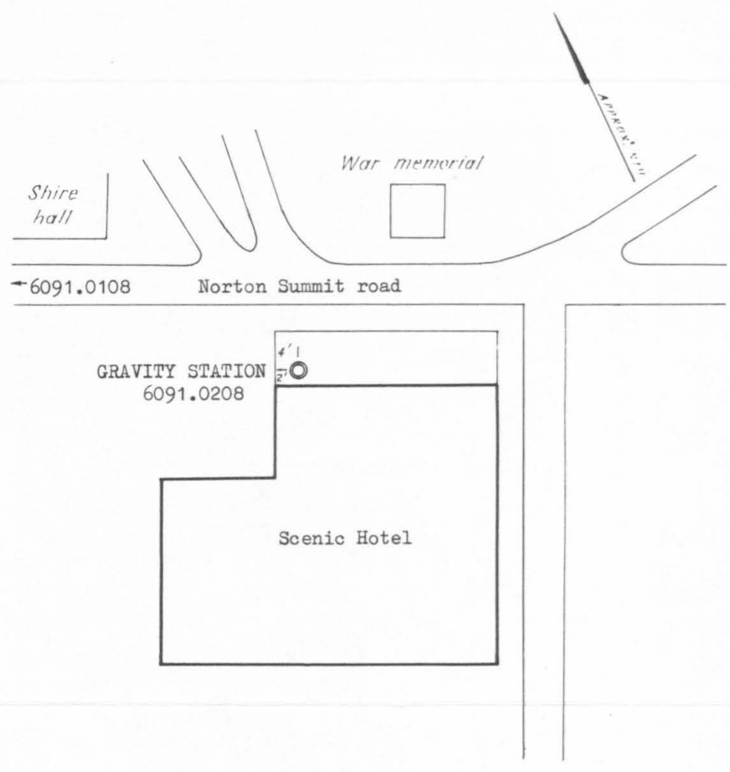



Fig. 3




***Observed gravity interval***
*6091·0108 – 6091·0208 = 62·60 mgal (July 1962)*
*62.61 mgal (Feb. 1963)*

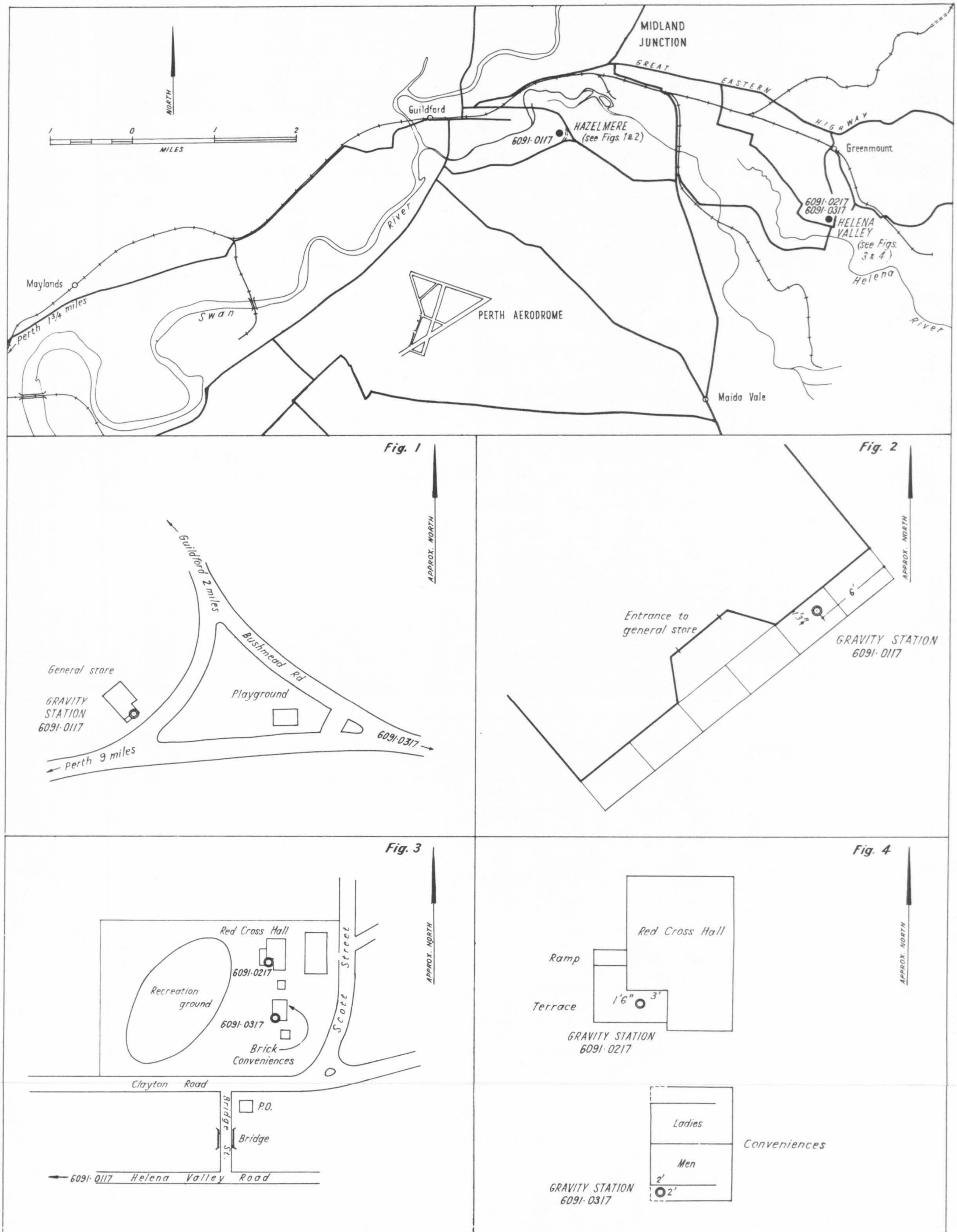
*Station 6091·0108 previously referred to as ACS 1*
*" 6091·0208 " " " " ACS 2*

GRAVITY METER CALIBRATION RANGE

ADELAIDE

PLATE 3

G24-3




***Observed gravity interval***
***6091·0217– 6091·0117 = 53·97 mgal*** *(July 1962)*
***53.98 mgal*** *(Feb. 1963)*

*Observed gravity at 6091·0217 is greater than that of 6091·0117*

## GRAVITY METER CALIBRATION RANGE

## PERTH

PLATE 4

*Station 6091·0117 previously referred to as PCS 1*
*" 6091·0217 " " " " PCS 2*
*" 6091·0317 " " " " PCS 2A*

G24-4

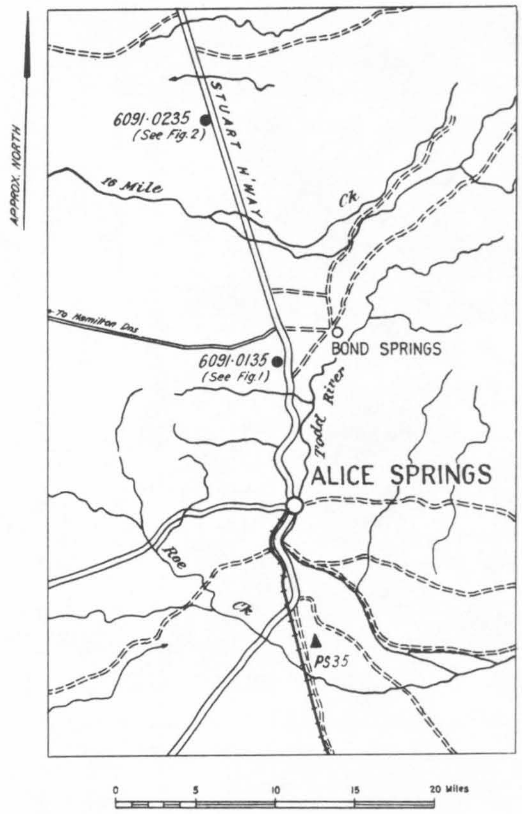



Fig. 1

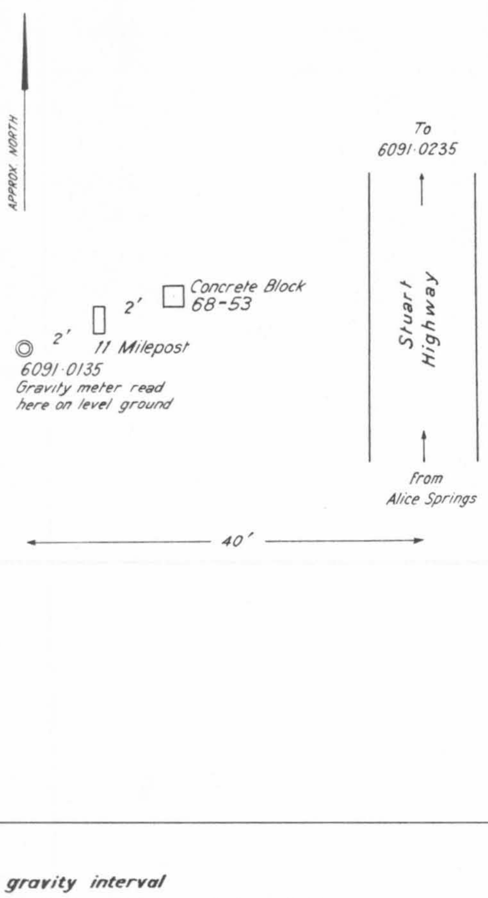
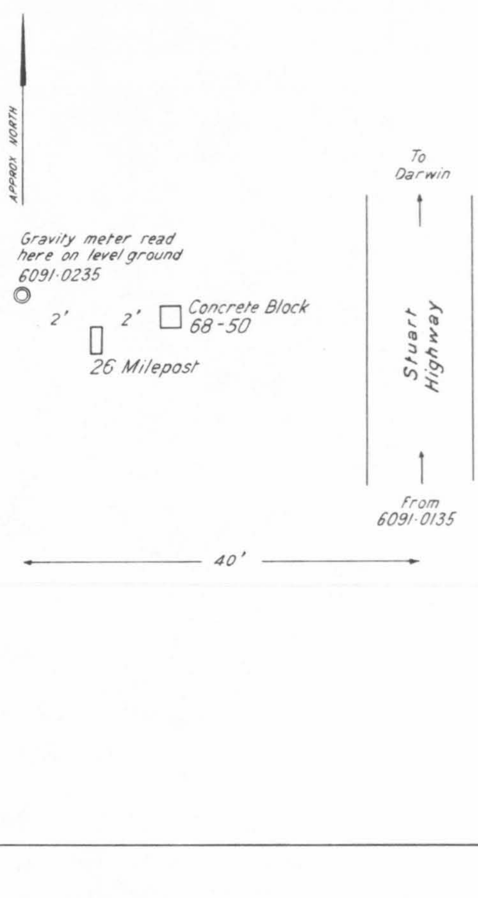



Fig. 2




***Observed gravity interval***

*6091·0135 – 6091·0235 =* ***52·09 mgal*** *(July 1962)*
*52.10 mgal (Feb. 1963)*

*Station 6091·0135 previously referred to as* ***ASCS 1***
*" 6091·0235 " " " "* ***ASCS 2***

GRAVITY METER CALIBRATION RANGE

ALICE SPRINGS

PLATE 5

G24-5

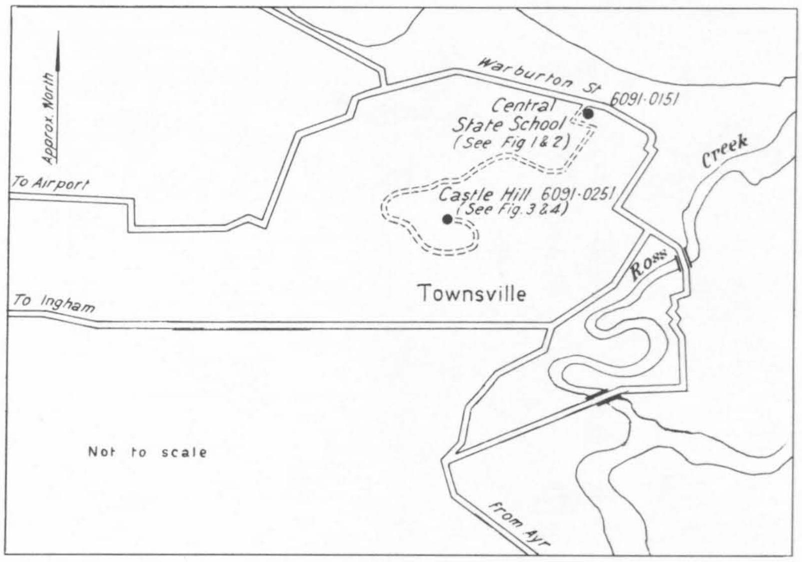



Fig. 1

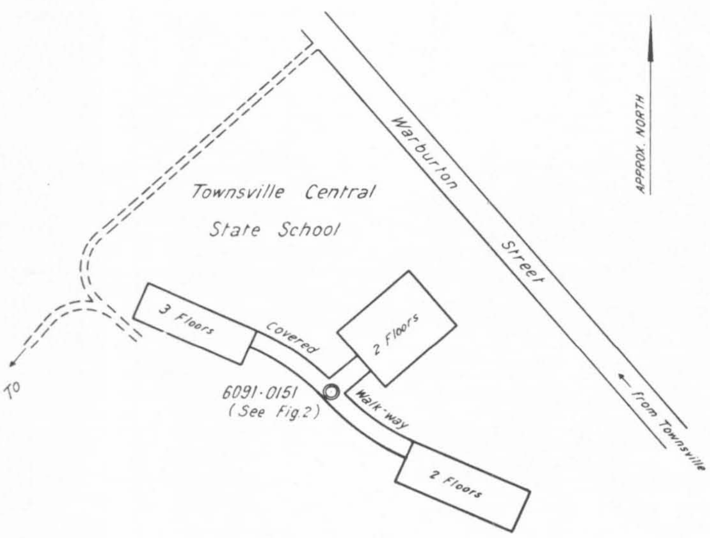



Fig. 2

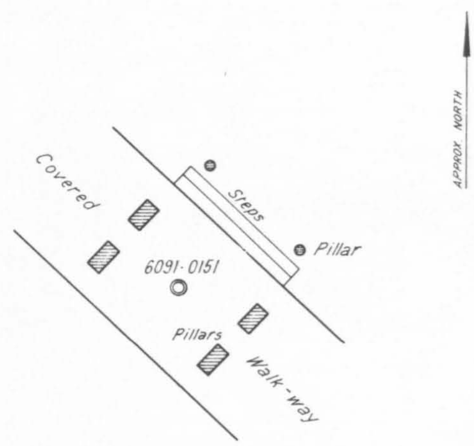



Fig. 3

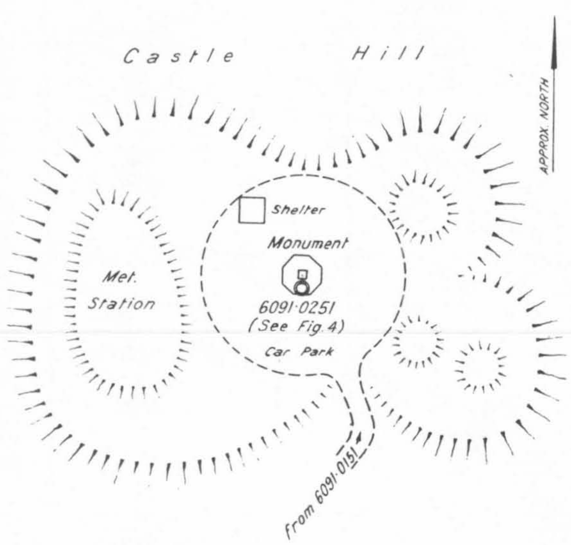
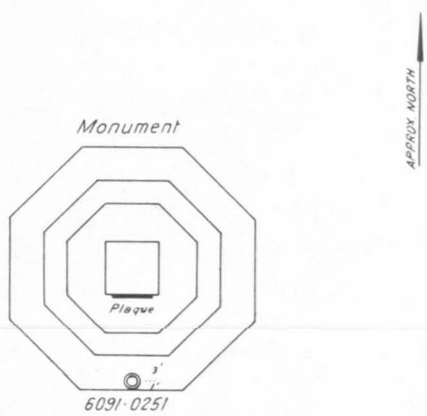



Fig. 4




***Observed gravity interval***

*6091-0151 - 6091-0251 = **60·50 mgal** (July 1962)*
*60.51 mgal (Feb. 1963)*

*Station 6091-0151 previously referred to as TCS 1*
*" 6091-0251 " " " " TCS 2*

GRAVITY METER CALIBRATION RANGE

TOWNSVILLE

PLATE 6

G24-6

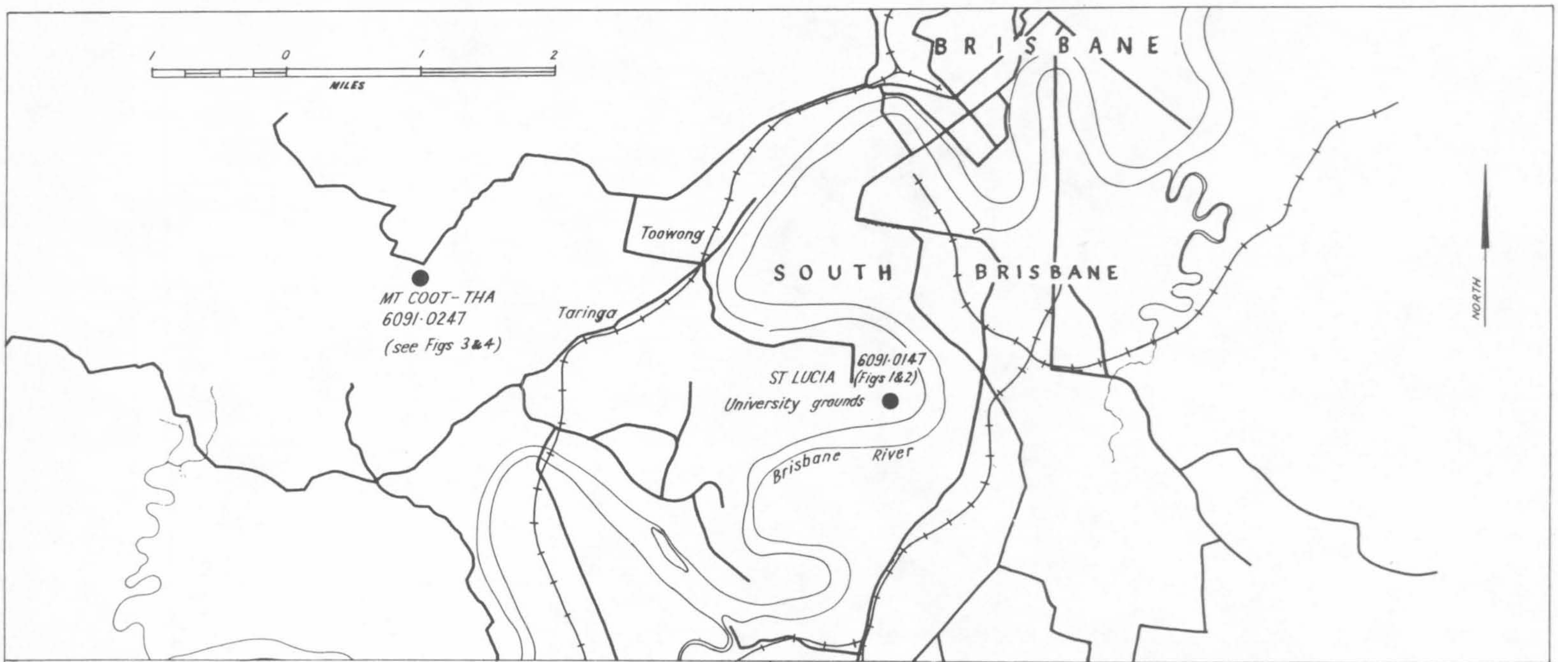



Fig. 1

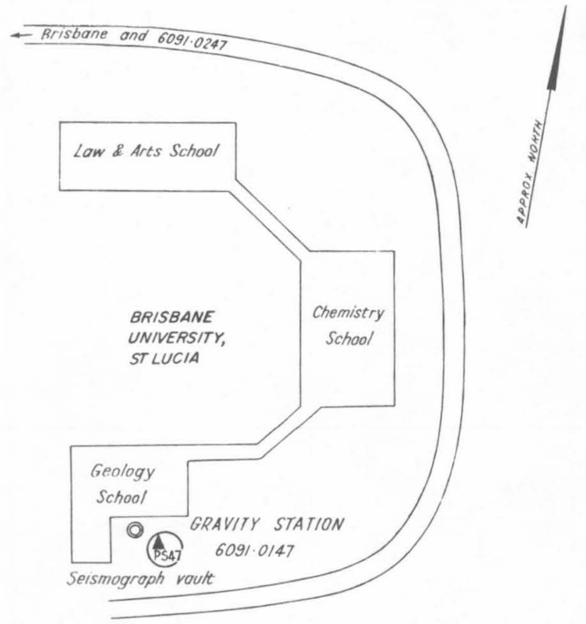



Fig. 2

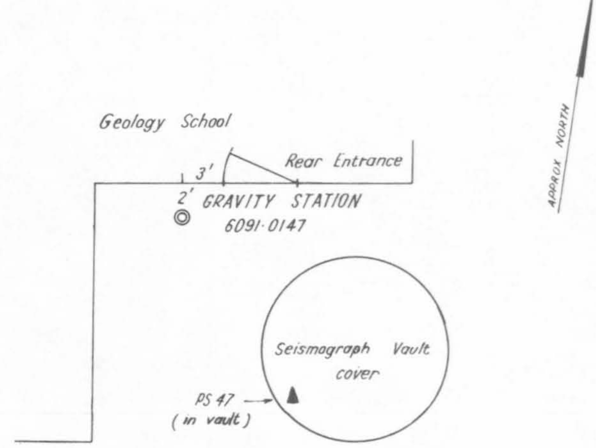



Fig. 3

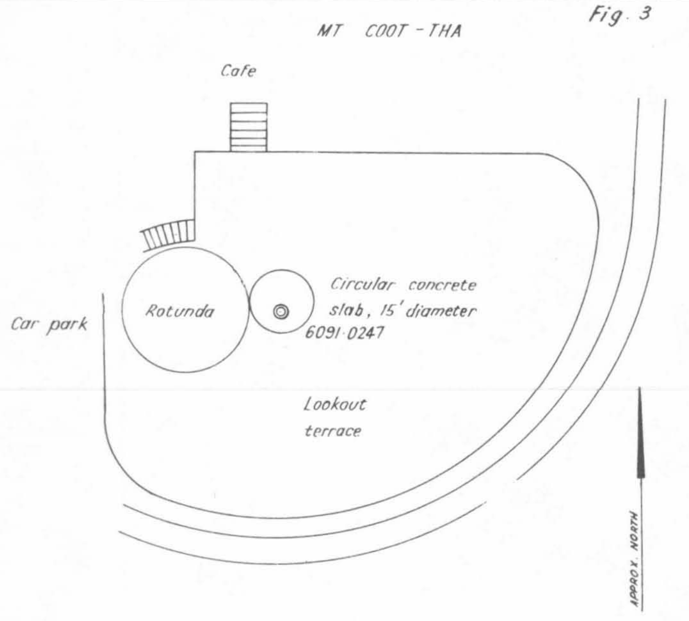
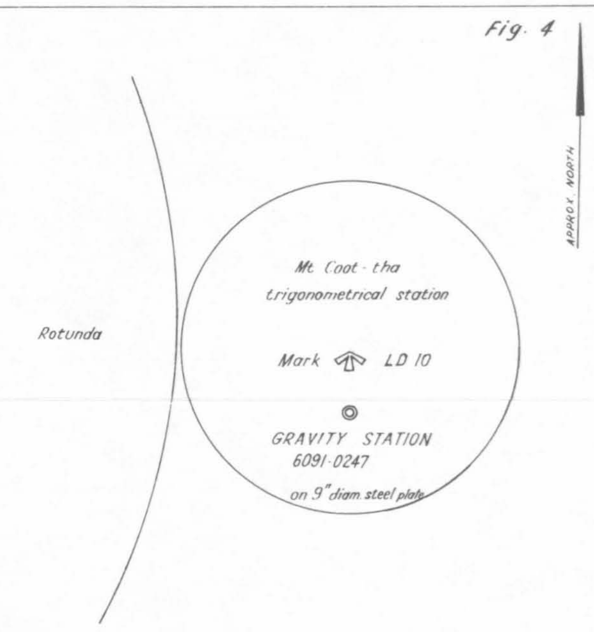



Fig. 4




***Observed gravity interval***

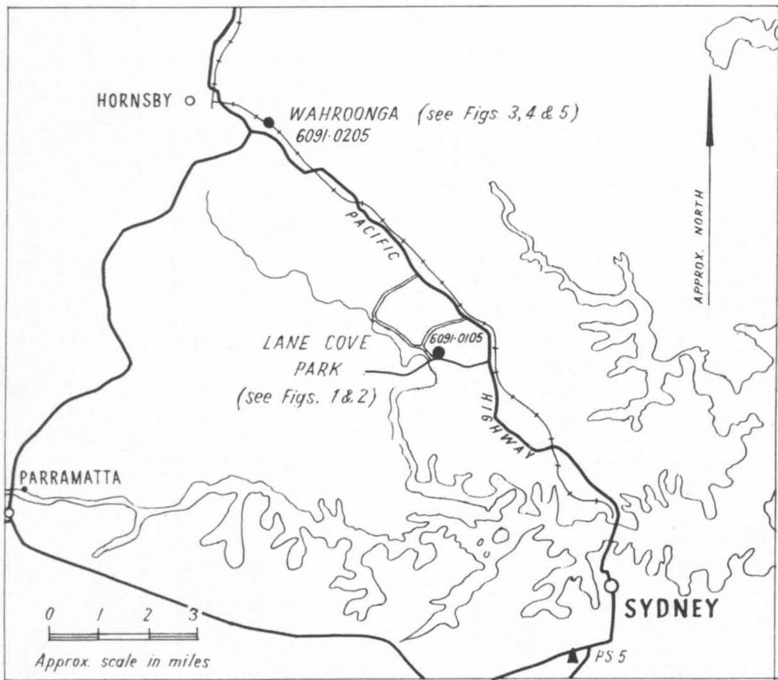
*6091·0147 – 6091·0247 = **58·27 mgal** (Nov. 1961)*
*58.26 mgal (Feb. 1963)*

*Station 6091·0147 previously referred to as BCS 1*
*" 6091·0247 " " " " BCS 2*

## GRAVITY METER CALIBRATION RANGE
## BRISBANE

PLATE 7

G24-7



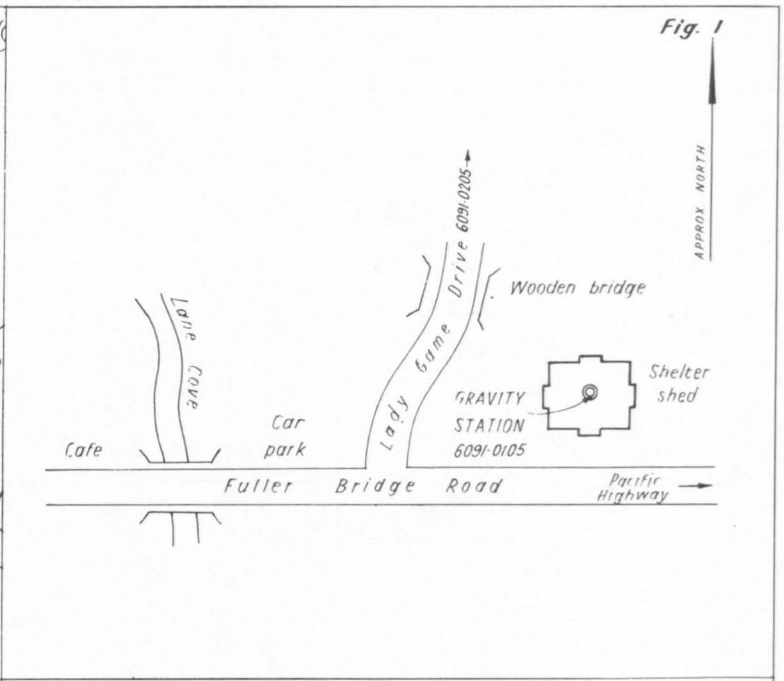




Fig. 1

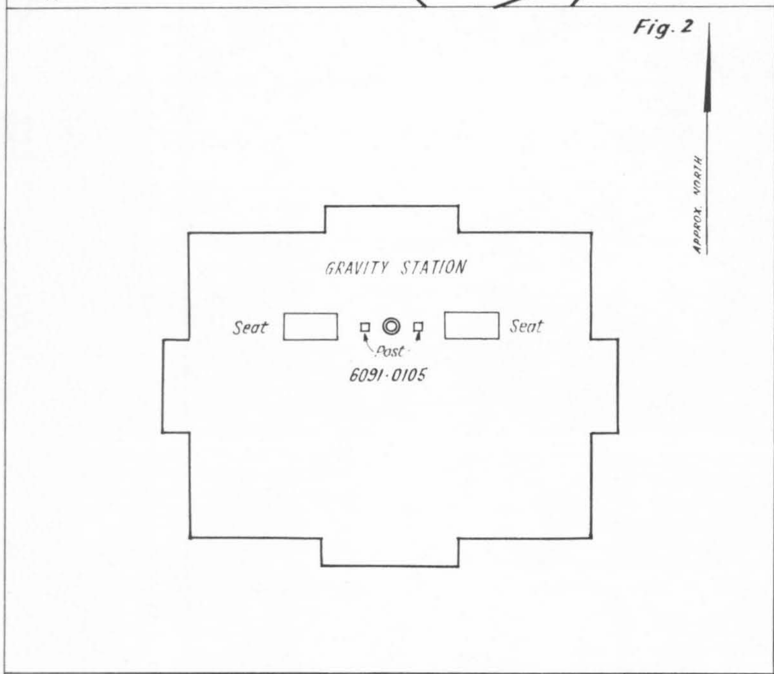



Fig. 2

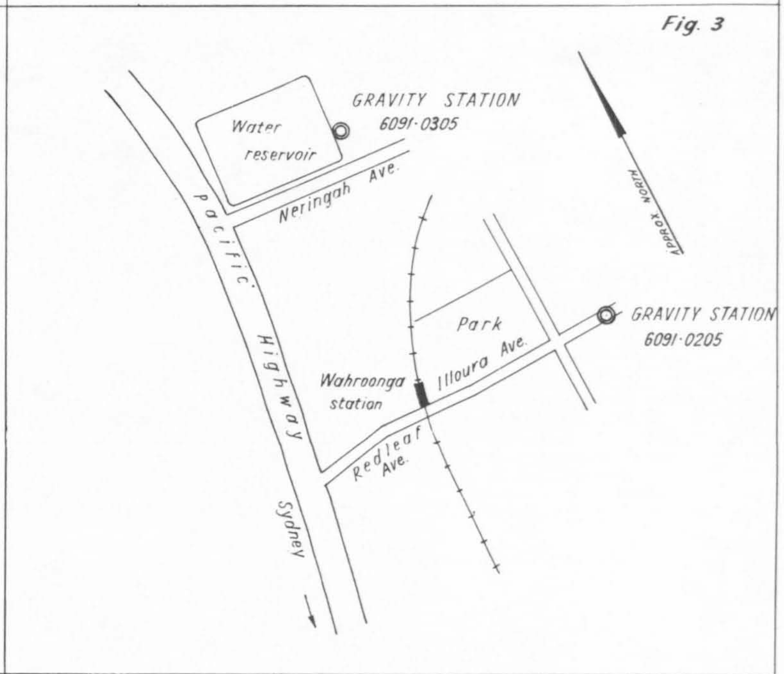



Fig. 3

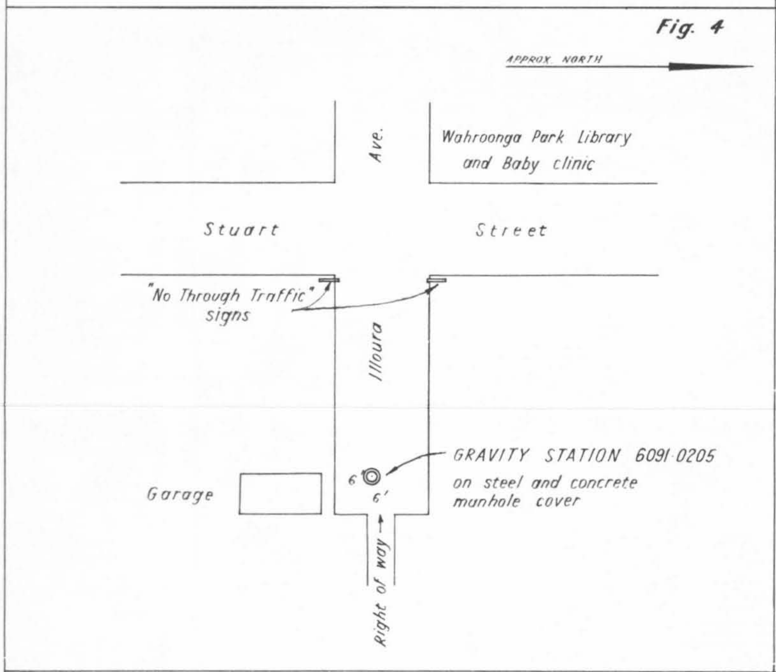



Fig. 4

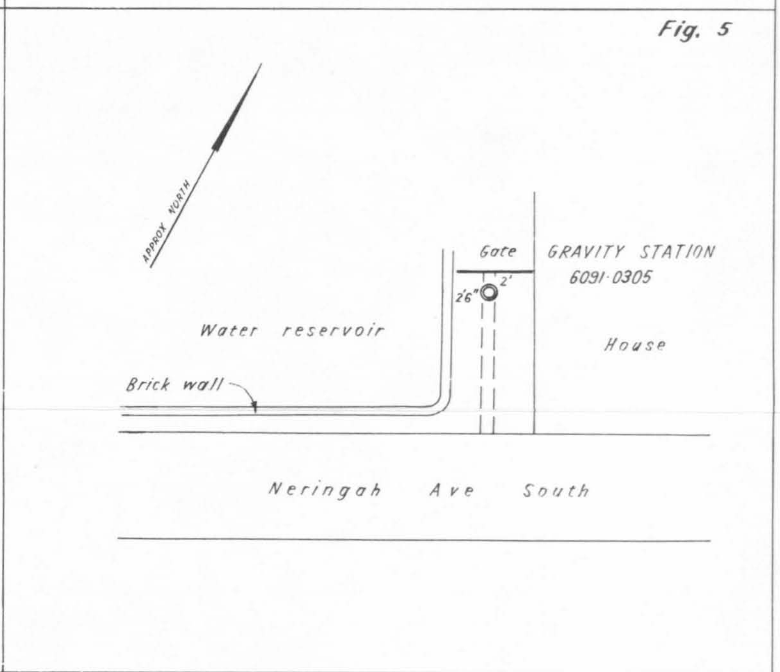



Fig. 5

**Observed gravity interval**

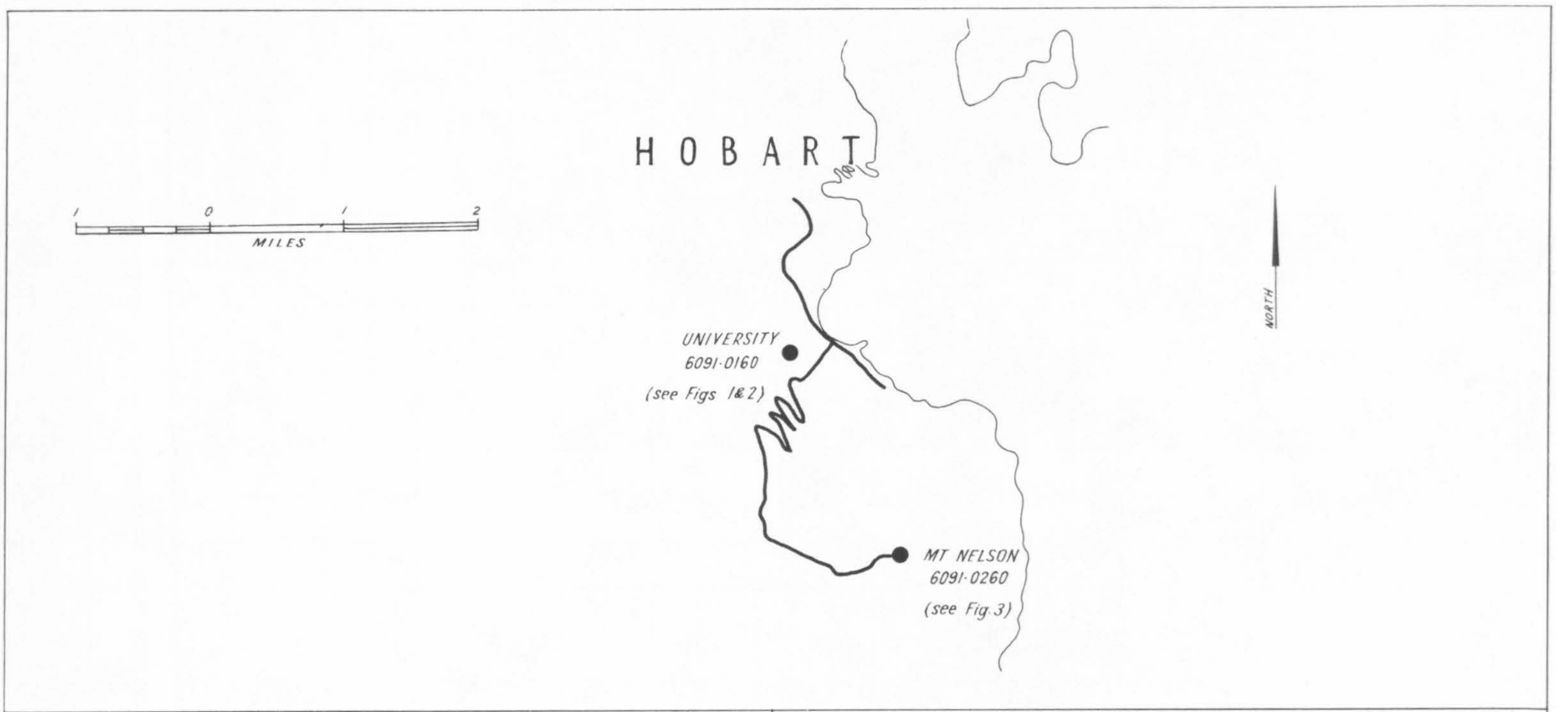
6091·0105 – 6091·0205 = 59·00 mgal (Nov. 1961)
 58.99 mgal (Feb. 1963)
6091·0105 – 6091·0305 = 61·99 mgal (Feb. 1963)

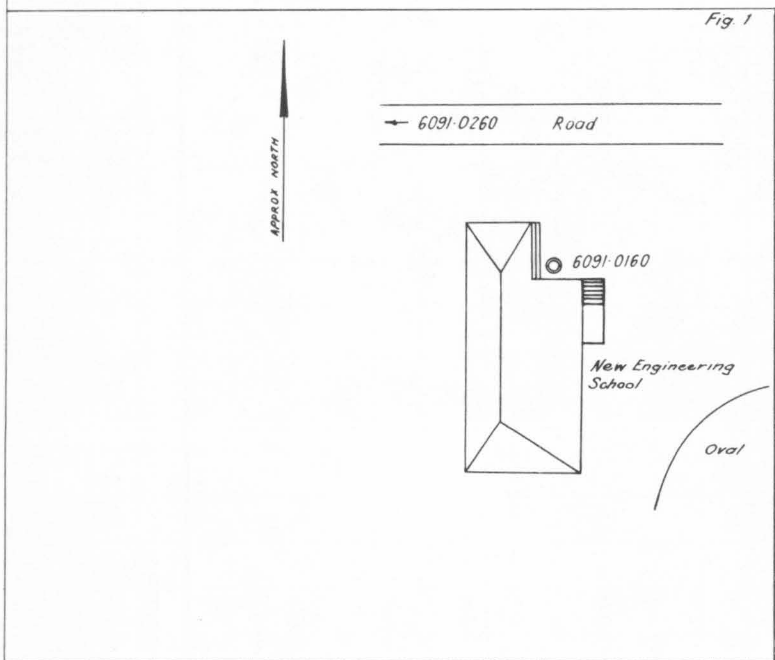
Station 6091·0105 previously referred to as SCS 1
" 6091·0205 " " " " SCS 2
" 6091·0305 " " " " SCS 2A

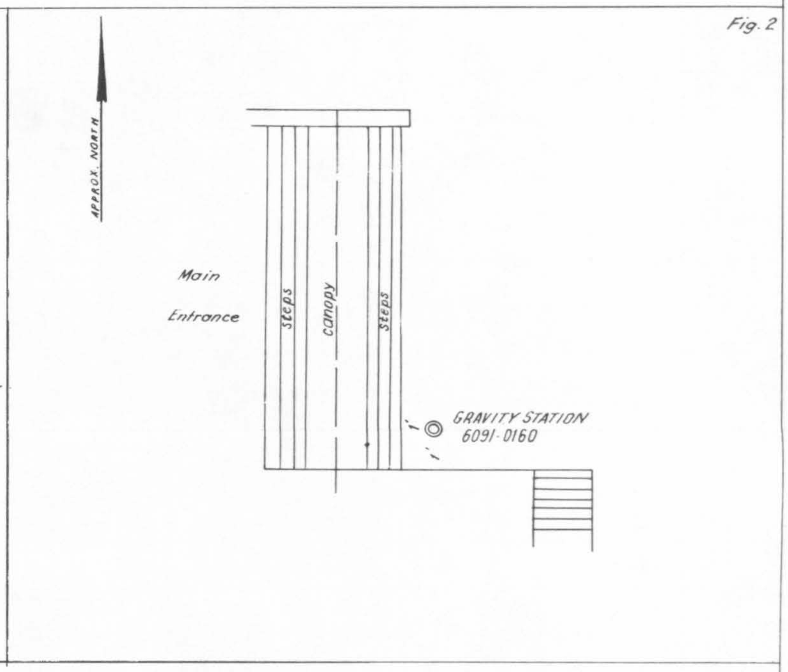
## GRAVITY METER CALIBRATION RANGE
## SYDNEY

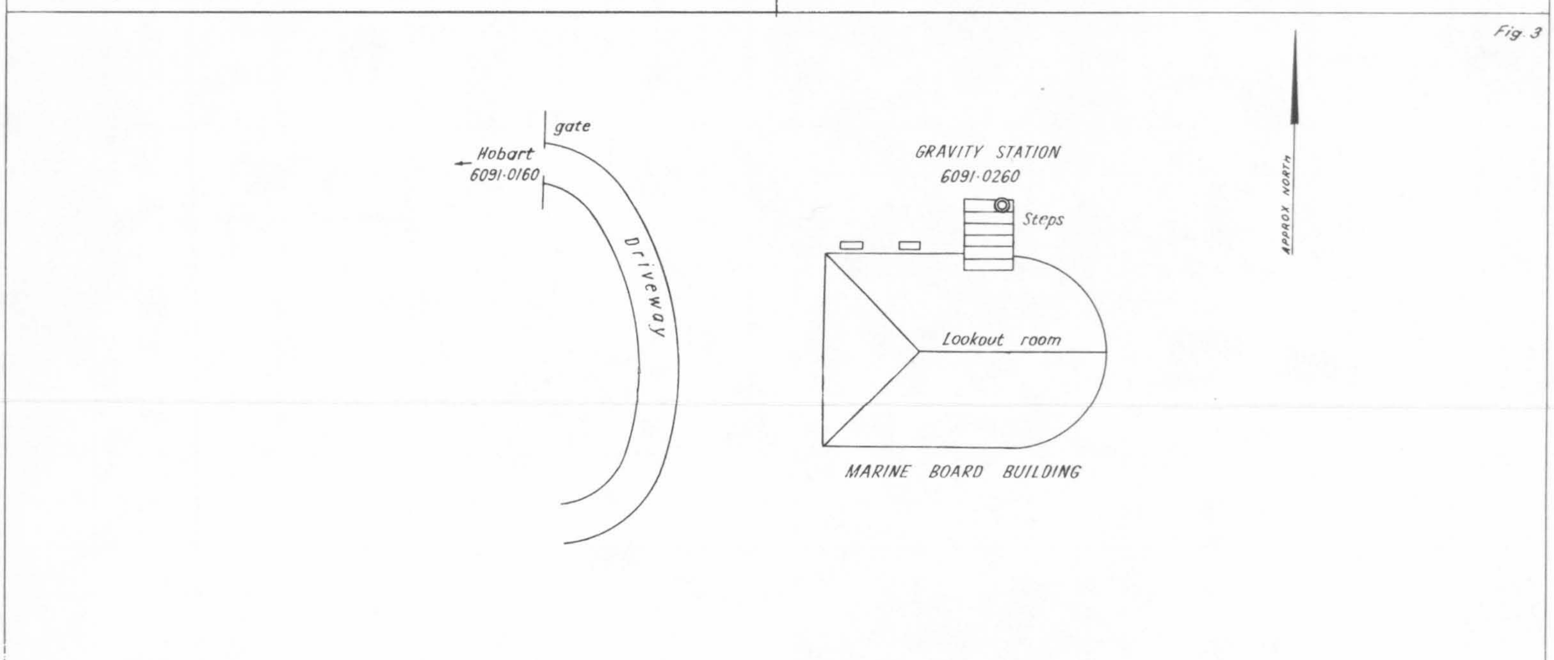
PLATE 8

G24-8



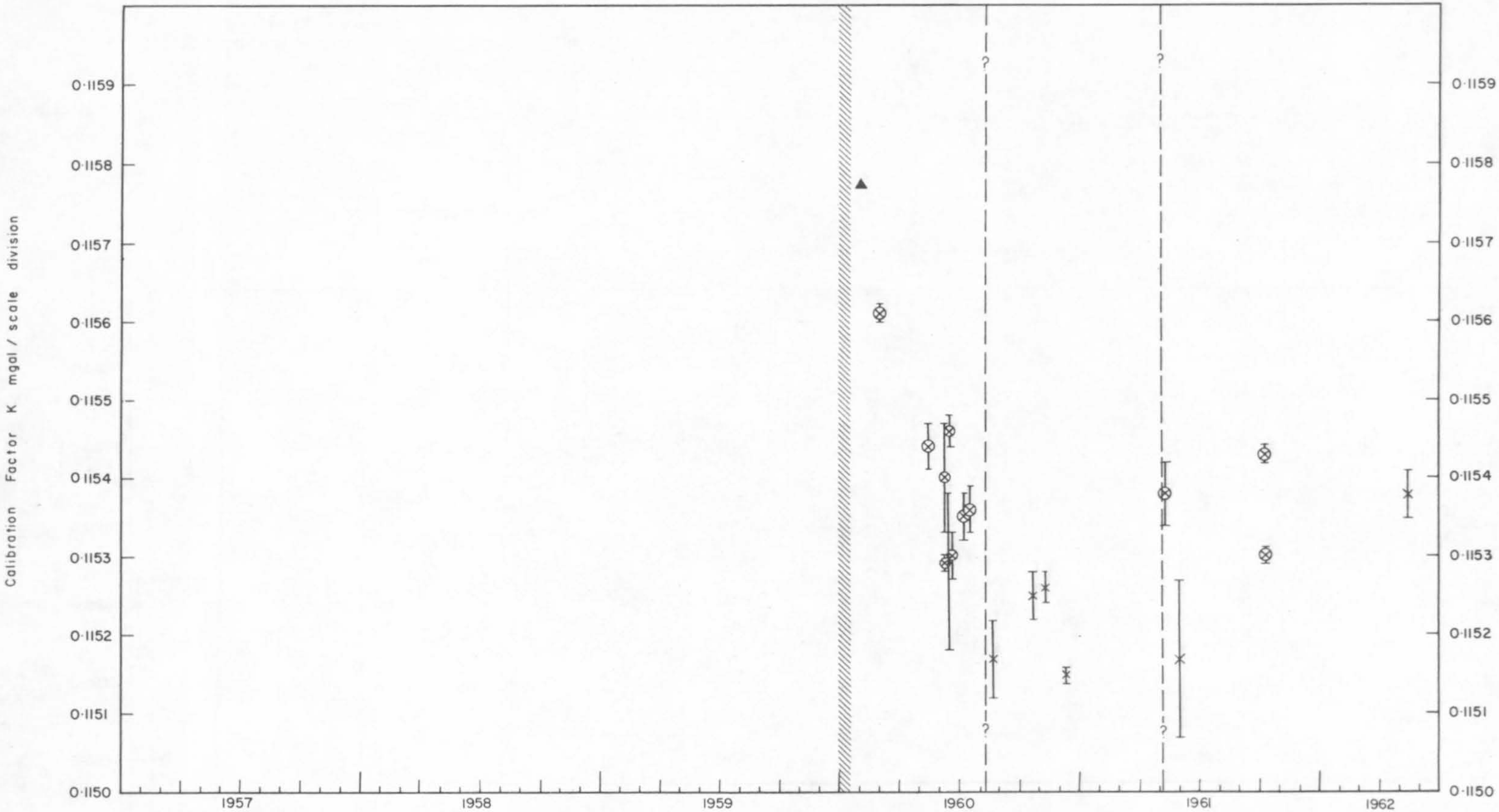

*Observed gravity interval*
*6091·0160 – 6091·0260 = 54·71 mgal (July 1962)*
*54·71 mgal (Feb. 1963)*

*Station 6091·0160 previously referred to as HCS 1*
*" 6091·0260 " " " " HCS 2*

## GRAVITY METER CALIBRATION RANGE
## HOBART

PLATE 9

G24-9




NOTE : Calibrations are plotted chronologically but may not be shown on exact date

LEGEND

Adjusted or repaired by manufacturer

Meter evacuated by BMR

Exact date of evacuation not known

"Absolute" calibration factor supplied by manufacturer

Bureau calibration :

K + $E_K$

K

K − $E_K$

K = Calibration factor

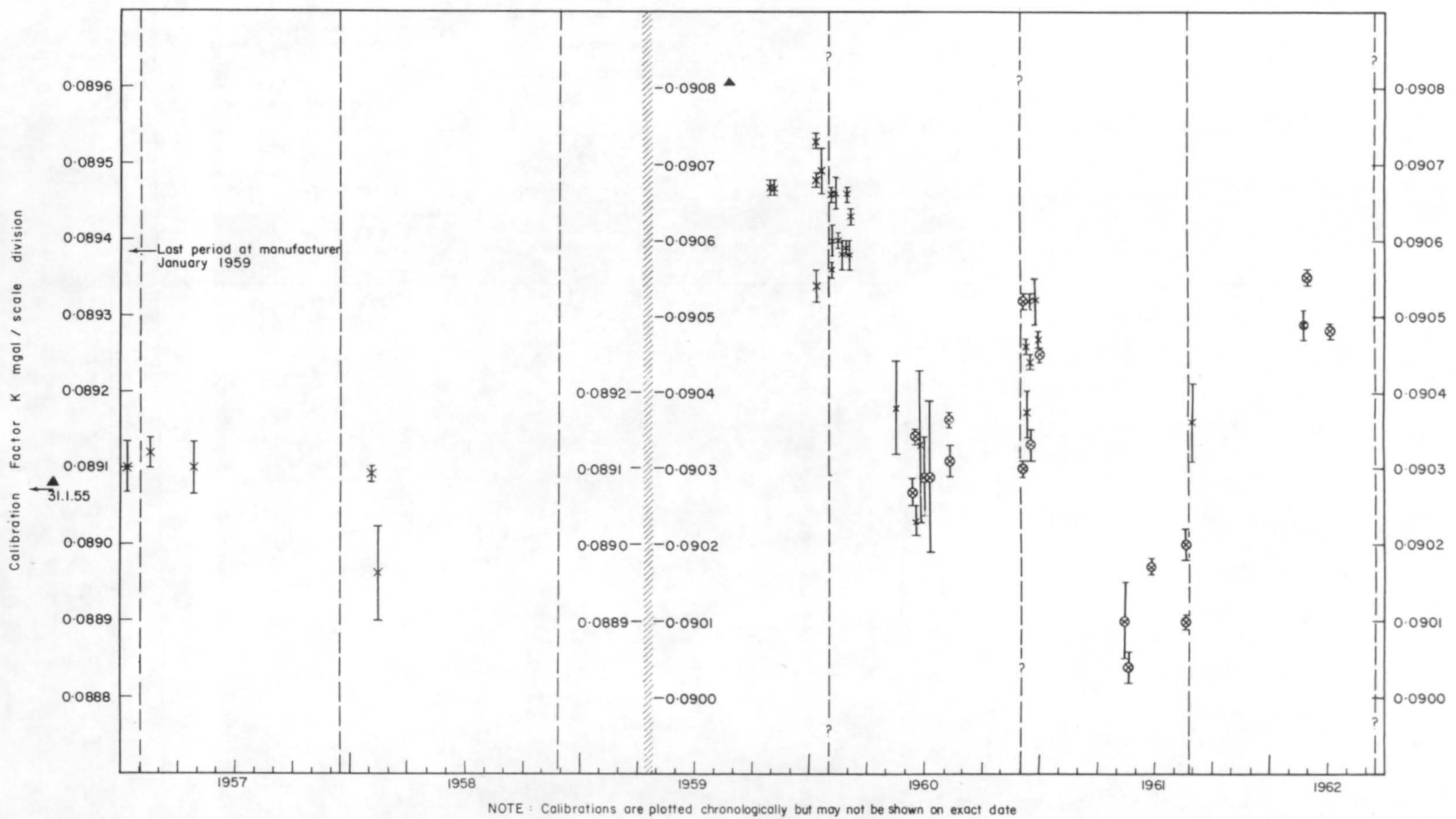
$E_K$ = "Maximum probable error" in K

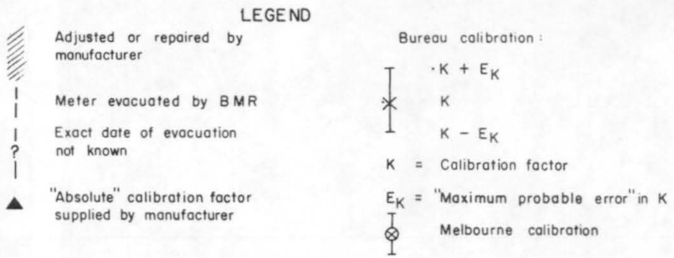
Melbourne calibration

# SUMMARY OF CALIBRATION RESULTS
# WORLD-WIDE 35

PLATE 10

G65-85-1

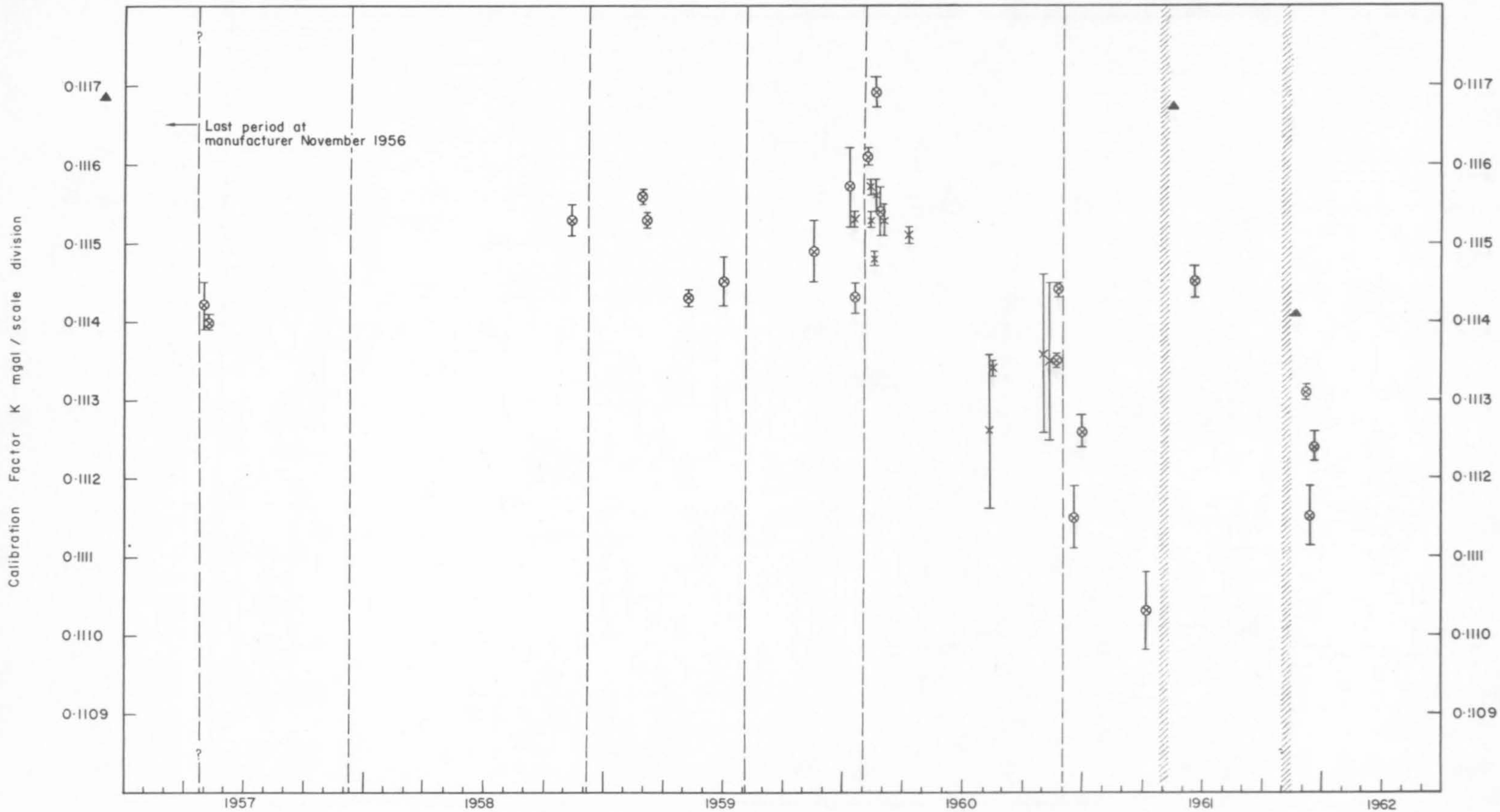



## SUMMARY OF CALIBRATION RESULTS
## WORDEN 61

PLATE II

G65-85-2




NOTE : Calibrations are plotted chronologically but may not be shown on exact date

LEGEND

Adjusted or repaired by manufacturer

Meter evacuated by BMR

Exact date of evacuation not known

"Absolute" calibration factor supplied by manufacturer

Bureau calibration :

$K + E_K$

$K$

$K - E_K$

$K$ = Calibration factor

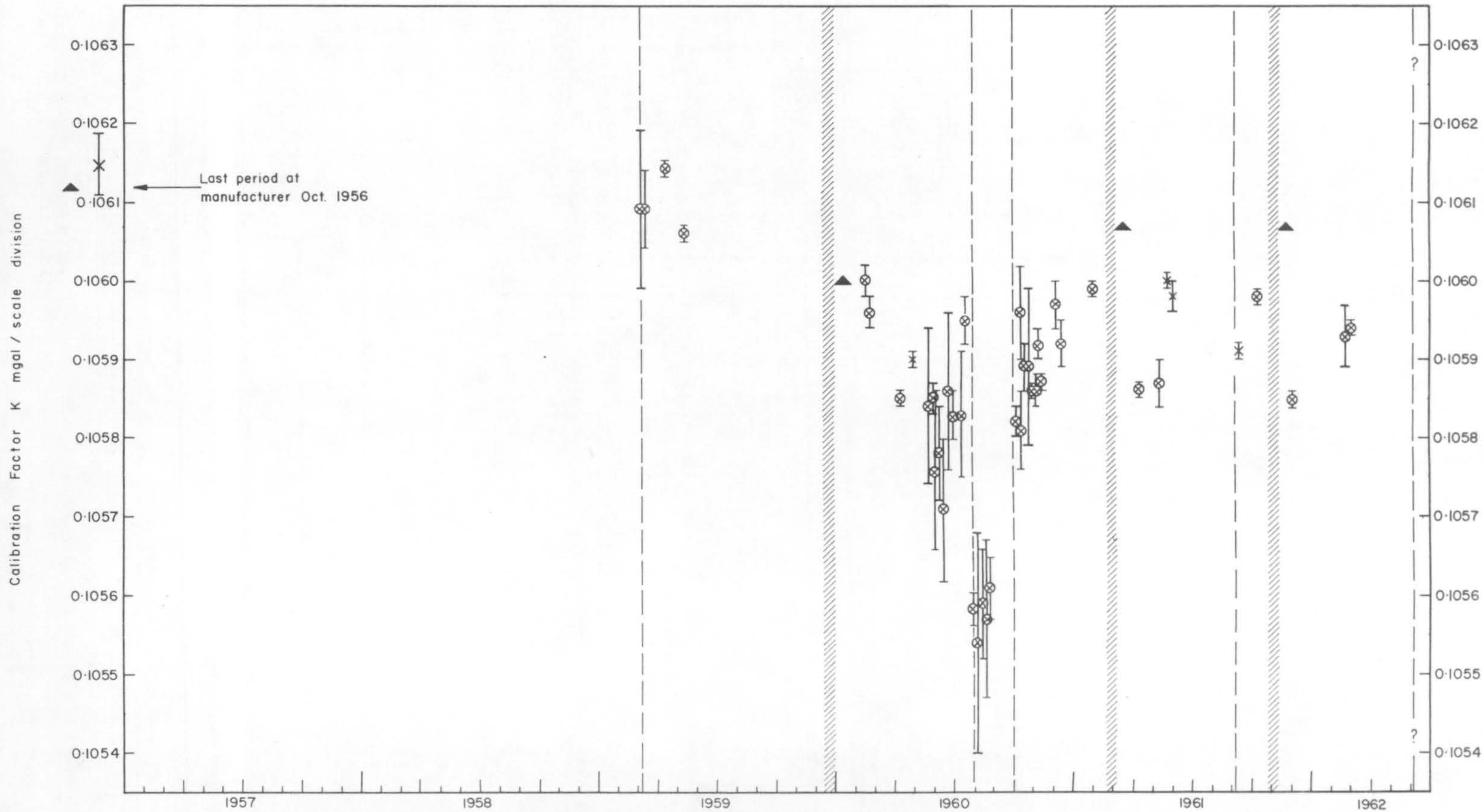
$E_K$ = "Maximum probable error" in $K$

Melbourne calibration

# SUMMARY OF CALIBRATION RESULTS
# WORDEN 140

PLATE 12

G65-85-3




NOTE: Calibrations are plotted chronologically but may not be shown on exact date

LEGEND

Adjusted or repaired by manufacturer

Meter evacuated by BMR

Exact date of evacuation not known

"Absolute" calibration factor supplied by manufacturer

Bureau calibration:

$K + E_K$

K

$K - E_K$

K = Calibration factor

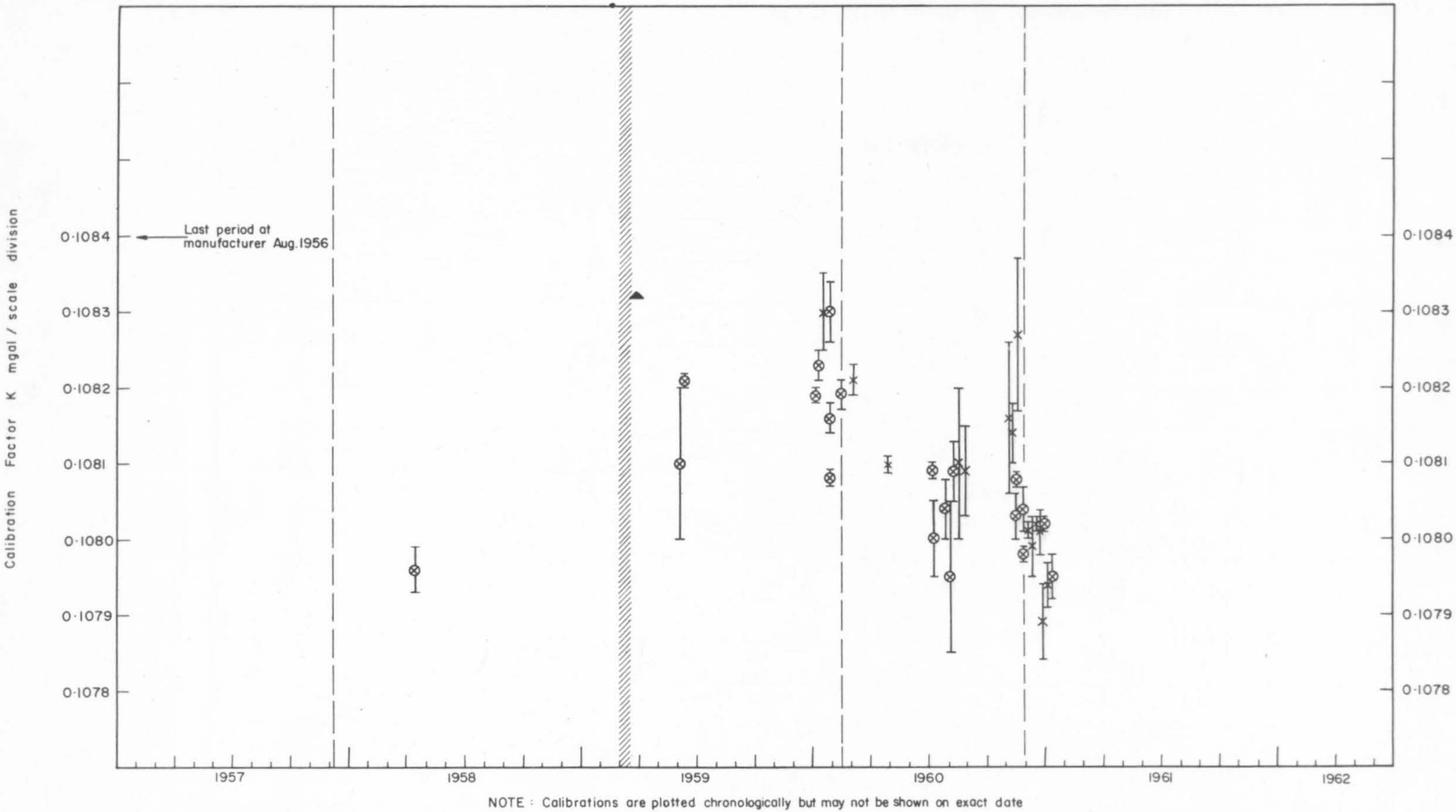
$E_K$ = "Maximum probable error" in K

Melbourne calibration

## SUMMARY OF CALIBRATION RESULTS WORDEN 169

PLATE 13

G65-85-4




NOTE : Calibrations are plotted chronologically but may not be shown on exact date

LEGEND

- Adjusted or repaired by manufacturer
- Meter evacuated by BMR
- Exact date of evacuation not known ?
- "Absolute" calibration factor supplied by manufacturer

Bureau calibration :

- K + $E_K$
- K
- K − $E_K$

K = Calibration factor

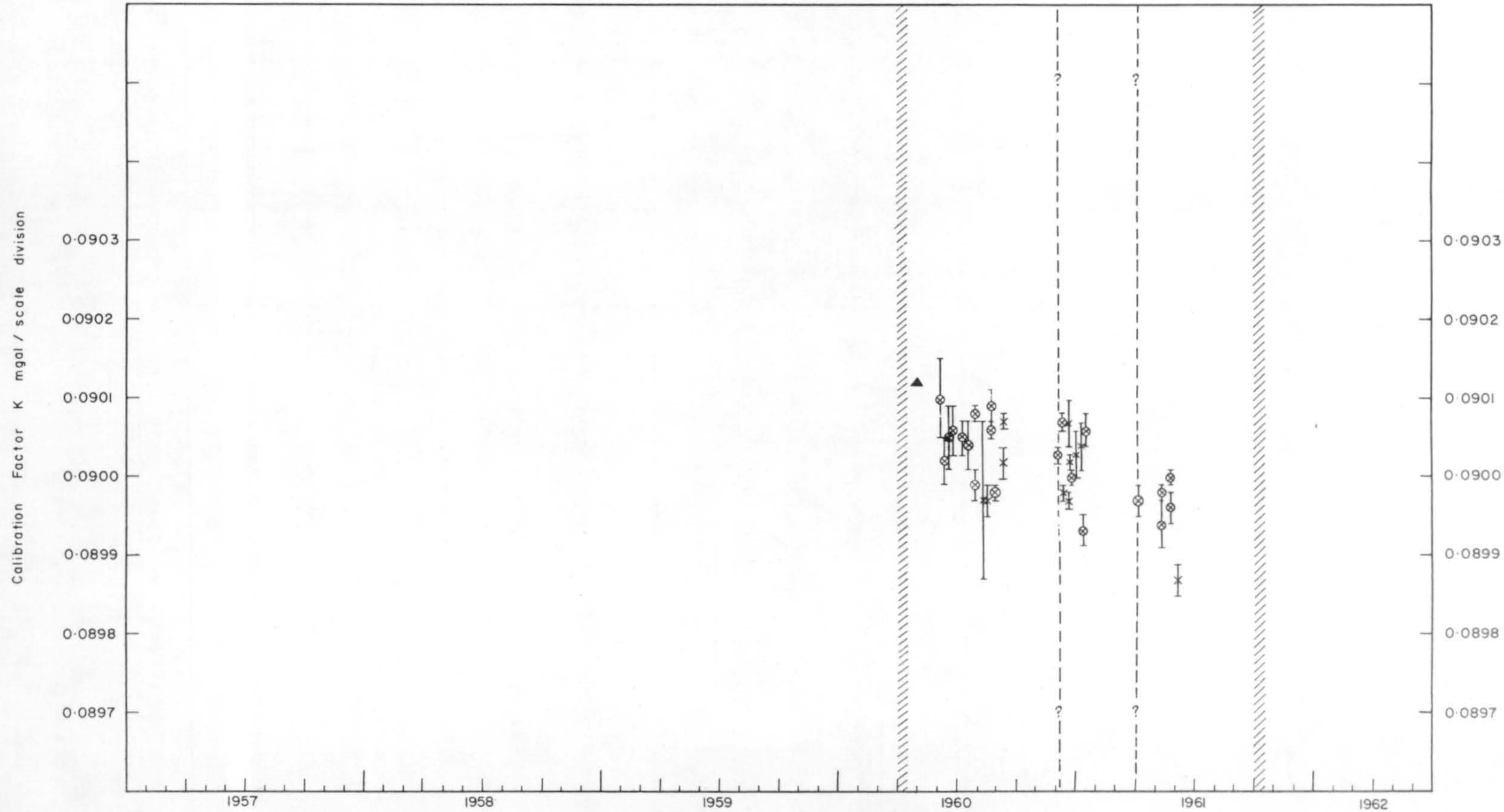
$E_K$ = "Maximum probable error" in K

Melbourne calibration

# SUMMARY OF CALIBRATION RESULTS WORDEN 260

PLATE 14

G65-85-5




NOTE : Calibrations are plotted chronologically but may not be shown on exact date

LEGEND

Adjusted or repaired by manufacturer

Meter evacuated by BMR

Exact date of evacuation not known

"Absolute" calibration factor supplied by manufacturer

Bureau calibration :

$K + E_K$

K

$K - E_K$

K = Calibration factor

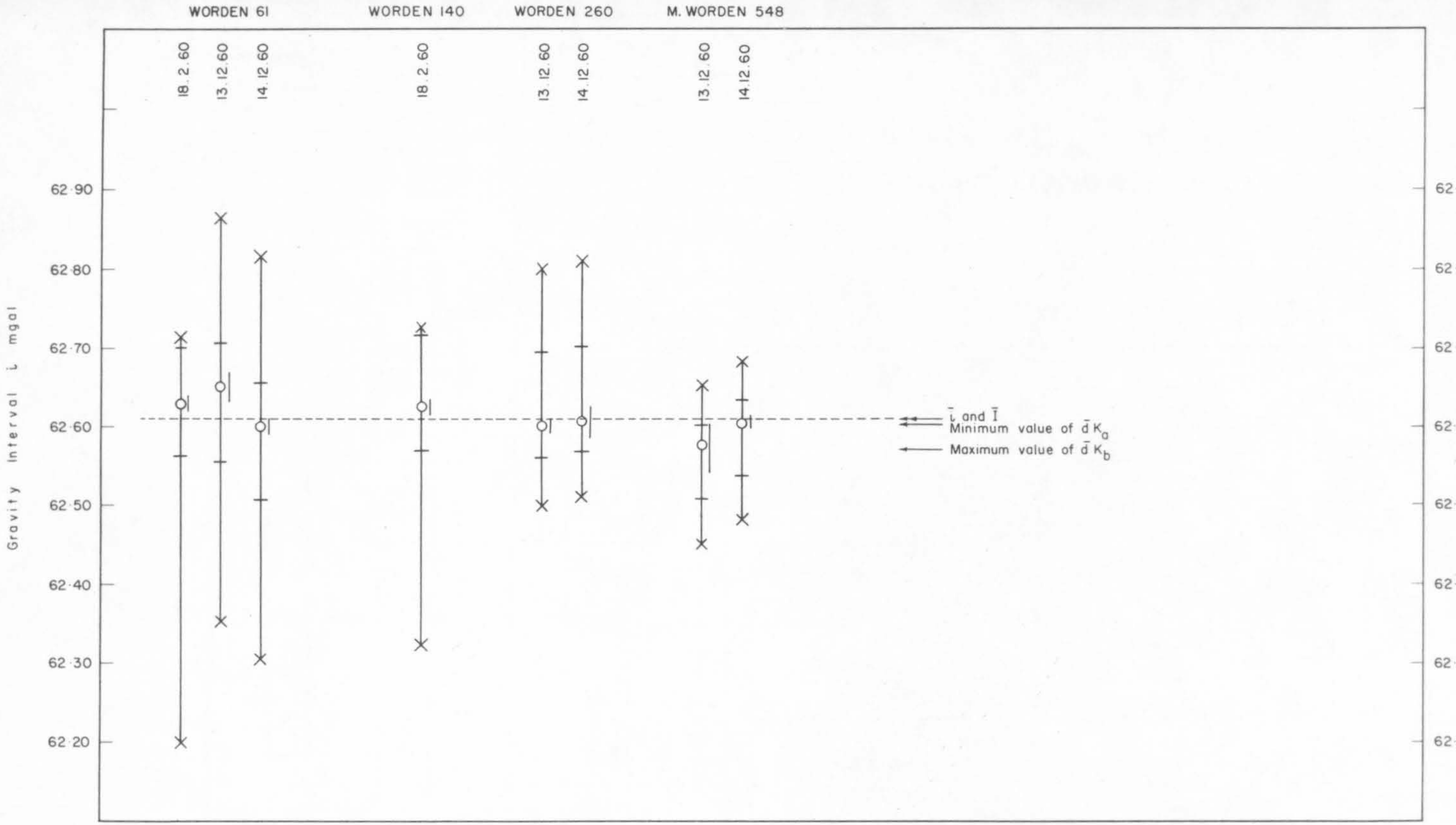
$E_K$ = "Maximum probable error" in K

Melbourne calibration

# SUMMARY OF CALIBRATION RESULTS
# MASTER WORDEN 548

PLATE 15

G65-85-6




LEGEND

- × $\bar{d}\,K_A$
- + $\bar{d}\,K_a$
- ○ $\bar{d}\,\bar{K}$
- + $\bar{d}\,K_b$
- × $\bar{d}\,K_B$
- | $\bar{d}\,\bar{K} \pm \bar{K}E_d$
- – – – ←I Weighted Mean Value
- ←ι Mean Value

K = Calibration factor of gravity meter (mgal / scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

d = Interval measured in scale division

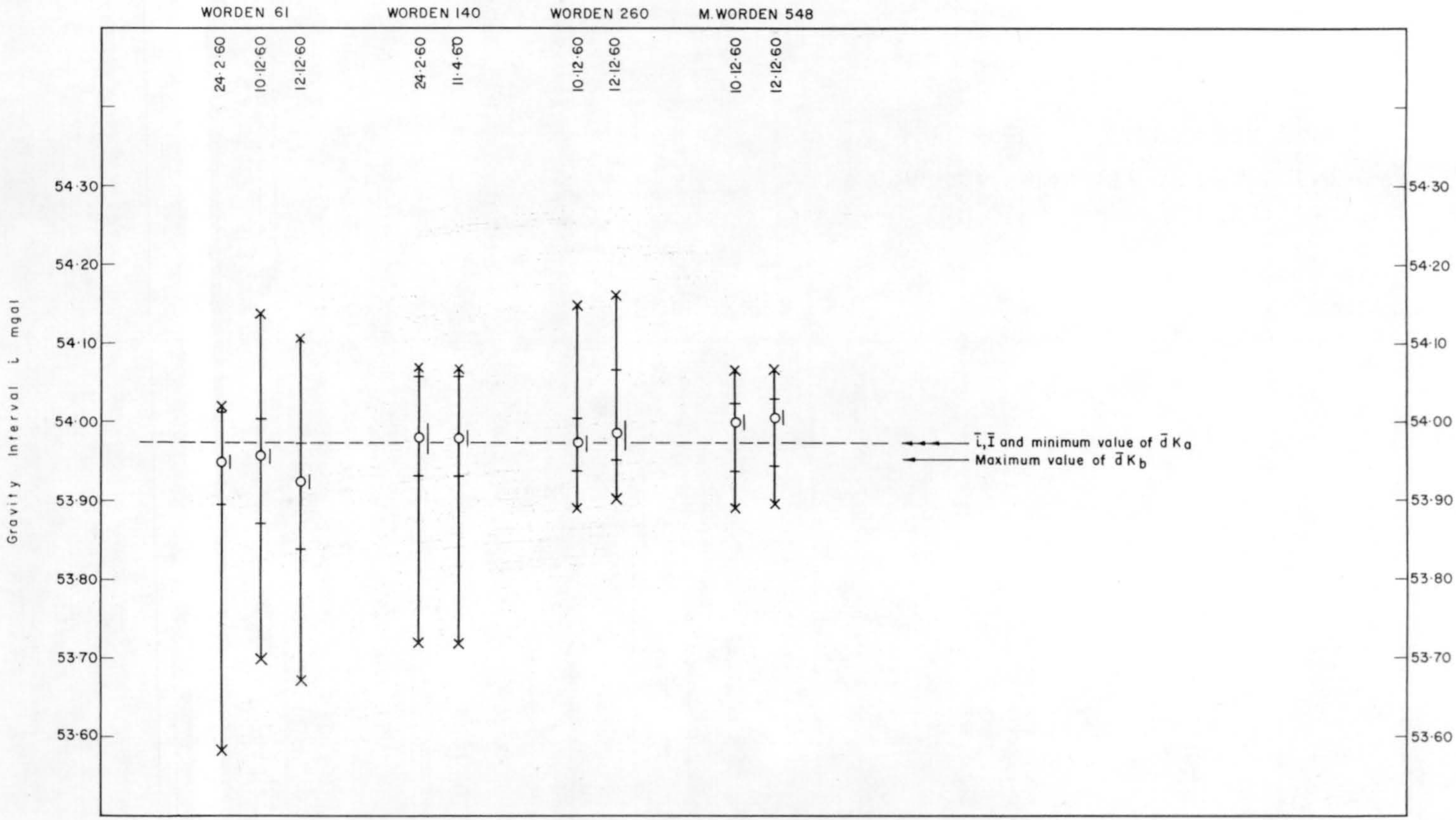
$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

## GRAPHICAL SUMMARY OF MEASUREMENTS
## ADELAIDE CALIBRATION RANGE

PLATE 16

G24-10-1




LEGEND

- ✕ $\bar{d}\ K_A$
- ┼ $\bar{d}\ K_a$
- ○ $\bar{d}\ \bar{K}$
- ┼ $\bar{d}\ K_b$
- ✕ $\bar{d}\ K_B$
- | $\bar{d}\ \bar{K} \pm \bar{K} E_d$
- --- ←I Weighted Mean Value
- ←i Mean Value

K = Calibration factor of gravity meter (mgal / scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

d = Interval measured in scale division

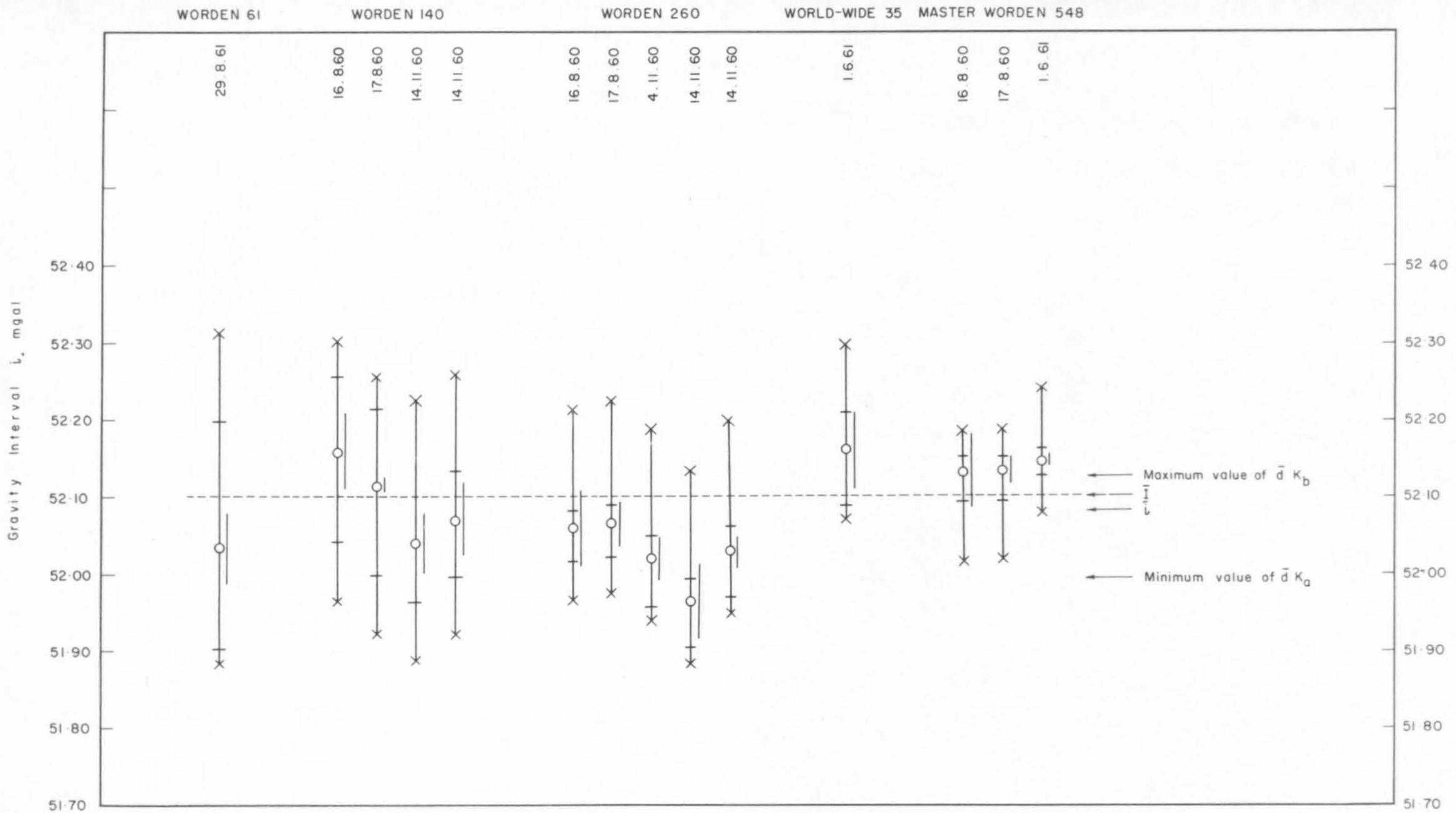
$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

# GRAPHICAL SUMMARY OF MEASUREMENTS
# PERTH CALIBRATION RANGE

PLATE 17

G24-10-2




LEGEND

- × $\bar{d}$ $K_A$
- + $\bar{d}$ $K_a$
- ○ $\bar{d}$ $\bar{K}$
- + $\bar{d}$ $K_b$
- × $\bar{d}$ $K_B$
- | $\bar{d}$ $\bar{K}$ ± $\bar{K}$ $E_d$
- --- ←$\bar{I}$ Weighted Mean Value
- ←ι Mean Value

$K$ = Calibration factor of gravity meter (mgal/scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

$d$ = Interval measured in scale division

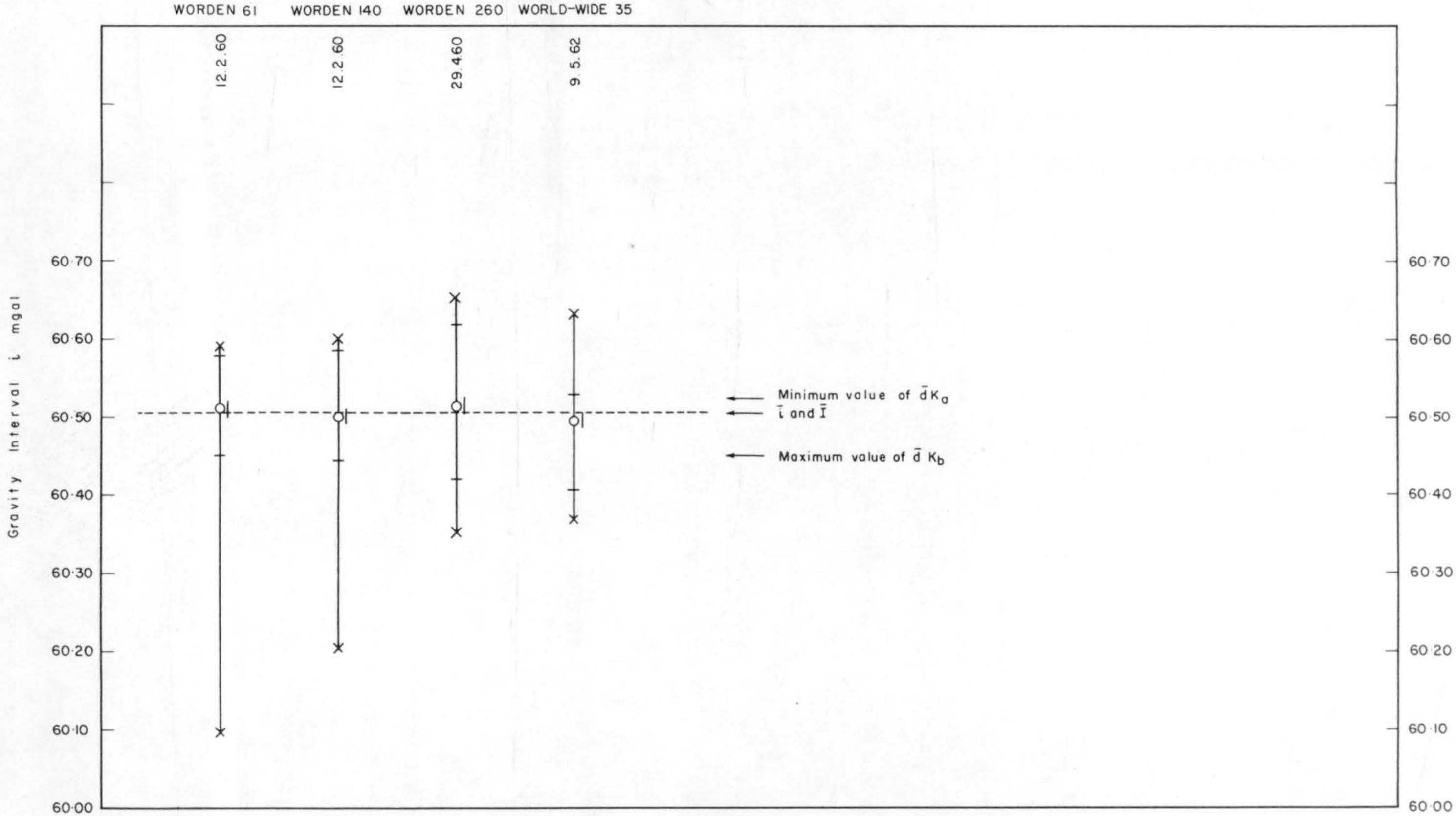
$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

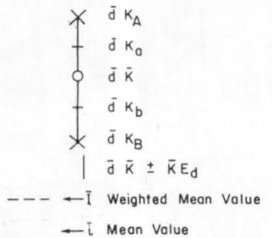
## GRAPHICAL SUMMARY OF MEASUREMENTS ALICE SPRINGS CALIBRATION RANGE

PLATE 18

G24-10-3




LEGEND




K = Calibration factor of gravity meter (mgal / scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

d = Interval measured in scale division

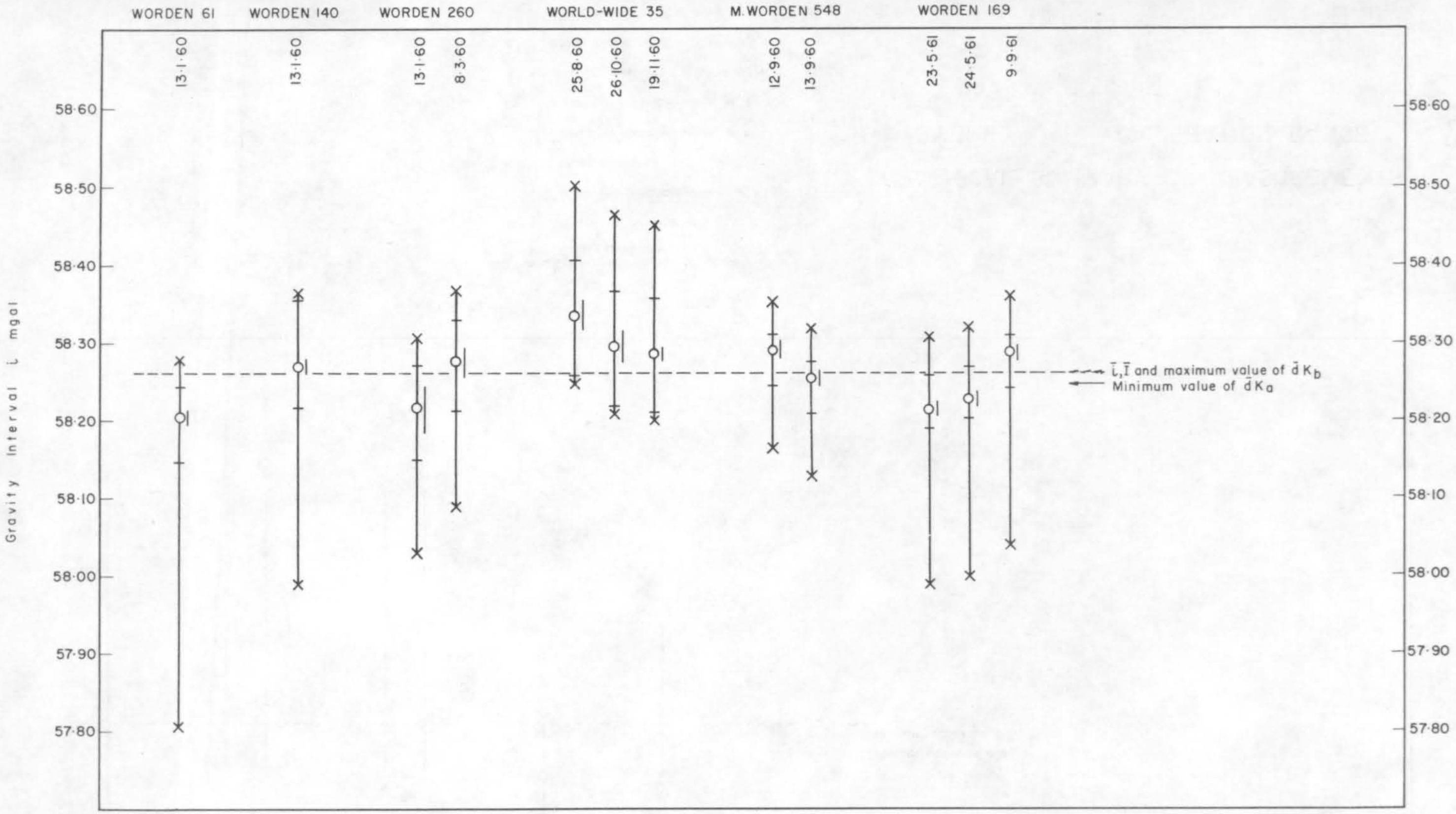
$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

## GRAPHICAL SUMMARY OF MEASUREMENTS
## TOWNSVILLE CALIBRATION RANGE

PLATE 19

G24-10-4




LEGEND

✕ $\bar{d}\ K_A$
\+ $\bar{d}\ K_a$
○ $\bar{d}\ \bar{K}$
\+ $\bar{d}\ K_b$
✕ $\bar{d}\ K_B$
| $\bar{d}\ \bar{K} \pm \bar{K} E_d$
--- ← I Weighted Mean Value
← ι Mean Value

K = Calibration factor of gravity meter (mgal/scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

d = Interval measured in scale division

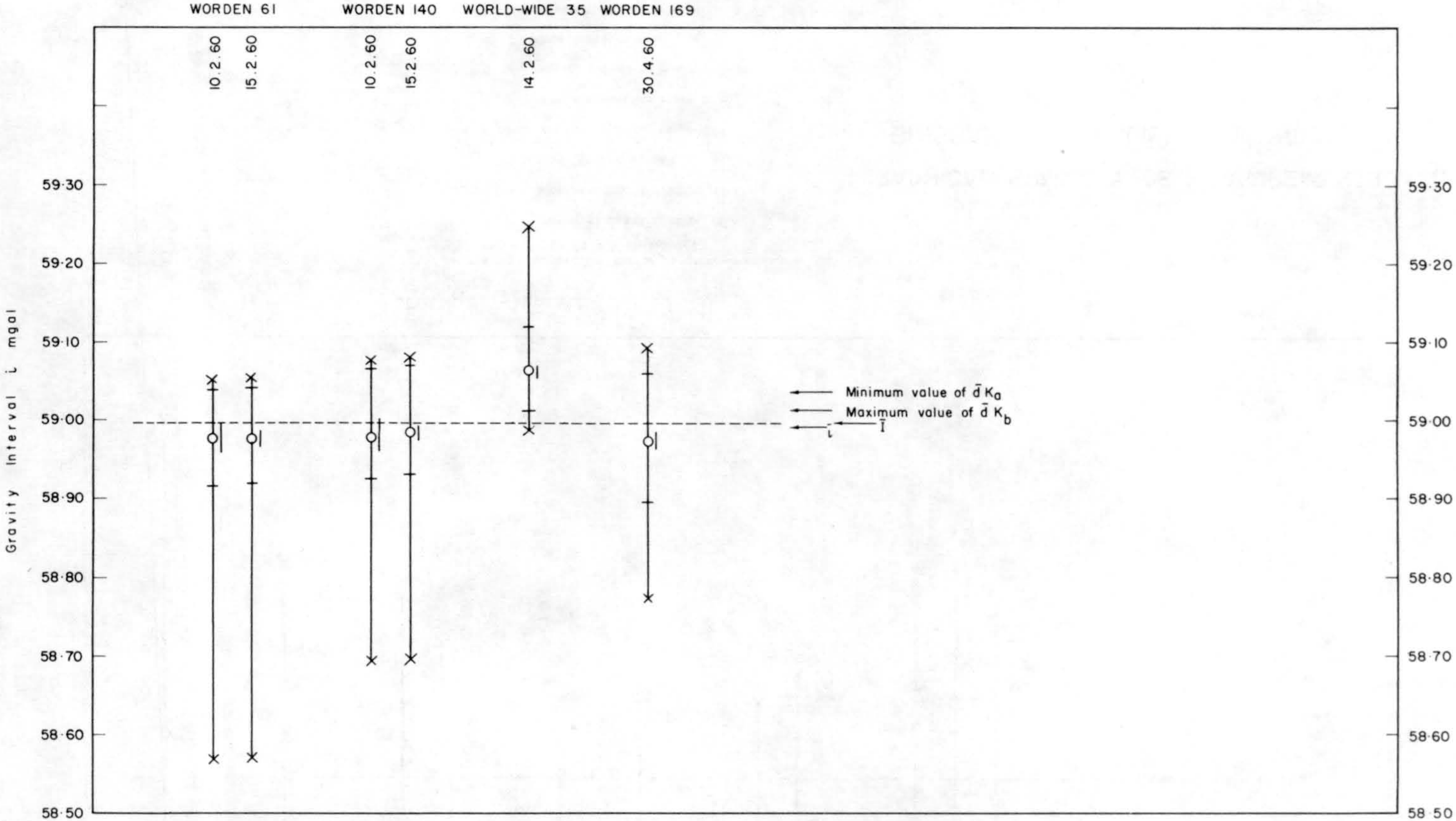
$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

## GRAPHICAL SUMMARY OF MEASUREMENTS
## BRISBANE CALIBRATION RANGE

PLATE 20

G24-10-5




LEGEND

d̄ $K_A$
d̄ $K_a$
d̄ $\bar{K}$
d̄ $K_b$
d̄ $K_B$
d̄ $\bar{K}$ ± $\bar{K} E_d$
--- ←I Weighted Mean Value
←i Mean Value

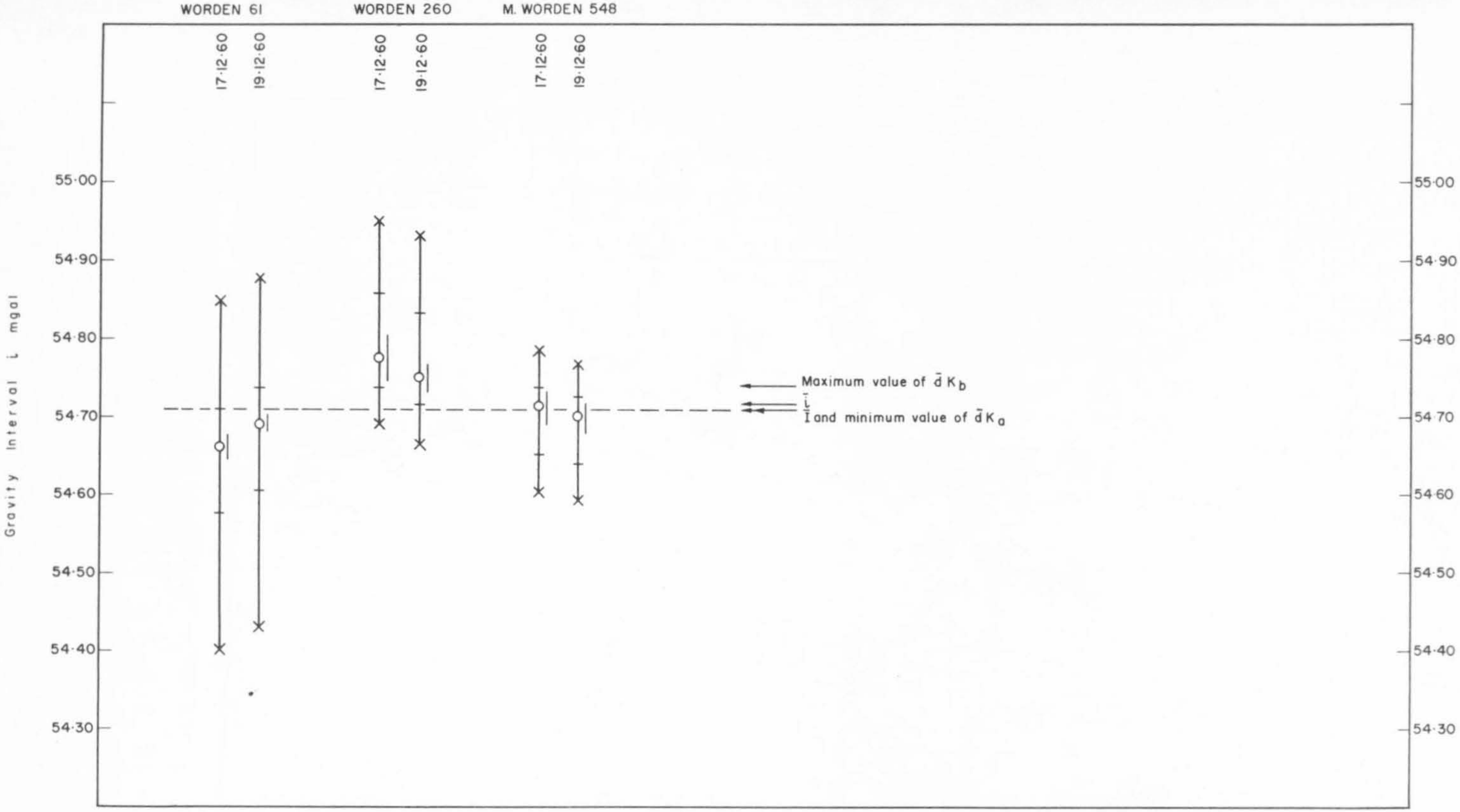
K = Calibration factor of gravity meter (mgal / scale division)
$K_A$ = "Maximum possible value" of K
$K_a$ = "Maximum probable value" of K
$\bar{K}$ = "Most probable value" of K
$K_b$ = "Minimum probable value" of K
$K_B$ = "Minimum possible value" of K
d = Interval measured in scale division
$\bar{d}$ = Mean value of d
$E_d$ = "Maximum probable error" in $\bar{d}$

GRAPHICAL SUMMARY OF MEASUREMENTS

SYDNEY CALIBRATION RANGE

PLATE 21

G24-10-6




LEGEND

- ✕ $\bar{d}$ $K_A$
- ┼ $\bar{d}$ $K_a$
- ○ $\bar{d}$ $\bar{K}$
- ┼ $\bar{d}$ $K_b$
- ✕ $\bar{d}$ $K_B$
- | $\bar{d}$ $\bar{K}$ ± $\bar{K}$ $E_d$
- - - - ←I Weighted Mean Value
- ←i Mean Value

K = Calibration factor of gravity meter (mgal / scale division)

$K_A$ = "Maximum possible value" of K

$K_a$ = "Maximum probable value" of K

$\bar{K}$ = "Most probable value" of K

$K_b$ = "Minimum probable value" of K

$K_B$ = "Minimum possible value" of K

d = Interval measured in scale division

$\bar{d}$ = Mean value of d

$E_d$ = "Maximum probable error" in $\bar{d}$

GRAPHICAL SUMMARY OF MEASUREMENTS

HOBART CALIBRATION RANGE

PLATE 22

G24-10-7

TABLE 3: RELATIONSHIPS OF PERMIAN SUBDIVISIONS PROPOSED BY DIFFERENT AUTHORS

**This Report (Also Mollon, in press)**

| Age | Serocold Anticline | Springsure Anticline | Springsure Shelf |
|---|---|---|---|
| Upper Permian | Blackwater Group* (Malone, Olgers & Kirkegaard, in press) | | |
| Upper Permian | Black Alley Shale* | | |
| Upper Permian | (Mantuan Productus Bed) Peawaddy Formation* (Mollan, Kirkegaard, Exon & Dickins, 1964) | | |
| Lower Permian | Catherine Sandstone | | Colinlea Sandstone |
| Lower Permian | Ingelara Formation* (Raggatt & Fletcher, 1937) | | |
| Lower Permian | Aldebaran Sandstone | upper transition member | |
| Lower Permian | | middle conglomerate member | |
| Lower Permian | | lower sandstone member | Hiatus |
| Lower Permian | Cattle Creek Formation | Sirius Formation* (Webb, 1956) | |
| Lower Permian | | Staircase Sandstone | |
| Lower Permian | | Stanleigh Formation* (Phillips in Hill & Denmead, 1960) | |
| Lower Permian | | Orion Formation (Webb, 1956) | |
| Lower Permian | Reids Dome Beds* | | |

**Reid (1930)[1]**

| Serocold Anticline | | Springsure Anticline |
|---|---|---|
| Upper Bowen | | |
| ? — ? — ? — ? — ? | | |
| Middle Bowen Marine Series* | | |
| Lower Bowen* | Catherine Sandstone* | Serocold Sandstone* |
| | Coral Stage* | |
| | Aldebaran Sandstone* | |
| | Gypseous Marine Stage* | Dilly Beds* |
| | Staircase Sandstone* | |
| ? | Base of outcrop | |

**Hill (1957)**

| Serocold Anticline | Springsure Anticline | Springsure Shelf |
|---|---|---|
| Bandanna Formation* | 'Upper part' | Cheshire Formation* (includes Triassic Rewan Formation) |
| | 'Lower part' | |
| Mantuan Productus Bed* | | Colinlea Formation* |
| Catherine Sandstone | | |
| Ingelara Formation ? | | |
| Aldebaran Sandstone ? | | |
| | | ? — ? |
| Cattle Creek Formation* | | |
| | Staircase Sandstone | |
| | Dilly Beds | |

**Power (1966)**

| Springsure Anticline | |
|---|---|
| Black Alley Shale | |
| Peawaddy Formation | |
| Catherine Sandstone | |
| Ingelara Formation | |
| Freitag Formation* | |
| Aldebaran Sandstone | |
| Cattle Creek Formation | Sirius Mudstone Member |
| | Staircase Sandstone Member |
| | Riverstone Sandstone Member* |
| | Middle Mudstone Member |
| | Lower Mudstone Member |
| Orion Formation | |
| (Reids Dome Beds) | |

**Other names used in Permian stratigraphy**

| Laing (1961)[2]: Southern part of Serocold Anticline | Laing (1961)[2]: Reids Dome part of Serocold Anticline | | |
|---|---|---|---|
| Dry Creek Shale[3] | | Consuelo Stage* (including Consuelo Sandstone* Catherine Sandstone of this Report) (Reeves, 1947) | |
| Early Storms Sandstone[4] | Dry Creek Shale* | | |
| | Early Storms Sandstone* | | |
| | | 'Undivided fresh-water beds' and 'Lower shales and mudstones' (Webb, 1956) | Rolleston Conglomerate* Cundill, Meyers & Associates 1965. |

* First published reference to name

1. Reid mapped Serocold Sandstone and Dilly Beds above the Catherine Sandstone in the East flank of the Springsure Anticline because he did not recognize the Consuelo Anticline, and postulated a non-existent major Consuelo Fault (down on south) between the Springsure and Serocold Anticlines.
2. The ambiguity arose essentially because the wedge-out of the Catherine Sandstone at the southern end of Reids Dome was not recognized.
3. First published Allen (1962)
4. First published Sanker (1962)