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National Report on Gravity in Australia,

July 1965 to June 1970

by

B.C. Barlow

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ILLUSTRATIONS

SUMMARY

Between July 1965 and June 1970, gravity activities in Australia have continued to increase steadily.

During this 5-year period, reconnaissance gravity coverage was obtained over 3¼ million square kilometres of the Australian continent, 80 percent of which has now been covered; at least half of the Territory of Papua & New Guinea (TPNG) now has at least regional coverage. Helicopter transport has been a deciding factor in achieving this rate of production. A substantial portion of the continental shelf also was covered by marine gravity surveys.

Excellent results have been obtained from an absolute determination of gravity by a rise and fall method at the National Standards Laboratory in Sydney.

Australia's pendulum apparatus has continued to give unsatisfactory results but it is hoped that new pendulums having extremely low-angle knife-edges will give better results when used with a new timing system. Successful pendulum observations have been made in Australia by visitors from overseas.

Gravity meter observations have been made on the Western Pacific and Australian Calibration Lines by Australian and overseas observers. Observations of the 'Isogal' project are now complete, and an excellent set of values are available for base stations of the gravity reference network of Australia and TPNG.

Automatic data processing is assisting in the reduction and interpretation of data from current surveys, but re-computation and compilation of earlier surveys to modern standards is proceeding only slowly. A preliminary Bouguer anomaly map showing contours for most of Australia is available.

No useful records of tidal gravity have been obtained in Australia, but recording gravity meters are under development and it is hoped that a set of horizontal pendulums will be installed soon.

The orientation of the Australian spheroid is being studied at the University of New South Wales. Data calculated from the well-established gravity field in Australia compare favourably with astro-geodetic results in this important research into physical geodesy.

1. INTRODUCTION

This report is intended for presentation at the 6th Meeting of the International Gravity Commission (IGC) of the International Association of Geodesy, to be held in Paris in September 1970. The Commission normally meets triennially, but the 6th Meeting was postponed from 1968 to 1970. The present report therefore covers activities for the period from July 1965 to June 1970.

National reports to the previous meetings of IGC held in 1959, 1962, and 1965 were prepared by Dooley (1959), Langron (1966a), and Dooley (1965a) respectively. National reports including a section on gravimetry have also been prepared for the general assemblies of the International Association of Geodesy. The gravimetry section for the last report in this series was prepared by Barlow (1968) and covers the period January 1963 to December 1966. It therefore overlaps the present report to some extent.

Acknowledgement is made for information supplied by other Commonwealth Government Departments; the National Standards Laboratory of the Commonwealth Scientific and Industrial Research Organisation, Sydney; the Mines Departments of South Australia and New South Wales; various universities throughout Australia and particularly the geodetic contribution of the School of Surveying, University of New South Wales. The contribution made to the gravity coverage of Australia by numerous petroleum and mineral exploration companies is also acknowledged.

The Bureau of Mineral Resources, Geology & Geophysics (BMR) is the responsible government authority on gravity matters in Australia. This report has been prepared in the Geophysical Branch of BMR.

2. ABSOLUTE MEASUREMENT OF GRAVITY, AND NATIONAL GRAVITY BASE STATION

Satisfactory progress is being made at Sydney in the absolute determination of gravity by the National Standards Laboratory (NSL) of the Commonwealth Scientific & Industrial Research Organisation. The National Gravity Base Station remains the First Order World Gravity Station at Melbourne.

The absolute measurement is being made at NSL which is located in the grounds of Sydney University, NSW. The method is free rise and fall in vacuum of a metal corner reflector through horizontal planes defined interferometrically. A separate report on this work will be presented to the 6th Meeting of the IGC (Bell, 1970).

A preliminary value based on 51 determinations is 979 671.34 mgal with a standard deviation of 0.2 mgal at the site of the measurement. This site is 1.1 metres above floor level and 2 metres south of the brass disc marking BMR station 5099.9905 (Sydney A). The corresponding value of gravity at floor level is 979 671.7 mgal. This may be compared with the BMR value to Potsdam datum of 979 685.74 mgal at station 5099.9905 and indicates a correction of -14.0 mgal to the present Potsdam datum.

It is possible that the absolute measurement may be influenced by systematic errors, and various possible sources of systematic errors are now being investigated.

The First Order World Gravity Station at Melbourne has been the National Gravity Base Station for over twenty years. Although control of the building in which this station is located has passed out of the hands of BMR, access to the site can usually still be arranged. The problem of selecting a new National Base has not yet arisen (see Dooley, 1965a). The base is protected by excentres which have been tied accurately to it, and access to many of these excentres is always available.

Because of the importance of the absolute determination of gravity in Sydney, it is recommended that Sydney be included in the itinerary of any proposed international gravity tie to Australia. It is requested that organisations planning to make such ties should contact BMR well ahead of the proposed work, so that access to sites can be arranged and so that BMR can provide the observers with up-to-date station descriptive material for designated base stations in Australia or its Territories.

3. PENDULUM MEASUREMENTS

Although BMR made some pendulum observations in Australia during the period 1965-70, the gravity differences resulting from this work cannot be used because of the poor quality of the data. Major development of the BMR pendulum apparatus, including the construction of the new pendulums and timing gear, is under way. Overseas organisations have made international pendulum ties to Australia.

Reports have been issued on the earlier work carried out with the BMR pendulums, which were manufactured by Sokkisha Ltd to the design of the Geographical Survey Institute (GSI) of Japan. Langron (1966b) reported the results of the 1962-64 pendulum tie between Tokyo and Melbourne which showed a discrepancy of about 2½ mgal from previously published values. Shirley (1966a) reported on BMR pendulum measurements at various base stations of the Australian Calibration Line (ACL) on the east coast of Australia. The results of these measurements revealed even more serious discrepancies, and examination of the knife-edges and agate bearing plates indicated flaws thought to be the main sources of error.

The pendulums and swinging chamber were returned to Sokkisha which re-worked the knife-edges and agate bearing plates during 1966. The apparatus was tested thoroughly during 1967 (Cooke, in preparation a), when BMR was fortunate in having available the services of Mr T. Seto of GSI who has had considerable experience with this type of apparatus. A very large number of swings were made at Canberra to test repeatability of period determination, period-amplitude relationship (which was found to be anomalous), amplitude decay, and temperature coeffecients of the pendulum periods. A pendulum tie was made over the small (70 mgal) interval Canberra-Sydney, the BMR apparatus being swung side-by-side with the Japanese set (see below). Another pendulum tie, with long series of extended swings at two temperatures, was made over the large (1300 mgal) interval Canberra-Darwin. The results of these tests showed that, although gross discrepancies had been eliminated, inconsistencies in the measured periods were still such as to give an experimental error of ± 1 mgal in measured intervals. The preliminary values for the above two ties agree with accepted values to within these limits. The decay of the amplitude of swing of the pendulums was investigated, with unexpected results. It appears that the decay constant slowly increases as a swing proceeds; in fact the fourth root of the amplitude was found to be linear against time for single swings of up to 3 hours. During a series of swings the constant derived from this relationship tends to increase. Both of the constants had been expected to decrease as the knife-edge and bearing plate became "run-in".

It was decided to construct a new set of quartz pendulums having extremely low-profile knife-edges, and to develop concurrently a new set of timing apparatus to provide more detailed period data. Extremely low-profile knife-edges have been developed by NSL for use on the beams of precision balances. Caw (1969) has shown that the deformation in a knife-edge and its bearing plate is purely elastic provided the angle of the knife edge is within a few degrees of 180°. It is expected that the elimination of non-elastic deformation from the operation of the knife-edge during pendulum swings will improve the accuracy of pendulum measurements. NSL has constructed the new pendulums and approximately equalised their periods.

In the meantime, BMR has designed and constructed new solid-state electronic timing equipment. The time reference is a rubidium frequency standard. The counting circuitry is such that the average of ten swings is counted automatically and displayed on indicator tubes every fifty swings. The new timing equipment will provide more detailed period data than was available from the cumbersome earlier unit and will virtually eliminate the time involved in data scaling and reduction.

It is now proposed to test both the new and the old pendulums using the new timing equipment. A need for an accurate record of amplitude decay is foreseen and apparatus for this purpose is in the design stage.

Cambridge University, U.K. made pendulum gravity observations at the National Gravity Base Station in 1967 as part of measurements on the Western Pacific Calibration Line (WPCL) (Browne & Honkasalo, 1970). The unfortunate illness of Mr B.C. Browne at Singapore prevented repeat observations being made in Melbourne prior to final swings in Teddington, U.K. This weakened the international ties made between Australia and other countries of the WPCL and also the direct tie Teddington-Melbourne.

GSI, Japan made a pendulum tie between Tokyo and Sydney and Canberra in 1967. As mentioned earlier in this chapter, the BMR and GSI sets of pendulum apparatus were used side-by-side in Sydney and Canberra.

In May 1967 the above three sets of pendulum apparatus were swinging in Australia!

During 1970, GSI made another pendulum tie to Australia, this time between Tokyo and Brisbane. The results of this work are not yet to hand.

4. INTERNATIONAL GRAVITY METER MEASUREMENTS

International gravity meter ties to Australia by several Australian and overseas organisations have further strengthened world networks.

During 1966, the United States Air Force (USAF) made gravity ties connecting Australian stations directly to Johannesburg, Singapore, and Fiji as part of a series of east-west international ties designed to link together the various north-south international calibration lines. The four La Coste & Romberg gravity meters used for this work were the same meters as had been used during 1965 for measurements on the Western Pacific Calibration Line (WPCL) and that portion of the Australian Calibration Line (ACL) which lies between Melbourne and Cairns. Results of the 1965 work are reported by Whalen (1966) and Shirley (1966b). Results of the 1966 work have not yet been published.

The Dominion Observatory of Canada used two La Coste meters to measure gravity intervals on the WPCL and ACL during 1966. The places visited were the same as those which had been observed by USAF during 1965. Observations were also made at a few stations on a north-south line passing through the centre of Australia.

Other international ties to Australia by overseas organisations were made by the Royal Thai Survey Corps during 1967, and by the United States Navy Hydrographic Office as part of Project Magnet during the period being reviewed.

In 1966, the Antarctic Division of the Commonwealth Department of Supply made a gravity tie between Melbourne (Australia), Christchurch (New Zealand), and McMurdo and Byrd Stations (Antarctica) using the Antarctic Division La Coste meter and one borrowed from BMR. Transport for this ladder sequence tie was by USAF aircraft. Most of the difference of 1 mgal between the results of the two meters for the large gravity interval Christchurch-McMurdo is accounted for by a scale difference between meters for the almost equivalent tie Japan-Alaska made in 1969 by BMR.

During 1967 BMR made a three-meter tie between the Australia/TPNG gravity network and Honiara, British Solomon Islands Protectorate - see Chapter 5.

During 1969 BMR measured the gravity intervals along most of the WPCL and the most northern part of the North American Calibration Line as shown in Plate 1 (Cooke, in preparation b). A complete ladder sequence Sydney-Darwin......Point Barrow......Darwin-Sydney was observed, and ladder sequences to the north and south of Tokyo gave measurements on the Japanese Calibration Line extending from Sapporo to Kumamoto. Four La Coste meters were used - three BMR meters plus the Antarctic Division meter. On this run, two of the meters gave excellent results that require only linear scale factor correction to give gravity intervals in very good agreement with the mean result of the four La Coste meters used by USAF in 1965. The behaviour of the other two meters was not so consistent and their results are considered to be less reliable. Cooke (in preparation c) is analysing the results of this work together with measurements made on the ACL during 1970 (see Chapter 5); he will give gravity values for the international stations based on accepted Australian datum and milligal standards. An early result of this analysis is that the scales and datums of the Japanese and Australian gravity networks are in good agreement.

5. AUSTRALIAN NATIONAL GRAVITY NETWORK - ISOGAL PROJECT

The Australian National Gravity Network (ANGN) has been considerably strengthened by a series of surveys using groups of gravity meters. These surveys have established a grid of east-west and north-south traverses including a strong calibration chain on the east coast of Australia.

The history of the establishment of the ANGN up to June 1965 is given by Dooley (1965a). Two dates are of particular significance - 1950/51 which saw the establishment of the Cambridge pendulum stations throughout Australia (Dooley et al., 1961), and 1962 when the values at these stations were revised by Dooley (1965b) on the basis of gravity meter and pendulum ties up to that date.

Dooley (1965a) also reported on the early stages of what is now referred to collectively as the "Isogal Project" which was completed during the period under review. The base stations of the present ANGN and the traverses of the Isogal regional surveys are shown in Plate 2.

The ANGN places heavy reliance on the Australian Calibration Line (ACL), a north-south chain of base stations which follows the east coast of Australia for most of its length (see Plate 2). On the Australian mainland the east-west traverses carry the east coast values across Australia, while north-south traverses through the centre of Australia and along the west coast provide links for distribution of loop misclosures. It was not possible to establish such a uniform network in TPNG because erratic variations of observed gravity in that area make it difficult to establish Isogal traverses which follow lines of almost equal observed gravity.

The 1962 values at Melbourne, Cairns, and Darwin were considered to be particularly good, being based on several pendulum measurements as well as gravity meter ties. The 1962 value of 979 979.00 mgal at NGBS has been accepted by BMR and is still retained as the datum for the ANGN. The mean milligal defined by the average given by the two intervals Melbourne-Cairns and Melbourne-Darwin, as calculated from the 1962 values, has been accepted as the "mean Australian milligal".

Values for these two intervals were calculated from the 1965 USAF/BMR observations on the WPCL & ACL (see Chapter 4) using calibration tables obtained at the La Coste & Romberg factory. The mean intervals for the five La Coste meters required a correction factor of 0.9997 to give the best fit to the intervals expressed in mean Australian milligals. Datum values relative to NGBS for the ACL between Melbourne and Cairns and a value for Darwin were calculated from the USAF/BMR observations using this correction factor.

Most of the east-west traverses were flown in 1964-65 (Barlow, 1968, Plate 3). Forty-seven of the 1950 Cambridge pendulum stations were re-occupied and accepted as primary base stations. Some additional stations in suitable locations were also designated as primaries, being on permanent sites suitable for future pendulum measurements and so placed as to give a more uniform distribution of primary bases throughout Australia. The remaining (intermediate) stations were designated as secondary bases.

After rejecting a small percentage of doubtful data and taking account for repeat ties, the mean intervals, as determined by the three or four meters, were used to calculate values of observed gravity. For each east-west traverse these are based on the relevant east coast datum. These values at the base stations of the ANGN are referred to as the "May 1965 Isogal values".

For each Cambridge pendulum station the new Isogal value was compared with that given by the 1950 pendulum measurement (result computed without magnetic correction). The difference was plotted against observed gravity value. The regression line is parallel to, and close to, the observed gravity axis, giving the important result that the mean Australian milligal, as defined above, is compatible with the mean milligal defined by this set of 47 Cambridge pendulum measurements.

During 1967 the remaining east-west traverses on the Australian mainland were completed and north-south traverses were flown through the centre of Australia and along the west coast (Volframs, in preparation). The east-west traverses were used to determine May 1965 Isogal values for the primary and secondary base stations established during this work, which entailed preparation of airstrips in desert areas (van Son, 1968). The results of the north-south traverses have not been used to adjust the results of the east-west traverses, although loop closures have been checked (Generally less than 0.2 mgal for loops of several thousand km). It has been estimated that the standard error in the gravity value at a station relative to the east-west traverse passing through that station is 0.1 mgal, and that the standard error in the gravity value at a station relative to the network as a whole is 0.2 mgal.

The Australian network was extended to cover the whole of TPNG during 1967 by reading a series of Isogal-type traverses (Milsom, in preparation). The rugged terrain of the inland parts of TPNG and extraordinarily large gravity anomalies throughout the whole area precluded the design of a set of Isogal lines of equal observed gravity value. However measurements could be made around loops which, at least for most intervals, satisfy the requirements laid down for Isogal traverses. May 1965 Isogal values for all base stations were calculated from a value established at Daru by Barlow (1966). The TPNG Isogal network was extended to Munda and Honiara in the British Solomons Islands Protectorate.

Each place (city, town, homestead, or desert airstrip) which contains an Isogal base station also has a number of excentres which have been tied to the base by a number of gravity meters. These excentres protect the base and tie in earlier gravity work in the locality. Most stations were established on existing concrete and follow-up surveys are marking these sites with brass discs glued to the concrete. A continuing problem is the demolition of some station sites and the need to establish replacement stations. The most accurate Isogal station at a particular place is not necessarily the base station itself, especially in the case of a primary base, but will be that station at the airstrip which was directly connected to neighbouring places on the traverse by Isogal air ties.

May 1965 Isogal values for the bases occupied during the 1964-65 traverses have been available since that date, and values for the remaining taverses since 1967. All Australian surveys subsequent to the establishment of the Isogal stations have been tied to them, and, with few exceptions, the May 1965 Isogal values have been used as datums.

Station descriptive diagrams were preparedand made available as required for tie purposes. Diagrams for all stations are now ready for publication with observed gravity values and all known names and numbers used by earlier observers to identify the sites (Barlow, in preparation).

In view of the gravity coverage over most parts of Australia, it has not been necessary to compute anomalies for the Isogal base stations, and a lower priority was given to obtaining the horizontal and vertical co-ordinates of the stations. This work has now been put in hand and is proceeding.

During 1966, the Dominion Observatory of Canada made observations along the ACL between Melbourne and Cairns using two La Coste meters. The results do not appear to be as consistent as those of the USAF/BMR meters, and no account has been taken of them as yet.

BMR planned a multi-meter run on the ACL to follow the measurements on the WPCL during 1969, to strengthen the intervals between Melbourne and Cairns and to extend the chain to its full length - Hobart (Tasmania) to Mount Hagen and Laiagam (TPNG). This work was postponed to 1970 but has now been completed. Three observers made concurrent readings on nine gravity meters - 3 La Coste, 4 Worden, and 2 Sharpe Canadian meters. A chartered aircraft was used to transport the team, which included an observer and gravity meter from the Geological Survey of NSW. Full drift control was obtained by repeat observations in the order ABAB for each interval. Although many of the gravity intervals were beyond the limited (120 mgal) range of the Sharpes, all intervals were within small dial (240 mgal) range of the Wordens and could, of course, also be measured by the La Costes. The accurate intervals established by this group of seven (or nine) meters will be taken into account in the next adjustment of the ANGN. This work also established correction factors to be applied to the calibration factors of the BMR La Coste meters. These will permit calculation of results expressed in mean Australian milligals for those intervals along the WPCL and Japanese Calibration Line which were measured by BMR during 1969 (see Chapter 4).

Other valuable results of the 1969 measurements on the ACL were the re-determination by nine meters of the seven gravity meter calibration ranges located on the ACL, and the accurate determination of the interrelationship between the "Australian calibration range milligal", as defined by the accepted intervals on the gravity meter calibration ranges, and the mean Australian milligal. These appear to be compatible to within 0.02% (Cooke, in preparation d).

After publication of the May 1965 Isogal values it is proposed to adjust the ANGN over the whole of Australia and TPNG. This adjustment, which will take several years, will take into account all ties that have been made in Australia both between Isogal places and between the base and excentres at each place. It is hoped that a new value for Potsdam will have been chosen by then, and that accepted values will be available for the First Order World Gravity Network (FOWGN) so that the new set of values can be put on a more correct datum.

6. CALIBRATION AND PERFORMANCE CHARACTERISTICS OF GRAVITY METERS

Calibration of gravity meters

Gravity meter calibration ranges have been strengthened by multi-meter surveys which have re-determined the gravity intervals of most of the ranges in terms of each other and the Australian Calibration Line (ACL).

The establishment of eight local gravity meter calibration ranges throughout Australia by BMR during 1960-61 has been described by Barlow (1967). Each of these ranges has an interval of 50 to 60 milligals, and was established by using a group of at least three gravity meters calibrated on the original calibration range Ferntree Gully-Kallista.

A gravity meter calibration range was established at Canberra in 1965. Results obtained during multi-meter control surveys indicated that the provisional value of 52.72 mgal ascribed to this range was in error. A re-determination made in 1968 with six meters (Milsom & Nik Mohamed, 1969) gave the value 52.76 mgal.

An adjustment of several hundredths of a milligal will need to be made to the accepted value of the Hobart Calibration Range, which was re-determined during the 1970 measurements on the ACL. During these measurements re-determinations were also made of the calibration ranges at Canberra, Sydney, Brisbane, and Townsville in terms of the Melbourne range; the values of these ranges are within the limits of accuracy specified by Barlow (1967). The 1970 ACL measurements also established a new local gravity meter calibration range at Port Moresby (Cooke, in preparation e). This range replaces a temporary range which had been used intermittently over a number of years, although the gravity interval had never been determined accurately.

The establishment of the ACL has made possible the calibration of geodetic meters in terms of the mean Australian milligal (for definition see Chapter 5) and the intercomparison of geodetic and exploration meters. The ACL consists of 25 base stations with a maximum gravity interval of 203 mgal, the difference in the gravity values at the two ends of the line being 2946 mgal. Commercial air transport is available between most of the stations, although several would need to be overflown, so that regular airline flights can be used only when calibrating geodetic meters. The seven local calibration ranges which are located on the line provide short-range calibration facilities.

Measurements made with geodetic gravity meters on the ACL and WPCL during recent years enable the Australian calibration standards to be compared with intervals on the WPCL, and hence with international calibration standards. As far as can be assessed at this stage, the Australian and international standards agree to within 1 part in 3000.

All gravity meters used in Australia during the period under review have been calibrated on at least one of the ranges to facilitate integration of results. Many meters have been calibrated repeatedly on more than one range. In particular, all BMR meters have been calibrated on the ACL and on nearly all ranges, with an average of 25 calibrations on the Canberra range alone.

Performance characteristics of gravity meters

The repeated calibration runs, together with multi-meter control surveys, in which several different types of meters are read concurrently, have continued to give useful information regarding the performance characteristics of gravity meters.

There is a clear indication that it is rarely possible to measure even a small gravity interval over a relatively short distance to better than 0.05 mgal using only one meter. Frequently errors of more than 0.1 mgal and occasionally more than 0.2 mgal occur, even with good drift control and apparently sound observations made independently by more than one observer.

Barlow (1967) encountered this type of problem when establishing calibration ranges of 50-60 mgal throughout Australia. He ascribed the effect to erratic changes of 0.1-0.25% in the calibration factors of the group of quartz-type meters which he was using. Evidence obtained during the Isogal surveys showed that the effect was virtually independent of the size of interval being measured, and therefore could not be related to the calibration factor. As mentioned by Barlow (1968) it is now thought that these erratic effects are due to some fluctuating environmental effect at the gravity stations. Ground vibration is currently thought to be the source of the problem, which appears to affect only quartz-type meters, but further investigations are needed.

La Coste & Romberg gravity meters do not appear to suffer from the above erratic effects, possibly owing to the relatively massive steel main spring, but irregularities in the calibration curves of these meters can be troublesome. The Canberra Calibration range has been measured with eleven La Coste meters, and the eleven intervals computed using the calibration tables supplied with the meters range between 54.67 and 54.84 mgal, although each meter gives a result which varies only one or two hundredths of a mgal.

The mean result of three gravity meters (preferably of different types), which have been read concurrently, can be accepted as being sufficiently accurate for most network ties, but results of BMR work, using larger numbers of meters concurrently, show that even this mean result may be in error by more than 0.05 mgal, even for excentre ties. To guarantee an accuracy of 0.03 mgal for excentre ties as requested by the International Gravity Bureau (IGB) necessitates measurement by perhaps 10-15 gravity meters, as has been done for some of the excentre ties in Australia.

Shortage of staff has prevented BMR from carrying out further laboratory tests on the performance characteristics of gravity meters, particularly tests on erratic behaviour induced by vibration and possibly other factors, except for a few tests made to assess performance of quartz-type gravity meters used for ties to Antarctica (Langron, 1966a).

7. GRAVITY COVERAGE IN AUSTRALIA AND THE TERRITORY OF PAPUA & NEW GUINEA

The gravity coverage of the continent of Australia has been further accelerated by increasing the area covered annually by BMR reconnaissance gravity surveys (Dooley, 1965a). A steady increase has occurred also in the extent of gravity surveys conducted by State Mines Departments, Universities, and private oil search companies, many of which have also used helicopter transport to speed up those surveys. Regional coverage has been obtained over much of the Territory of Papua & New Guinea (TPNG). The distribution of gravity stations in Australia and TPNG as at June 1970 is shown in Plate 3, which may be compared with the distribution as at December 1966 given by Barlow (1968).

One of the main features of the improved regional coverage in Australia has been the continued use of helicopters by BMR to accelerate the reconnaissance gravity survey of potentially oil-bearing sedimentary basins and ultimately the whole of the continent. The station density obtained by this reconnaissance coverage is 1 station per 130 square km. A description of the method has been given by Vale (1962) and Hastie & Walker (1962).

Having developed the techniques during 1959-62 to the point where the conduct of this type of survey was virtually routine, BMR has continued the survey since 1963 by letting annual contracts for the whole operation to geophysical contractors. An annual output of 700,000 square km is currently being achieved. During the period under review a total area of more than 3 million square km was surveyed, and 80 percent of the continent of Australia is now covered by at least reconnaissance gravity observations.

Many important contributions to the gravity coverage of Australia have been made by private exploration companies mostly operating under the Petroleum Search Subsidy Acts, under which approved oil-search geophysical surveys are subsidised by the Commonwealth. Some companies have used helicopters to obtain reconnaissance coverage in areas where there was little or no gravity data. For example, an area of about 200,000 square km in the northeast corner of South Australia (SA) has been covered by subsidised BMR-pattern surveys with at least 1 station per 42 square km. This station density is higher than that achieved by BMR reconnaissance surveys but is the minimum used by oil-search companies, which have now covered considerable areas at even higher station densities.

Important contributions have also been made by State Mines Departments (notably those of SA and NSW) and by Universities (notably that of Tasmania). During the period under review, the SA Mines Department added 700,000 square km to the area already covered by them at 1 station per 42 square km, using both road and helicopter transport. They also made regional road traverses and conducted detailed surveys in several areas of SA. The Geological Survey of NSW (Mines Department) has made regional road traverses and conducted detailed surveys in NSW. The Geology Department of the

University of Tasmania has completed the reconnaissance coverage of that State (partly by helicopter) and conducted some detailed surveys.

In addition to the detailed coverage made available by outside organisations, BMR has itself carried out many detailed and semi-detailed surveys over comparatively small areas in various parts of Australia.

The gravity coverage of TPNG has been improved by BMR regional gravity surveys using helicopter transport, and by a reconnaissance gravity survey of the Sepik River area. During 1966-68 regional coverage was obtained over the southeastern portion of the mainland of TPNG, and the coverage extends farther to the southeast, stations being established by helicopter on all islands and all reefs exposed at low tide. Landing sites, suitable even for a helicopter, are difficult to find in many parts of both the onshore and offshore areas, and stations could not always be established on an 11-km grid. Similar regional coverage was obtained during 1969 over New Britain, New Ireland, and the islands off the east coast of New Ireland. During 1968 a special effort was made to obtain reconnaissance gravity coverage of the Sepik River area with stations on a 6-7 km grid. Although most readings were obtained by the conventional helicopter gravity technique, the hover-site method was tested in the Sepik swamp, using a remote-reading underwater gravity meter lowered from a hovering Jet Ranger helicopter; this work showed that the new technique had promise but required further development (Watts, 1969; Darby et al., 1969).

Plate 4 shows the gravity coverage of Australia and TPNG as at June 1970. The classification of the types of coverage has been changed from that used in earlier National Reports (e.g. Plate 1 in Dooley, 1965a). This change was necessary because BMR now uses the metric system and because of the improved coverage of Australia.

During 1970, BMR and the SA Mines Department plan to complete the coverage of SA at 1 station per 42 square kilometres. This work is now (August 1970) well underway. The western part of the State is being covered by a BMR contract survey, the specifications of which have been amended to give the denser coverage. The SA Mines Department is co-operating in the supervision of this contract, and will itself complete the required coverage in the remaining area in the eastern part of the State.

It is expected that the reconnaissance gravity survey of mainland Australia will be completed by 1972/73.

8. GRAVITY MEASUREMENTS AT SEA

BMR has covered 0.8 million square km of the continental shelf of Australia by three contract marine geophysical surveys to the northwest of the continent of Australia - see Plates 3 and 4. BMR proposes further marine work which will complete the coverage of the Australian continental shelf and slope within nine years. Isolated marine gravity traverses have been made in the Australian area by overseas organisations and more are planned.

The BMR surveys have been carried out primarily to extend the reconnaissance gravity coverage of the mainland over the continental shelf, and to obtain seismic reflection data. Continuous recordings were made along traverses spaced 16 km (9 nautical miles) apart at a ship speed of about 18 km per hour (10 knots), this speed being a compromise between the requirements of the gravity and seismic systems. These surveys have gradually incorporated other geophysical methods for relatively small additional costs. Feasibility tests of geophysical methods not previously used on surveys in Australia and experience with advanced navigational techniques have made a large contribution to improving the methods of operation, and to the geophysical coverage of offshore Australia.

A La Coste & Romberg gimbal-mounted surface gravity meter was used during the 1965 survey (Smith, 1966; Geophysical Associates Pty Ltd, 1966). An underwater gravity meter was used to establish sea bottom bases for control of the surface gravity meter, which gave good results, the standard deviation of the gravity difference at line intersections being 3 mgal. Navigation was by the Toran hyperbolic radio location system which, though accurate, is expensive to install and only operates satisfactorily during daylight hours.

An Askania Gss2 Seagravimeter mounted on an Anschutz gyro-stabilised platform was used during the 1967 survey (United Geophysical Corporation, 1968; Jones, 1969). An underwater gravity meter, which was to have been used to establish control bases, failed to operate satisfactorily. The mean misclosure at 170 line intersections was 2.5 mgal with a corresponding standard deviation of 2.8 mgal. Most of this error is probably due to poor navigation data, particularly velocity information. Navigational aids used on this survey were such as to permit 24-hour-a-day operation of the vessel. They comprised a v.l.f. radio relative navigation system, which made use of various v.l.f. stations including some of the OMEGA system, and a sonar doppler navigation system, which unfortunately was ineffective during most of the survey. Celestial fixes and, where possible, land sightings and radar ranges were therefore used to provide a rigid framework on which to base the v.l.f. results.

A La Coste & Romberg surface marine gravity meter, mounted on a gyro-stabilised platform, was used during the 1968 survey (Whitworth, 1969; Ray Geophysics, in preparation). An underwater meter was not considered necessary for control of the surface meter. A preliminary estimate of the mean misclosure at traverse intersections is 1.37 mgal, corresponding to a standard deviation of 1.6 mgal. At intersections where marker buoys were recovered, misclosures were very small, indicating that errors in position were significant at other intersections. Navigation was by satellite doppler, pulsed sonar doppler, E.M. log, radar, astro and sun fixes, and for some areas by Raydist. The v.l.f. equipment was used as a support system.

A BMR contract marine geophysical survey, which is just getting under way (August, 1970), will provide reconnaissance gravity data over the continental shelves of mainland TPNG and the Bismarck Archipelago, at a traverse spacing of 16 km (9 nautical miles). An area of about 0.4 million square km will be covered. Traverses across the deeper waters of the Bismarck, Solomon, and northern Coral Seas will provide regional gravity data for crustal studies and other purposes over another 0.3 million square km. Navigation will be by aids similar to those used in the 1968 survey.

Arrangements are being finalised for a two-year contract marine geophysical survey, which will provide regional coverage of the whole of the continental slope surrounding the Australian mainland and continental shelf. The area to be covered is about 5 million square km. The shelf itself will be covered by successive reconnaissance surveys, and it is expected that the whole of the shelf will be covered by 1979.

Hawaii Institute of Geophysics made surface gravity meter observations along traverses to the north of TPNG and in waters around the Bismarck Archipelago in the Royal Navy vessel "HMS Dampier" during 1965. The US Coast & Geodetic Survey read a gravity traverse down the west coast of Australia, across the Great Australian Bight, along the southeast coast of Australia, and across the Tasman Sea in the vessel "USCGSS Oceanographer" during 1967; Australian observers participated in this cruise.

Hawaii Institute of Geophysics in co-operation with BMR and the University of Queensland is currently (August 1970) making gravity observations east of mainland TPNG in the research vessel "Mahi". The Soviet Geophysical Committee of the Academy of Sciences of the USSR will make gravity observations east of Australia during 1970-71 in the research vessel "Vitiaz".

Lamont-Doherty Geological Observatory of Columbia University (LGO) read gravity traverses in the Coral Sea between the Australian mainland and TPNG. Observations were made on the research vessels "Conrad" and "Vema" and on the National Science Foundation vessel "USNS Eltanin". LGO also read regional gravity traverses to the south of Australia on "USNS Eltanin". The University of NSW participated with LGO in the gravity work in both of these areas, and joint reports are in preparation.

9. AUTOMATIC COMPUTING AND COMPILATION OF GRAVITY DATA - GRAVITY MAPS OF AUSTRALIA

Automatic computing of gravity data

Automatic computing has greatly facilitated the reduction, compilation, storage, retrieval, presentation, and interpretation of gravity data.

BMR has an extensive suite of gravity programmes which are run on the CDC3600 computer at the Commonwealth Scientific & Industrial Research Organisation (CSIRO) Computer Centre at Canberra. Other organisations involved in gravity work also make use of automatic data processing (ADP). SA Department of Mines use a programme, developed on their behalf by Australian Mineral Development Laboratories, for the distribution of closure errors for helicopter networks, and for subsequent reduction of gravity results. The University of Tasmania uses an Elliot 503 computer to periodically update and provide data from a master file of principal facts of all gravity stations in Tasmania. The University of New South Wales makes extensive use of ADP for the calculation of isostatic anomalies and geodetic parameters.

The BMR suite of programmes has been developed by BMR, in conjunction with the Computer Research Section of Monash University, Victoria in the early stages.

The basic reductions programme was originally written for use on a Ferranti "Sirius" computer at Monash University but was converted for use on the CSIRO CDC3600 after the BMR Geophysical Branch moved to Canberra in 1965. This programme corrects field gravity observations for meter drift and makes a least-squares adjustment of the gravity network onto base station values; computes height differences from field and base barometer observations, correcting for atmospheric parameters, and makes a least-squares adjustment of the height network to fixed elevations at benchmarks; and writes the basic principal facts for each gravity station on magnetic tape. This programme, and peripherals to retrieve principal facts and calculate free-air and Bouguer anomalies have been described by Bellamy et al., (in preparation).

Programmes are being continually written and revised to expand the applicability of the reduction system and to improve its efficiency. Improvements to the retrieval system are described by Townsend (in preparation), but further developments, including the introduction of buffered block input and output techniques, are still under way. The system can calculate gravity differences for exploration meters, using calibration factors determined on calibration ranges, and for La Coste & Romberg meters using the tables supplied by the manufacturer. Least-squares adjustments can be made for networks containing up to 400 nodes (intersections of traverses) and up to 1600 links (sides of loops). Entry points are provided so that principal facts from manually reduced gravity surveys can be introduced without total recomputation from the original field sheets;

adjustments can be made to the principal facts as required to update the data to modern datum and milligal scale standards. Anomalies can be calculated from principal facts obtained during land, surface marine, sea-bottom, and submarine surveys. Manually-computed terrain corrections (where these exist) are taken in account. Recently-developed programmes can be used to apply tidal corrections to the gravity observations (Towers, in preparation) and convert grid coordinates in northings and eastings to latitudes and longitudes. The data stored on magnetic tape can be extracted as required, for example by nominating the area of interest.

Various programmes have been written to assist in the visual presentation and interpretation of gravity. One such programme will extract, plot, and contour gravity data at any required map scale and projection, while another produces isometric sketches of the anomaly field. Residual anomalies can be separated from regional effects, provided the station spacing is adequate. The gravity effects of 2-dimensional and 3-dimensional bodies can be computed using programmes written by the Dominion Observatory of Canada. A programme has been written to plot profiles of the gravity effect of vertical cylindrical bodies (Cull, in preparation). Further programmes are being developed to assist pluton and basin studies by iteratively fitting a body to observed anomaly profiles.

Compilation of gravity data

Geodetic investigations, crustal studies, and geological interpretation of gravity data over broad areas, such as extensive sedimentary basins, require integration of a number of gravity surveys to a common datum and a common milligal scale. The compilation of all available gravity data in Australia and its Territories and presentation of gravity maps of Australia are functions of BMR.

The establishment of an accurate network of base stations by the Isogal project and the establishment of gravity meter calibration ranges have made an accurate compilation of all gravity data in Australia at least feasible. ADP has provided the means whereby the huge volume of data can be handled. Present and future gravity surveys do not provide many difficulties, as these are based on the modern standards; many are processed entirely by ADP, and the principal facts of the remainder can be put on to magnetic tape without an excessive amount of labour. The accurate integration of existing data is, however, a long-term project, as all the data have to be re-assessed and much require complete recomputation to adjust them to values provided by the base stations and by ties between modern surveys and the earlier gravity work. Computation of revised gravity values to Isogal datum and elevations to mean sea level datum has proved troublesome, but even more difficulty has been experienced in representing on modern maps those earlier traverses whose locations have been identified on poorly-controlled base maps.

An essential pre-requisite to the compilation by ADP of the principal facts of all Australian gravity stations has been the introduction of an eight-figure station numbering system, within which every gravity station in Australia will be uniquely numbered. Four figures before the decimal point specify the year and identifying serial number of the survey, and four figures after the decimal point specify the individual station within the survey. The introduction of this system, and the overhaul of the Australian National Gravity Repository to conform with it, have involved a very large amount of work, but have been necessary to provide storage of hand-written field data and gravity reduction sheets in a computer-orientated filing system. Key maps showing areas covered by all known gravity surveys also facilitate retrieval of data for outside organisations and recomputation.

About 500,000 gravity stations have been observed in Australia, and the principal facts for about 100,000 of these have been put on to magnetic tape. About half of this information has been released to the Aeronautical Chart and Information Center (ACIC), St Louis, through the Hawaii Institute of Geophysics (HIG). HIG has compiled other Australian data supplied by BMR to approximately the same datum and forwarded it to the ACIC. All of these data are held in the Department of Defence (DOD) Gravity Library, USA and are available internationally from there.

Eventually all usable gravity data will be recomputed to modern standards and stored on magnetic tape. The output from this compilation will be used to prepare an accurate free-air anomaly map of Australia and Bouguer anomaly maps, each computed for a particular density. The data will be in a readily usable form suitable for various geodetic and structural investigations.

Gravity maps of Australia

Because of the delay necessary in the production of an accurate compilation, and because a less rigorous integration provides data in a form suitable for many purposes, BMR has compiled and published several editions of a preliminary Bouguer anomaly map of Australia.

The base map of the Tectonic Map of Australia (1 inch = 40 miles or 1:2,534,400) was used for the compilation of computed Bouguer anomalies to facilitate a direct comparison between Bouguer anomalies and known regional geological structure. This Bouguer anomaly map is too large for inclusion in this report, but may be purchased separately*, either as a black and white print or as a transparent overlay (both are in 4 sheets). The third edition of this map incorporated data available at the end of 1967, and a reduced version of the mainland portion of this map (1 inch = 270 miles or about 1:17,000,000) is presented in Plate 5. Substantial areas of Australia were covered in 1968 and 1969 (compare Plates 4 and 5), but the results of this work are not yet available for inclusion in this report. Plate 5 was presented to 1969 ECAFE Conference in Canberra by Darby and Vale (1969), who explain the significance of the gravity provinces indicated on the map. In the 1 inch = 40 miles compilation the Bouguer anomalies used are as originally computed for the purposes of the individual surveys. The demarcation of areas having different assumed density values used in the Bouguer anomaly calculations and the assumed densities used have been marked on the map.

Organisations requiring more detailed gravity information than can be obtained from the 1 inch = 40 miles Gravity Map of Australia are referred to the Bouguer anomaly maps of the individual 1:250,000 sheet areas. Each of these covers one degree of latitude by one and a half degrees of longitude and is published at a scale of 1:500,000. Except in areas of detailed coverage, individual stations are shown on these maps, together with elevation and Bouguer anomaly values. Several hundred of these maps are now available*.

Organisations requiring mean anomaly and mean height data for Australia are referred to Mather (1969a).

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* Available from:

Production Section,
Commonwealth Printing Office,
Wentworth Avenue,
KINGSTON. A.C.T. 2604.
AUSTRALIA.

10. GRAVITY MEASUREMENTS IN ANTARCTICA AND ON OCEANIC ISLANDS

Two gravity meter ties have been made between Australia and Antarctica by the Antarctic Division of the Commonwealth Department of Supply. Gravity measurements were made in selected parts of Antarctica both by Antarctic Division and by BMR. No gravity measurements have been made on oceanic islands during the period under review. The Antarctic gravity work is shown in Plate 6.

The Antarctic Division tie Melbourne-Christchurch-McMurdo-Byrd is considered a useful international tie and is referred to in Chapter 4. A weak tie between Melbourne and Wilkes with a La Coste & Romberg gravity meter was obtained by Antarctic Division from observations made before and after ship transportation of the meter to and from a two year survey in Antarctica.

BMR geologists used helicopters to make a few poorly distributed gravity observations, as opportunity arose, during geological work in Antarctica. Stations were established near the Amery Ice Shelf in the 1968/69 summer (Cooke, 1970) and in the Prince Charles Mountains during the 1969/70 summer (Cooke, in preparation f). During this work a few stations were established near Mawson.

During the past nine years, gravity observations have been made by BMR and Antarctic Division as part of glaciological investigations of the Law Ice Dome (previously known as the Wilkes Ice Dome). Stations at 1.6-km (1 mile) intervals have been observed on a regular 16-km grid of traverses over an area of 7000 square km. Irregularly spaced traverses extend the gravity coverage over a further 5000 square km (Allen & Whitworth, 1968). The gravity technique has proved useful in measuring ice thickness and also ice accumulation, as the gravity meter can detect vertical shifts of the ice surface more quickly and more accurately than levelling surveys.

Work in progress during 1970 will extend the regular 16 km grid over the remainder of the Law Ice Dome. Proposals for Australian work in Antarctica during 1970-71 include further work on the Law Ice Dome, a reconnaissance traverse into inland Antarctica, and gravity observations on Heard and Macquarie Islands. It is hoped to strengthen the gravity ties to Antarctica during these and subsequent gravity surveys. Langron (1966 c and d) assessed all gravity ties made to Antarctic bases by BMR during 1953-63 and concluded that these ties have possible errors of $\pm$ 7 mgal.

11. EARTH TIDE RECORDING

Although some progress was made towards the development of recording gravity meters, no usable records of the tidal variation of gravity have been made in Australia.

In 1968, work recommenced on the modification of a North American remote reading (underwater) meter to enable it to record tidal variations of gravity. This meter had been used experimentally for this purpose intermittently during the period 1960-64 but tests carried out in 1968 showed that the earlier gravity records would be unreliable because of inadequate temperature records.

Temperature control and temperature recording, both for the meter and for the associated electronics, have proved to be major problems. However, by controlling the ambient temperature of the room, the internal temperature of the meter can be kept constant to better than 10^{-3} degrees Centigrade. Short-term temperature variations can be recorded so as to be read to about 10^{-5} degrees Centigrade.

All temperature-sensitive elements of the associated electronics (oscillator, amplifier, and bridges) were enclosed in thermostatically controlled enclosures. Highly stable d.c. power supplies were used to provide stable voltages for heating the meter, for the temperature-measuring bridges, and for powering the amplifier. Nevertheless short-term fluctuations of about 10 microgals were traced to the electronics, which are of an obsolete type employing valves, and it was then obvious that only a completely new set of solid-state electronics would provide better reliability. The new electronics are now ready for testing.

The meter has been calibrated on the Canberra Calibration Range over an interval of 55 mgal. It has also been calibrated by raising and lowering it through 40 cm on the table of a Cincinatti milling machine. Careful observations of two La Coste & Romberg geodetic gravity meters gave the gravity interval as 0.116 and 0.120 mgal. The sensitivity of the instrument is more than adequate and, in fact, the gain of the amplifier must be reduced so that 400 microgal can be accommodated on 25.4 cm (10 inch) wide paper record.

Long-term drift in the gravity and temperature records are under investigation at present.

No attempt has been made to bring back into service the Heiland gravity meter which was modified for use as a recording tidal gravity meter by Burch (1965). It is hoped that the North American and Heiland meters can both be made sufficiently accurate and reliable that side-by-side operation of the two meters will verify observed tidal variations.

BMR has a pair of Verbaandert-Melchior quartz horizontal pendulums but has not been able to install these in a suitable site as yet.

12. RESEARCH IN PHYSICAL GEODESY

The programme of research in physical geodesy commenced by Dr R.S. Mather at the South Australian Institute of Technology has been continued by him at the University of NSW from February 1966. The Commonwealth Division of National Mapping is making increasing use of gravity data to adjust geodetic survey results.

In the period 1966-67, trial computations for the geoid were made by Mather (1968) from a combination of surface gravimetry and satellite data for a test region in South Australia. The technique adopted in all the Australian geoidal studies from gravimetry was as follows. The globe was divided into a spherical cap of limiting angular distance equal to 20 degrees about the point of computation together with an outer zone beyond this limiting radius. The gravity fields within the spherical caps were represented by surface gravity data sets prepared principally from the records of BMR (for the Australian mainland and adjacent continental shelf regions) and the Aeronautical Chart and Information Center, St Louis, for the adjacent regions. The outer zone gravity data sets were prepared by using satellite-determined low-order harmonics for carrying out field extensions on the available surface gravity.

The geoidal determinations were extended to the whole of the Australian mainland in 1968 (Mather, 1969a), and carried a step further when the gravimetric and astro-geodetic geoids for Australia were compared after allowing for translation of reference systems. These tests indicated errors in the gravimetric solution, primarily owing to incompatibility between the different gravity data sets used in the solution (Mather & Fryer, 1970).

A homogeneous data set was prepared in 1969 and the resulting 1970 free-air geoid was computed for Australia (Mather, 1970a). The accuracy of the gravimetric geoid compared very favourable with that of an astrogeodetic geoid based on a station density of 1 station per 10,000 square km. The 1970 data set, which is of acceptable accuracy for first-order geodetic determinations, was used to determine the location of the Australian Geodetic Datum (AGD) in Earth Space (Mather, 1970b), the project being financed by a grant from the Australian Research Grants Committee. The results obtained in this Australian study indicate that it is feasible to establish a world geodetic system to first-order geodetic accuracy from gravity data currently available. Research is currently being carried out on compiling a fully automated system for connecting individual geodetic datums to a world geodetic system using gravimetry and available astro-geodetic data.

In addition, a research group at the University of NSW is associated with Dr Mather in current studies of various problems in physical geodesy which were brought to light by previous work. One project is the investigation of the nature of systematic errors in gravimetric solutions of the geoid (Mather, 1969b). This is a joint venture with the Royal Australian Army Survey Corps, financial support being provided by the Nuffield Foundation. A second project is a study of the exact nature of surface deflections of the vertical. A third project being planned is an analytical study of the nature of geoid undulations.

The accepted lengths of several geodetic base lines, which had been previously measured by invar tapes, were adjusted by the Commonwealth Division of National Mapping to include corrections for the observed gravity values at the stations. At the end of 1970, about 85,000 km of levelling, covering the whole of the Australian mainland, will be adjusted to form a homogeneous system of heights called the Australian Height Datum. This datum will be related to 30 tide gauges around the coast of Australia. A least-squares adjustment will be made of observed differences in elevation after these have received orthometric corrections based on gravity. During 1970-71 some 1200 astro-geodetic stations will be used to form loops of geoidal profiles which will be adjusted by least squares. Geoid contours of areas within the loops will be drawn by using the gravity field, meaned over 30 minute by 30 minute squares, to estimate the geoid-spheroid separation in support of the local values determined astro-geodetically.

13. REFERENCES

ALLEN, G.A. and WHITWORTH, R., 1968 - Ice thickness determinations at Wilkes. Inter. Symposium on Antarctic Glaciological Exploration, Hannover N.H., USA, 1968.

BARLOW, B.C., 1966 - Isogal gravity base stations, Thursday Island (Queensland) and Daru (TPNG), 1966. Bur. Min. Resour. Aust. Rec. 1966/141 (unpubl.).

BARLOW, B.C., 1967 - Gravity meter calibration ranges in Australia. Bur. Min. Resour. Aust. Rep. 122.

BARLOW, B.C., 1968 - National report on gravity in Australia, January 1963 to December 1966. Bur. Min. Resour. Aust. Rec. 1968/21 (unpubl.).

BARLOW, B.C., - The Australian Isogal regional survey, 1964-69. Ibid. (in prep.).

BELL, G.A., 1970 - Absolute measurement of gravity at Sydney. (To be presented at 6th Meeting of Int. Grav. Comm. Paris, 1970).

BELLAMY, C.J., LODWICK, G.D., and TOWNSEND, D.G., - BMR gravity reductions, storage, and retrieval system. Bur. Min. Resour. Aust. Rec. (in prep.).

BROWNE, B.C. and HONKASALO, T., 1970 - Cambridge pendulum measurements of gravity differences on the West Pacific Calibration Line. U.S. Gov. Res. Development Rep. v.70, No. 2, p. 76, 25th Jan. 1970 (Report No. AFCRL 69-0394).

BURCH, W.M., 1965 - A phototransistor transducer for tidal gravity recording with a Heiland gravity meter. J. sci. Instrum. 42, pp. 140-143.

CAW, W.A., 1969 - The elastic behaviour of an obtuse but sharp wedge impressed on a plane. J. sci. Instrum (J. Phys. E) Vol. 2, p. 73.

COOKE, R.J.S., 1970 - Reconnaissance gravity observations near Amery Ice Shelf, Antarctica, summer 1968/69, with appendix by I.R. McLeod. Bur. Min. Resour. Aust. Rec. 1970/31 (unpubl.).

COOKE, R.J.S., (a) - Pendulum gravity measurements in Australia by BMR, 1967. Ibid. (in prep.).

COOKE, R.J.S., (b) - Gravity meter measurements on the Western Pacific Calibration Line, 1969. Ibid. (in prep.).

COOKE, R.J.S., (c) - Gravity meter measurements on the Western Pacific, Japanese, and Australian Calibration Lines, 1969/70. Geophys. J. (to be submitted).

COOKE, R.J.S., (d) - Australian Calibration Line gravity survey, 1970. Bur. Min. Resour. Aust. Rec. (in prep.).

COOKE, R.J.S., (e) - Establishment of a new gravity meter calibration range in Port Moresby, Papua, 1970. Ibid. (in prep.).

COOKE, R.J.S., (f) - Reconnaissance gravity observations in the Prince Charles Mountains, Antarctica, summer 1969/70, with appendix by I.R. McLeod. Ibid. (in prep.).

CULL, J., - A Fortran programme to calculate profiles of the gravity effect of cylindrical bodies. Ibid. (in prep.).

DARBY, F. and VALE, K.R., 1969 - Progress of the reconnaissance gravity survey of Australia. ECAFE Conference, Canberra, Australia, 1969.

DARBY, F., WATTS, M.D., and VALE, K.R., 1969 - Helicopter gravity survey techniques in tropical swamps and jungles. Ibid.

DOOLEY, J.C., 1959 - National report on gravity in Australia and Australian Territories, May 1959. Bur. Min. Resour. Aust. Rec. 1959/97 (unpubl.).

DOOLEY, J.C., 1965a - National report on gravity in Australia, January 1962 to June 1965. Ibid. 1965/162 (unpubl.).

DOOLEY, J.C., 1965b - Australian gravity network adjustment, 1962. Bur. Min. Resour. Aust. Rep. 72.

DOOLEY, J.C., McCARTHY, E., KEATING, W.D., WILLIAMS, L.W., and MADDERN, C.A., 1961 - Pendulum measurements of gravity in Australia, 1950-51. Bur. Min. Resour. Aust. Bull. 46.

GEOPHYSICAL ASSOCIATES PTY LTD, 1966 - Timor Sea/Joseph Bonaparte Gulf marine gravity and seismic sparker survey, north-west Australia, 1965. Bur. Min. Resour. Aust. Rec. 1966/116 (unpubl.).

HASTIE, L.M. and WALKER, D.G., 1962 - Two methods of gravity traversing with helicopters. Ibid. 1962/134 (unpubl.).

JONES, B.F., 1969 - Timor Sea gravity, magnetic and seismic survey, 1967. Ibid. 1969/40 (unpubl.).

LANGRON, W.J., 1966a - National report on gravity in Australia, January 1960 to December 1962. Ibid. 1966/108 (unpubl.).

LANGRON, W.J., 1966b - Pendulum gravity ties between Tokyo and Melbourne, 1962-64. Ibid. 1966/109 (unpubl.).

LANGRON, W.J., 1966c - Problems associated with Antarctic gravity measurements. Ibid. 1966/117 (unpubl.).

LANGRON, W.J., 1966d - Gravity ties to Australian Antarctica, 1953-63. Ibid. 1966/24 (unpubl.).

MATHER, R.S., 1968 - The free air geoid for South Australia and its relation to the equipotential surfaces of the earth's gravitational field. Univ. of NSW UNISURV Rep. 6.

MATHER, R.S., 1969a - The free air geoid for Australia. Geophys. J. 18, 499-516.

MATHER, R.S., 1969b - The verification of geoidal solutions by the adjustment of control networks using geocentric cartesian co-ordinate systems. Univ. of NSW UNISURV Rep. No. 14.

MATHER, R.S., 1970a - The Australian Geodetic Datum in earth space. Ibid. No. 19.

MATHER, R.S., 1970b - The geocentric orientation vector for the Australian Geodetic Datum. Geophys. J. R. Astr. Soc. (in press).

MATHER, R.S. and FRYER, J.G., 1970 - Geoidal studies in Australia. Survey Review 156, 268-282.

MILSOM, J.S., - New Guinea Isogal gravity survey, 1967. Bur. Min. Resour. Aust. Rec. (in prep.).

MILSOM, J.S. and NIK MOHAMED, 1969 - Revision of the gravity meter calibration range, Canberra 1968. Ibid. 1969/31 (unpubl.).

RAY GEOPHYSICS - Report on marine geophysical survey, Northwest Continental Shelf for the Bureau of Mineral Resources, Australia. Ibid. (in prep.).

SHIRLEY, J.E., 1966a - Pendulum gravity measurements in Australia, 1964. Ibid. 1966/162 (unpubl.).

SHIRLEY, J.E., 1966b - Gravity meter measurements in connection with the Western Pacific Calibration Line (Australian segment), 1965. Ibid. 1966/160 (unpubl.).

SMITH, E.R., 1966 - Timor Sea/Joseph Bonaparte Gulf marine gravity and seismic "spark array" survey, North-west Australia, 1965. Ibid. 1966/72 (unpubl.).

TOWERS, R.L., - A Fortran programme to apply tidal corrections to gravity field observations. Ibid. (in prep.).

TOWNSEND D.G., - Improvements to the BMR gravity retrieval system. Ibid. (in prep.).

UNITED GEOPHYSICAL CORPORATION, 1968 - Timor Sea gravity, magnetic and seismic survey, 1967. Ibid. 1968/132 (unpubl.).

VALE, K.R., 1962 - Reconnaissance gravity surveys, using helicopters, for oil search in Australia. Ibid. 1962/130 (unpubl.).

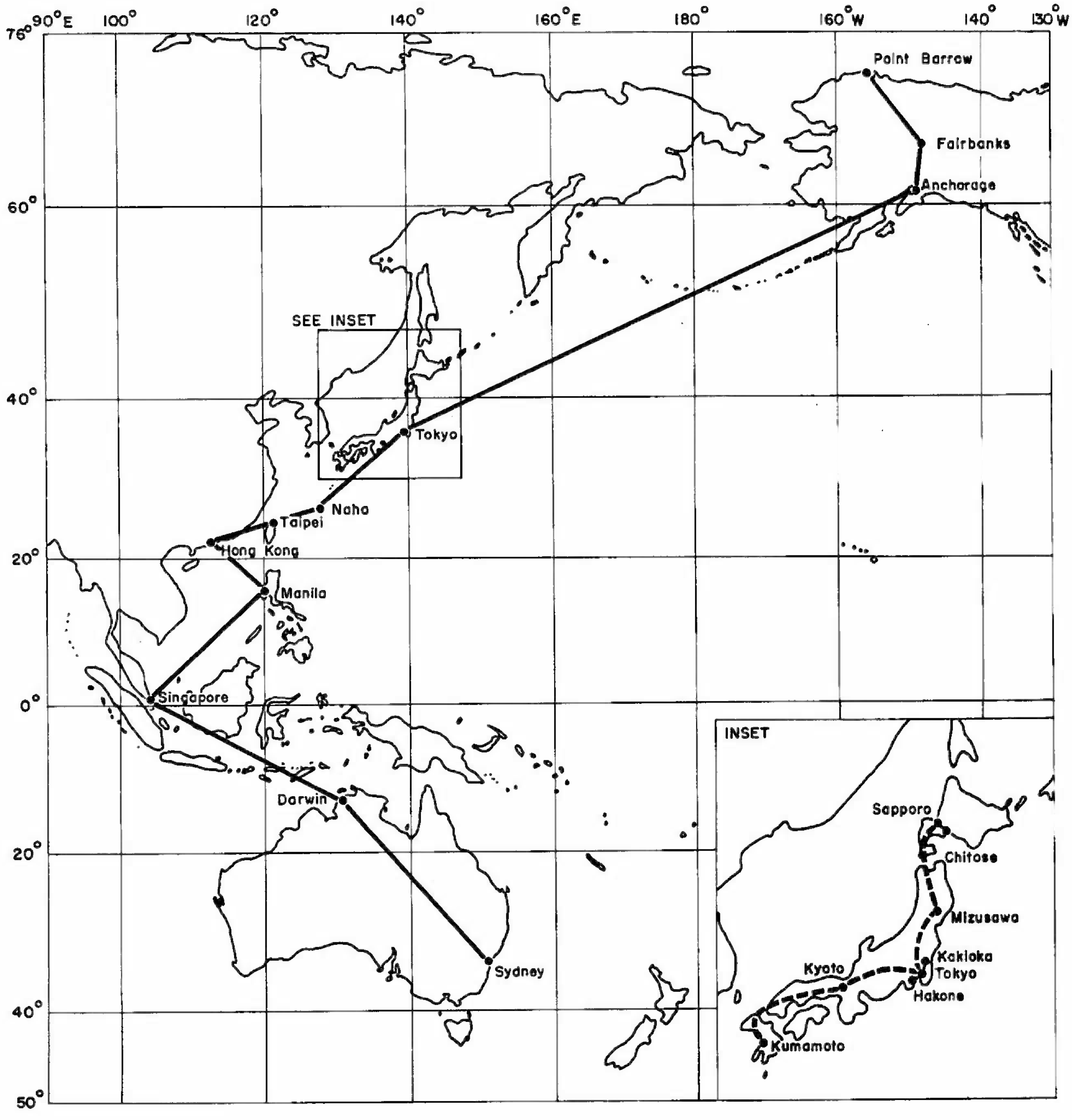
VAN SON, J.R.H., 1968 - Airstrip preparation and ground ties for 1967 Isogal survey. *Ibid.* 1969/48 (unpubl.).

VOLFRAMS, A., - The Australian Isogal regional survey, 1967. *Ibid.* (in prep.).

WATTS, M.D., 1969 - Sepik River helicopter gravity survey, TPNG 1968. *Ibid.* 1969/124 (unpubl.).

WHALEN, C.T., 1966 - The West Pacific Calibration Line survey, 1964-65. *United States Air Force* APCS OPLAN 503, Phase Report No. 3.

WHITWORTH, R., 1969 - Marine geophysical survey of the North-west Continental Shelf, 1968. *Bur. Min. Resour. Aust. Rec.* 1969/99 (unpubl.)



GRAVITY METER MEASUREMENTS

ON THE

WESTERN PACIFIC CALIBRATION LINE, 1969

NM/MISC/70/255

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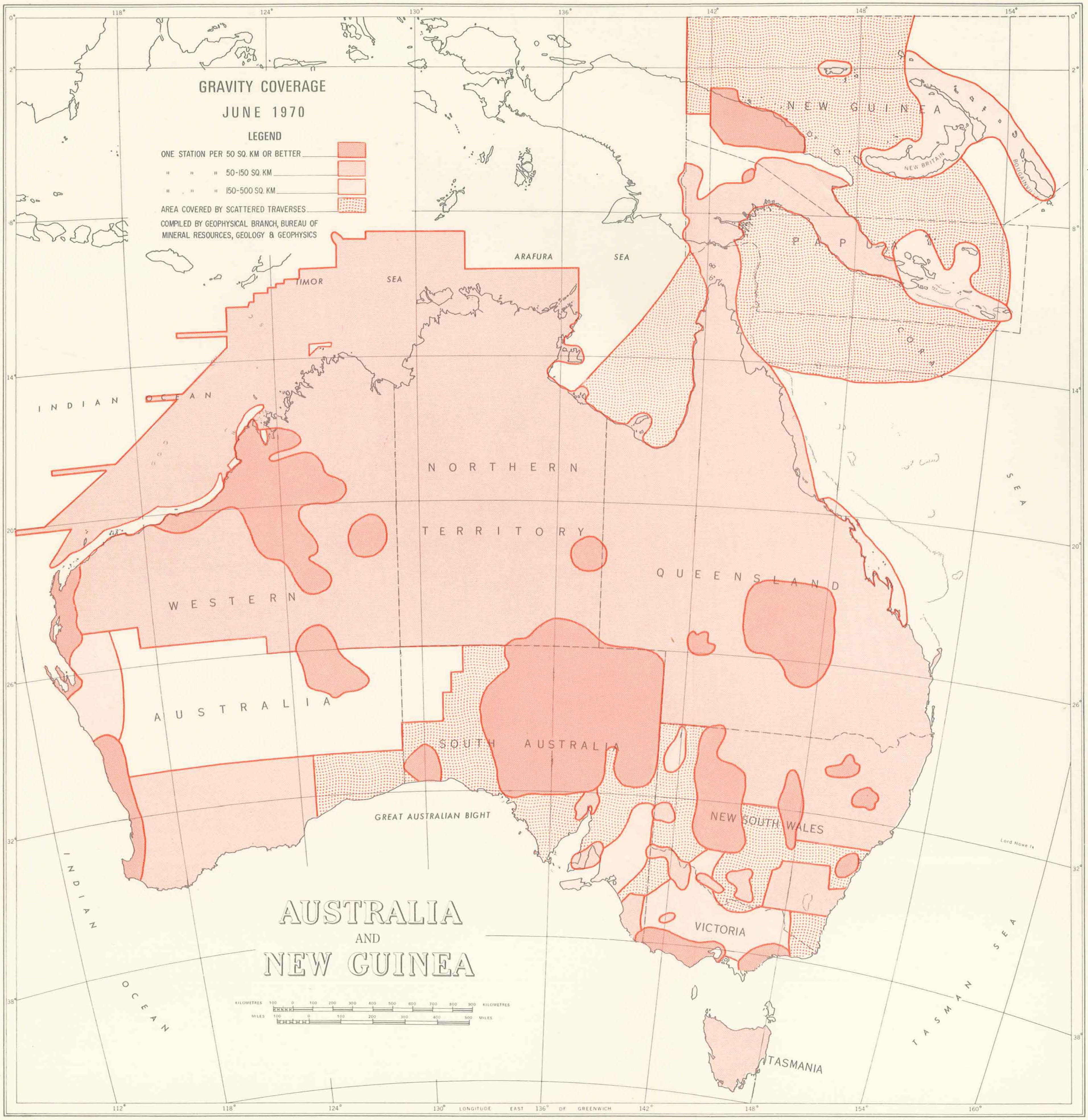

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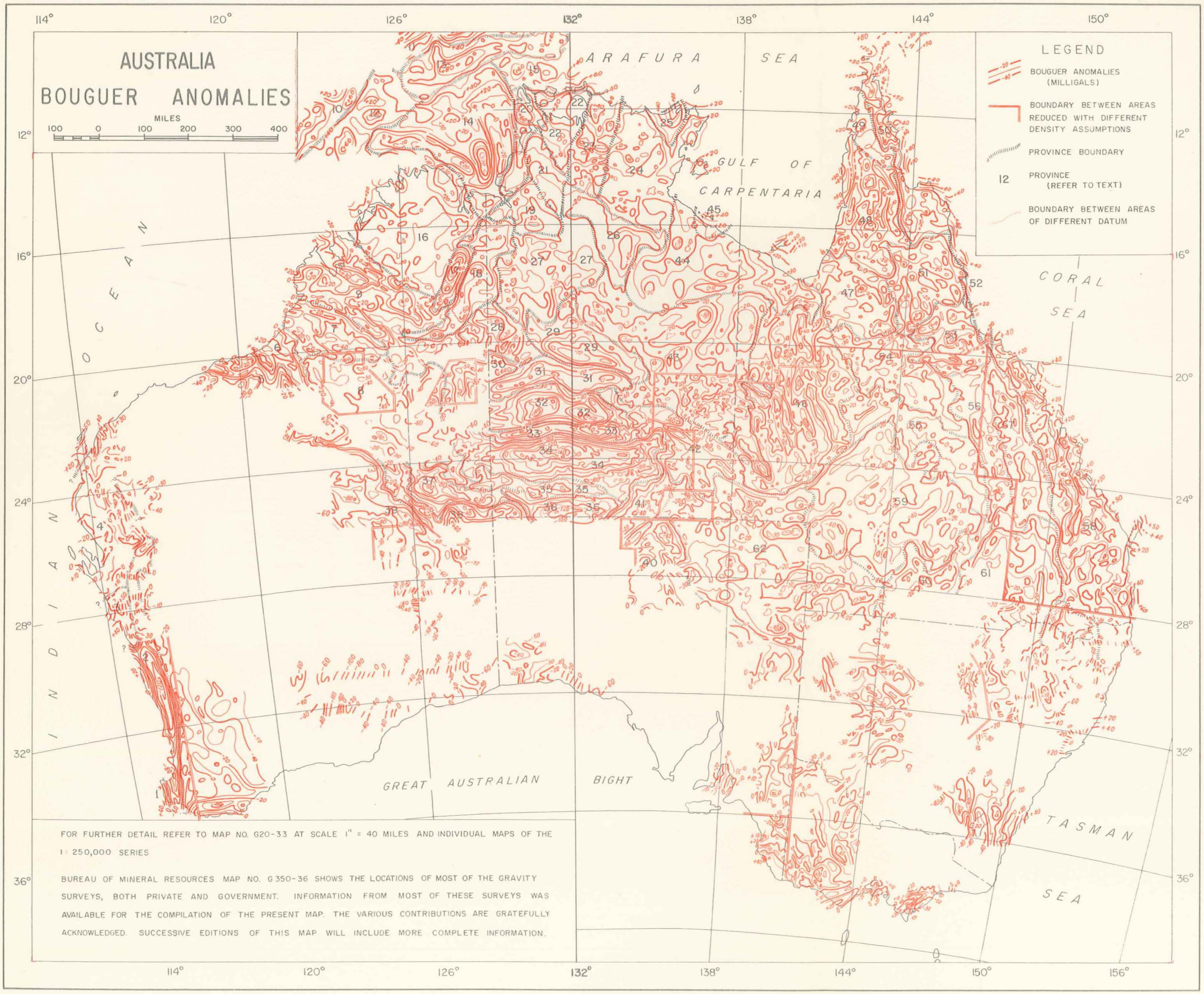

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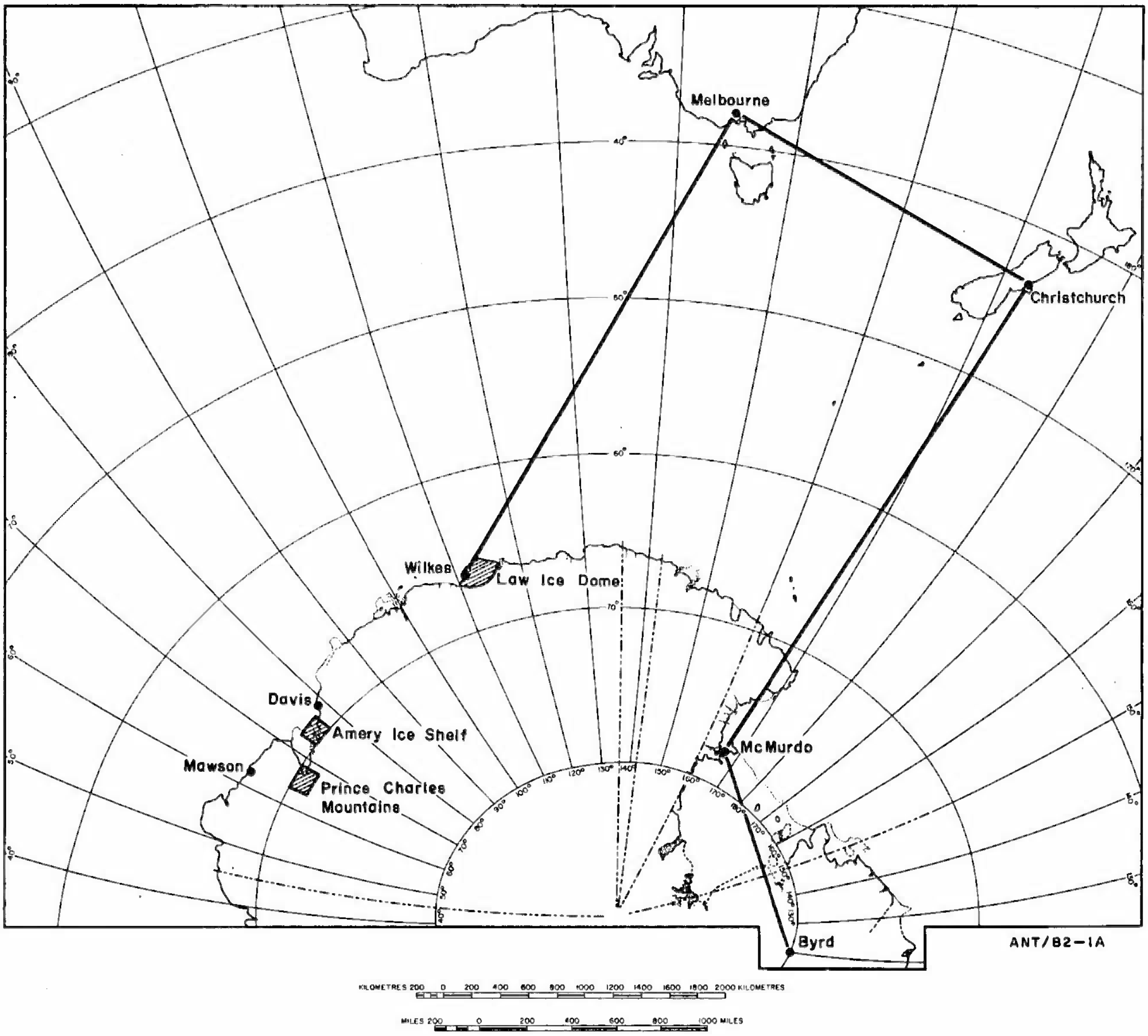

AUSTRALIAN GRAVITY MEASUREMENTS IN ANTARCTICA

Gravity tie

Gravity observations