DEPARTMENT OF
MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1973/14

CENTRAL HIGHLANDS HELICOPTER GRAVITY SURVEY, NEW GUINEA, 1970

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I. Zadoroznyj and D.A. Coutts

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SUMMARY

The Bureau of Mineral Resources (BMR) carried out a reconnaissance helicopter gravity survey in the New Guinea Highlands during July and early August 1970. Readings were taken at 87 new stations located in the southern part of the RAMU* 1:250 000 Sheet area and in the northern part of KARIMUI, the adjacent Sheet area to the south. It was tied to stations established in RAMU during the BMR reconnaissance helicopter gravity survey in 1968 (Watts, 1969). The same station spacing was used as in 1968, about 6 km (4 miles).

The results delineated three major gravity features, the Hagen Gravity Gradient, the Wahgi Gravity Low and the Bismarck Gravity Low and one minor but intense feature, the Mount Wilhelm Gravity High. A fourth feature in the south, the Kubor Gravity High, was only partly delineated.

Except for the Hagen Gravity Gradient, the features have been related to mapped geological formations and structures. The Wahgi Gravity Low coincides with the Yaveufa Syncline but gravity interpretation indicates a more asymmetrical form than may be deduced from the geological mapping. The Bismarck Gravity Low lies over part of the Bismarck Intrusive Complex. The Mount Wilhelm Gravity High is the most prominent of several surrounding highs which also fall over the intrusive complex or adjoining intrusive bodies. The low indicates a core of lower density in the complex and a granite batholith is proposed. The Hagen Gravity Gradient has no obvious surface expression and its form is characteristic of a deeply buried body. Therefore it has been interpreted to represent a large intrusive of dense, possibly deep crustal, material.

* In this report the names of the 1:250 000 Sheet areas are written in capital letters to distinguish them from ordinary place names.

1. INTRODUCTION

From 6 July to 5 August 1970, a helicopter gravity survey was carried out by BMR in the southern half of the RAMU and the northern KARIMUI Sheet areas (Plate 1). It used a helicopter attached to a BMR geological mapping party working in that area. Since the geological party required the helicopter only to move field parties from area to area at intervals of a few days, considerable flying time was available for helicopter gravity work.

The survey extended the coverage commenced in RAMU during the Sepik River Helicopter Gravity Survey in 1968 (Watts, 1969). It was intended to complete the gravity coverage of the Sheet area but this goal proved unattainable.

Stations were occupied on a 6 km (4 mile) grid where possible as in the 1968 survey. A Bell 47-G3B1 helicopter was used to transport the observer, a LaCoste and Romberg gravity meter for gravity readings and Mechanism microbarometers and a Wallace and Tiernan altimeter for elevation readings.

A total of 87 new stations were occupied. The northwest corner and the middle of the RAMU Sheet area have yet to be covered. Appendix 1 gives a detailed description of field-observing procedures and operational progress and problems. The principal topographic features are shown in Plate 2.

The survey area referred to in the interpretation comprises the southern half of RAMU and a small part of KARIMUI adjoining it on the south. The interpretation covers the data from the 1970 survey and some from the 1968 survey.

2. GEOLOGY

This account of the geology is largely from a report by Bain, Mackenzie, & Ryburn (1970).

The survey area straddles what is believed to have been, during Palaeozoic time, the northeast margin of the Australian continental block (Plate 3). It covers part of the New Guinea Mobile Belt (Dow, Smit, Bain & Ryburn, 1968), a tectonically active zone within younger continental crust which accreted to the north of the continent during Mesozoic time. Uplift of the northern edge of the older continental block resulted in gravity sliding which has strongly deformed the uppermost layers of the overlying Mesozoic and Tertiary sediments. The lower layers of this sedimentary sequence are only broadly folded and faulted, as in the Kubor Anticline, for example. Within the mobile belt, however, these sediments also have been strongly deformed and intensely folded. The extensive Bismarck Fault Zone (Rickwood, 1955), which marks the southern margin of the New Guinea Mobile Belt, runs through the middle of the survey area. The Jimi Fault and the Bundi Fault Zone (Dow & Dekker, 1964) also lie within it, the latter exhibiting active movement up to the present.

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Structure

Bundi Fault Zone. About 50 km of the Bundi Fault Zone lies in the northeast corner of the survey area where it strikes west-northwesterly and separates the Marum Basic Belt on its northeast from the Bismarck Intrusive Complex (Plate 3). It consists of many anastomosing faults which appear to occupy vertical shear zones up to 400 m wide (Bain et al., 1970). There is present-day activity along this zone.

Bismarck Fault Zone. The Bismarck Fault Zone trends northwest across a major part of the survey area. It is a highly disturbed zone, 20 km wide, of subparallel, anastomosing faults and tight, overturned folds. The vertical displacement over the width of the fault zone is at least 3 km, the north side upthrown. Near Mount Udon, a number of divergent faults show a more northward trend towards the Jimi Fault and Bundi Fault Zone.

The Yaveufa Syncline. The Yaveufa Syncline is a sinuous, arcuate Tertiary structure, subparallel to the eastern end of the Kubor anticline (Plate 3). It is about 15 km wide in the survey area but broadens towards the southeast. Deformation within the Bismarck Fault Zone has been so intense that the original synclinal form has been almost obliterated. The syncline was probably a sinking basin of deposition during most of the Tertiary Period.

The Kubor Anticline. The Kubor Anticline is a broad, gentle dome at least 60 km wide extending for about 125 km west-northwest to Mount Hagen. Only 40 km of the northwestern end lies in the survey area. The maximum width of basement exposed in the triangular-shaped core is about 35 km. This is found some 20 km from the northwestern end of the anticline. The basement rocks consist mainly of granitic types with some other igneous and low-grade metamorphic rocks. Surrounding the basement outcropping formations are strongly arched Mesozoic sediments which thicken down the flanks. A number of small faults have been mapped in the basement and the surrounding sediments.

3. PREVIOUS GEOPHYSICS

Gravity surveying is the only geophysical method which has been applied in the area.

During the 1968 Sepik River Helicopter Gravity Survey (Watts, 1969), about 120 stations were occupied in the present survey area, particularly on the western side. They are identified on Plates 4 and 5 by the letter C or D before the station number. Comparison of the values obtained for stations occupied in both 1968 and 1970 is discussed in Appendix 5.

V.P. St John and others (St John, 1967) occupied many widely spaced stations in Papau New Guinea, including about 40 in the survey area. They are taken into account in his regional interpretation.

4. DESCRIPTION AND INTERPRETATION OF RESULTS

Some of the simple Bouguer anomaly values in the survey area (Plate 4) show apparent correlation with topography. Such a correlation was only to be expected because the topography is mountainous and the choice of landing places is too restricted by general inaccessibility to permit rejection due to terrain effects. Therefore local terrain corrections were calculated. A graphical method was used (Hammer, 1938; Bible, 1962) to a radius of 1.5 km from the selected stations. In this way, only the local terrain effect was involved and the calculation could be restricted to those stations so affected. It is recognized that this is only an approximate solution. However, most of the topographic control in the area is the heighting from the gravity survey itself. The details of local terrain were derived from examination of aerial photographs and form lines on the topographic maps, which were correlated with the actual heights determined from the survey or obtained from the sparse level control in the area. Under these circumstances the considerable computation required for full terrain correction, which would necessarily apply to every station, could not be justified.

Plate 5 shows the Bouguer anomalies with terrain corrections applied. This is the map referred to in the following discussion and interpretation. A brief discussion of terrain effects and methods of correction is given in Appendix 4.

Hagen Gravity Gradient. The gravity values rise for about 50 km northeastwards from -134 mgal to -70 mgal (Plate 5). The contour lines roughly follow a northwest trend. Gravity stations north of the survey area indicate that the trend will peak at -60 mgal or higher (Watts, 1969); lack of coverage between does not permit the position of the maximum to be determined precisely, but it appears that it will be in the region of the Jimi-Wahgi Divide (Plate 2).

The gradient is deformed near the western end of the survey area, where several gravity contour lines swing sharply in a north-northeast direction conforming to the topographic trend of the Mount Hagen Range. It is not possible to tell whether this represents a geological feature of the crust or a residual terrain anomaly, at least in part. The three stations largely responsible for the disturbance are in the highest part of the Mount Hagen Range, where they are subject to very large terrain effects. Corrections of about 30 mgal have been applied. With such rugged topography, considerable error may be introduced in the terrain corrections through lack of detailed knowledge of terrain in the vicinity of the station.

The extent of the Hagen gradient suggests that it may be attributed to a variation in crustal thickness. Contour lines forming a reverse gradient near the Jimi River and Jimi Fault (Plate 5) also may suggest a northwest trend. There is thus a suggestion of a gravity high elongated northwest near the Jimi-Wahgi Divide. Geological evidence (D.E. Mackenzie, pers. comm.) suggests that the region between the Jimi Fault and the Bismarck Fault Zone is a horst structure with an uplift of at least 3 km.

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St John (1967) showed a positive isostatic anomaly centred on the Jimi-Wahgi Divide and he proposed, as the cause, a large near-surface body. In this report, intrusion of sub-crustal material is proposed, elongated parallel to the gravity contours. Numerous simple two-dimensional models were tested by calculating their theoretical gravity anomalies for comparison with the measured anomaly. Three possibilities are shown in Plate 6, the first assuming a crustal thickness of 30 km, the second 40 km, and the third 55 km. In each case, the theoretical anomaly is shown superimposed on the terrain-corrected Bouguer anomaly profile along C-D (Plate 5).

Wahgi Gravity Low. The low extends for about 50 km in a northwest direction and much of it is about 20 km wide. It narrows to the north and probably ends near the northerly limit of the gravity coverage. The southern end lies beyond the present coverage. The axis of the low is parallel to, and slightly north of, the Wahgi River.

The low coincides with the position of the Yaveufa Syncline. It seems likely therefore that it will follow the syncline into the KARIMUI Sheet area and will increase in prominence as the syncline deepens.

Using a cross-section across the Yaveufa Syncline based on one proposed by Bain et al. (1970), a two-dimensional model was constructed and its theoretical gravity calculated. This is shown in Plate 7, in which the calculated profile is superimposed on the observed Bouguer anomaly gravity profile along A-B. The model is restricted in depth to little more than the postulated geological section which has the effect of setting it in a regional mass of crustal density.

In designing the geophysical model, the geological section was modified by steepening the southwest flank of the syncline and locating its axis farther southwest, to coincide with the lowest value of observed gravity. However, comparison of the calculated anomaly profile with the observed gravity profile shows that still greater asymmetry must exist.

Similarly, a body of high density, not represented in the postulated geological section, was included near the left end of the geophysical model to increase the gradient at the left end of the theoretical gravity profile and so more nearly match the observed profile. In this case too, the effect is insufficient. It is concluded that the mapped body of Kubor granodiorite at the southwest end of the profile is of minor proportions and more dense Omung Metamorphics, such as appear to cause the Kubor Gravity High, predominate near the southwest end of the geological section.

Kubor Gravity High. This high lies south of the Wahgi Gravity Low and generally follows a northwest trend. It is not well defined by the present coverage, which is confined to parts of the northern flank. The highest observed Bouguer anomaly value is -22 mgal at station 9037 west northwest of Mount Kubor, but higher values may be reached in areas not yet covered to the southeast. However, in the area surveyed there is sufficient coverage to indicate that the gravity high has an amplitude of at least 20 mgal, and possibly in excess of 40 mgal.

The high corresponds in position with the denser Omung Metamorphics (2.83 ± 0.13 g/cm^3). Outcrops of the metamorphics beyond the northwest flank of the high may be outliers of minor dimensions and perhaps of a lower grade of metamorphism.

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The station which has the maximum value in the Kubor Gravity High lies close to the boundary between the Kubor Granodiorite and the Omung Metamorphics. Another station with a relatively high gravity value lies well inside the area of outcropping Kubor Granodiorite. The table of densities for Kubor Granodiorite (Appendix 6) shows a mean value of 2.71 ± 0.05 g/cm^3. However, this value omits from consideration almost two-thirds of the measurements because the collecting geologist described those specimens as atypical. (Bain, pers. comm.). The group so omitted may be divided into two sub-groups: one having values of density less than the typical group and the other having values greater than typical. The former sub-group may represent weathered rock having a higher porosity, and possibly alteration minerals less dense than the primary minerals of the fresh granodiorite. The sub-group of higher density values comprises twelve measurements having a mean value of 2.89 ± 0.04 g/cm^3. It may represent a denser phase of the granodiorite. The high gravity values suggest that the stations concerned lie in an area of the denser phase.

St John's profile A10-B10 (St John, 1967, p. 128) crosses the Kubor High, but he shows an amplitude of only about 10 mgal, because his widely spaced observations did not detect the total amplitude. He suggests that the Kubor Granodiorite has a density contrast of +0.05 and is the cause of the high. However, this contrast is too small to account for the more intense high revealed by the more detailed present data.

The gravity contour pattern shows little influence from the granodiorite, apart from the two values mentioned above. This suggests a crustal density for the main mass of granodiorite and confirms the opinion of the geologist in distinguishing the various specimens. His set of typical specimens gave the mean density value of 2.71 g/cm^3 mentioned previously.

Bismarck Gravity Low. This partly elongated low has a diameter of about 20 km and an amplitude of about -30 mgal (from -90 mgal to -120 mgal). It lies mostly within the surface limits of the Bismarck Intrusive Complex in the Bismarck Range. The contour pattern suggests that a batholithic intrusion, lower in density than the surrounding formations, is the cause.

The formula for the gravitational attraction along the axis of a vertical cylinder, having a diameter of 10 km, a length of 10 km and a density contrast of -0.12 g/cm^3, gives a theoretical anomaly of about -30 mgal, indicating that a low density batholith could well be the cause. Bott (1967) has noted that granitic batholiths in general have an attendant gravity low and has computed profiles across various models of such batholiths.

Gabbroic phased exist on the western flank of the intrusive complex and are mapped separately as the Oipo Intrusive (Dow & Dokker, 1964). The Mount Wilhelm High, which is considered in greater detail later, coincides with the outcropping gabbro, suggesting that gabboic phases of the intrusion may also be the cause of other small peripheral highs.

Mount Wilhelm Gravity High. This is a small intense high centred on Mount Wilhelm. The station near the peak of the mountain gives rise to a terrain-corrected Bouguer anomaly of -34 mgal, which is about 40 mgal higher than the adjacent stations. Thus the intense high is based largely on this one observation.

According to McMillan & Malone (1960, p. 41) and Dow et al. (1964), the slopes of Mount Wilhelm above 3500 m show exposures of predominantly basic gabbro and ultrabasic rocks which apparently are denser than the rest of the Bismarck Intrusive Complex. If the bulk of the mountain is made up of such rocks of density contrast +0.3 g/cm^3, it would account for the high.

5. CONCLUSIONS

Total coverage of the RAMU Sheet area was not achieved, for reasons outlined in Appendix 1.

The existing coverage shows reasonable correlation with geology. There is fairly close correlation between the position of the Wahgi Gravity Low and sediments in the northwest end of the Yaveufa Syncline. The Bismarck Gravity Low indicates that a large and fairly uniform body makes up the bulk of the Bismarck Intrusive Complex.

The gravity pattern of the Hagen Gravity Gradient southwest of the Jimi-Wahgi Divide suggests that a basement intrusion may have uplifted this area and given rise to the many small basic intrusions. More gravity stations over the Kubor Anticline in the KARIMUI Sheet area are needed to better define the Kubor Gravity High revealed by the present coverage. This high, unless it has a deep-seated cause, suggests that dense rocks occur more commonly in the area than has been revealed by geological mapping. The Mount Wilhelm Gravity High may be attributed to a somewhat more dense phase of the Bismarck Intrusive Complex.

These conclusions and the interpretations leading to them are based on incomplete gravity coverage of the area and, in some cases, on only a few values which may be established at inappropriate points to give good relationship to terrain and geological structure. Further consideration and some re-interpretation is foreseen when the gravity coverage is more complete.

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APPENDIX 1

OPERATIONAL REPORT

by

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Introduction

During the months of October-November 1968, the Sepik River Helicopter Gravity Survey (Watts, 1969) moved into the New Guinea highlands and began to cover the Wahgi and Jimi Valleys in the RAMU 1:250 000 Sheet area from bases in Wabag and Mount Hagen. Owing to the inclement weather during this period, the wet season in the highlands, it was not possible to secure stations in the Kubor and Bismarck Ranges or the Sepik-Wahgi Divide which separates the Wahgi and Jimi Valleys. Consequently, the RAMU Sheet area was left incomplete, mainly in the southeastern and northwestern segments.

The broad objective of the 1970 survey was to extend the 1968 coverage in the highlands and, in so doing, to complete the RAMU Sheet area if possible. This objective appeared to be attainable because the survey was to be carried out in the dry season in the highlands and local informants had declared in 1968 that the mountain peaks are clear for longer periods during this season.

Survey Planning

Projected date and place of commencement of the survey was 1 July 1970 at Goroka. The helicopter was to be used on a share basis with a BMR geological party from Canberra led by J. Bain, and was to be positioned at Baiyer River from 15 July to fit in with the geologists' requirements. The geophysical party was due to return to Canberra by 9 August, thus leaving six weeks for the survey to be carried out.

The helicopter contract provided for a choice between a turbo-charged 360 h.p. Bell 47-G3B1 or a Bell 206A Jetranger. The former was chosen because of its ability to operate at altitudes above 3000 m, necessary for terrain clearance over about 70% of the survey area. The highest station which could be occupied in 1968 using a Jetranger was about 3500 m above sea level. The turbine outlet temperature reached its maximum safe limit before take-off at this altitude. As it was planned to put in stations as high as Mount Wilhelm (4690 m) on this survey, the G3B1 was selected.

Survey Procedure

Procedure generally followed closely that used in 1968, i.e. same flight patterns, 6-km (4-mile) station interval, navigation by aerial photographs. Mechanism microbarometers were used for altitudes up to 2000 m (800-1050 mb range) and a Wallace and Tiernan altimeter for higher altitudes. Some overlap was available with these two systems. Instrumental drift was good throughout considering the extremes of altitude often encountered in a single flight.

Terrain

The survey area is distinguished by terrain ranked among the most inhospitable in the Territory. Long searches were involved seeking suitable landing spots on the precipitous slopes of the major peaks, and these were complicated by dwindling fuel owing to the necessity to reduce the all-up-weight to a minimum before such flights. Despite this, only two high-altitude stations were missed and these were inaccessible by any means. Eight stations were occupied above 3000 m, the highest being at 4200 m near the peak of Mount Wilhelm. Tundra was usually encountered above 3500 m and at these places it was necessary for the helicopter to vacate the station site whilst the reading was taken to avoid creating vibration in the unstable base.

By contrast, the Wahgi and Asaro Valleys are comparatively flat and densely populated, with a network of roads and rivers and a multitude of village clearings providing eminently suitable landing sites.

The intermediate terrain, i.e. the gorges and stream beds of the main ranges, yielded mostly marginal landing sites for the Bell 47-G3B1 which requires a considerable amount of translational lift to climb away after take-off. Sites with an unobstructed into-wind path were necessary to permit a safe exit. As these occur infrequently in such areas, landing sites often had to be selected well away from the planned location or else omitted altogether.

The Jimi Valley consists largely of impenetrable jungle and very narrow streams, apart from the broad Jimi-Yuat river system. During the 1968 survey, stations were sited along all accessible streams and this coverage could not be extended in 1970. The upper, sparsely populated reaches of the valley appeared at first more accessible, but after several transit flights over this area it was considered there would be a high station rejection rate owing to the limited manoeuvrability of the G3B1 helicopter.

Climate

The highlands area experienced its wettest 'dry' season for some years during the period of this survey.

Cloud was the most unpredictable obstacle from day to day and severely hampered movements throughout the area. A ground mist usually persisted at Goroka until about 0900 hours, which delayed take-off but left the objective area, the mountain peaks, clear. The valleys and peaks would then be clear until about 1100 hours, by which time cloud would begin to form rapidly around the peaks and gradually descend into the higher valleys. By mid-afternoon this cloud had generally developed into cumulonimbus, when severe storms were experienced along the ranges and occasionally in the broad Asaro Valley as well.

Most of the loops flown in this area involved an equal amount of mountain and valley flying, so not a great deal of time was available each day when both were clear. On the mornings when ground mist did not materialize, maximum use was made of the opportunity by organizing a first-light take-off.

As the ranges skirting Goroka are devoid of low-level passes through which to fly when cloud-cover prohibits ridge flying, there were several occasions when the helicopter was cut off from the base station or the next station in the loop for want of a clear path over a cloud-obscured ridge. Rarely the cloud-base would lift briefly to reveal a low point on the ridge which could be used if the helicopter was in the immediate vicinity at the time.

Conditions at Kundiawa were similar to those at Goroka, although the mountains in the area are not quite as high and deep passes are more prevalent. Afternoon thunderstorms curtailed operations twice due to the very real hazard of catabatic winds (down-draughts) in the mountains.

The weather prevailing during work in the Baiyer River area showed a marked improvement over that experienced earlier in the survey and resulted in better helicopter utilization. Station coverage was not noticeably higher, however, as longer transit flights were necessary to reach the work areas. Occasionally cloud closed in before arrival. A heavy ground mist, which appeared to affect only the area adjacent to the base, frustrated most attempts to make early take-offs. A trial was made to circumvent the mist by positioning the helicopter outside the affected area but this had to be abandoned when there was evidence of tampering overnight.

There were four days in the survey period when the presence of high-level cirrus clouds prevented any lower cloud formation whatsoever, so that even the peak of Mount Wilhelm remained clear almost throughout these days. Unfortunately, helicopter unserviceability was experienced on two of them.

<u>Station occupancy</u>

The problem of semi-permanent marking of cell centres and other points assumes greater magnitude in New Guinea. The chief form of station identification during the 1968 survey consisted of orange, angle-iron pickets with red and white streamers attached. These naturally proved a great attraction to the New Guineans, so that few now remain. Orange paint, sprayed on to rocks and trees, was used as a back-up to the stakes but failed to withstand the prevailing climatic conditions. Pin-pricked aerial photography, and ground photography with a Polaroid camera, completed the station identification.

Experience gained in 1968 showed that there was too great a visual gap between aerial photographs taken at 25 000 feet and ground photographs, so that ideally some form of intermediate low-level oblique photography was desirable for speedier station identification. A Polaroid camera alone is not convenient for this as at least two ground shots from different angles plus two oblique aerial shots are required, and the process of disposing of the corrosive developing agents, manipulating the coating fluid and stowing the wet print in the liberally-ventilated cabin of an airborne helicopter is not the easiest of tasks for the observer.

Black-and-white 35-mm photography was used almost exclusively for the 1970 survey, with the appropriate frame numbers noted on field sheets to facilitate identification after developing. Whilst this type of photography is quicker and more convenient to use under the existing conditions, there remains the risk that any malfunction of film or camera will not become apparent until the film is later processed, with the consequent possibility of missing valuable site photographs. For this survey the 35 mm film was accumulated and processed on the party's return to Canberra. Local commercial processing involved a 2-week's delay. An ideal combination would appear to be the use of 35 mm photography for the ground and oblique aerial shots with perhaps a single ground or oblique Polaroid shot as a back-up of tie points. The latter could be developed on the ground at the completion of the loop.

Tie points and cell centres in the 1970 survey were mainly sited at European establishments, such as missions, for ease of future identification - the only disadvantage being that these missions rarely show on the 1955 aerial photographs currently available.

Re-occupation of ten 1968 tie points was achieved, although in only one case was the orange stake found in position. Fortunately 90% of the 1968 points were positioned by the author and the precise position of the station could be recalled from memory where the stake was missing, but this could pose a problem for future observers new to the area.

Pilot proficiency is a point which must be considered when choosing tie points. Experienced pilots may have no qualms about landing at a difficult site whereas less experienced pilots may (rightly) reject the same site on the grounds of their inability, or that of the helicopter, to cope with the intricate manoeuvres involved. When the time comes for later re-occupation of a difficult site, perhaps some years later, a different pilot and/or helicopter more than likely will be involved and the site may be rejected. Therefore new tie points should be selected, among other considerations, for the ease of landing.

<u>Conclusions</u>

1. The period from May to October appears to be the best for helicopter survey work in the highlands area, but even then it can be expected that progress will be slowed by the ubiquitous cloud.

2. The gaps now remaining in the RAMU Sheet area would best be filled by using a Jetranger, or a similar machine with high manoeuvrability, to ensure a low incidence of station rejection. The Kubor Range and the area immediately to the south in the KARIMUI Sheet area poses quite a problem, since it is precipitous and largely uninhabited, with tight landing situations complicated by high altitudes.

3. Some adaption of the hover meter technique used in 1968 would appear necessary to extend the coverage into the densely-jungled lower Jimi Valley.

4. Revision of the means for identifying tie points in remote localities is needed. The combination of 35 mm and Polaroid photography mentioned in this report worked well, but would be further improved if some fixed object close to the station were sprayed with white paint after reading, to more precisely pinpoint the spot in the oblique aerial photographs taken immediately after. This need not, of course, apply to settlements, where local features are generally sufficient to secure identification.

The use of 12-exposure 35-mm cassettes and simple, portable developing apparatus with the party would permit daily processing and viewing of the exposed negatives, thus lessening the risk of irrecoverable loss due to malfunction. This might be a preferable alternative to the dual system of 35 mm and Polaroid photography.

APPENDIX 2

Survey logistics, staff & equipment

Operating bases were established at Goroka (2 weeks), Kundiawa (1 week), and Baiyer River (3 weeks).

Fuel was available from tankers at Goroka and Mount Hagen airports, and was positioned by road in 45 gallon drums at Kundiawa, Baiyer River, and Banz. Later in the survey several drums were positioned by air at Ruti airstrip in the Jimi Valley. A temporary dump of four jerrycans was established at Ambulua Mission (Station No. 7025. 9339) when it became necessary to reduce the all-up-weight of the helicopter to a minimum for the flight over Mount Wilhelm into Keglsugl.

Camp shifts were greatly simplified by the fact that this was a small party (pilot, observer, field hand), so that it was necessary to forward only a small amount of excess baggage by Twin Otter commercial flight. Heavy, non-essential items were transported via the Highlands Highway by BMR Landrovers operated by the geological party.

Hotel accommodation was used at Goroka and Kundiawa, and at Baiyer River the party was accommodated at the residence of the local patrol officer, Mr R. Cruickshank.

Party Organisation

BMR staff

D.A. Coutts	Party Leader, Technical Officer
R.L. Chapman	Field hand

Crowley Airways Pty Ltd Pilots

J. Byrnes

R. Brown

Equipment

LaCoste & Romberg gravity meter G 132

Mechanism microbarometers No. 579, 583

Wallace & Tiernan altimeter

Bell 47-G3B1 helicopter VH-CSL (Crowley Airways)

APPENDIX 3

Survey statistics

Commenced survey (Goroka)	6 July 1970
Completed survey (Baiyer River)	5 August 1970
Total days available	31
- on survey	16
- in transit	2
- pilot rest days	1
- helicopter unserviceable	6
- inclement weather	6
Total helicopter days	25
Percentage helicopter unserviceability	24.0
Total loops completed	21
New Stations occupied *	87
Total stations occupied (i.e. readings)	187
Helicopter hours	74

* Does not include stations in loops that were abandoned due to inclement weather.

APPENDIX 4

Terrain corrections

The simple Bouguer correction approximates the effect of the topography by that of a horizontal plate of infinite extent. In areas where the topographic relief is gentle and small, this approximation is usually adequate to reduce the topographic effect on the observed gravity value to a negligible amount.

In hilly areas the Bouguer correction is less satisfactory; a better approximation for the variations in topography is needed to minimize its effect on the observed gravity. For example, a right circular conical hill located on a flat plain, both composed of the same rocks, would exert on a gravity station at its peak a field:

$$g_{cone} = 2\pi\gamma\sigma h\,(1 - \sin\alpha)$$

where,

γ = gravitational constant

h = height

σ = density of material

α = angle between side and base

The gravitational attraction at the upper surface of an infinite slab of the same height and density is:

$$g_{slab} = 2\pi\gamma\sigma h$$

The difference, $g_{slab} - g_{cone}$, represents the difference between the simple Bouguer correction and a topographic correction more strictly correct in this situation

$$\Delta g = g_{slab} - g_{cone} = 2\pi\gamma\sigma h \sin\alpha$$

Using values, $\gamma = 66.7 \times 10^{-9}\ m^3/Mgs^2$,

$\sigma = 2.67\ Mg/m^3$,

and h in metres,

this becomes,

$$\Delta g = 1.12\ h \sin\alpha\ \mu m/s^2$$

or

$$= 0.112\ h \sin\alpha\ \text{mgal.}$$

When $r > 3\,h$, where r is the base radius of the cone, in metres,

$$\sin\alpha \approx \tan\alpha = \frac{h}{r}, \text{ (within 5\%)}$$

and

$$\Delta g = 0.112\ \frac{h^2}{r}\ \text{mgal,}$$

For $\frac{h}{r} = 0.2$ and $h = 1200$ m

$$\Delta g \approx 27\ \text{mgal}$$

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Differences of this order would apply to most of the mountain top stations in RAMU. However, this would not provide a practical method of general topographic correction. Hayford & Bowie (1912) produced a set of tables to evaluate the total topographic correction. They approximated the topography by segments of a continuous set of concentric, cylindrical annuli, each segment having a height equal to the average elevation above datum of the ground surface within its horizontal limits. Successive radii were so chosen that equal segments of any one annulus each carried a gravity effect of one unit per unit height and unit rock density of that segment. Hammer (1939) published a more precise set of tables based on those of Hayford and Bowie, which evaluate, not the total topographic correction, but only the revision to the simple Bouguer correction. These tables considerably improved the speed and accuracy with which terrain corrections could be calculated.

Nevertheless, the Hammer tables are inadequate for gravity reductions in the New Guinea highlands because the relief exceeds the limits of the tables. Bible (1962) expanded Hammer's tables for use in more rugged topography and changed the number of compartments in some of the zones. These expanded tables were used in computing terrain corrections for this survey.

Digital computers have been used to compute terrain connections at least from 1959 (Bott, 1959). The primary data for computer use are the mean terrain elevation in squares distributed over the surface in a specific rectangular array rather than in the radial zonal compartments of Hayford and Bowie, and Hammer. In this way it is possible to create a single array for a whole area instead of recomputing it for each datum point. The smaller the size of each square the greater the accuracy, to the limits of elevation control, but also the greater the cost in computer time. This method was not used for the data in RAMU because the elevation control was insufficient.

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APPENDIX 5

Comparison between 1968 and 1970 data

The 1970 survey was tied to the 1968 survey at stations which were internal tie points in both surveys. Stations at trig points having elevation values and a station occupied four times in 1968 were assigned fixed heights for computing 1970 height values. Fixed gravity values were given by three isogal stations and the station mentioned above. Among the stations common to both surveys, some large differences were found between the height and observed gravity values obtained in 1970 and those obtained in 1968 as may be seen from table 1.

TABLE 1

Station	Difference in observed gravity	Difference in height
6791-9027	Isogal	31.2 m
6810-5418	1.25 mgal	1.5 m
6810-9145	0.76 mgal	8.8 m
6810-9150	1.00 mgal	33.1 m
6810-9378	0.10 mgal	24.8 m
6810-9415	1.10 mgal	39.5 m
6810-9421	1.13 mgal	0.9 m
6811-0527	0.29 mgal	trig.
6811-0645	1.18 mgal	"

The differences have probably arisen from poor meter performance in conditions of large, rapid elevation changes and propagation of closure errors in adjustment of weakly linked networks. There are two additional factors which may have contributed to the height differences in particular:

1. Nature of the Terrain

Accurate barometric levelling requires simple, stable pressure gradients between stations. These are unlikely to persist for more than brief periods in areas of such extreme relief as the New Guinea highlands.

2. Malfunction of Instruments

Watts (1969, Appendix 1) mentioned that the Mechanism microbarometers were modified before departure for New Guinea to permit reading at altitudes above 2000 m. He also mentioned that they behaved erratically, possibly owing to stressing of the pressure capsule beyond designed limits. In his opinion, the Wallace and Tiernan micro-altimeter, used late in the 1968 survey, proved more reliable at high altitudes.

APPENDIX 6

Densities of rock samples from survey area

The densities of rock samples taken from the survey area were measured in the Petroleum Technology Section of the Mineral Resources Branch of BMR. The samples were collected by Dow & Dekker (1964) and Bain et al. (1970). The densities are listed in Table 2.

The values obtained were used only as a guide to assist in interpretation. This is because a simple mean of the densities of samples from a particular formation often does not give a good representation of the mean density of the formation for three main reasons:

1. The samples were chosen for geological reasons and may be atypical of the formation.

2. The formations often exhibit a marked difference in composition from place to place.

3. Surface samples may be more or less weathered with consequent reduction, generally, in bulk density by comparison with the unweathered formation.

TABLE 2

Densities of New Guinea highlands formations

All values are given in Mg/m^3

BMR Reg. No.	Density	BMR Reg. No.	Density	BMR Reg. No.	Density
		Oipo Intrusives			
R13384	2.84				
R13386	2.88	Mean = 2.91			
R13393	3.01	s.d.= 0.07			
		Bismarck Intrusives			
R13350	2.54	20NG1270A	2.77	20NG1270L	2.84
R13351	2.76	" B	2.74	" M	2.90
R13354	2.72	" C	2.96	" N	2.98
R13347	2.55	" D	2.98	" O	2.91
R13346	2.77	" E	3.04	" P	3.05
		" F	3.01	" Q	2.89
R13355	2.76	" G	2.87	" R	2.90
		" H	2.87	" S	2.85
		" J	3.05	" T	3.04

Mean = 2.86

s.d. = 0.14

BMR Reg. No.	Density	BMR Reg. No.	Density	BMR Reg. No.	Density
		Kumbruf Volcanics			
R13365	2.72	R13371	2.62		
R13367	2.72	R13357	2.78	Mean = 2.77	
R13389	2.91	R13364	2.84	s.d. = 0.09	
		Chim Formation			
21NG0592A	2.65	21NG0614	2.66		
" C	2.66	21NG0620	2.63	Mean = 2.62	
21NG0593B	2.60	21NG1441	2.53	s.d. = 0.05	
		Kondaku Tuff			
20NG1167	2.78	21NG1035B	2.70	21NG1304A	2.74
20NG1169	2.75	" C	2.76	" B	2.80
20NG1239	2.68	21NG1050A	2.76	21NG1312	2.71
21NG0556	2.65	" B	2.67	21NG1321	2.67
21NG1024B	2.71	" E	2.70	21NG2584A	2.61
" C	2.65	21NG1101	2.61	" B	2.64
" D	2.64	21NG1109	2.69		
			Mean = 2.70		
			s.d. = 0.05		
		Maril Shale			
20NG0598A	2.63	21NG1142B	2.69		
21NG0004	2.27*	21NG2557	2.59		
21NG0501	2.63	21NG2562	2.54	* value excluded from mean	
21NG1069	2.70	21NG2589	2.47	Mean = 2.59	
21NG1142A	2.68	21NG2592B	2.72	s.d. = 0.08	
		KANA VOLCANICS			
20NG0608	2.71	20NG2602B	2.78	R13362	2.55
20NG0619B	2.79	" D	2.63	R13352	2.61
20NG1283A	2.75	" E	2.76	R13363	2.67
" B	2.75	20NG2687	2.64		
" C	2.66	20NG0024	2.61		
" G	2.84	R13339	2.93		
" H	2.79	R13358	2.65		
" J	2.67	R13360	2.63	Mean = 2.70	
" L	2.89	R13361	2.72	s.d. = 0.10	

BMR Reg. No.	Density	BMR Reg. No.	Density	BMR Reg. No.	Density
		KUBOR GRANODIORITE			
20NG1148J	2.91*	20NG1198G	2.81*	20NG1198T	2.91*
" L	2.86*	" H	2.92*	21NG0595	2.63*
20NG1194	2.68	" J	2.89*	21NG0597	2.86*
20NG1198A	2.59*	" K	2.62*	21NG1048	2.82*
" B	2.63	" N	2.72	21NG1141	2.86*
" C	2.75	" P	2.72	21NG1143	2.86*
" D	2.90*	" Q	2.66	21NG2542	2.70
" E	2.90*	" R	2.96*	21NG2547	2.79
" F	2.93*	" S	2.74		

* value excluded from mean

mean = 2.71

s.d. = 0.05

BMR Reg. No.	Density	BMR Reg. No.	Density	BMR Reg. No.	Density
		OMUNG METAMORPHICS			
20NG1198N	2.89	20NG0539	2.72	21NG1032F	3.05
" L	2.92	21NG1032A	2.95	" G	2.93
" M	2.65	" B	2.68	" H	2.82
" O	2.92	" G	2.80	" J	3.05
20NG2602A	2.64	" D	2.73	21NG2540	2.73
21NG0523	2.66	" E	2.88	21NG2541	2.87

Mean = 2.83

s.d. = 0.13

Densities adopted for modelling purposes

Bismarck Intrusives	2.92 Mg/m^3
Chim Formation	2.61
Kondaku Tuff	2.65
Maril Shale	2.61
Kana Volcanics	2.69
Kubor Granodiorite	2.74
Omung Metamorphics	2.83

Some of the adopted values differ slightly from the mean value in the table. A few individual values were omitted in calculating the adopted mean, on Bain's recommendation that the specimen was atypical of the formation (pers. comm.).

APPENDIX 7

Miscellaneous survey details

1. Stations assigned fixed gravity values

Station	Why used	Observed Gravity
6791-0178	Isogal	977677.92 mgal
6791-9027	"	977484.16 "
6791-9033	"	977699.11 "
6810-9347	Multiple occupations in 1968	977708.63 "

2. Stations assigned fixed height values

Station	Why used	Height
6810-9347	Multiple occupations in 1968	1434.75 m
6811-0527	Trig (T527)	2051.75 m
6811-0645	" (T645)	1564.04 m
6811-0688	" (T688)	973.15 m
7025-0616	" (T616)	1619.48 m
7025-0699	" (T699)	1743.46 m

3. LaCoste and Romberg Gravity meter G132 was used for the survey. It was calibrated at the Canberra calibration range on 25 June 1970 before the survey, and on 29 January 1971 after the survey. A scale factor of 1.059 mgal/division was obtained from both sets of observations.

4. Elevation measurements were made using Mechanism microbarometers 583M, 579M, and a Wallace and Tiernan altimeter.

5. The station positions were pin-pricked on aerial photographs.

6. A density of 2.67 g/cm^3 was adopted in preparing the Bouguer anomaly contour map. The same value was used in 1968 (Watts, 1969). Terrain corrections were made to stations in the southern half of RAMU and the northern part of KARIMUI.

7. The Survey Number for the survey in the Regional Gravity Filing System is 7025.

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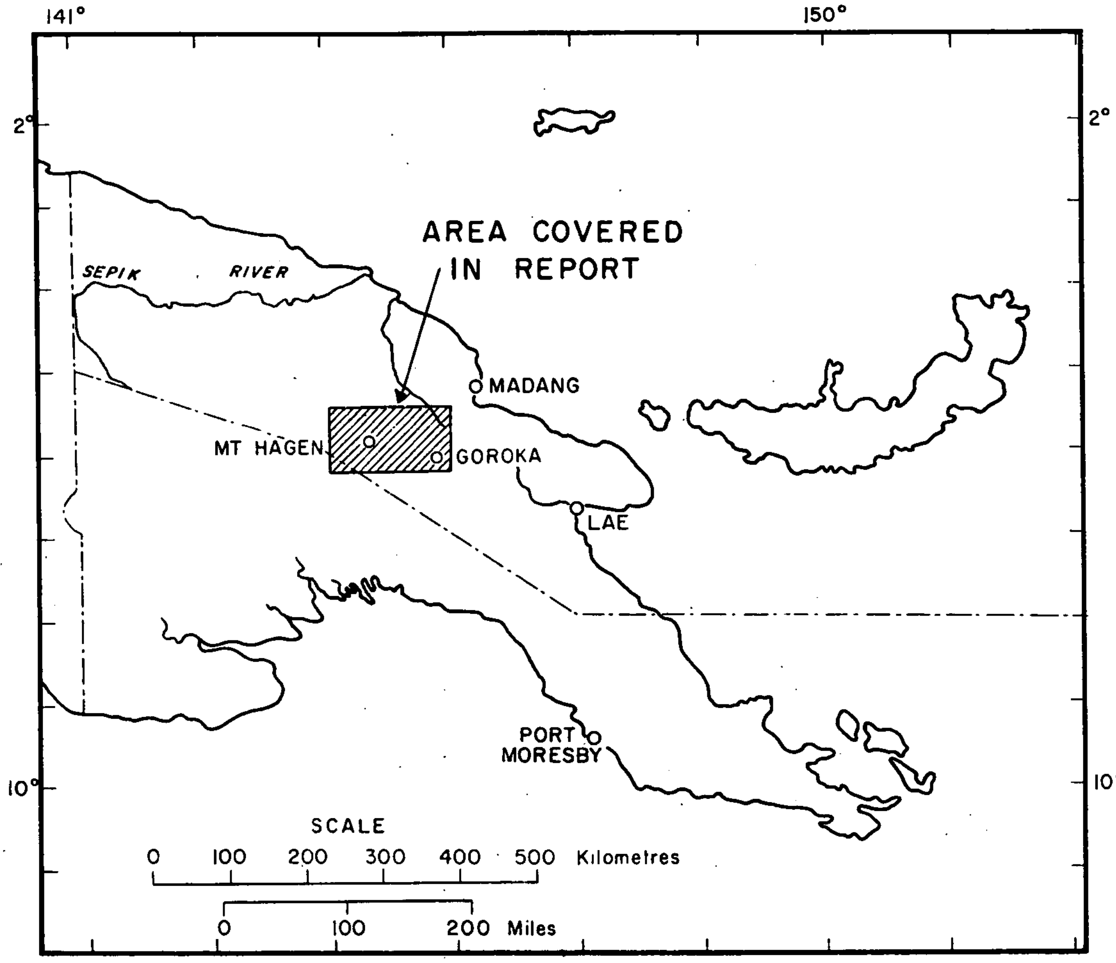
PLATE I



NEW GUINEA HIGHLANDS
HELICOPTER GRAVITY SURVEY, 1970
LOCALITY MAP

To Accompany Record No 1973/14

B 55/B2-38A

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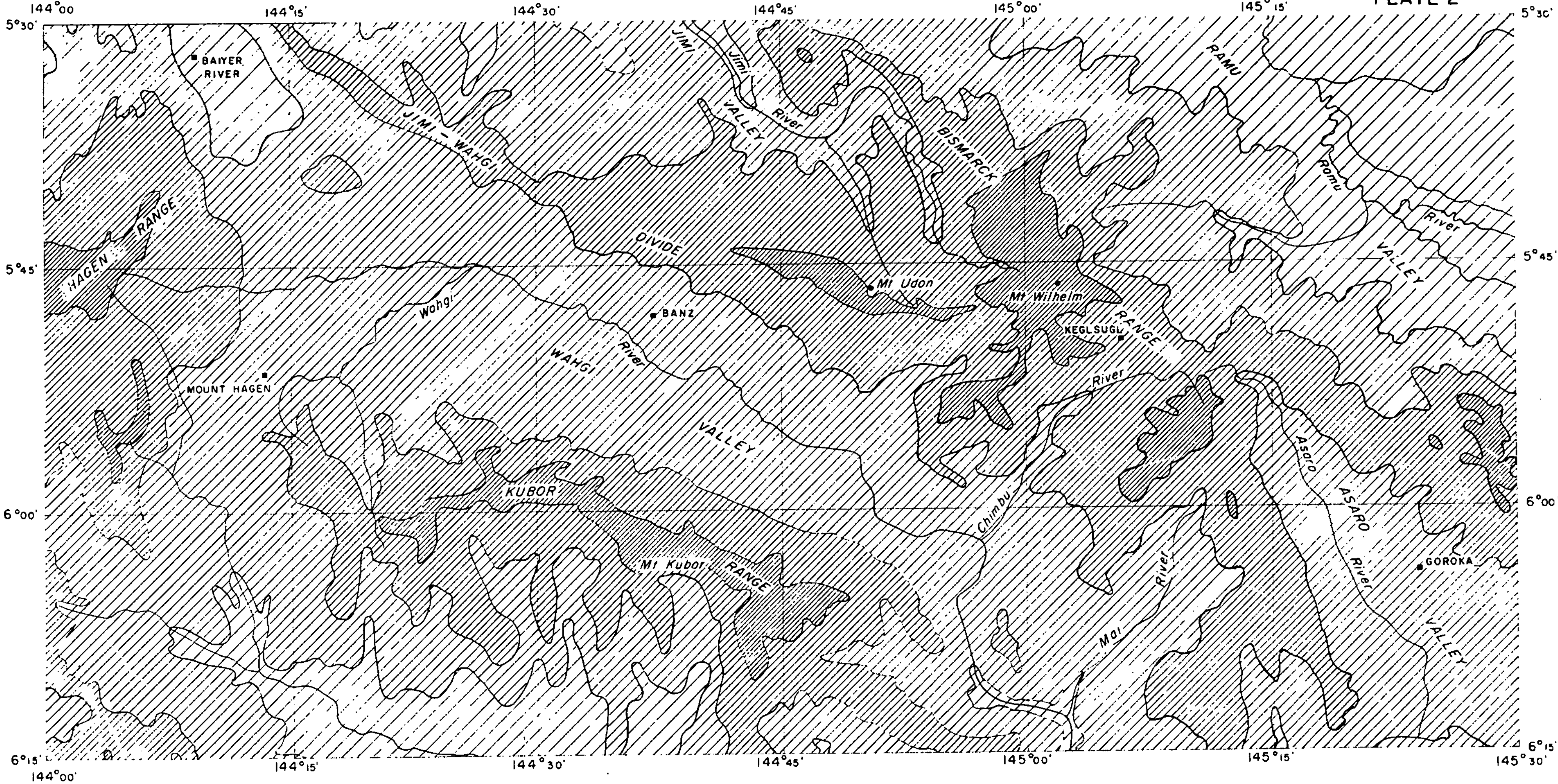
PLATE 2



HEIGHT ABOVE SEA LEVEL

> 3000 m

1000 - 2000 m

2000 - 3000 m

< 1000 m

PHYSIOGRAPHY

SCALE

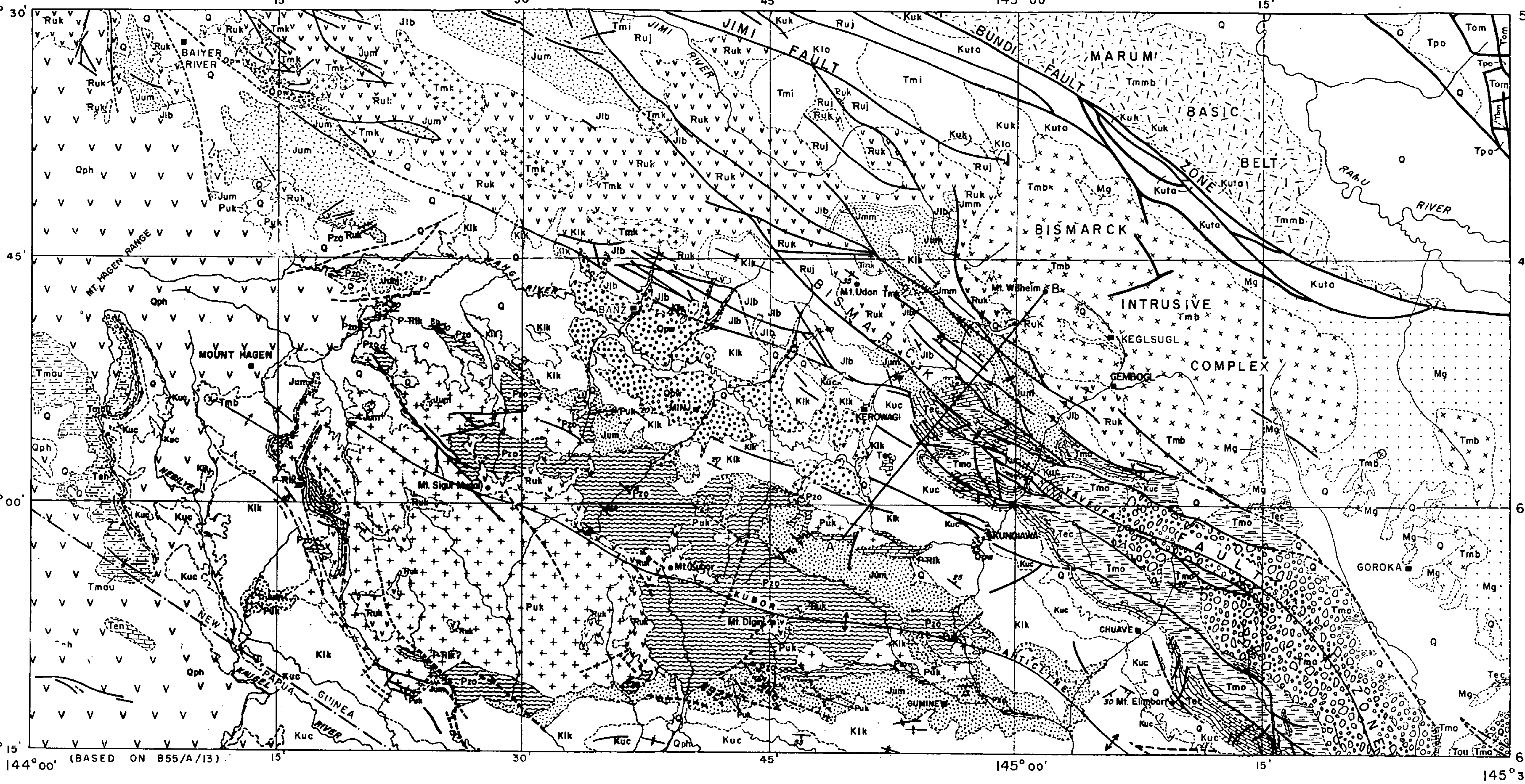
0 5 10 15 20 25 50 Kilometres

0 5 10 15 20 25 Miles

To accompany Record No 1973/14

B 55/B2 - 39

PLATE 3



REFERENCE

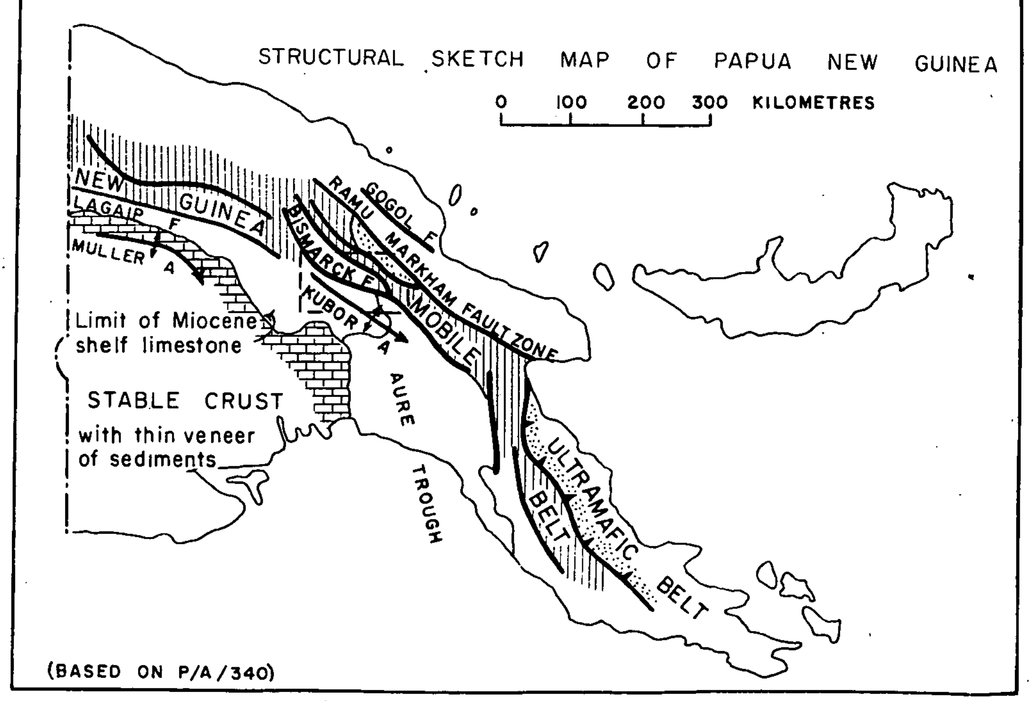
CAINOZOIC	QUATERNARY	Pleistocene to Recent		Q	Alluvium, talus, moraine
			Wahgi Fanglomerate	Qpw	Alluvial fan deposits
		Pleistocene	Highlands Volcanics	Qph	Basaltic lava, pyroclastics, lahar deposits
	TERTIARY	Pliocene	Ouba Beds	Tpo	Sedimentary rocks
		Middle Miocene	Marum Basic Belt	Tmmb	Gabbro, norite, anorthosite, dunite, serpentinite, pyroxenite
			Oipo Intrusives	Tmi	Gabbro, granodiorite, tonalite, diorite, pyroxenite, lamprophyre
			Bismarck Intrusive Complex	Tmb	Gabbro, diorite, mangerite, granodiorite, tonalite, granite
			Kimil Diorite	Tmk	Diorite, tonalite, granodiorite
			Asaro Beds and Daulo Volc. Member	Tma	Andesitic volcanics, volcanolithic sediments, limestone
		Lower to Middle Miocene	Movi Beds	Tmo	Tuffaceous sediments, limestone
		Upper Oligocene to Middle Miocene	Aure Group	Tmau	Mudstone, greywacke, limestone
		Upper Oligocene	Omaura Greywacke	Tou	Greywacke, siltstone, limestone, arkose, conglomerate
			Mebu Beds	Tom	Intermediate to basic agglomerate and lava, marine clastic sediments
		Eocene to Oligocene	Nebilyer Limestone	Ten	Limestone
			Chimbu Limestone	Tec	Limestone, calcarenite
MESOZOIC		Upper Cretaceous to Eocene	Asai shale	Kuta	Shale, siltstone, mudstone, limestone, calcarenite, greywacke, conglomerate
	CRETACEOUS	Upper	Kumbruf Volcanics	Kuk	Basaltic agglomerate and lava, tuff, greywacke, siltstone
			Chim Beds	Kuc	Shale, siltstone, tuffaceous sandstone
		Lower	Kompiai Beds	Klo	Shale, siltstone, greywacke, sandstone, conglomerate
			Kondaku Tuff	Klk	Volcanolithic sandstone, tuff, agglomerate
	JURASSIC	Upper	Maril Shale	Jum	Pyritic shale, sandstone, arkose, limestone, basal breccia
		Middle	Mongum Volcanics	Jmm	Basic submarine volcanics
		Lower	Balimbu Greywacke	Jlb	Greywacke, siltstone
	TRIASSIC	Upper	Kana Volcanics	Ruk	Intermediate to acid lavas, tuff, volcanolithic sediments
			Jimi Greywacke	Ruj	Greywacke, conglomerate, shale
			Goroka Beds	Mg	Schist, silicified shale, altered volcanic rocks, marble
PALAEOZOIC		Upper Permian to Lower Triassic	Kuta Beds	P-Rik	Limestone, calcarenite, arkose
	PERMIAN	Upper	Kubor Granodiorite	Puk	Granodiorite, tonalite, diorite, gabbro
	PRE PERMIAN		Omung Metamorphics	Pzo	Metagreywacke, phyllite, metavolcanics, hornfels

INDEX TO 1:250 000 SHEETS

AMBUNTI	BOGIA	KARKAR ISLAND
WABAG	RAMU	MADANG
LAKE KUTUBU	KARIMUI	MARKHAM

REFERENCE

- *Geological boundary*
- *Anticline*
- *Syncline*
- *Fault*
- *Concealed Fault*
- 35 *Strike and dip of strata, measured*
- *Overturned strata*
- *Trend line*
- A—B *Line of Cross section A-B (Plate 7)*



Geology after J.H.C. Bain et al., 1968, 1970, and 1971

GEOLOGICAL AND STRUCTURAL MAP

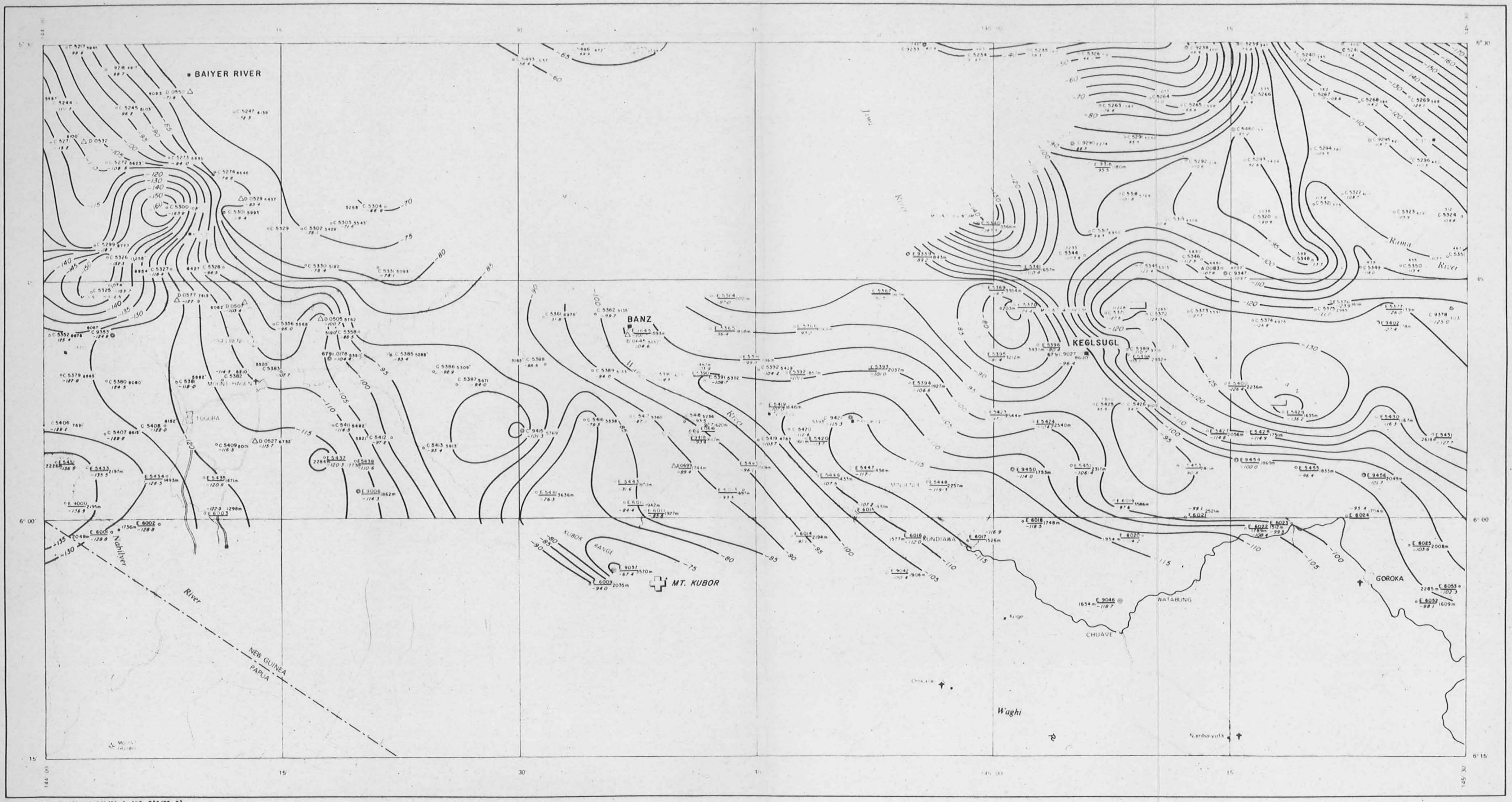
SCALE

0 5 10 15 20 25 30 35 40 45 50 Kilometres

0 5 10 15 20 25 30 Miles

To accompany Record No 1973/14

B 55/B2-40



(BASED ON B55/B2-5 AND B55/B2-9)

LOCATION DIAGRAM

REFERENCE TO PAPUA AND NEW GUINEA STANDARD MAP SERIES

AMBUNTI	BOGIA	KARKAR ISLAND
WABAG	RAMU	MADANG
LAKE KUTUBU	KARIMUI	MARKHAM
AWORRA RIVER	KIKORI	WAU

Projection: Transverse Mercator (Universal Co-ordinates, International Spheroid)

Planimetry: After the U.S. Army Map Service and the Royal Australian Survey Corps 1:250,000 topographic series maps SB 55-5 and SB 55-9

Elevation datum: M.S.L. from Admiralty tide tables.

Station Bouguer Anomaly reliability
Standard Deviation ~3 milligals

BOUGUER ANOMALIES

SCALE

0 5 10 15 20 25 30 35 40 Kilometres

0 5 10 15 20 Miles

Contour interval 5 milligals

KEY TO GRAVITY STATION NUMBERING

A: 6351 E: 7025
C: 6810 D: 6811

TOPOGRAPHY

- Built-up area
- Named place
- Native village
- Road
- Track
- River or creek
- Hill feature
- Reef
- Aerodrome or landing ground

GRAVITY

- Primary base station
- Secondary base station
- Gravity station
- Permanently marked gravity station
- Trig station
- Bouguer anomaly (milligals)
- Elevation (metres/feet)
- —-5— Isogals
- 'High' anomaly
- 'Low' anomaly

Bouguer anomalies are based on the "May 1965" observed gravity values at Isogai gravity base stations in and near the area.

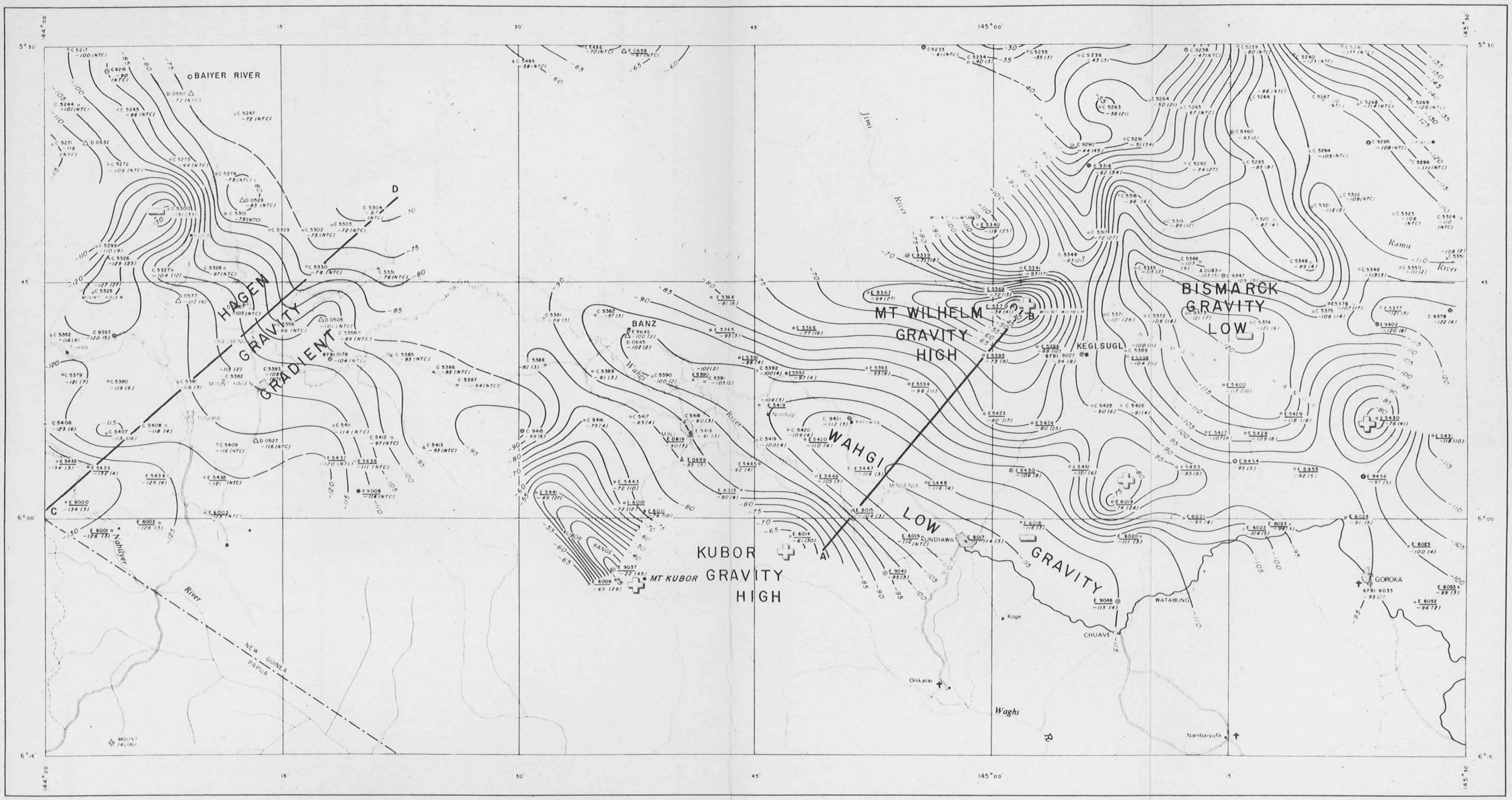
For the calculation of Bouguer anomalies 2.67 g/cm³ has been adopted as an average rock density.

Geophysical field data from BMR gravity and microbarometer surveys in 1963, 1968 and 1970.

Terrain corrections have not been applied to Bouguer anomaly values.

B55/B2-42

To accompany Record No 1973/14



(BASED ON B55/B2-5 AND B55/B2-9)

LOCATION DIAGRAM

REFERENCE TO PAPUA AND NEW GUINEA STANDARD MAP SERIES

AMBUNTI	BOGIA	KARKAR ISLAND
WABAG	RAMU	MADANG
LAKE KUTUBU	KARIMUI	MARKHAM
AWORRA RIVER	KIKORI	WAU

Projection: Transverse Mercator (Universal Co-ordinates, International Spheroid)

Planimetry: After the U.S. Army Map Service and the Royal Australian Survey Corps 1:250,000 topographic series maps SB 55-5 and SB 55-9

Elevation datum: M.S.L. from Admiralty tide tables

Station Bouguer Anomaly reliability: Standard Deviation ~3 milligals

BOUGUER ANOMALIES

WITH TERRAIN CORRECTION

SCALE

0 5 10 15 20 25 30 35 40 Kilometres

0 5 10 15 20 Miles

Contour interval 5 milligals

KEY TO GRAVITY STATION NUMBERING

A = 6351 C = 6810
D = 6811 E = 7025

TOPOGRAPHY

- Built-up area
- Named place
- Native village
- Road
- Track
- River or creek
- Hill feature
- Reef
- Aerodrome or landing ground

GRAVITY

- Primary base station
- Secondary base station
- Gravity station
- Permanently marked gravity station
- Trig. station
- 12 Bouguer anomaly (milligals)
- -5 Isogals
- (5) Terrain correction (milligals)
- (NTC) No terrain correction
- 'High' anomaly
- 'Low' anomaly

Bouguer anomalies are based on the "May 1965" observed gravity values at Isogal gravity base stations in and near the area.

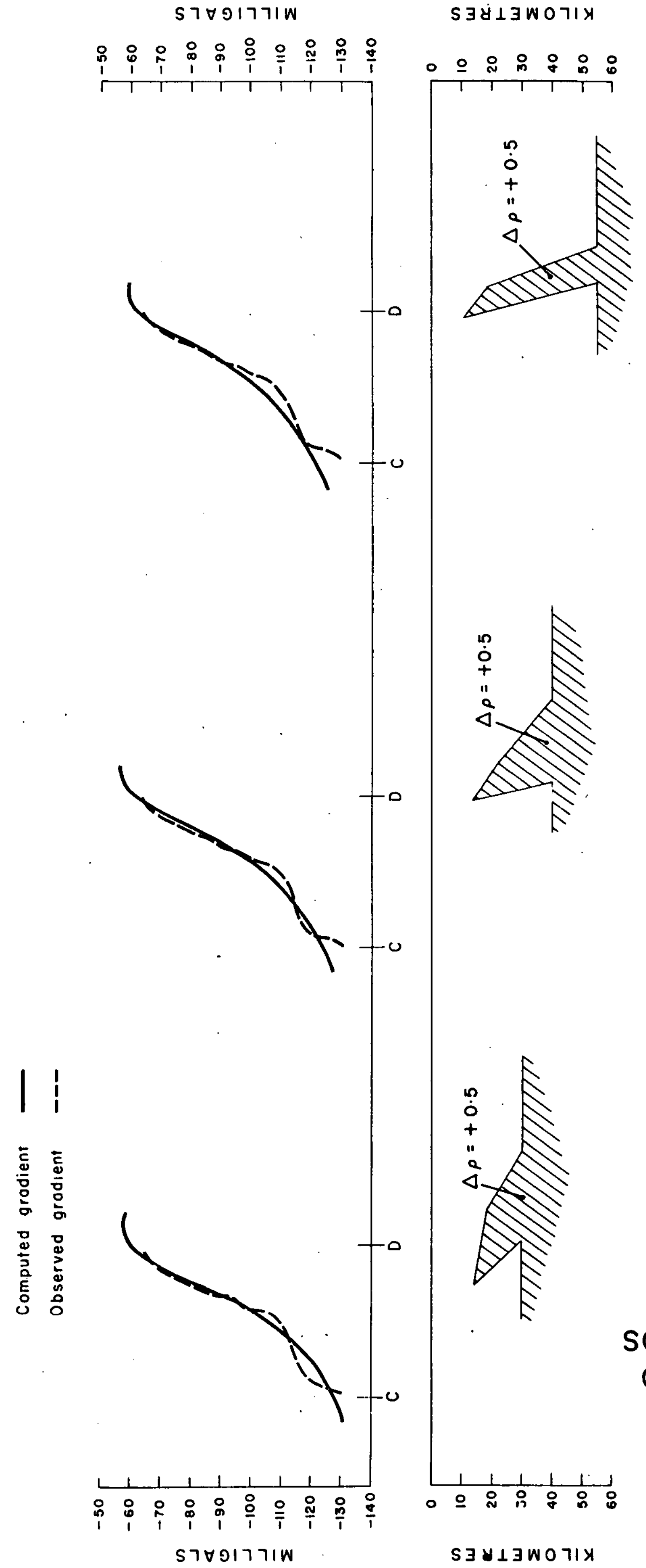
For the calculation of Bouguer anomalies 2.67 g/cm³ has been adopted as an average rock density.

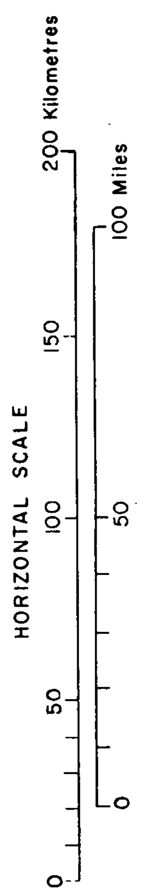
Geophysical field data from BMR gravity and microbarometer surveys in 1963, 1968 and 1970

B55/B2-43

To accompany Record No 1973/14

PLATE 6



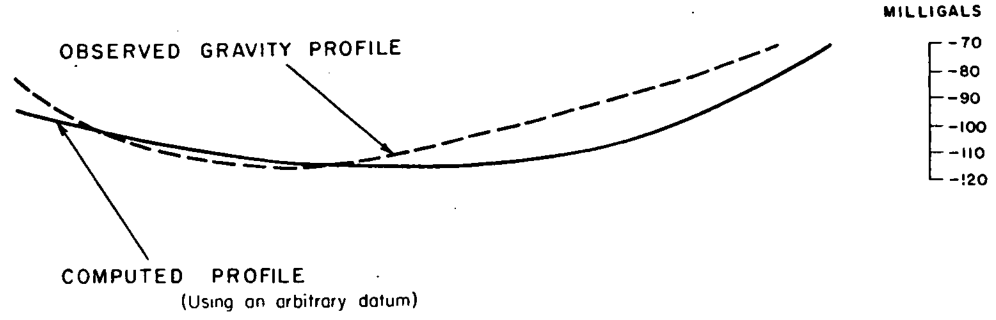


THREE POSSIBLE SOURCES OF HAGEN GRAVITY GRADIENT

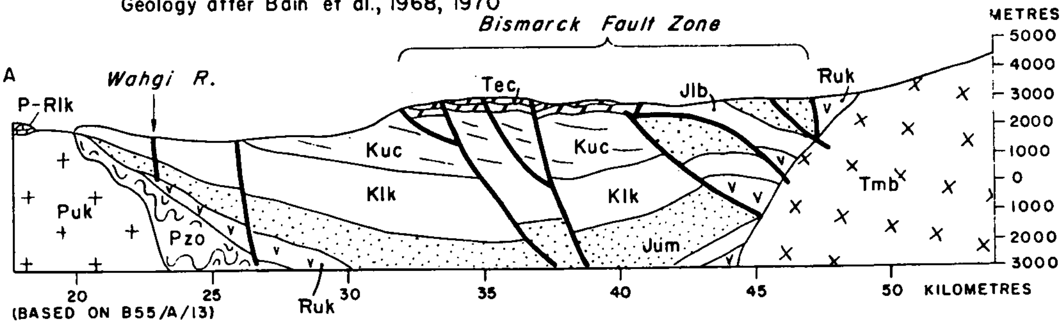
To accompany Record No 1973/14

B55/B2-44A

PLATE 7

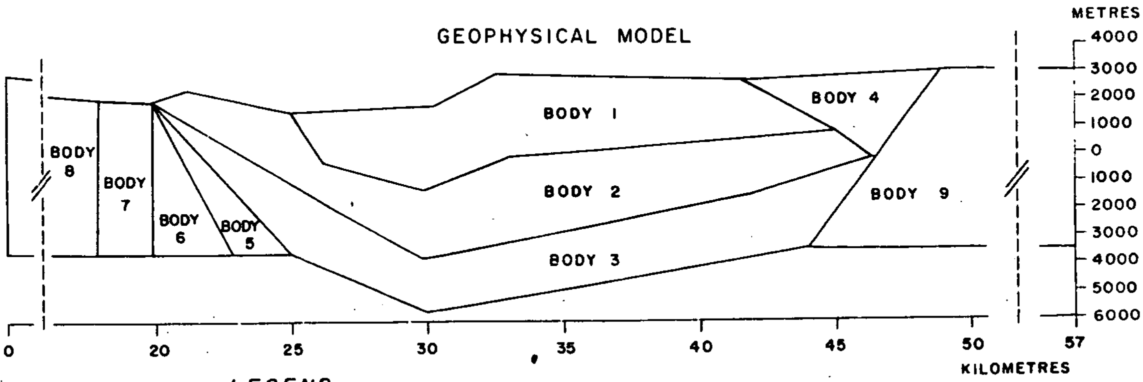


SECTION A - B
Geology after Bain et al., 1968, 1970



GEOLOGICAL SECTION

GEOPHYSICAL MODEL



LEGEND

Body 1 $\Delta\rho$ = -0·10 *Chim Formation (Kuc)*
Body 2 $\Delta\rho$ = -0·06 *Kondaku Tuff (Klk)*
Body 3 $\Delta\rho$ = -0·10 *Maril Shale (Jum)*
Body 4 $\Delta\rho$ = -0·05 *Undifferentiated Mesozoic*
Body 5 $\Delta\rho$ = -0·02 *Kana Volcanics (Ruk)*
Body 6 $\Delta\rho$ = 0·12 *Omung Metamorphics (Pzo)*
Body 7 $\Delta\rho$ = 0·20 *Postulated body*
Body 8 $\Delta\rho$ = 0·03 *Kubor Granodiorite (Puk)*
Body 9 $\Delta\rho$ = 0·21 *Bismark Intrusives, (gabbros) (Tmb)*
For actual formation densities see Appendix F

$\Delta\rho$ = Density contrast in g/cm³

OBSERVED AND COMPUTED GRAVITY PROFILES - WAHGI GRAVITY LOW

To accompany Record No 1973/14

B55/B2-45A

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