71/38
4

COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

500485

Record No. 1971/38

Airborne Gamma-Ray Spectrometer Survey of the Thorntonia and Burke River Areas of Northwest Queensland, 1969

by

D. R. Waller, R. D. Beattie and D. N. Downie

RECORD NO. 1971/38

AIRBORNE GAMMA-RAY SPECTROMETER SURVEY OF THE THORNTONIA AND BURKE RIVER AREAS OF NORTHWEST QUEENSLAND, 1969

by

D.R. WALLER, R.D. BEATTIE

and D.N. DOWNIE

CONTENTS

ILLUSTRATIONS

SUMMARY

An airborne radiometric survey was flown during September and October 1969 over two areas of phosphate-rich Cambrian sediments marginal to the Cloncurry Complex of northwest Queensland. The object of the survey was to conduct extensive tests of the gamma-ray spectrometer equipment recently acquired by the Bureau of Mineral Resources, Geology & Geophysics, and to determine the potential of this equipment as a prospecting and geological mapping tool in a phosphate environment.

Spectrometer operation techniques and data interpretation procedures are discussed in the light of experience gained during the survey.

The equipment proved to be of sufficient stability and sensitivity to delineate zones of distinctive radiometric character, and the spectrometer shows promise of being a useful aid to geological mapping. Good correlation was obtained between uranium anomalies and known phosphate outcrops. Prospecting of potential phosphatic areas with this equipment is recommended.

1. INTRODUCTION

A gamma-ray spectrometer was purchased by the Bureau of Mineral Resources, Geology & Geophysics (BMR) in September 1968. After laboratory testing in late 1968 the equipment was installed in the Bureau's Aerocommander aircraft VH-BMR. Preliminary testing of the spectrometer over Plen's Deposit near Dubbo, New South Wales and three sölvsbergite outcrops near Woodend, Victoria, was carried out during December 1968 and January 1969.

The object of the present survey was to conduct more extensive tests of the equipment than was possible over the localized radioactive outcrops, and to determine its potential as a prospecting and geological mapping tool. Two areas of northwest Queensland were selected for investigation. These areas contain phosphatic deposits which were known to be radioactive.

The survey was flown during September and October 1969, and during this period approximately 4000 line-kilometres of survey data were collected. Lines were spaced at 320 metres (0.2 miles) and oriented east-west. Full proton precession magnetometer coverage was obtained in addition to gamma-ray spectrometer coverage. Details of operations and equipment are given in the Appendix.

The phosphates are contained in two areas of Cambrian sediments marginal to the Cloncurry Complex (Plate 1), which forms part of the Australian Precambrian shield. One survey area lies northwest of Mount Isa on the boundary between the Georgina Basin and the Cloncurry Complex. This is referred to as the Thorntonia Area. The other lies on the western boundary of the Burke River Complex, southeast of Duchess, and is referred to as the Burke River Area.

In both areas Proterozoic Rocks are overlain by sediments of Middle Cambrian age, which represent a Cambrian transgression flanking the present western, southwestern, and southern margins of the Cloncurry Complex.

The sea gradually withdrew southwards in Upper Cambrian and Ordovician times. The phosphates are concentrated in the Beetle Creek Formation, of Middle Cambrian age.

Previous geophysical investigations in the survey areas are confined to aeromagnetic coverage of the CAMOOWEAL 1:250,000 Sheet area (Wells, Milsom & Tipper, 1966) in which the Thorntonia Area lies, and reconnaissance traverses over parts of the Burke River Outlier (Jewell, 1960). These surveys are not of sufficient resolution to assist the understanding of the geology of the survey areas. Although BMR has conducted many radiometric surveys in the Mount Isa region, no radiometric work is known to have been flown over either the Burke River Area or the Thorntonia Area.

In 1908, Strutt demonstrated the presence of radium and uranium in phosphorites. Since then, most of the large marine phosphate deposits of the world have been found to be notably radioactive (Davidson & Atkin, 1952). Certain phosphate rocks of the USSR were found to be associated with both uranium and thorium (Rusakov, 1933). The uranium content of phosphate deposits is generally in the range 0.006 to 0.014 percent equivalent uranium oxide, but values as low as 0.001 and as high as 0.054 percent have been detected in phosphate deposits in the USA (Thompson, 1951). Phosphorus pentoxide concentrations in these rocks are typically of the order of 30 percent.

The phosphorus in the sea is believed to be derived from submarine and coastal vulcanism, and from erosion of phosphorus-containing sediments (De Kun, 1965). Micro-organisms may play an important part in concentrating the phosphate. The basic phosphate mineral is apatite, $Ca_5(PO_4)_3F$, but substitution of sodium, strontium, uranium and thorium for calcium, and of CO_3 and SO_4 for PO_4, is possible. Uranium for substitution is readily available in seawater, which at the present time contains 3 parts per billion equivalent uranium oxide. Since uranium is dispersed in the phosphate mineral lattice, it is not susceptible to leaching (Adams & Fryer, 1964; Chentsov, 1961; Richardson, 1963), whereas from 20 to 90 per cent of the uranium can be leached from a fresh granite (Chentsov, 1961; Krylov & Atrashenok, 1959).

2. GEOLOGY

The survey areas lie on the margin of the Cloncurry Complex as shown in Plate 1, which also indicates the distributions of the major Precambrian units.

The Complex is a shield comprising Proterozoic and Archaean rocks, which have undergone extensive granitization, metamorphism, and diastrophism (Carter, Brooks & Walker, 1961).

The sediments in the Thorntonia Area were deposited in a shallow shelf environment, whereas those in the Burke River Area belong to the Burke River Outlier and were deposited in a meridional basin 100 km long by 30 km wide.

In both areas the phosphate deposits are associated with the early stages of a Middle to Upper Cambrian transgression, during which the rocks of the Beetle Creek Formation were deposited. It is in this Formation and its erosional derivations that all significant phosphate concentrations have been found.

Thorntonia Area

The geological information on this area was supplied by De Keyser (pers. comm.). The sediments in this area are predominantly of Middle Cambrian age, and in the west and south are frequently covered by laterite and some Mesozoic deposits (Plate 2).

The Precambrian basement, which crops out in the east of the Thorntonia Area, consists of quartzite, siltstone, chert, and dolomite belonging to the Paradise Creek Formation. The rocks are generally steeply to moderately tilted and folded.

A basal conglomerate separates these rocks from the Thorntonia Limestone, of Middle Cambrian age. This Limestone contains dolomite and dolomitic limestone with intermittent nodules and layers of chert. The unit is weakly phosphatic, containing up to 2 percent P_2O_5.

The next unit in the succession is the Beetle Creek Formation, which overlies and interfingers with the Thorntonia Limestone.

The basal beds of the Beetle Creek Formation are sandstone, breccia, and dolomitic limestone, and are irregular in composition and extent. There is evidence to indicate that a small diastem separated these beds from the Beetle Creek Formation proper, which consists mainly of an irregular chert and silt-shale sequence, with interbeds and lenses of phosphorite and phosphatic siltstone. Bedding surfaces are uneven and wavy, resembling shallow-marine bottom surfaces. The sequence is commonly calcareous, and west of West Thornton Creek it grades into fossiliferous limestone. Phosphorite and phosphatic siltstone intervals occur at various levels, generally near the base of the formation.

The maximum thickness is estimated to be over 30 m, but it thins rapidly to the north. It is bounded in the south by a large fault system, which must have strongly influenced the depositional history, for the Beetle Creek Formation is sparse south and west of the fault.

The Formation shows rapid facies changes, and this is also noticeable in the phosphorite beds, which are irregularly developed. Thus a lens of phosphorite containing over 30 percent P_2O_5 and 3 m thick may grade within a hundred metres into a thin phosphatic siltstone.

The Beetle Creek Formation is unconformably overlain by the Inca Formation, which comprises flaggy or bedded siltstone and fine sandstone with some thin-bedded chert. Thin lenses of pelletal phosphorite are enclosed in the basal section, and some siltstones are phosphatic. The thickness of the Inca Formation is irregular, and outcrops are poor. The Currant Bush Limestone is a calcareous facies of the Inca Formation, and comprises bituminous limestone with marly interbeds and chert layers.

The Currant Bush Limestone is overlain by the V-Creek Limestone, which resembles the former very much but seems to include a larger variety of calcareous beds.

Much of the southern and western boundaries of the Thorntonia Area are covered by laterite or Mesozoic sandstone, or both, and the margins of many of the creeks in the area are characterized by alluvium and soil accumulation.

Folding of the Cambrian beds caused by differential compaction and by drag along faults is evident, but dips rarely exceed 10 degrees. Of more importance is faulting, which appears to have influenced the depositional pattern of the sediments. Examples of this are the curved fault that terminates the Beetle Creek Formation to the south, and the fault system which separates the Cambrian from the Precambrian rocks in the southeast.

Burke River Area

The geology given below is taken mainly from the work of De Keyser (1968). The sediments preserved in the survey area are mainly of early to late Cambrian age, and are overlain by Ordovician formations towards the south (see Plate 7). Small remnants of Mesozoic cover are found in places along the margins of the Burke River Outlier. Outcrops of fresh, relatively unaltered rocks are confined to the limestone formations. In the Burke River Outlier, rocks were subdivided on the basis of their fossil assemblages; they are therefore biostratigraphic units, and rarely lithostratigraphic formations (Opik, 1960, 1961; Carter & Opik, 1963).

The rocks in the western portion of the survey area comprise a complex of porphyritic and foliated massive granodiorite and granite known as the Kalkadoon Granite.

The first sediments in the area were Upper Proterozoic (?) glacial tilloids followed by a predominantly sandstone and shale sequence, which rapidly filled the basin. During the Lower Cambrian, a littoral orthoquartzite and conglomerate sequence topped by massive mudstone covered the area and extended over the Precambrian borderland. All these units have been grouped together under the name of Mount Birnie Beds.

During the early Middle Cambrian, deposits of thick-bedded dolomitic Thorntonia Limestone or its cherty equivalents were laid down as a thin layer over the whole of the Burke River Outlier and, in the east, beyond its margin.

After a temporary regression, the Burke River basin was inundated by a Middle to Upper Cambrian transgression moving from south to north and east. The basal sediments were the siltstone, siliceous shale, fine sandstone, and chert of the Beetle Creek Formation, and conditions were favourable for the deposition of phosphorites. Russell (1967) subdivided the formation, from base to top, into a Lower Siltstone Member, a Lower Breccia Member, and a Monastery Creek Member which carries the main phosphorite deposits.

The Lower Siltstone Member is limited to the southern part of the Burke River Outlier, and gives way to the Lower Breccia Member in the northern half of the survey area.

The Monastery Creek Member is the most persistent member in the Beetle Creek Formation. It comprises phosphorite beds and phosphatic siltstone, phosphatic shale, and chert and phosphatic chert. The distribution of small outcrops and pebbles of high-grade phosphorite indicates that the Monastery Creek Member originally extended over most of the Burke River Outlier. The overlying formations are not known to be richly phosphatic, and are non-calcareous, whereas the genesis of the phosphate is probably closely associated with a calcareous environment. The distribution of the phosphates is indicated in Figure 1.

The Beetle Creek Formation underwent some marginal erosion during a short, slight regression, but then the transgression continued northwards. Free water circulation was impeded to some extent, and sedimentation was slow and quiet.

During this transgression the Inca Formation of shale, chert, sandstone, and some calcilutite limestone, and the Devoncourt Limestone (Opik, 1961) which contains small quantities of calcareous shale, were deposited within the Burke River Area.

At the beginning of the Upper Cambrian, the transgression was halted and gave way to a general regression during which the Chatsworth Limestone and the O'Hara Shale were deposited in the survey area. The O'Hara shale sediments are ferruginous as a result of lateritization, and are preserved in incised plateaux and mesas distributed over most of the Burke River Outlier.

In the south the Ordovician Ninmaroo Formation of calcarenite, calcilutite, intraformational breccia beds, limestone, and some marly interbeds, and the Swift Beds of sandstone and siltstone with chert and carbonate interbeds were deposited. The Swift Beds are extremely poorly preserved, and are somewhat lateritized.

The main deformation of the Burke River Structural Belt, of which the Burke River Outlier is the northernmost sector, took place during the Ordovician (Opik, 1960). From this period until the Lower Cretaceous, erosion, deep weathering, and leaching took place. The tops of the O'Hara Shale mesas and plateaux are remnants of the landscape formed at that time. A regional subsidence during the Lower Cretaceous was followed by widespread deposition of freshwater conglomerate and sandstone followed by marine siltstone and shale. This cover was eroded during the next uplift in the Tertiary, and was reduced to a few scattered mesa cappings. Lateritic alteration produced ferruginous cappings and greybilly surfaces.

Finally, at the beginning of the Quaternary (?), the Burke River Outlier was tilted to the south by the Selwyn Range Uplift; the old drainage system became rejuvenated in its headwaters region, and alluvial sediments were deposited on the Burke River Plain.

The Outlier is bounded by fault systems along its western and northern margins, and to some extent along its eastern margin. The western fault system passes through the survey area. These fault systems roughly coincide with the original depositional margins, and recurrent movements along them have produced a graben. They do not appear to have any significant lateral components, but vertical displacements of up to 300 m have taken place. Steep tilting and minor folds with sharp crests are present near the faults, but away from them the Cambrian strata are subhorizontal or show very gentle domes and folds with dips not more than a few degrees.

Phosphate deposits

The phosphorites in the Thorntonia Area are predominantly earthy, fine-grained deposits, whereas the Burke River Area is characterized by pelletal phosphorites. In both areas the distribution of the phosphatic Cambrian outcrops with respect to the Precambrian ridges, and the types of sediments, fossils, and bedding structures encountered, show that the following factors were present during the formation of the phosphorite beds:

Generally restricted seas

Irregular coast lines

Shallow, probably clear water

Slow and irregular sedimentation of biochemical and very fine-grained clastic deposits

A copious supply of nutrients, giving rise to an abundance of life.

These conditions correspond closely to the requirements of a favourable phosphate environment as listed by De Kun (1965).

It appears that the major phosphorite deposits were formed close to the old shore lines. Toward the open sea the grades become poorer, the thickness of the stratigraphic section increases considerably, and the depth of burial of the phosphorite beds becomes economically prohibitive (De Keyser, 1968).

3. SURVEY OPERATION

A theoretical background to gamma-ray spectrometry is given by Duivenstijn and Venverloo (1963). Problems of aeroradiometric interpretation with respect to regional geology are discussed by Gregory (1960). Darnley and Fleet (1968) compared the results of airborne spectrometry with ground spectrometry over the same region, and determined that anomaly profiles were closely analogous.

Of the naturally occurring radioelements, only potassium-40 and members of the uranium and thorium series give rise to significant gamma radiation of energies in excess of 1 MeV. The gamma-ray spectrometer is set to monitor the following radiation peaks:

(1) The K40 1.46-MeV peak.

(2) The Bi214 1.76-MeV peak (uranium series).

(3) The Tl208 2.62-MeV peak (thorium series).

For convenience, these are referred to as the potassium, uranium, and thorium channels respectively, although in the case of uranium and thorium it is the distribution of a daughter product which is monitored. Counts in the three channels are interrelated since the uranium channel also detects gamma radiation due to thorium, and the potassium channel detects radiation due to uranium and thorium. Thorium and its daughter products are not very susceptible to leaching, and the thorium channel therefore gives a good indication of true thorium distribution. The uranium in the phosphate deposits is also not readily leached (see Introduction), but the uranium elsewhere is unlikely to be in equilibrium with its daughter products.

The airborne gamma-ray spectrometer

Figure 2 shows the equipment layout used to measure gamma radiation at the start of the survey. Signals from two detecting heads are amplified before being fed to the analysing modules.

The detectors each contain a thallium-activated sodium iodide crystal 15 cm in diameter and 10 cm thick, optically coupled to a photomultiplier tube. The pulse height analysers operate on input pulses from 0 to 10 volts; in order to monitor radiation of up to 2.8 MeV, the equipment was calibrated to give 1 volt output per 0.3 MeV of incident gamma-ray energy. For calibration purposes a caesium-137 source was used. Cs137 gives rise to a prominent peak at 0.662 MeV (see the spectrum, Fig.3).

Calibration of the equipment was achieved by adjusting the E.H.T. supply voltage and the gain of the linear amplifiers until the Cs137 peak occurred at 2.21 volts. Figure 4 shows the relationship between the E.H.T. and the amplifier gain for both heads. In the original layout (Fig.2) with one E.H.T. in use, the operating points used were those indicated by circles in Figure 4.

The resolution of a detecting system at the energy of a particular gamma peak is defined as the half maximum width of that peak divided by its energy (see Fig. 3). The resolution of the VH-BMR detectors is approximately 8.5 percent. The Cs137 source was placed between the detector heads during flight, and the peak produced was continually monitored by a spectrum stabilizer (Fig. 2), which adjusts the E.H.T. value to maintain the Cs137 peak output at the same level.

This system suffers from the disadvantage that unless the detector-preamplifier-amplifier chains drift at the same rate, loss of resolution takes place during flight. To overcome this problem, independent E.H.T. and spectrum stabilizer units were installed for both heads during the survey (Fig.5). This proved to be a satisfactory arrangement, and adjustments to settings were rarely necessary. The operating values are shown as crosses in Figure 4.

Survey parameters

Channel widths were set as follows:

Channel 1: All pulses with energy greater than 1 MeV.

Channel 2: Pulses between 1.3 and 1.6 MeV (potassium).

Channel 3: Pulses between 1.6 and 1.9 MeV (uranium).

Channel 4: Pulses between 2.45 and 2.75 MeV (thorium). Thorntonia Area

" " 2.4 and 2.8 Burke River Area

These channel settings are shown superimposed on a uranium-caesium spectrum in Figure 6.

The caesium-137 peak gives rise to radiation of up to 0.8 MeV, and it was not considered desirable to include any of this radiation in the total-count channel. In addition, radioactive fallout can give rise to a prominent peak at 0.75 MeV attributed to Zr95 (Horwood, 1958; Doig, 1968); to avoid any possible contribution from this source it was decided not to monitor any radiation below 1.00 MeV.

The potassium and uranium channels straddle the 1.46-MeV potassium-40 peak and the 1.76-MeV uranium peak. Slightly wider window settings than those of Doig (1968) were used, to increase count rates as much as possible.

The uranium 1.20-MeV peak and thorium 1.19-MeV peaks cannot be distinguished, and counts in this range were therefore not monitored.

The aircraft altitude should be as low as possible, and its velocity as slow as possible, for maximum response to a particular radioactive body. In practice a flight altitude of 80 m above ground level and a velocity of 100 knots (185 km/h) were realized; any reduction in these figures caused excessive pilot fatigue.

Lines were flown at 320 m spacing on an east-west grid.

At 80 m above ground level the aircraft monitors a strip of ground in the region of 150 m wide, but count rates are predominantly influenced by outcrop conditions below the aircraft. This spacing is probably inadequate for point source detection, but was considered suitable in view of the areal extent of the target outcrops of Beetle Creek Formation.

The time constants most suitable for a particular survey area depend on count rates and on the size of target bodies. Smaller time constants give rise to a wider statistical noise envelope, but define the position of a radioactive body with greater accuracy. The selection of time constants is discussed below.

Determination of time constant

Since the count rates in the different channels are related, and to permit comparison must be of the same order, it was decided that the same time constant should be used for all four channels. The uranium channel was of most potential significance for phosphate detection, and this channel was therefore chosen for investigation. Lines were flown intermediate to the main survey flight-lines over a test area of approximately 40 square kilometres on the eastern boundary of the Thorntonia area (Plate 3 and Figs 8-13). All four channels on the spectrometer were set to monitor radiation between 1.6 and 1.9 MeV (the uranium channel), and the time constants on the ratemeters were set to 0.5, 2.0, 10.0 and 40.0 seconds. Figure 7 shows typical portions of the traces obtained, together with interpreted smoothing.

Smoothing was unnecessary on the 40-second and 10-second channels, but statistical noise is prominent on the 2-second and 0.5-second channels. Particularly on the latter the statistical noise tends to obscure anomalies, and the smoothing process becomes extremely subjective.

Increase of the time constant introduces a lag in data presentation, which varies for different source configuration. A lag of half the time constant was taken to be a reasonable correction factor to apply. Clearly this lag becomes a more serious factor with increasing length of time constant, until in the 10- and 40-second channels it plays a dominant role in the location of contour cuts.

Figures 8 to 12 show geology together with contour configurations for the different time constants. Figures 8, 9 and 10, which show respectively the results using 0.5-second time constant, 2-second time constant, and 2-second time constant with a 1-second delay correction are similar, and show approximately the same degree of complexity. Detail on these sheets is far greater than that on the geological base maps.

Figure 11, which shows the results using a 10-second time constant with a delay correction of 5 seconds, shows broad fluctuations in background but the boundaries of radiometric units are inadequately defined and the small anomalies apparent in Figs 8, 9 and 10 tend to disappear. The 40-second time constant contours as shown in Figure 12, are totally inadequate for interpretation, owing to their lack of resolution and their positional uncertainties.

On the basis of this test it was decided to use a 2-second constant on the survey. The application of a 1-second delay correction does not appear to be warranted, and no correction was therefore applied to the survey data.

Comparison of figure 9 with Plate 3 shows that although the general outlines of the anomalies are the same for independent grids at 320-m flight-line spacing, differences in detail are apparent. Thus closer spacing of flight-lines would be required to define the radiometric anomalies fully.

Pre-flight checks

Early in the survey, tests wer carried out with a ground station to determine the constancy of background radiation due to radioactive dust, P.10

radon and cosmic rays. Overnight monitoring of radiation with energies greater than 1.6 MeV showed a variation of 15 percent. No sudden changes were observed. The vertical variation was monitored by flying at different altitudes over a lake - again no significant variations were detected.

Three factors were checked daily: (1) the background radiation level, (2) the sensitivity of each channel, (3) the radiation from a ground source. The last check was necessary to determine whether meteorological conditions were affecting natural radiation levels.

For the Thorntonia Area, the base level was set before each flight by flying over Lake Moondarra, the Mount Isa reservoir. The aircraft was then flown over Mary Kathleen spoil-heap to monitor sensitivity and ground emission variations. Each survey flight commenced with the last line of the previous flight; radiation levels were compared to ensure that base levels remained constant. This method proved to be unsatisfactory owing to the extra flying involved in traversing Lake Moondarra and Mary Kathleen, and also owing to the impossibility of maintaining the same position, altitude, velocity, and heading on each flight over the Mary Kathleen spoil-heap.

For the Burke River Area therefore the background was monitored at 760 m above ground level, the sensitivity was checked with a source inside the aircraft, and a baseline was flown in the survey area before and after each flight. It was found to be unnecessary to overlap adjacent flights under this system. In some instances the base level was found to drift during a flight, and in these circumstances a linear drift was assumed. The maximum drift recorded was 10 percent of the chart width.

Truckborne spectrometer

The layout for the truckborne system is shown in Figure 15. A sodium iodide crystal 10 cm in diameter and 5 cm thick was used in the detector, and the system had a resolution of about 10 percent at 0.662 MeV.

The object in mounting a truckborne system was to pinpoint anomalies previously detected from the air, and, where necessary, to collect samples to assist geophysical interpretation. This would be particularly useful in an area with sparse geological information.

The recorder for this system was mounted in the cab of the truck, and after anomalies were pinpointed on the aerial photographs, the truck was driven over the area until a region of maximum anomaly was detected. If the anomaly was of sufficient magnitude a spectrum was obtained to confirm the radioelement preponderance deduced from the aircraft record.

In places where a more accurate distribution of a particular radioelement in an area of interest is required, it would be feasible to survey using the truckborne equipment by driving on a predetermined grid. Anomaly location would be considerably improved by gearing the recorder drive to the speed of the vehicle.

12

4. INTERPRETATION PROCEDURE

This section discusses the preliminary processing required to convert the data to an easily interpretable form, and considers interpretation methods.

A sample of the traces obtained for the four channels over a short portion of the survey area is given in Figure 14. Pen parallax has been removed, and the radio-altimeter trace is shown for comparison and timing purposes. The fiducial marks on this trace occur at 6-second intervals. A 2-second time constant makes some degree of smoothing necessary to remove the statistical noise variation. Smoothing by hand is necessarily a subjective process and is particularly likely to introduce error at low count rates. Digital acquisition coupled with filtering would remove this subjective element.

Three different methods of presenting the data in contour form were considered:

(1) In terms of "geological background"; i.e. the background level of radiation from the ground recorded at survey height after correction for the effect of atmospheric radiation and cosmic rays.

(2) In terms of the standard deviation of the statistical variations.

(3) In measured counts per second.

The first two methods have advantages in interpretability, but their basic contour intervals are arbitrary, and the third method was therefore adopted.

Thorium channel counts ranged from 2 to 16 counts per second (c.p.s.) above background in the Thorntonia Area, and from 2 to 26 c.p.s. above background in the Burke River Area. The difference in maximum count rate is partly attributed to the wider window setting in the latter area. The standard deviation of this channel ranges from 1 to 2.8 c.p.s., and a contour interval of 2 c.p.s. was considered adequate for data presentation.

The uranium channel count rate ranged from 5 to 50 c.p.s. above background. The standard deviation range is thus about 2.5 to 4.5 c.p.s. Contour significance is affected by the contribution from the thorium radiation, and a contour interval of 5 c.p.s. was considered adequate for this channel.

The potassium channel count rate ranged from 10 to 70 c.p.s., giving rise to a standard deviation range from 3.2 to 5 c.p.s. In this channel the overlap from both thorium and uranium series channels degrades the significance of anomalies, and a contour interval of 10 c.p.s. was utilized.

The channel displaying total count for radiation over 1 MeV measured count rates from 25 to 150 c.p.s. above background. The standard deviation ranged up to 8 c.p.s., and this channel was contoured at 25-c.p.s. intervals. The total count contours for the Thorntonia Area are shown in Plate 5. When the data from the other three channels are available for geophysical interpretation, it was found that the total count data provided no additional information. The total count channel was therefore not contoured in the Burke River area.

In general terms, in both the Thorntonia and Burke River Areas anomalies on the uranium channel correlate with the Beetle Creek Formation, and Precambrian rocks correlate with anomalies on the thorium channel or the potassium channel, or both.

The significance of an anomaly depends on the surrounding level of radiation, and is best assessed by comparison with the known geology of an area. Contour levels of approximately 2 times the "geological background" of the survey areas give good correlation with the mapped geology. Thus in the thorium channel the "geological background" is approximately 4 c.p.s., and the significant level was taken as 8 c.p.s. On the uranium channel the "geological background" ranges from 5 to 10 c.p.s., and a level of 15 c.p.s. was taken as significant. The potassium channel "geological background" ranges from 10 to 20 c.p.s.; a significant level of 30 c.p.s. was adopted.

On the basis of the contour maps for the individual channels, and with due regard for interference between the channels, areas of similar radioactive character were delineated. In the Burke River Area it was also possible to delineate areas characterized by extremely low count rates in the thorium channel (see Interpretation, Plates 6 and 10). Some generalization of the anomalous areas is warranted in view of the herringboning due to variations in altitude and velocity of the aircraft.

It is possible to 'strip' the effect of one channel on another and obtain count levels attributable to one radioactive series only (Doig, 1968). The Uranium channel to Potassium channel stripping factor for the airborne equipment on the settings given was 1.15. The thorium channel to Uranium channel and Potassium channel factors could not be determined, as no thorium source was available. These latter factors are constant only if the thorium daughter products are in equilibrium, since more than one thorium daughter gives rise to radiation of energies in excess of 1 MeV. By dividing the count rate of one channel by that in another, contours of channel ratios can be drawn, thus eliminating the effect of altitude variations. Taking the stripping factor from the thorium contribution to the Uranium channel to be a constant C, then

$$\frac{\text{Observed U channel counts}}{\text{Observed Th channel counts}} = \frac{\text{Counts actually due to U}}{\text{Counts actually due to Th}} + C$$

i.e. the ratio U channel counts/Th channel counts can be contoured directly from the collected data and interpreted without it being necessary to strip the thorium contribution from the uranium channel. However, ratio calculation is a time-consuming technique, and is generally impracticable without digital processing of the data. It was not attempted in the present survey.

An alternative method of interpreting the data is to divide the original charts into sections of similar radioactive character. The transition points can then be transferred to base maps to define zones of similar character. A zonal map built up in this way is shown in Figure 13 together with geology for the test section of the Thorntonia Area. This method of interpretation eliminates the need to smooth traces, and is far more rapid than that based on contouring. However, it is highly subjective, with a tendency to over-simplify areas of rapid variation and over-interpret areas of low radioactivity. It was therefore not applied to the full survey area.

Over several flights in the southern half of the Burke River area the radio-altimeter was suspect because it gave rise to sudden variations in recorded altitude. The loss of altitude reliability was expected to give rise to hour-glass structures in the contours, but little evidence of this can be seen on the Burke River Area contour sheets. It thus appears that some degree of altitude variation can be tolerated.

Ground investigation of anomalous areas located from the airborne work showed that surface counts were low. The airborne anomalies were probably due to extended sources of anomalous radioactivity. Little difficulty was encountered in locating the areas that gave rise to anomalies, and sample collection and in situ rock investigation were thus facilitated with the truckborne unit. Few of the ground spectra obtained gave well resolved peaks, but it was possible to assess the radio-elements present qualitatively. As an approximate guide, airborne anomalies of over 16 c.p.s. in the thorium channel and of over 30 c.p.s. in the Uranium channel gave rise to satisfactory ground spectra. In the Burke River Area it was possible to locate and investigate ground sources, previously pinpointed on aerial photographs from airborne surveying, at the rate of one per hour. As the terrain here was fairly flat, however, far more time would be required in regions of high relief.

By calibration of the truckborne equipment along the lines suggested by Doig (1968), it would be possible to determine the percentages of thorium daughter thallium -208, uranium daughter bismuth -214, and potassium present in rock outcrops.

5. GEOPHYSICAL INTERPRETATION

The survey areas were divided into zones of similar radiometric character on the basis of the significant contour levels of the radiometric channels, as discussed in Chapter 4. In this chapter the zones are assessed in relation to the mapped geology.

Thorntonia Area (Plate 6)

The Precambrian rocks that lie along the eastern border of the Thorntonia Area are characterized by strong potassium anomalies which are frequently associated with thorium, and less commonly by uranium anomalies.

The dominant feature of the southeast of the Thorntonia Area is a broad zone of anomalous K-Th-U which strikes approximately NNE. The aerial photographs of this region show that it is an elevated area, as is the NNE-trending zone of K-Th-U and K-Th a few kilometres to the west. The intervening area is low lying, and the paucity of strong anomalies is probably due partly to increased flight altitude and partly to alluvial deposits.

The Thorntonia Limestone generally shows low count rates in all channels, and could not be correlated with radiometric zones.

The Beetle Creek Formation shows generally good correlation with anomalous uranium zones. The stongest uranium anomalies in the survey area (over 45 c.p.s.) occur over Beetle Creek Formation outcrops 5 km southeast of Thorntonia Homestead and 2 km west of Bean Tree Bore. Correlation between the uranium anomalies and the phosphates as such could not be investigated in detail owing to the inadequacy of information on the distribution of the phosphate beds. However, where phosphate beds are marked on the geological maps, in general strong uranium anomalies are present, e.g. west of Bean Tree Bore, southeast of Thorntonia Homestead, and along the southern margin of the Beetle Creek Formation outcrop 6 km south of D-Tree Bore. Southwest of D-Tree Bore the Thorntonia Limestone facies of the Beetle Creek Formation predominates, and correlation of outcrops with uranium anomalies is generally poor.

The Inca Formation, Currant Bush Limestone and V-Creek Limestone do not correlate with significant anomalies on any channel.

The Jurassic rocks that occur as scattered outcrops south of Chummy Bore in the north western part of the area probably give rise to the thorium anomalies in this area, although the correlation is poor. There is also anomalous uranium activity in this area, but the anomalies are of minor amplitude.

The Mesozoic laterites show good correlation with thorium anomalies. The highest thorium count in the Thorntonia Area (16 c.p.s.) was recorded over one of these laterite areas on the southern boundary of the survey area. The surface distribution of thorium in the laterites may have increased during lateritization, owing to selective weathering. In view of this close correlation, it appears probable that the area of Jurassic outcrops in the northwest of the Thorntonia Area has undergone some degree of lateritization.

In the northern portion of the Thorntonia Area, a strong correlation was observed between alluvial (river) deposits and thorium anomalies, with subsidiary uranium and potassium anomalies. The distribution indicates that the thorium is derived from outcrops on both sides of Thornton Creek. It is probable that the rivers have mechanically and chemically increased the relative abundance of thorium-rich minerals along their courses. This is to be expected if the thorium-rich mineral is monazite, which is particularly resistant to mechanical and chemical attack.

Localized uranium anomalies occur both in the sedimentary and Precambrian metamorphic sequences without correlating with mapped outcrops of Beetle Creek Formation. Uranium anomalies over the sediments are possibly due to unmapped inliers of Beetle Creek Formation at or near ground level, but more probably represent uranium concentrations in the younger sediments. Anomalies over the Precambrian rocks may be due to erosional remnants or erosional derivatives of the Beetle Creek Formation, which have been mapped in several places. Both types of anomaly are recommended for ground investigation in view of their possible association with phosphates.

Burke River Area (Plates 8-10)

The Precambrian Kalkadoon Granite gives rise to potassium and thorium anomalies of large magnitude. Potassium count rates range up to 60 c.p.s., and thorium anomalies of over 16 c.p.s. were recorded. The eastern limit of outcrop of this unit is well defined in the south; farther north there lies a broad zone of scattered thorium and potassium anomalies immediately to the west of the mapped Cambrian outcrops. The sparsity of anomalies may be due to weathering, or to changes in the potassium and thorium concentrations. Uranium anomalies also occur in this area, but they are generally less than 20 c.p.s. and are unlikely to have economic significance - they may, however, assist geological interpretation of the granites.

The Mount Birnie Beds and Thorntonia Limestone do not correlate with any particular radiometric channel. The latter crops out in narrow, elongate bands and is of little significance in this area.

The Beetle Creek Formation as mapped shows generally good correlation with uranium anomalies, but the anomalies considerably overlap adjacent formations. There are, however, some outcrops which give rise to no anomalies or to restricted anomalies. Better correlation is obtained by comparing the uranium anomalies with the known phosphate distribution within the Beetle Creek Formation (de Keyser, 1968; See Fig. 1). The main exception to this correlation is in the outcrop of Beetle Creek Formation which stretches southwards for approximately six kilometres from Mount Birnie. This is not indicated as phosphate-rich area, but uranium anomalies range up to 45 c.p.s.; investigation of the cause of these anomalies is recommended.

The area of Beetle Creek Formation five kilometres southeast of Mount Aplin, and areas around and north of Mount Murray, are phosphatic and give rise to strong uranium anomalies. The Mount Murray anomalies are particularly intense, rising to over 50 c.p.s.

A tongue of Beetle Creek Formation near Mount Bruce gives rise to only a small, localized uranium anomaly of 20 c.p.s. This outcrop is not highly phosphatic except at one location.

East of Galah Bore, in the extreme south of the survey area, lies an approximately annular deposit of phosphatic rock. This area is partially obscured by alluvium, and only where phosphatic outcrops occur are strong uranium anomalies observed. The central outcrops of Beetle Creek Formation are not phosphatic, and do not give rise to large uranium anomalies.

The tongue of Beetle Creek Formation which intersects the southern boundary of the survey area is not phosphatic, and has no associated uranium anomalies.

None of the phosphate deposits appears to correlate with thorium anomalies.

The Inca Formation gives rise to higher than normal thorium anomalies; the high degree of laterization of this unit is probably the cause.

The Chatsworth Limestone outcrop adjacent to Mount Murray is clearly defined by a thorium low, but the elongate areas of this limestone 7 km to the east do not give rise to thorium lows. These areas lie predominantly along a creek bed, and probably do not crop out extensively. If low thorium count rates prove to be a characteristic of limestone outcrops, the value of the spectrometer for geological interpretation will be enhanced.

The Ordovician Swift Formation also correlates well with a zone of low thorium-channel counts. It is composed of sandstone and siltstone with chert, and carbonate interbeds.

In general the laterites show good correlation with thorium anomalies. The strongest thorium anomaly in the survey area, of over 26 c.p.s., occurs over lateritized Inca Formation. It is possible that most of the thorium anomalies detected over alluvial deposits are due to lateritization , but local concentration of thorium-rich minerals is more probable.

The nature of the formation lateritized appears to have little effect upon thorium anomaly levels.

The alluvium gives rise to sparsely scattered thorium, uranium, or potassium anomalies, but these are generally of low count rates. There is, however, a correlation between creek channels and potassium anomalies in some places. Petticoat Creek has several potassium anomalies along its course; Pilgrim Creek and Monastery Creek display strong correlation with high potassium count rates. Some of the tributaries of Monastery Creek are also associated with highs. Dead Horse Creek, and the tributary which joins it near Galah Bore, show good correlation with potassium highs. These tributaries originate in the potassium-rich Kalkadoon Granite, but other tributaries from the same area do not give rise to anomalies. Ground investigation would be required to determine the geological significance of the anomalies and their relationship to the Kalkadoon Granite.

The small uranium anomalies which do not lie on mapped Beetle Creek Formation are of doubtful significance in view of their low count rates, but may be worthy of ground investigation.

6. CONCLUSIONS

The equipment layout and stabilization discussed in Chapter 3 virtually eliminated equipment drift. In the two survey areas, outcrop distributions and radiometric intensities were such that the survey and equipment parameters adopted were adequate to permit resolution of the areas into zones of distinctive radioactive properties.

A number of correlations between zone type and geology can be made:

(1) The Precambrian rocks in both survey areas exhibit predominantly potassium and thorium anomalies with only occasional uranium anomalies.

(2) The Beetle Creek Formation in both areas can be correlated with uranium anomalies, but not with thorium anomalies. In the Burke River Area a more specific correlation is evident between the known phosphate deposits within the Beetle Creek Formation and the uranium anomalies.

(3) In the Burke River Area the Chatsworth Limestone and the Swift Formation correlate with low count rates in the thorium channel.

(4) In both areas the laterites show good correlation with thorium anomalies.

(5) A correlation can be observed between several river systems and radiometric anomalies. In the Thorntonia Area, correlation is primarily with thorium anomalies, with subsidiary uranium and potassium anomalies. In the Burke River Area correlation is with potassium anomalies.

The good correlation observed between the known phosphate deposits and the uranium anomalies indicates that the spectrometer has a high potential as a prospecting tool for phosphates in this part of Australia. The equipment is recommended for evaluation of prospective phosphate areas in this region.

The diversity of radiometric characteristics observed over the rocks of the survey areas demonstrates the high potential of the spectrometer as a geological mapping tool.

The uranium anomalies which are unaccounted for, particularly the large anomaly south of Mount Birnie in the Burke River Area, are recommended for ground investigation. The potassium anomalies associated with some of the rivers in the Burke River Area should also be investigated; if the potassium originates in the Kalkadoon Granite, it may be indicative of hydrothermal deposition.

The source of the strong thorium anomalies over the laterites and some of the alluvial deposits in both areas should be investigated. A survey over an area of known thorium mineralization (e.g. a monazite-bearing beach sand) would assist evaluation of the commercial significance of thorium anomalies.

The feasibility of digital aquisition of the spectrometer data should be considered. Digitization would assist data evaluation by facilitating chart smoothing, channel stripping, and channel ratio determination. There is also a need for calibration of the ground equipment along the lines suggested by Doig (1968), to permit in situ analysis of thorium, uranium, and potassium concentrations.

7. REFERENCES

ADAMS, J.A.S. and FRYER, G.E., 1964 - Portable gamma-ray spectrometer for field determination of thorium, uranium, and potassium. In THE NATURAL RADIATION ENVIRONMENT, edited by J.A.S. Adams and W.M. Lowder. Chicago, University of Chicago Press.

CARTER, E.K., BROOKS, J.H., and WALKER, K.R., 1961 - The Precambrian mineral belt of north-western Queensland. Bur. Miner. Resour. Aust. Bull. 51.

CARTER, E.K., and OPIK, A.A., 1963 - Explanatory notes on the Duchess Geological Sheet. Bur. Miner. Resour. Aust. explan. Notes No. 23.

CHENTSOV, I.G., 1961 - The entry of uranium into some rock-forming minerals. Intern. Geol. Rev., pp. 5-25.

DARNLEY, A.G. and FLEET, M., 1968 - Evaluation of airborne gamma-ray spectrometry in the Bancroft and Elliot Lake areas of Ontario, Canada. Proc. Fifth Symposium on Remote Sensing of Environment, Willow Run Laboratories Institute of Science and Technology, University of Michigan, pp. 833-853.

DAVIDSON, E.F. and ATKIN, D., 1952 - On the occurrence of uranium in phosphate rock, Origine des gisements de phosphates de chaux. Fascicule x1. Congress Geologique International pp. 13-31.

DE KEYSER, F., 1968 - The Cambrian of the Burke River Outlier. Bur. Miner. Resour. Aust. Rec., 1968/67 (unpubl.).

DE KUN, N., 1965 - THE MINERAL RESOURCES OF AFRICA. Elsevier Publishing Co. New York.

DOIG, R., 1968 - The natural gamma-ray flux: In-situ analysis. Geophysics v. 33, p. 311-328.

DUIVENSTIJN, A.J. and VENVERLOO, L.A.J., 1963 - PRACTICAL GAMMA SPECTROMETRY. Philips Technical Library.

GREGORY, A.F., 1960 - Geological interpretation of aeroradiometric data. Bull. geol. Surv. Can. 66.

HORWOOD, J.L., 1958 - Gamma-ray analysis of atmospheric dust samples: Dept of Mines and Technical Surveys Research Report R24.

JEWELL, F., 1960 - Great Artesian Basin aeromagnetic reconnaissance survey, 1958. Bur. Miner. Resour. Aust. Rec. 1960/14 (unpubl.).

KRYLOV, A.Ya. and ATRASHENOK, L.Ya., 1959 - The mode of occurrence of uranium in granites: Geochemistry (USSR) (English Transl.), pp. 307-313.

OPIK, A.A., 1960 - Cambrian and Ordovician geology. In: The geology of Queensland. J. geol. Soc. Aust. 7, 89-109.

OPIK, A.A., 1961 - The geology and palaeontology of the headwaters of the Burke River, Queensland. Bur. Miner. Resour. Aust. Bull. 53.

RICHARDSON, K.A.R., 1963 - Thorium, uranium and potassium in the Conway Granite, New Hampshire: Ph.D. Thesis, Rice University, Houston, Texas.

RUSAKOV, V.P., 1933 - O Soderzhanii Radija: Toriya v Tosfaritakh. Akad. Nauk. U.S.S.R. Doklady. Leningrad-Moscow. Review A. No. 3 pp. 25-33.

RUSSELL, R.T., 1967 - Discovery of major phosphate deposits in north-west Queensland. Qld Govt Min. J. 68 (786), 153-157.

STRUTT, R.J., 1908 - The accumulation of helium in geological time. Proc. Roy. Soc. (London) Series A, v. 81, p. 272 and v. 83, p. 96.

THONPSON, M.E., 1951 - Distribution of uranium in rich phosphate beds of the Phosphoria Formation. U.S. Geol. Survey Rep. TEI-142. Oak Ridge.

WELLS, R., MILSOM, J.S., and TIPPER, D.B., 1966 - Georgina Basin aeromagnetic survey, Queensland and Northern Territory 1963-1964. Bur. Miner. Resour. Aust. Rec. 1966/142 (unpubl).

APPENDIX

OPERATIONAL DETAILS

Personnel

BMR	D.R.	Waller	Party Leader
	R.D.	Beattie	Geophysicist (Part time)
	D.N.	Downie	" "
	L.	O'Toole	Draftsman "
	R.	Curtis-Nuthall	Technical Officer (Part time)
	H.	Alexander	Technical Officer
	C.	Carling	Technical Assistant (Part time)
TAA	J.	Brown	Captain

Equipment

Aircraft: Aerocommander VH-BMR

Gamma-ray spectrometer: Detector-Harshaw 15 cm diameter by 10 cm thick thallium-activated NaI crystals optically coupled to photomultiplier
Electronics-Hamner modules
Stabilization-Cs137 10-micro Curie source
Recorders-DeVar, three-channel

Magnetometer: Airborne - Proton precession magnetometer MNS2 of BMR design
Ground -Proton precession magnetometer MNS1 of BMR design

Ancillary: Radar Altimeter - Bonzer
Camera - 35-mm fisheys

Equipment parameters

Spectrometer: Calibrated to 1 volt = 0.3 MeV

Spectrometer: Channel settings
- Ch. 1 3.33 Volt (integral)
- Ch. 2 4.33 to 5.33 Volt
- Ch. 3 5.33 to 6.33 Volt
- Ch. 4 8.17 to 9.17 Volt (Thorntonia Area)
- " " (8.00 to 9.33 Volt (Burke River Area)

Time Constants: 2 seconds, all channels

Sensitivity:

Ch. 1	500 c.p.s. f.s.d.		
Ch. 2	100 c.p.s.	"	
Ch. 3	50 c.p.s.	"	Thorntonia Area
	100 c.p.s.	"	Burke River Area
Ch. 4	20 c.p.s.	"	Thorntonia Area
	20, 50 c.p.s	"	Burke River Area

Magnetometer: Airborne sensitivity 500 gammas f.s.d.
5000 gammas f.s.d.

Ground station sinsitivity 200 gammas f.s.d.

Survey parameters

Flight altitude	80 m (260 ft) above ground level
Flight velocity	185 km/h (100 knots)
Line disposition	east west
Line spacing	320 m (0.2 mile)

Magnetometer data

Values of total magnetic field strength were recorded along all flight-lines in the two survey areas. These data have not been analysed, but are available for inspection by interested persons.

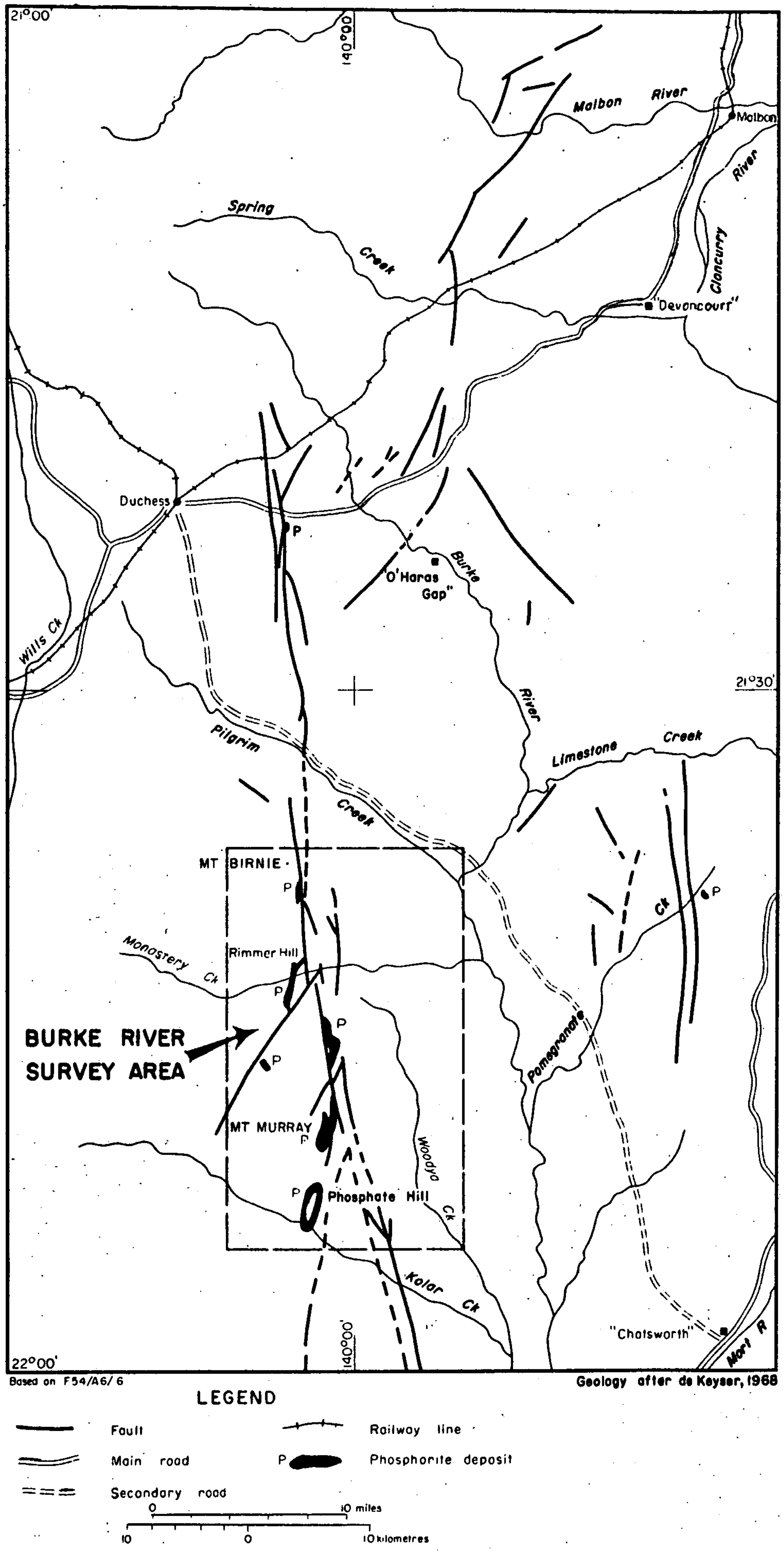


FIG. 1 DISTRIBUTION OF PHOSPHATE DEPOSITS, BURKE RIVER AREA

TO ACCOMPANY RECORD No 1971/38 E54/B1-39A

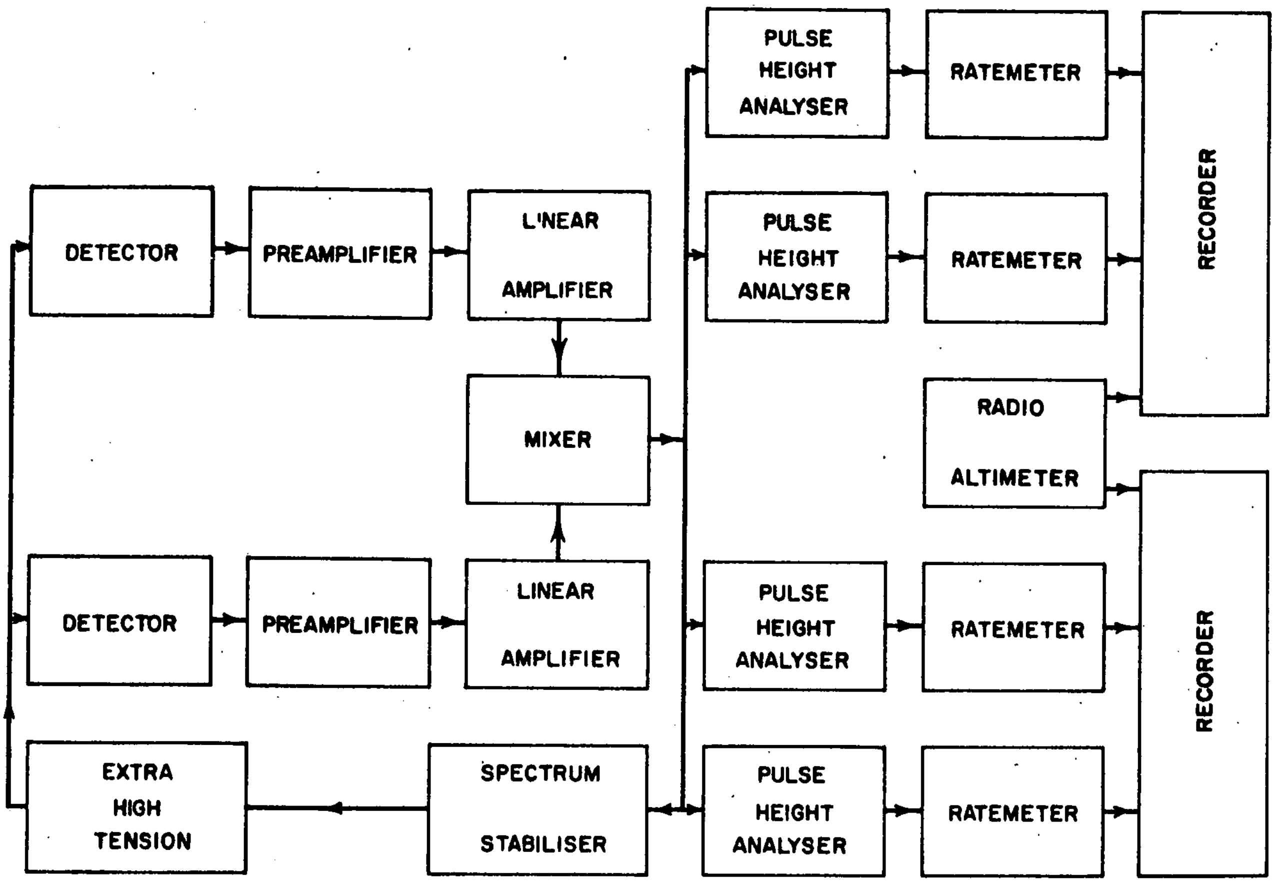


Fig. 2 AIRBORNE GAMMA-RAY SPECTROMETER LAYOUT AT START OF SURVEY

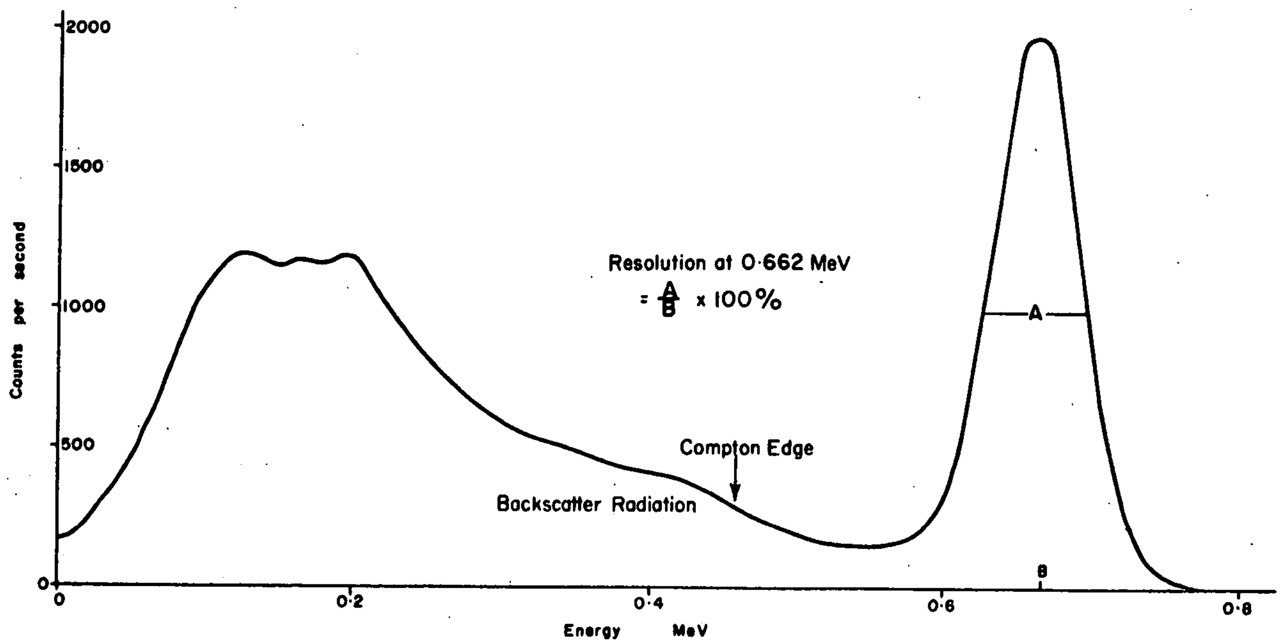


Fig.3 CAESIUM 137 SPECTRUM

TO ACCOMPANY RECORD No. 1971/38 E54/B1-40A

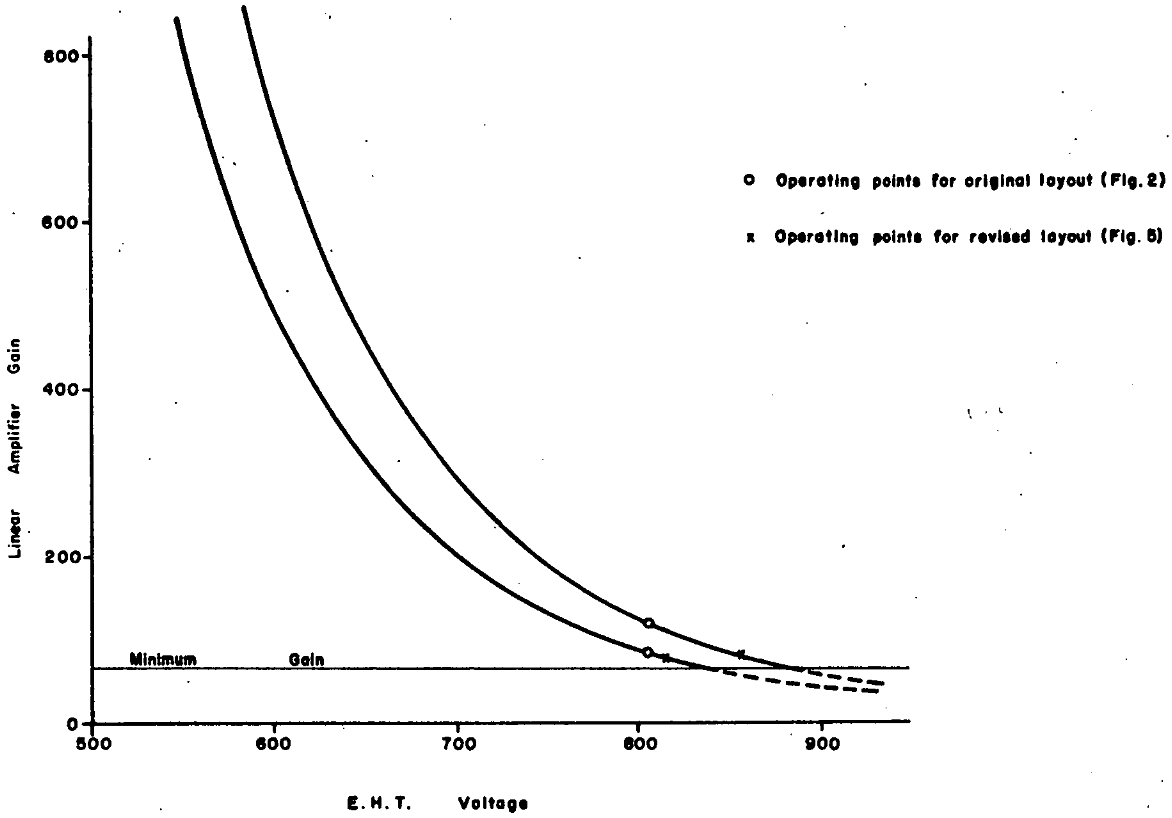


Fig. 4 RELATIONSHIP BETWEEN E.H.T. AND AMPLIFIER GAIN FOR CONSTANT CALIBRATION OF 1 VOLT PER 0·3 MeV

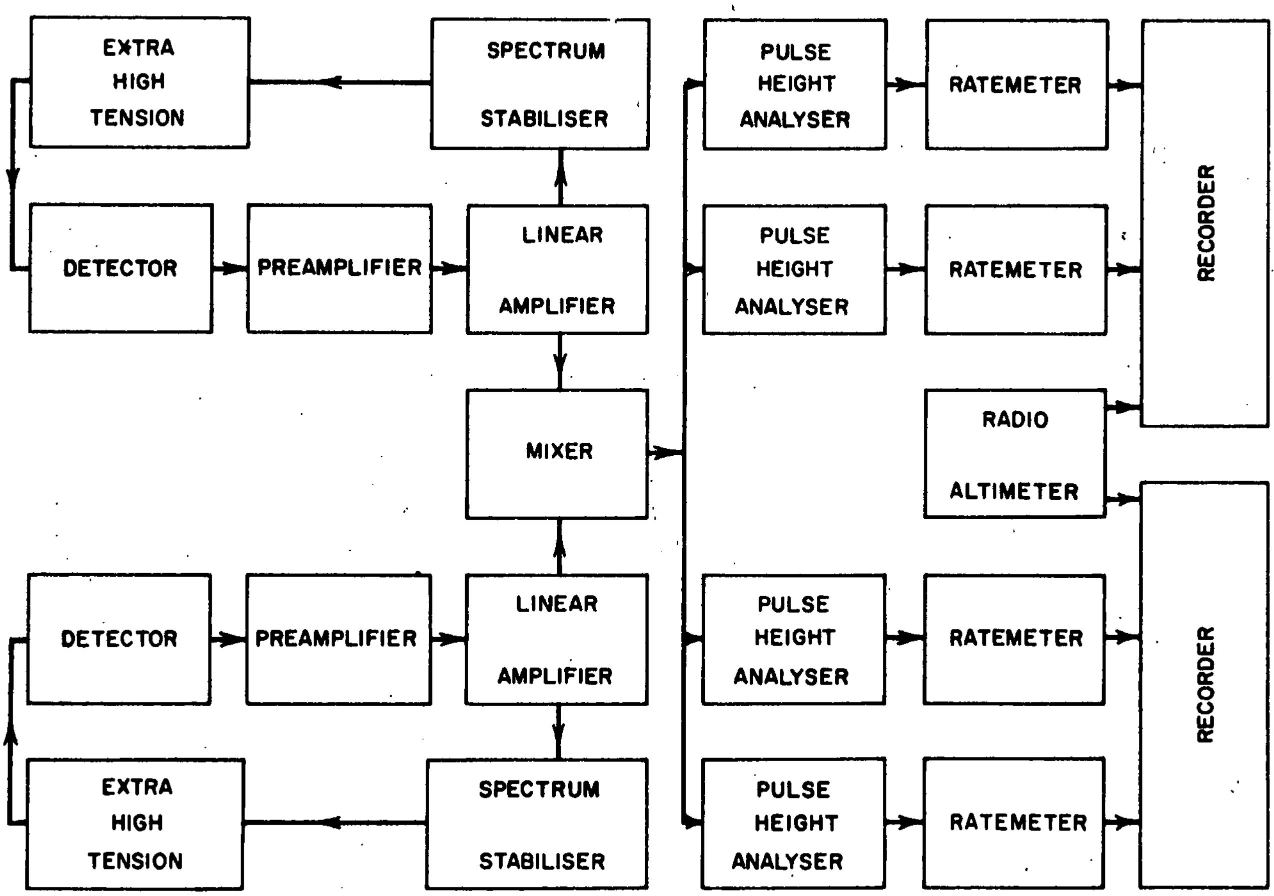


Fig 5. REVISED AIRBORNE GAMMA-RAY SPECTROMETER LAYOUT

TO ACCOMPANY RECORD No 1971/38 E54/B1-41A

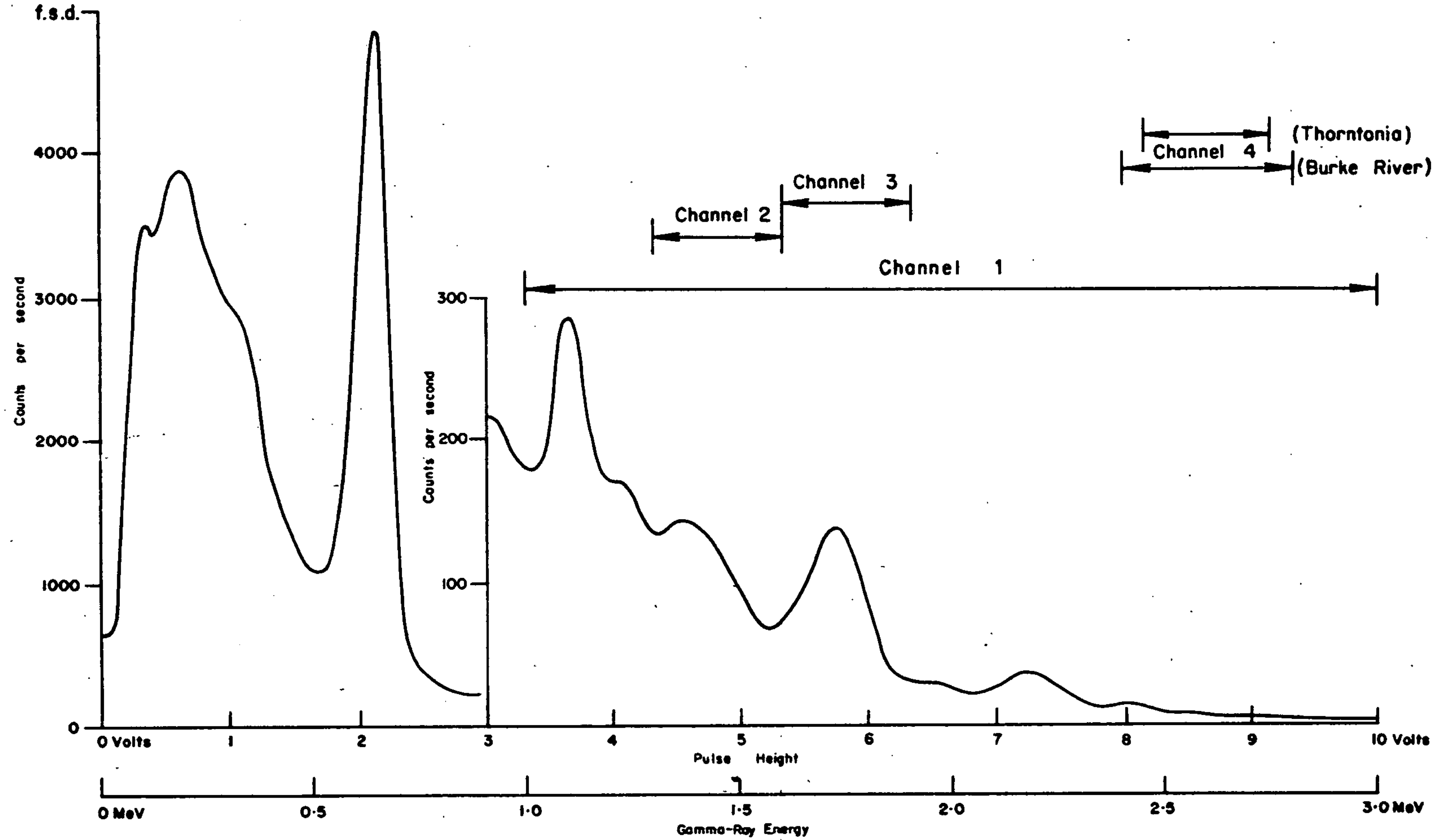


Fig. 6 URANIUM SERIES PEAKS TOGETHER WITH CAESIUM 137 CALIBRATION PEAK

TO ACCOMPANY RECORD No 1971/38 E54/B1-42A

28

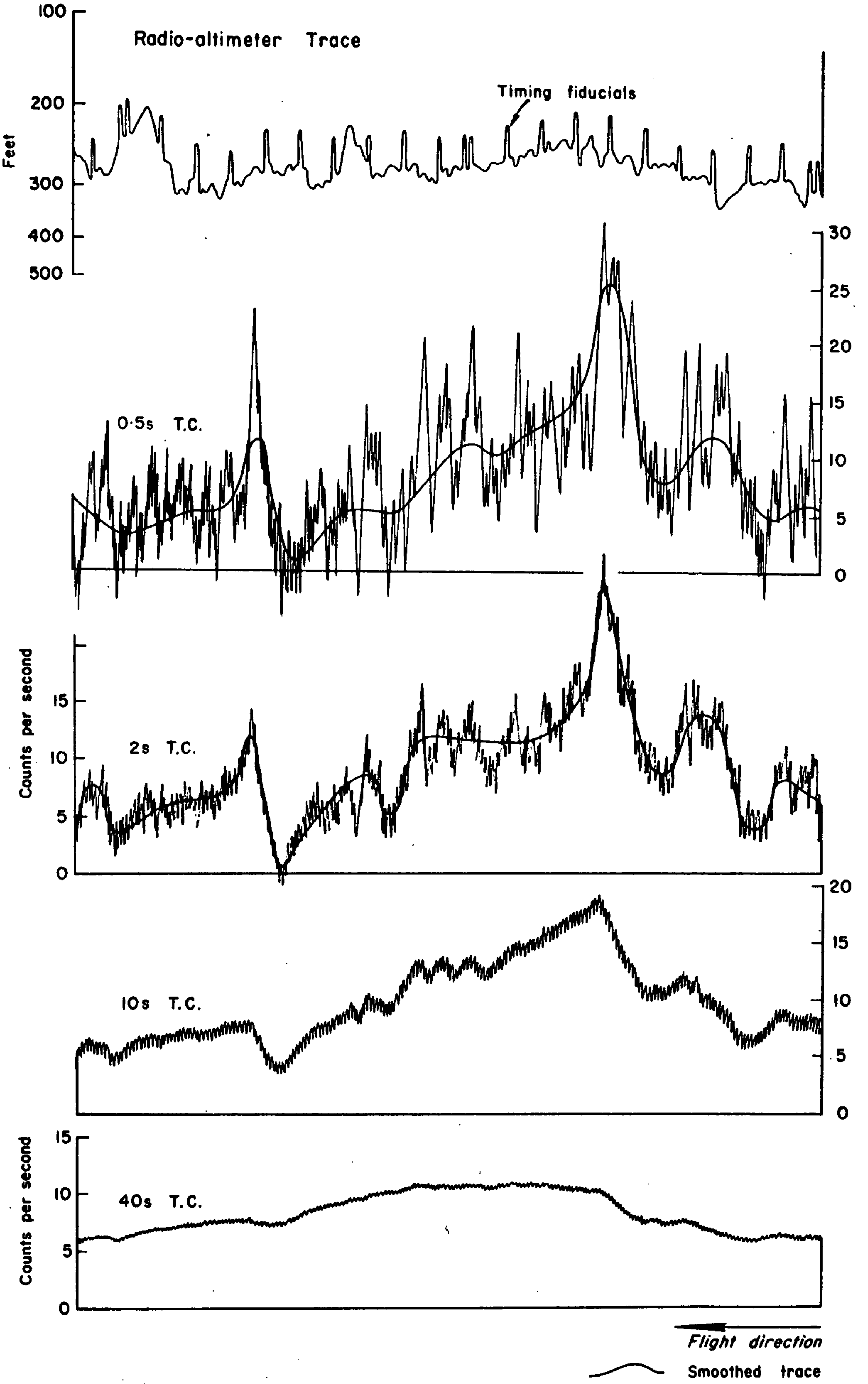


Fig. 7 THE EFFECT OF TIME CONSTANT (T.C.) ON THE RADIOMETRIC TRACE

TO ACCOMPANY RECORD No 1971/38 E54/B1-38A

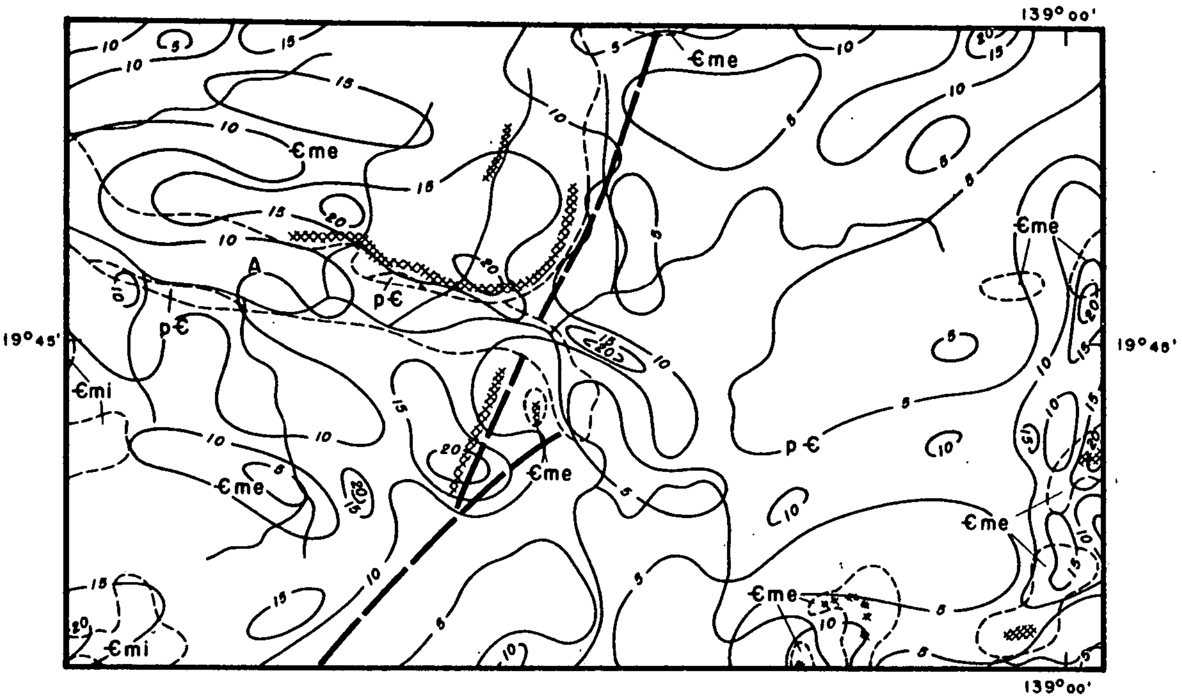


Fig. 8 CONTOURS OF 0·5-SECOND TIME CONSTANT CHANNEL

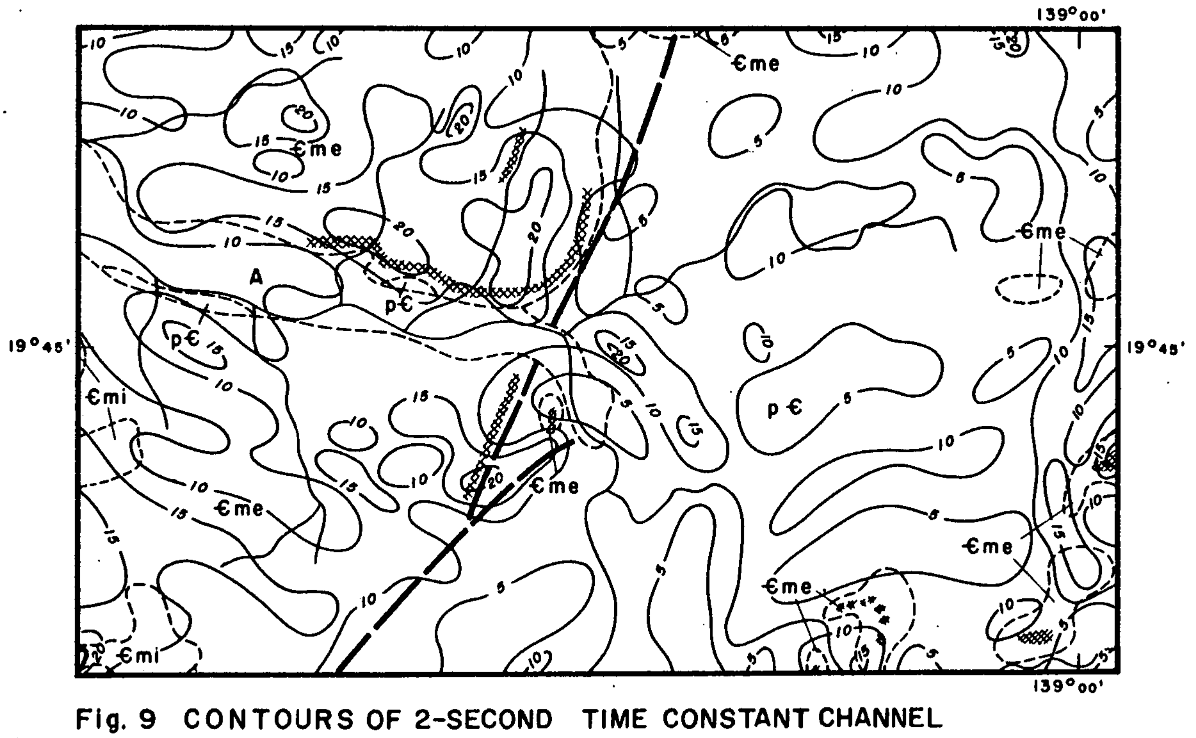


Fig. 9 CONTOURS OF 2-SECOND TIME CONSTANT CHANNEL

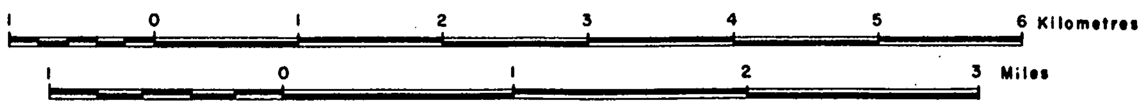
GEOLOGICAL LEGEND

A	ALLUVIAL DEPOSITS
€mi	INCA FORMATION
€me	BEETLE CREEK FORMATION
p€	PARADISE CREEK FORMATION

PHOSPHORITE OR PHOSPHATIC SILTSTONE

FAULT, PROBABLE

GEOLOGICAL BOUNDARY



(BASED ON E54/B0-32A)

TO ACCOMPANY RECORD No 1971/38 E54/B1-43A

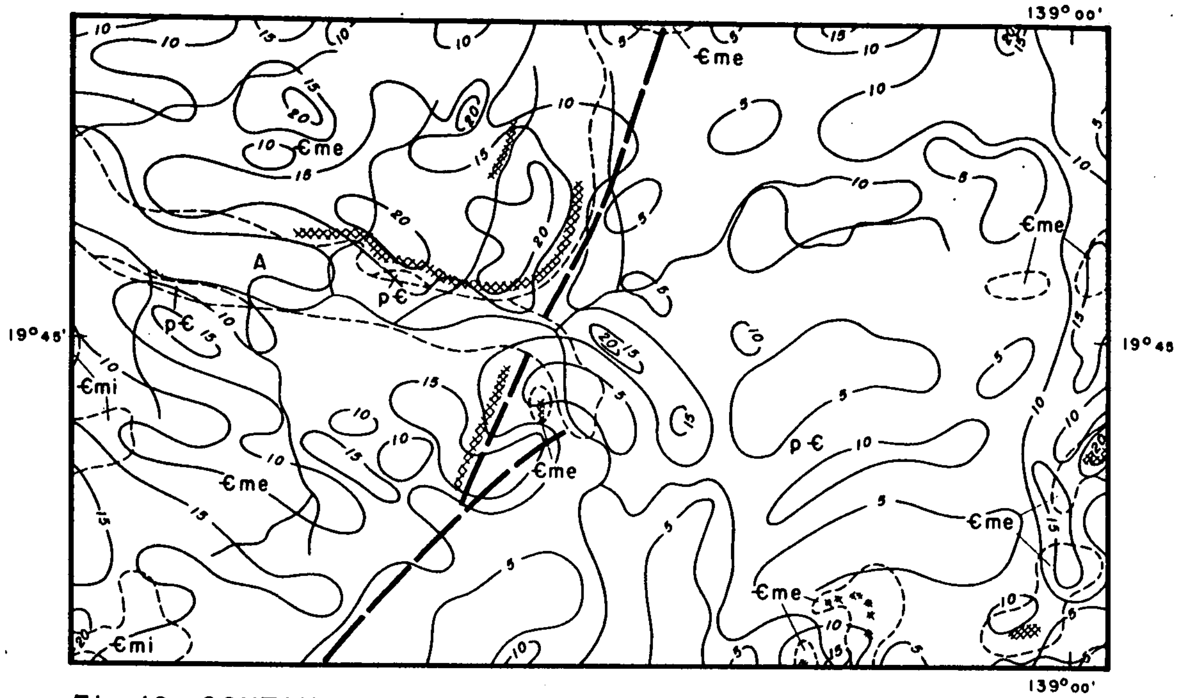


Fig. 10 CONTOURS OF 2-SECOND TIME CONSTANT CHANNEL WITH 1-SECOND CORRECTION

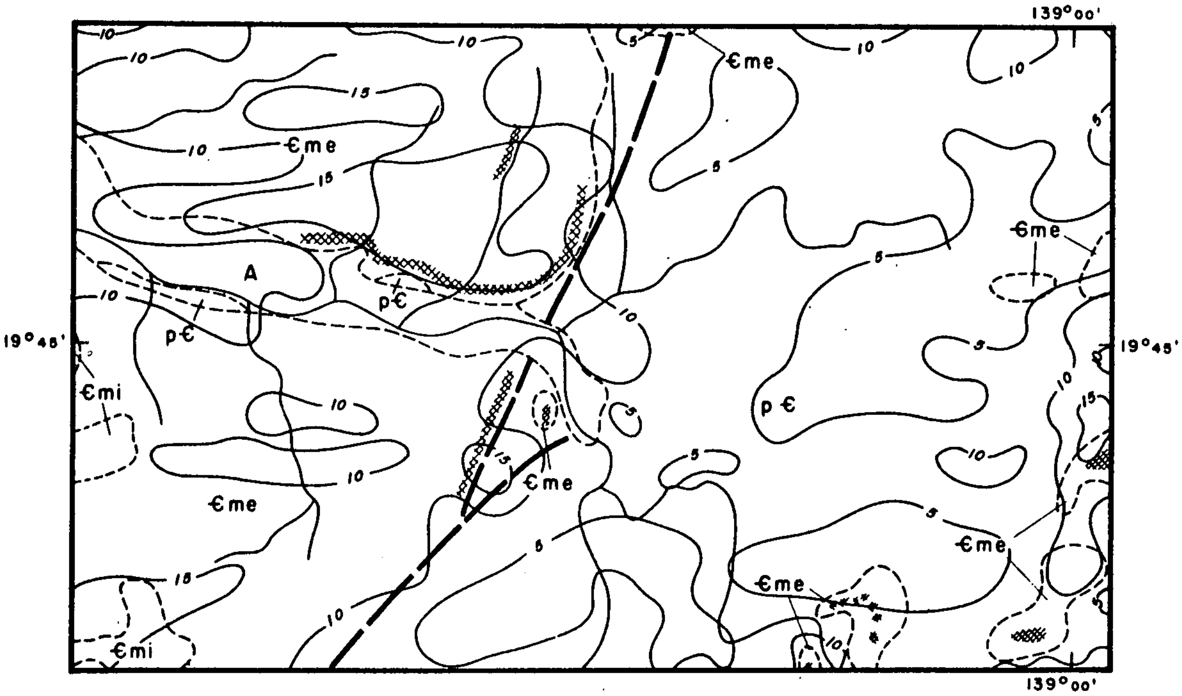


Fig. 11 CONTOURS OF 10-SECOND TIME CONSTANT CHANNEL WITH 5-SECONDS CORRECTION

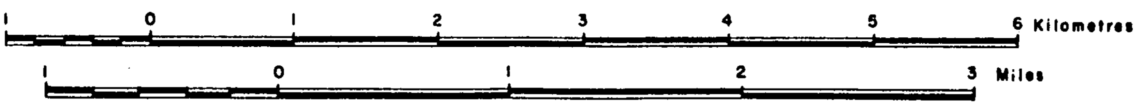
GEOLOGICAL LEGEND

A	ALLUVIAL DEPOSITS
€mi	INCA FORMATION
€me	BEETLE CREEK FORMATION
p€	PARADISE CREEK FORMATION

PHOSPHORITE OR PHOSPHATIC SILTSTONE

FAULT, PROBABLE

GEOLOGICAL BOUNDARY



(BASED ON E54/B0-32A)

TO ACCOMPANY RECORD No 1971/38 E54/B1-44A

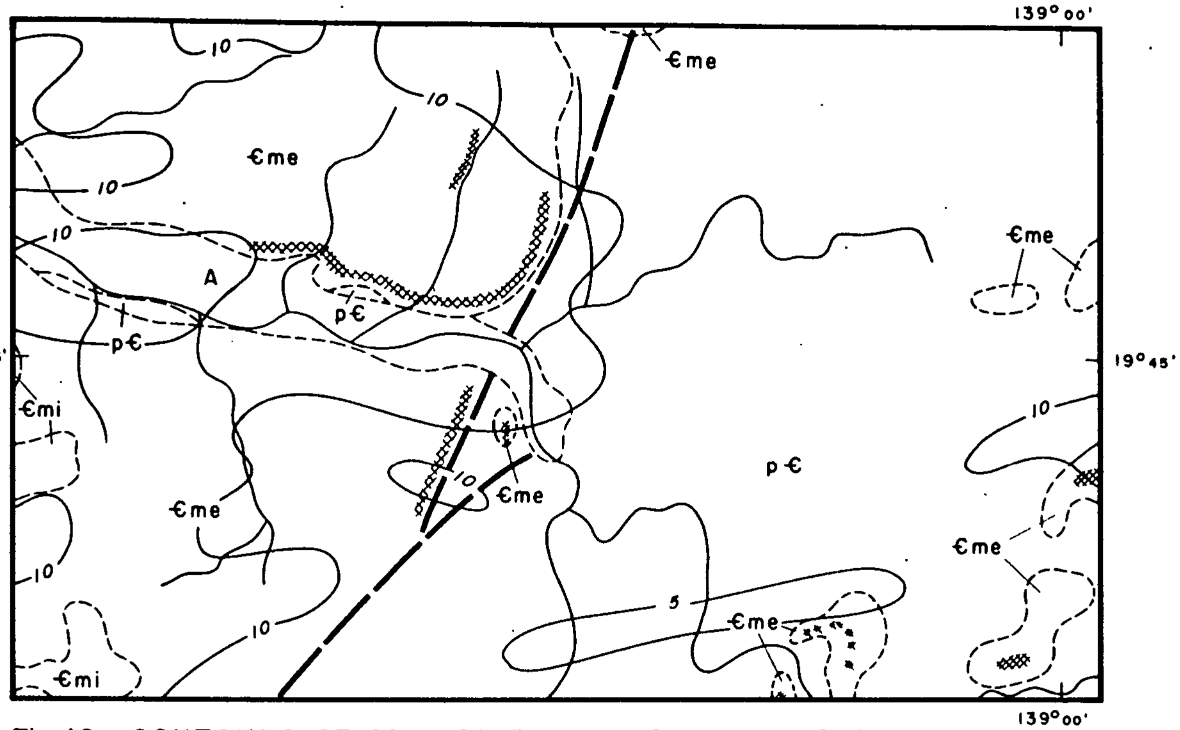


Fig.12 CONTOURS OF 40-SECOND TIME CONSTANT CHANNEL WITH 20-SECONDS CORRECTION

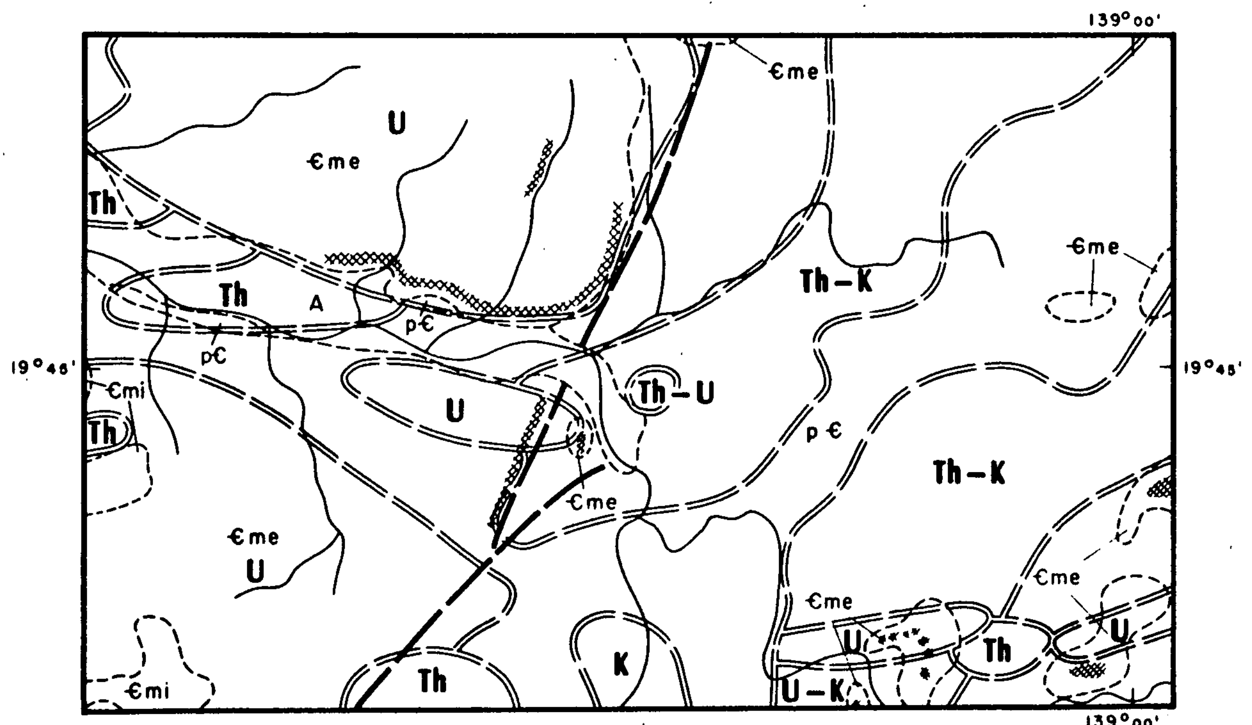


Fig. 13 INTERPRETATION BASED ON EXAMINATION OF ORIGINAL CHARTS

K POTASSIUM
U URANIUM
Th THORIUM
ZONE BOUNDARY

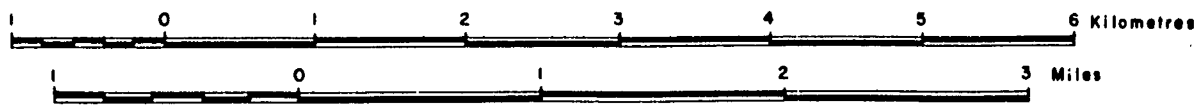
GEOLOGICAL LEGEND

A	ALLUVIAL DEPOSITS
€mi	INCA FORMATION
€me	BEETLE CREEK FORMATION
p €	PARADISE CREEK FORMATION

PHOSPHORITE OR PHOSPHATIC SILTSTONE

FAULT, PROBABLE

GEOLOGICAL BOUNDARY



(BASED ON E54/B0-32A)

TO ACCOMPANY RECORD No 1971/38 E54/B1-45A 32

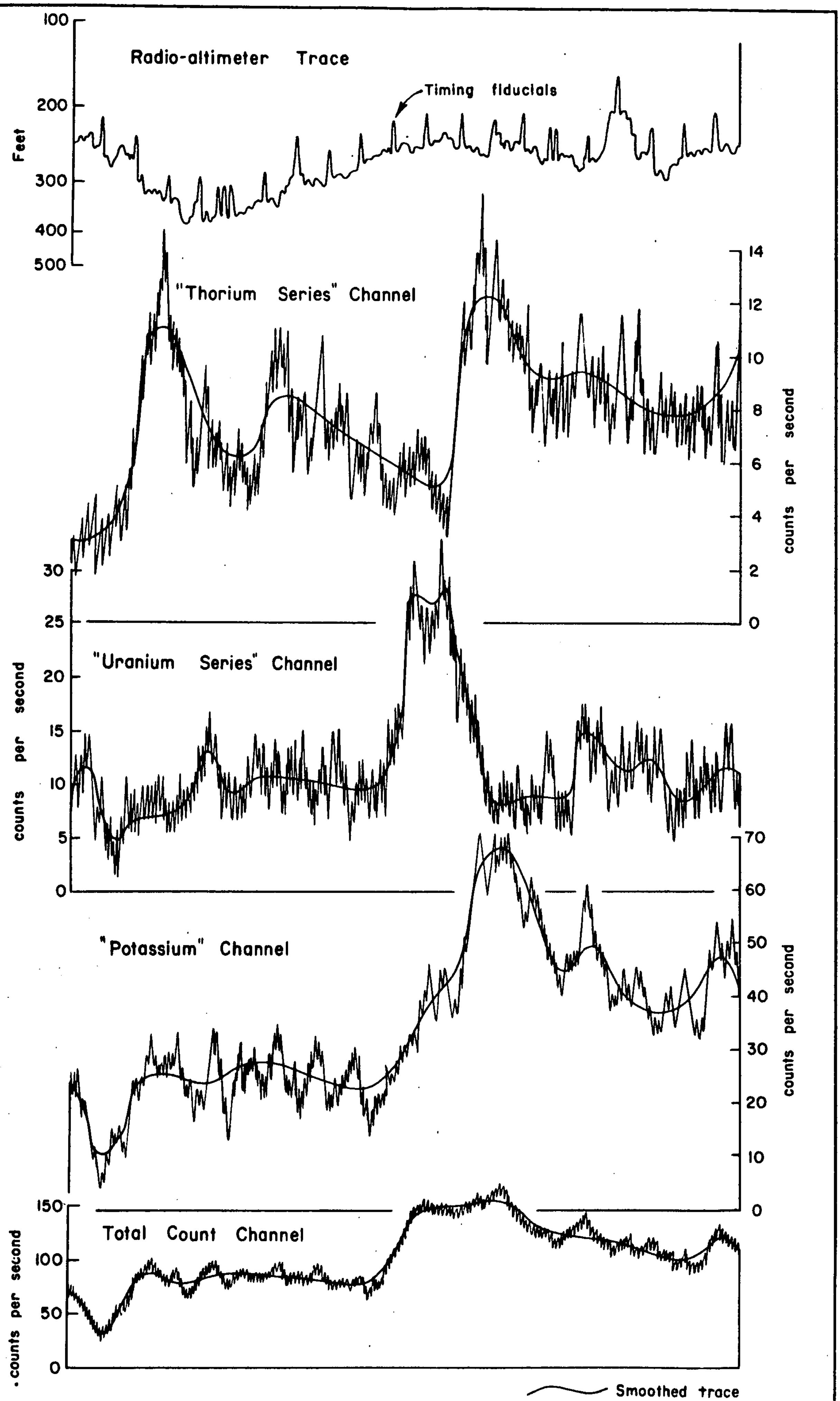


Fig. 14 THE DEGREE OF SMOOTHING APPLIED TO EACH CHANNEL

TO ACCOMPANY RECORD No 1971/38 E54/BI-46A

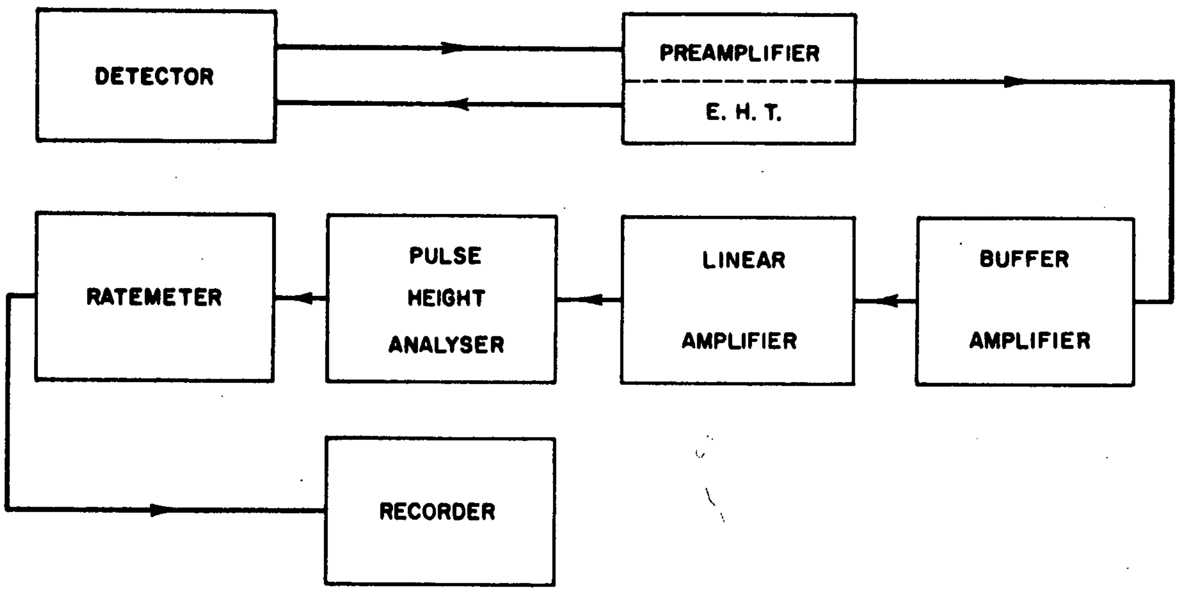
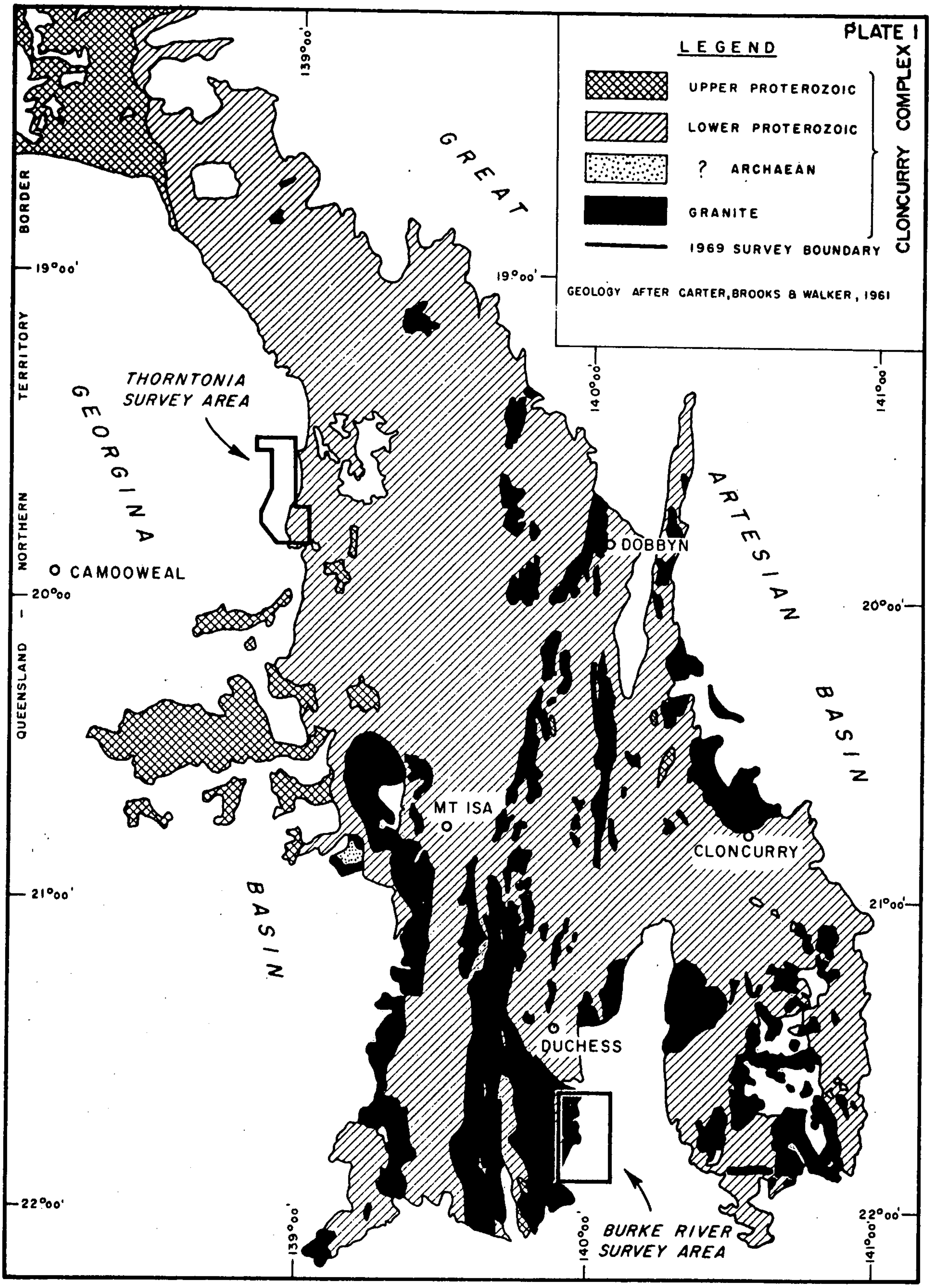


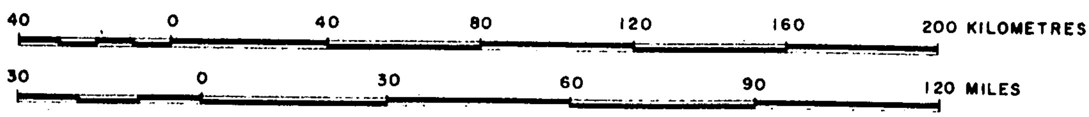
Fig. 15 TRUCKBORNE RADIOMETRIC EQUIPMENT LAYOUT



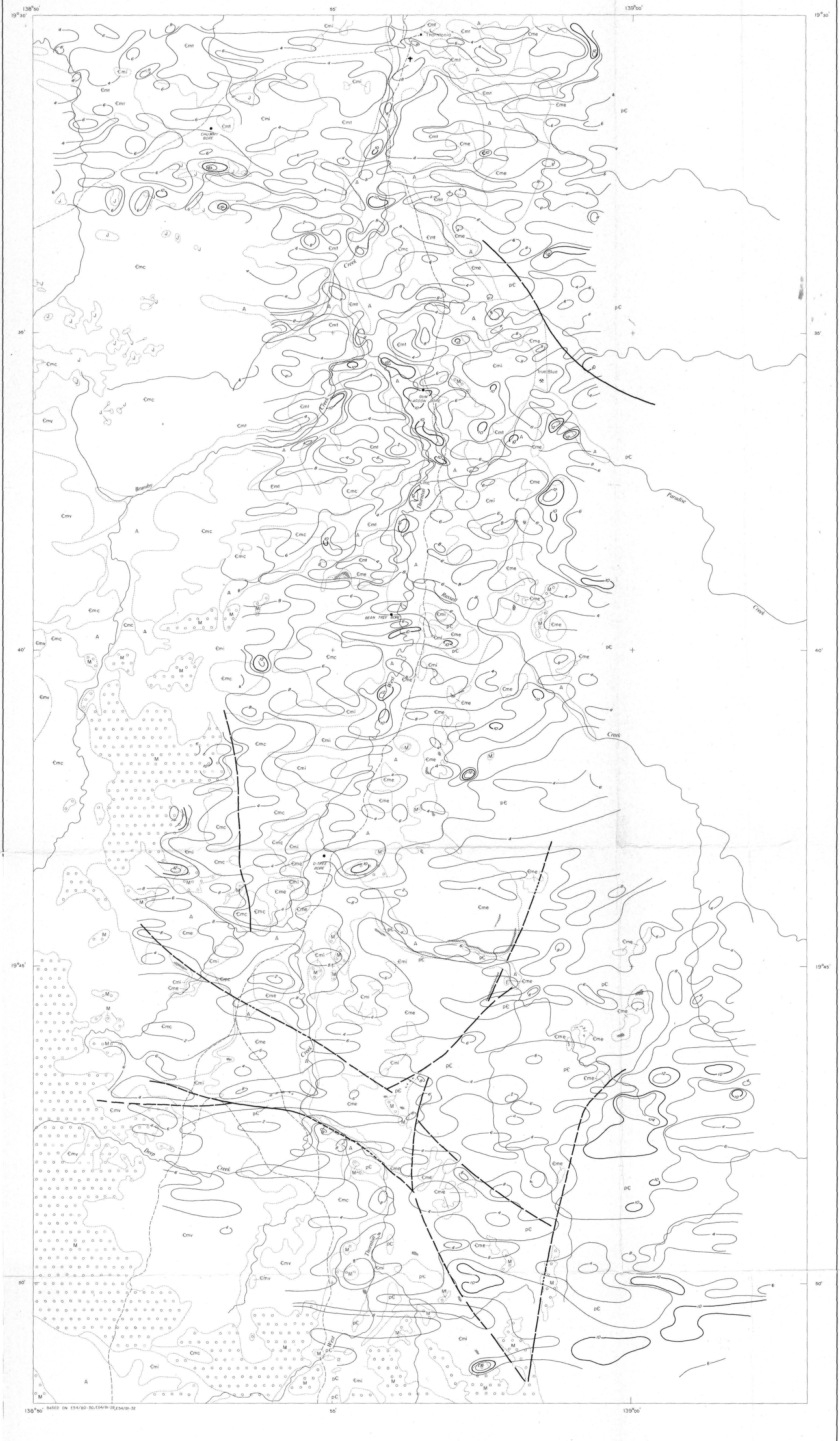
DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

LOCALITY MAP SHOWING

DISTRIBUTION OF MAJOR PRECAMBRIAN UNITS



TO ACCOMPANY RECORD No. 1971/38 E 54/B1-37A



GEOLOGICAL LEGEND

CAINOZOIC	A	Alluvial deposits
MESOZOIC	○ M ○	Laterite, in places some Mesozoic deposits
MESOZOIC JURASSIC	J	Sandstone
PALAEOZOIC CAMBRIAN	Ꞓmv	V-Creek Limestone
	Ꞓmc	Currant Bush Limestone
	Ꞓmi	Inca Formation
	Ꞓme	Beetle Creek Formation
	Ꞓmt	Thorntonia Limestone
PRECAMBRIAN	pꞒ	Paradise Creek Formation
		Phosphorite or phosphatic siltstone
		Fault
		Fault, probable
		Geological boundary

GEOLOGY AFTER SKETCH MAP BY DE KEYSER (UNPUBLISHED)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS
CHANNEL 4 - "THORIUM"
AND
GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 2 c.p.s.

CHANNEL WIDTH 2.45 - 2.75 MeV

TOPOGRAPHICAL LEGEND

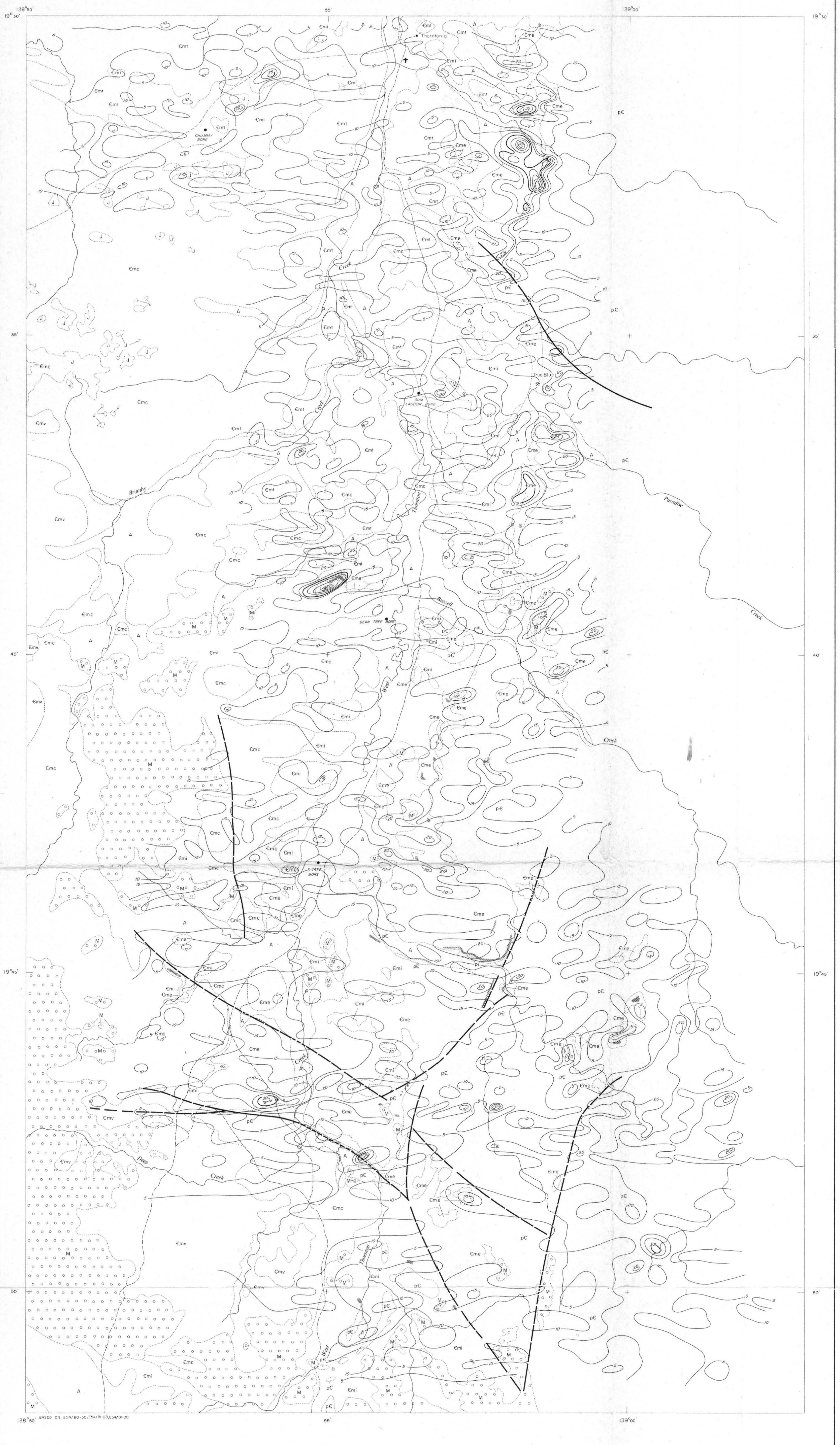
- Road or track
- River or creek
- Homestead
- Bore
- Mine
- Landing ground

GEOPHYSICAL LEGEND

- Radiometric contours

To Accompany Record No. 1971/38

E54/BI-36



GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
MESOZOIC		o M o	Laterite, in places some Mesozoic deposits
	JURASSIC	J	Sandstone
PALAEOZOIC	CAMBRIAN	Єmv	V–Creek Limestone
		Єmc	Currant Bush Limestone
		Єmi	Inca Formation
		Єme	Beetle Creek Formation
		Єmt	Thorntonia Limestone
PRECAMBRIAN		pЄ	Paradise Creek Formation
			Phosphorite or phosphatic siltstone
			Fault
			Fault, probable
			Geological boundary

GEOLOGY AFTER SKETCH MAP BY DE KEYSER (UNPUBLISHED)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS

CHANNEL 3 – "URANIUM"

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 5 c.p.s.

CHANNEL WIDTH 1.6 - 1.9 MeV

TOPOGRAPHICAL LEGEND

Road or track

River or creek

Homestead

Bore

Mine

Landing ground

GEOPHYSICAL LEGEND

Radiometric contours

To Accompany Record No. 1971/38

E54/BI-34

GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
MESOZOIC		o M o	Laterite, in places some Mesozoic deposits
	JURASSIC	J	Sandstone
PALAEOZOIC	CAMBRIAN	Ꞓmv	V-Creek Limestone
		Ꞓmc	Currant Bush Limestone
		Ꞓmi	Inca Formation
		Ꞓme	Beetle Creek Formation
		Ꞓmt	Thorntonia Limestone
PRECAMBRIAN		pꞒ	Paradise Creek Formation
			Phosphorite or phosphatic siltstone
			Fault
			Fault, probable
			Geological boundary

GEOLOGY AFTER SKETCH MAP BY DE KEYSER (UNPUBLISHED)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS
CHANNEL 2–"POTASSIUM"
AND
GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 10 c.p.s.

CHANNEL WIDTH 1.3 - 1.6 MeV

TOPOGRAPHICAL LEGEND

Road or track

River or creek

Homestead

Bore

Mine

Landing ground

GEOPHYSICAL LEGEND

Radiometric contours

To Accompany Record No. 1971/38

E54/BI-35

GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
MESOZOIC		o M o	Laterite, in places some Mesozoic deposits
	JURASSIC	J	Sandstone
PALAEOZOIC	CAMBRIAN	Ꞓmv	V–Creek Limestone
		Ꞓmc	Currant Bush Limestone
		Ꞓmi	Inca Formation
		Ꞓme	Beetle Creek Formation
		Ꞓmt	Thorntonia Limestone
PRECAMBRIAN		pꞒ	Paradise Creek Formation
			Phosphorite or phosphatic siltstone
			Fault
			Fault, probable
			Geological boundary

GEOLOGY AFTER SKETCH MAP BY DE KEYSER (UNPUBLISHED)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS

CHANNEL I – TOTAL COUNT

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 25 c.p.s.

CHANNEL WIDTH 1.0 - 3.0 MeV

TOPOGRAPHICAL LEGEND

Road or track

River or creek

Homestead

Bore

Mine

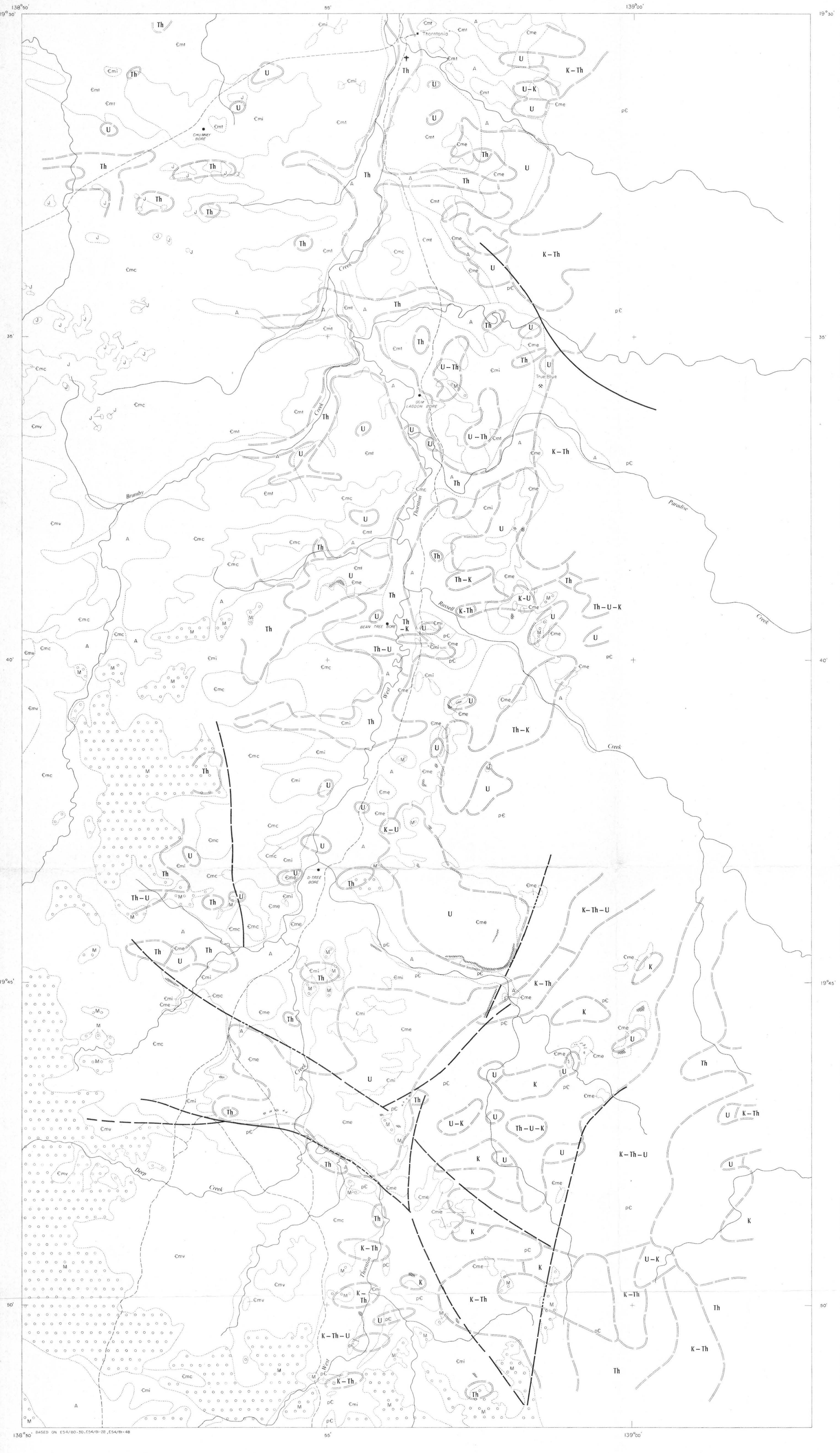
Landing ground

GEOPHYSICAL LEGEND

Radiometric contours

To Accompany Record No. 1971/38

E54/BI-33



GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
MESOZOIC		○ M ○	Laterite, in places some Mesozoic deposits
	JURASSIC	J	Sandstone
PALAEOZOIC	CAMBRIAN	Ꞓmv	V–Creek Limestone
		Ꞓmc	Currant Bush Limestone
		Ꞓmi	Inca Formation
		Ꞓme	Beetle Creek Formation
		Ꞓmt	Thorntonia Limestone
PRECAMBRIAN		pꞒ	Paradise Creek Formation
			Phosphorite or phosphatic siltstone
			Fault
			Fault, probable
			Geological boundary

GEOLOGY AFTER SKETCH MAP BY DE KEYSER (UNPUBLISHED)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

GEOPHYSICAL INTERPRETATION

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

TOPOGRAPHICAL LEGEND

- Road or track
- River or creek
- Homestead
- Bore
- Mine
- Landing ground

GEOPHYSICAL LEGEND

- K Potassium
- U Uranium
- Th Thorium
- Zone boundary

To Accompany Record No. 1971/38

E54/BI-56

GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
		o o	Laterite, lateritic rubble
MESOZOIC		M	Undifferentiated
PALAEOZOIC	ORDOVICIAN	Ols	Swifts Formation
		O'n	Ninmaroo Formation
	CAMBRIAN	Cuc	Chatsworth Limestone
		Cuh	O'Hara Shale
		Cmd	Devoncourt Limestone
		Cmi	Inca Formation
		Cme	Beetle Creek Formation
		Cmt	Thorntonia Limestone
		Clb	Mount Birnie Beds
PRECAMBRIAN		pC	Kalkadoon Granite
			Fault
			Fault probable
			Geological boundary

GEOLOGY AFTER DE KEYSER (1968)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS

CHANNEL 4 - "THORIUM"

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 2 c.p.s.

CHANNEL WIDTH 2.4 - 2.8 MeV

TOPOGRAPHICAL LEGEND

- Road or track
- River or Creek
- Hill feature
- Bore

GEOPHYSICAL LEGEND

- Radiometric contours

To Accompany Record No. 1971/38

F54/BI-57

GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
		o o	Laterite, lateritic rubble
MESOZOIC		M	Undifferentiated
PALAEOZOIC	ORDOVICIAN	Ols	Swifts Formation
		Oln	Ninmaroo Formation
	CAMBRIAN	Ɛuc	Chatsworth Limestone
		Ɛuh	O'Hara Shale
		Ɛmd	Devoncourt Limestone
		Ɛmi	Inca Formation
		Ɛme	Beetle Creek Formation
		Ɛmt	Thorntonia Limestone
		Ɛlb	Mount Birnie Beds
PRECAMBRIAN		pƐ	Kalkadoon Granite

Fault

Fault, probable

Geological boundary

GEOLOGY AFTER DE KEYSER (1968)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS

CHANNEL 3 – "URANIUM"

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 5 c.p.s.
CHANNEL WIDTH 1.6 - 1.9 MeV

TOPOGRAPHICAL LEGEND

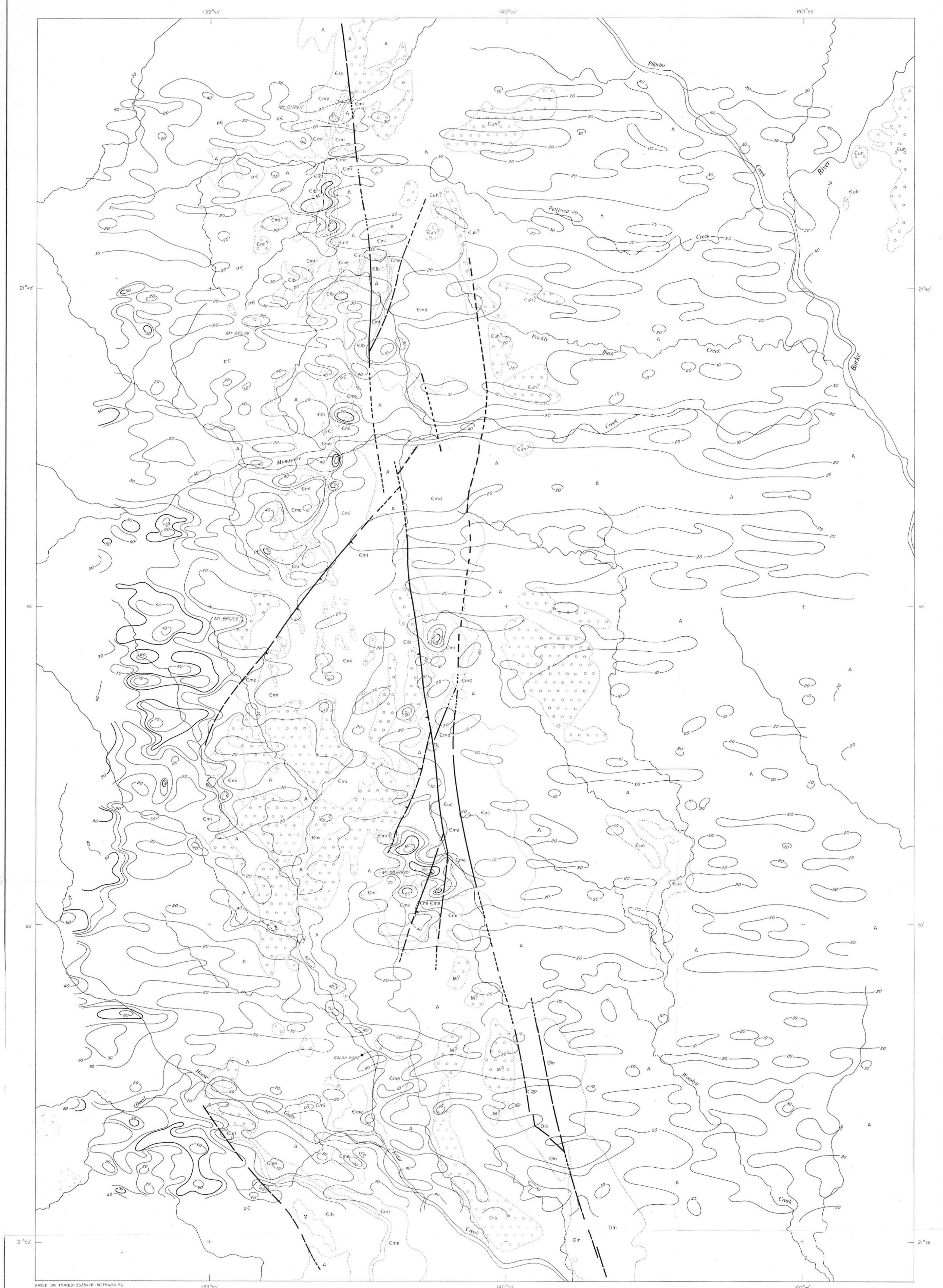
Road or track
River or Creek
Hill feature
Bore

GEOPHYSICAL LEGEND

Radiometric contours

To Accompany Record No. 1971/38

F54/BI-55



GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
		o o	Laterite, lateritic rubble
MESOZOIC		M	Undifferentiated
PALAEOZOIC	ORDOVICIAN	Ols	Swifts Formation
		Oln	Ninmaroo Formation
	CAMBRIAN	€uc	Chatsworth Limestone
		€uh	O'Hara Shale
		€md	Devoncourt Limestone
		€mi	Inca Formation
		€me	Beetle Creek Formation
		€mt	Thorntonia Limestone
		€lb	Mount Birnie Beds
PRECAMBRIAN		p€	Kalkadoon Granite

Fault

Fault, probable

Geological boundary

GEOLOGY AFTER DE KEYSER (1968)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

RADIOMETRIC CONTOURS

CHANNEL 2 – "POTASSIUM"

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

CONTOUR INTERVAL 10 c.p.s.
CHANNEL WIDTH 1.3 - 1.6 MeV

TOPOGRAPHICAL LEGEND

Road or track

River or Creek

Hill feature

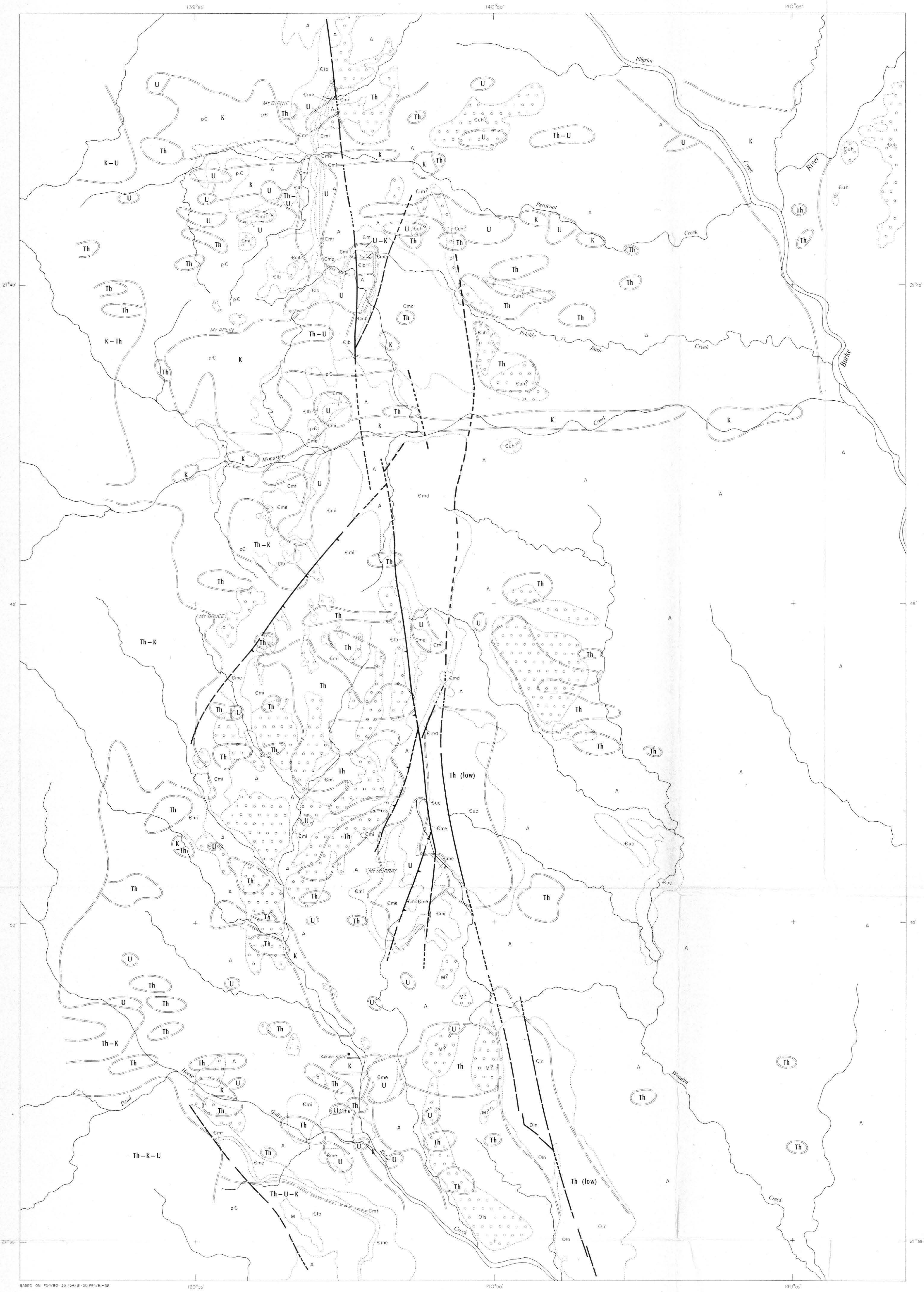
Bore

GEOPHYSICAL LEGEND

Radiometric contours

To Accompany Record No. 1971/38

F54/BI-56



BASED ON F54/BO-33, F54/BI-50, F54/BI-58

GEOLOGICAL LEGEND

CAINOZOIC		A	Alluvial deposits
		o o	Laterite, lateritic rubble
MESOZOIC		M	Undifferentiated
PALAEOZOIC	ORDOVICIAN	Ols	Swifts Formation
		Oln	Ninmaroo Formation
	CAMBRIAN	€uc	Chatsworth Limestone
		€uh	O'Hara Shale
		€md	Devoncourt Limestone
		€mi	Inca Formation
		€me	Beetle Creek Formation
		€mt	Thorntonia Limestone
		€lb	Mount Birnie Beds
PRECAMBRIAN		p€	Kalkadoon Granite

Fault

Fault, probable

Geological boundary

GEOLOGY AFTER DE KEYSER (1968)

DETAILED AIRBORNE GAMMA-RAY SPECTROMETER SURVEY, BURKE RIVER/THORNTONIA, QLD 1969

GEOPHYSICAL INTERPRETATION

AND

GEOLOGY

KILOMETRES 1 0 1 2 3 4 5 6 KILOMETRES

MILES 1 0 1 2 3 MILES

TOPOGRAPHICAL LEGEND

Road or track

River or Creek

Hill feature

Bore

GEOPHYSICAL LEGEND

K Potassium

U Uranium

Th Thorium

Zone boundary

To Accompany Record No. 1971/38

F54/BI-59