COMMONWEALTH OF AUSTRALIA

MINISTRY OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN No. 19

GEOPHYSICAL SURVEYS, OAKLANDS-COORABIN COALFIELD, NEW SOUTH WALES

by

R. F. THYER and K. R. VALE

WITH APPENDIX by J. C. DOOLEY

Issued under the authority of Senator the Hon. W. H. Spooner, Minister for National Development

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Minister—SENATOR THE HON. W. H. SPOONER

Secretary—H. G. RAGGATT

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ABSTRACT.

The Oaklands-Coorabin Coalfield in the Riverina Division of New South Wales has been known for many years. Coal is produced from a small colliery near Coorabin and a minor amount of exploratory drilling in the general vicinity of this mine has been carried out by New South Wales and Commonwealth Government authorities. This exploration has shown that coal seams extend over an area of a few square miles near Coorabin.

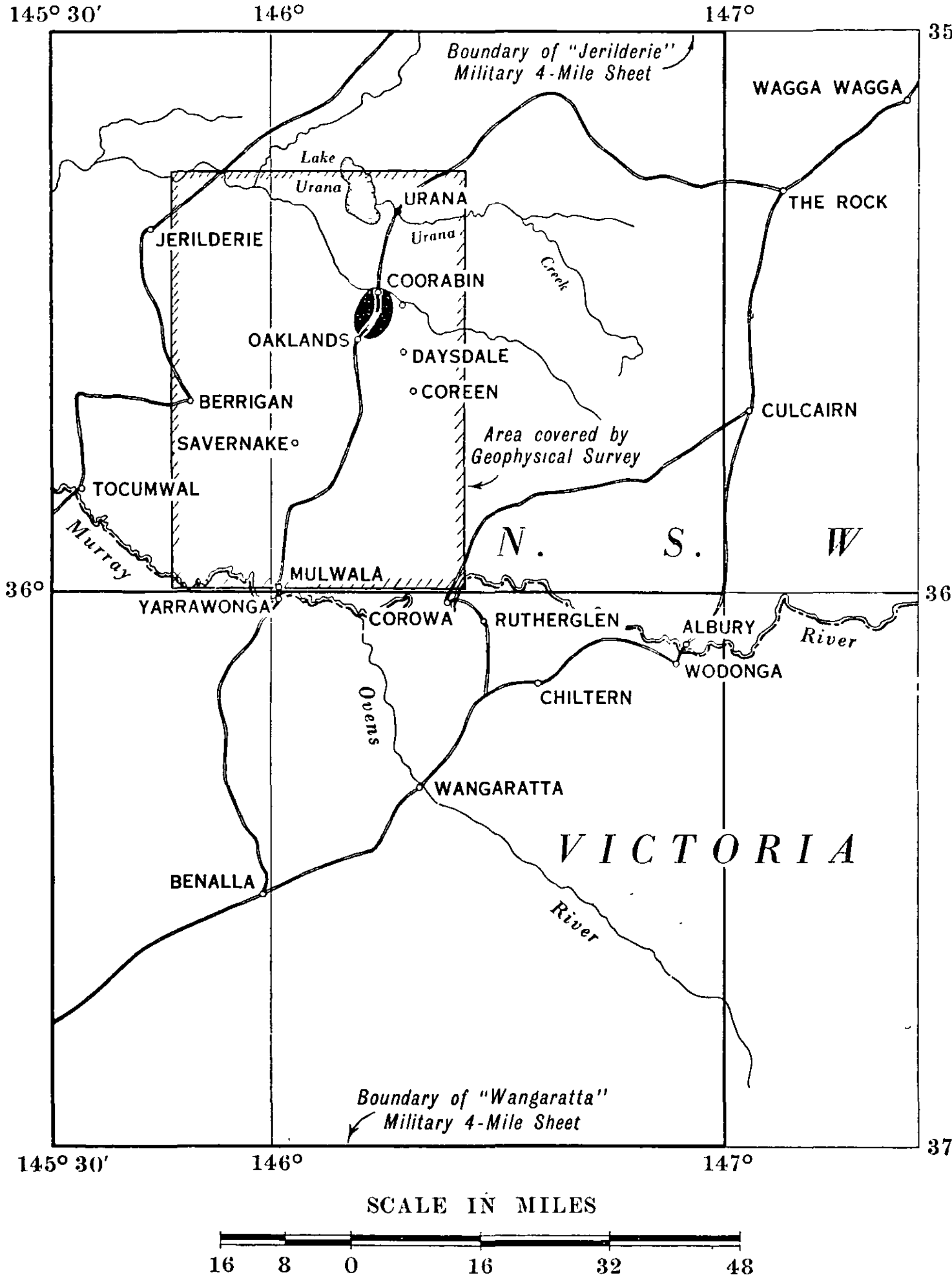
The coal occurs in Permian rocks which do not crop out but are covered by Tertiary and younger sediments with a minimum thickness of 100 feet.

Examination of the regional geology led to the conclusion that the coalfield is far more extensive than the limited area proved by drilling. Because of the Tertiary cover, normal geological methods cannot be used to map the boundaries of the Coal Measures and for this reason geophysical surveys, which have been used successfully on similar problems elsewhere, were undertaken to map the sedimentary basin. A gravity survey was carried out first and as the work proceeded it became obvious that a pronounced regional anomaly is present. Consequently, seismic methods were employed to try to obtain the thickness of the sediments at a number of critical places and to provide a control for separating the effect of the sediments from the regional effect. A residual gravity contour plan was obtained and indicates the general shape of the sedimentary basin. This plan provides a satisfactory basis for recommending drilling to test the potentialities of the basin.

An area of approximately 1,450 square miles was covered by the geophysical surveys and, after correcting for regional effect, the residual gravity pattern suggests the presence of a Permian basin approximately 600 square miles in area, with a possible extension in a north-westerly direction.

Recommendations are made for testing the geophysical results by drilling at five widely-spaced sites in the supposed basin. Five additional drilling sites are recommended and are designed to prove reserves near the known coal occurrences.

PLATE 1



Main Railways

Known extent of coal-bearing beds

OAKLANDS - COORABIN COALFIELD

LOCALITY MAP

GEOPHYSICAL SECTION, BUREAU OF MINERAL RESOURCES GEOLOGY AND GEOPHYSICS. G 46-6

INTRODUCTION.

The Oaklands-Coorabin Coalfield, in the Riverina Division of New South Wales, is situated about 40 miles north of Corowa—on the Murray River—and about 75 miles south-west of Wagga Wagga (Plate 1). In 1916 black coal was discovered by Mr. T. J. Lane while drilling for water on Portion 16, Parish of Gunambil, near Coorabin railway siding. In 1917 a colliery known as Lane's colliery was opened up at the site of the discovery and has been worked intermittently until the present day.

The New South Wales Department of Mines drilled five exploratory bores (Nos. 1 to 5) in 1920. Bores Nos. 1 and 2 were near Lane's colliery, No. 3 about 1½ miles north, and Nos. 4 and 5 about 3 miles south of this colliery.

In the succeeding years several unsuccessful attempts were made to open up other collieries. Some coal was won from the Clear Hill and Gunambil shafts but the coal seams were thin and of poor quality. The Carbery shafts about three-quarters of a mile south-south-west of Lane's colliery intersected aquifers which yielded heavy flows of water and the shafts were abandoned without any coal being produced.

During 1942 and 1943, eight additional bores were drilled by Water Conservation and Irrigation Commission of New South Wales under the geological supervision of the Bureau of Mineral Resources, Geology and Geophysics—seven bores were drilled for the Commonwealth Coal Commission and one for the Department of Supply and Shipping. Seven of the bores were drilled within a radius of one mile from Lane's colliery to prove reserves of coal. They all intersected coal but the thickness of the seams showed a considerable range and the quality, with one exception, was generally poor. The eighth bore (J) was drilled midway between Bores 4 and 5, almost 3 miles south of Lane's colliery, and confirmed the results obtained by those bores, that is that the seams are greater in thickness and better in quality in this part of the field than in the vicinity of Lane's shaft. Bore J intersected about 46 feet of coal containing workable sections averaging slightly more than 10,000 B.T.U. per lb.

The coal is of Permian age—the same age as the coals of the Main Coal Province of New South Wales. However, it contains more water and ash than the Newcastle coals and has consequently a lower fuel value. It is non-coking and is a low-rank bituminous coal well suited to domestic and power-house consumption.

The Coal Measures are overlain by Tertiary and younger sediments whose thickness generally exceeds 100 feet. Normal methods of geological mapping to define the limits of the Coal Measures are greatly hampered by lack of suitable outcrops, although the basement rocks (granite, and pre-Permian sediments partly metamorphosed) crop out through the Tertiary cover at widely scattered places within the area. Beyond determining isolated places where Permian Coal Measures do not exist, the basement outcrops provide no real evidence of the extent of the Coal Measures.

It seemed a reasonable hypothesis that the coalfield is far more extensive than the area proved by the limited testing to date and, because normal geological methods could not be used, a geophysical survey was recommended. The gravity method was applied first as this method had proved of considerable value in outlining sedimentary basins elsewhere, notably at Collie in Western Australia and at Leigh Creek in South Australia. Later, some seismic tests were carried out on a number of sections to assist in the interpretation of the gravity results.

The gravity work was initiated by Mr. G. B. Clarke in September 1948 and completed by Mr. S. Waterlander in July 1949. The seismic work was carried out by a party under the leadership of one of the authors (K.R.V.). The work was supervised and co-ordinated by the other author (R.F.T.). Substantial assistance was rendered by the Manager, Mr. C. F. Answerth, and Staff of Munitions Stores and Transport; Oaklands; and by the Manager, Mr. C. W. Stubbs, and Staff of the Commonwealth Explosives Factory, Mulwala. This assistance is gratefully acknowledged.

GEOLOGY.

Geological knowledge of the field was recently summarized in a report by E. K. Sturmfels (1950), to which reference should be made for a description of the known field and results of past drilling.

Briefly, the Permian Coal Measures occupy a basin, of unknown extent and depth, in pre-Permian rocks (which are referred to in this bulletin as the basement) and are covered unconformably by Tertiary and younger clays, gravels, sands, and sandstone. The Tertiary sediments are widespread and it is believed that they may, in places, be several hundred feet thick.

The Permian Coal Measures were exposed prior to the deposition of the Tertiary beds and consequently in some places the coal seams have been partly eroded and weathered. In the vicinity of Lane's colliery the coal seams vary in thickness and quality, partly because of the effects of such erosion and weathering. According to Sturmfels (1950, p.17) some of the variation can be attributed to the fact that this portion of the coalfield is on the margin of the basin.

Sturmfels has illustrated his report by two structural sketch maps, one showing approximate contours on the base of the Tertiary and the other on the base of the coal-bearing beds. Within the area investigated by bores the Permian strata are gently folded and have an average dip to the west-south-west. Comparing the two structural sketches, it will be seen that the base of the Tertiary reflects, in a general way, the structure of the Permian but the amount of dip in the Tertiary is less than that in the Permian rocks.

Sturmfels (1950, p.9) states that "it is not definite whether the Tertiary beds themselves are truly horizontal or slightly tilted and folded with a general dip to the south or south-west." He quotes certain evidence—based on the position of aquifers within the Tertiary beds—which suggests south-westerly dips between Bore J and Oaklands. However, there is no evidence to suggest what the dips might be elsewhere.

The maximum thickness of the Tertiary sediments revealed by boring in the Oaklands area is nearly 450 feet (at Bore 5). A test bore drilled by the seismic shot-hole drill at shot point 8A, about 7 miles west of Oaklands, reached a depth of 530 feet in what were assumed to be Tertiary sediments.

Elsewhere, except for results obtained from the geophysical survey, there is no data to indicate the thickness of the Tertiary sediments. For reasons that will be made clear in a later section of this bulletin, the gravity method cannot provide such evidence. On the other hand, it seemed possible that the velocity of seismic waves in the Tertiary sediments would be different from that in the Permian, and that the seismic method would thus provide evidence of the thickness of the Tertiary sediments. No conclusive evidence of such variation in velocity was obtained, although it is possible that a change in velocity at moderately shallow depth (300 to 600 feet) in certain parts of the basin corresponds to a change from Tertiary to Permian sediments.

The surface of the area examined is flat to gently undulating; grades of less than one foot to the mile extending over many square miles are common. The average elevation is approximately 400 feet above sea level, with sparsely scattered hills rising from 100 to 200 feet above the level of the plain. Near Coorabin, Oaklands and north of Savernake, the hills are composed of Recent sands which probably overlie Tertiary rocks. At other places however, notably east of Daysdale, north of Corowa, near Mulwala and between Mulwala and Berrigan, the hills are composed of basement rocks which crop out through the surrounding Tertiary cover. Plate 2 shows the position of all basement outcrops which are, without exception, topographically high places. The distribution suggests a possible limit to the Coal Measures in certain directions, principally to the east, south-east, and south-west.

The basement outcrops include several different rock types. East of Daysdale they consist of granite and metamorphic rocks such as schists, quartzites and slates. North of Corowa, on the Corowa Goldfield, they are chiefly slates and schists and are steeply folded. Near Mulwala, there are prominent outcrops of steeply-folded, slightly metamorphosed sediments which are shown on David's (1931) map as Devonian but which, according to Dr. D. E. Thomas (1949), Chief Government Geologist of Victoria, may be Ordovician. Outcrops between Mulwala and Berrigan are mainly granite with some metamorphic rocks in contact. There are no basement outcrops in the section between Berrigan and Jerilderie but to the north, around Urana, numerous bores have intersected basement rocks variously described in drillers' logs as granite, hard rock, schist, &c., but no samples are available to enable determination of the rock type. It is possible that the outcrops represent only the harder and more resistant parts of the basement, such as the igneous rocks and the highly-metamorphosed rocks adjacent to the intrusives, and that between them the basement rocks are softer and less metamorphosed. Most of the rock types that underlie the Tertiary sediments in the area between these outcrops have not been determined but it is believed that the geophysical results give some indication of their nature.

Little is known of the general structure of the Coal Measures; the test drilling near Coorabin has shown that the Permian Coal Measures are slightly folded; no evidence of faulting has been revealed in the colliery workings nor is there evidence of post-Permian faulting elsewhere in the immediate vicinity. However, 50 to 60 miles south of Oaklands, in the State of Victoria, there is evidence of post-Permian faulting on a major scale. The Ovens Valley, according to Dr. D. E. Thomas (1949), is a graben between major faults striking roughly north-north-west. Glacial beds believed to be of Permian age were disclosed by drilling in the Ovens Valley north of Wangaratta and it is believed that the beds have been down-faulted in the Ovens Valley graben and protected from erosion. Any prolongation of these faults across the Murray River could have resulted in blocks of Permian or earlier sediments being down-faulted and protected from later erosion. Some of the major features in the gravity pattern have the same strike as the Ovens Valley faults and it is possible that the main basinal structure may have been controlled by faulting in this general direction.

PART A—GRAVITY SURVEYS.

INTRODUCTION.

This part of the bulletin is primarily a description of the gravity results and their implications. The results of the seismic work, in so far as they affect the gravity interpretations, are described here but full discussions of the seismic results, the field methods and methods of interpretation are given in Part B.

The gravity work was carried out by Officers of the Bureau between September 1948 and July 1949, using portable gravimeters of high sensitivity. The investigation of the results, however, was not completed until many months later when the results of the refraction seismic survey, which was made after the gravity survey, were known.

GEOPHYSICAL PROBLEMS.

The gravity method was chosen to investigate the area because this method has proved very successful when applied to similar problems elsewhere, notably Collie, W.A. (Chamberlain, 1947), and Leigh Creek, S.A. (Zelman, 1948).

To state the problem in its simplest form, it was believed that a large sedimentary basin existed and that, because the sediments, Tertiary and Permian, were less dense than the basement rocks, the gravitational field would be reduced proportionately to the thickness of the sediments. It was realized that the gravity method would provide no means of distinguishing the effect of the Permian sediments from that of the overlying Tertiary sediments. However, such evidence as was available suggested that the Tertiary sediments are relatively uniform in thickness and that consequently the main variations in gravitational attraction would be due to variations in thickness of the Permian, and any older sediments in the basin.

As the survey progressed, however, it became evident that the gravitational field was profoundly disturbed by what may be called a regional effect. This was made evident by the big range of values of the gravitational attraction found over widely-scattered basement outcrops where, if the regional effect had been absent, a uniform gravitational field would have been observed. It was therefore decided to supplement the gravity work with seismic tests. It was hoped to determine the depth to the basement at a number of critical places in order that the " regional " gravity effect and ultimately the regional pattern for the whole area could be worked out.

In order that the results could be reduced to their final form it was necessary to make a critical analysis of the densities and velocities of the rocks contributing to the geophysical anomalies.

DENSITIES.

Tertiary Rocks.—The Tertiary strata have been penetrated by hundreds of water bores in the area surveyed and it is evident from the bore logs that the lithology varies very little from place to place. It is believed therefore that the densities obtained by sampling a section 120 feet thick exposed in Lane's No. 2 shaft may be regarded as being typical of the Tertiaries as a whole.

This sampling gave an average density of 2.04 gm./cc. with no significant variation with depth or lithology.

Permian Rocks.—The only Permian rocks exposed are the coal seams and carbonaceous shales in Lane's colliery. These were not sampled, however, as they are not typical and therefore can add little to the knowledge of the density of the Permian sediments as a whole. It has not been possible therefore to arrive at a value for the density of the Permian rocks by direct measurement. However, it is believed that a satisfactory value can be obtained by accepting the mean for similar sediments measured elsewhere, due regard being given to the known Permian lithology. Heiland (1940) has listed densities of sediments measured by various workers. Generally lithology is more or less closely related to density, although the degree of folding and depth of burial (and hence indirectly the age) do have some influence.

The little that is known of the Permian sediments in this area suggests that:—

(*a*) they are composed mainly of soft shales (some carbonaceous) and sandstone;

(*b*) they have probably not been deeply buried at any stage in their history;

(*c*) folding, and consequently its effect on densities, has been slight.

It is probable that the principal difference in density through the Permian section will be one normally associated with a difference in depth. Heiland (1940) quotes the following changes in density with depth for Gulf Coast (Tertiary) sediments:—

Depth. feet.	*Density.* gm./cc.
0 – 500	1·9 – 2·05
2,000 – 4,000	2·20
4,000 – 8,000	2·25

On the other hand, densities of Permian sediments or other sediments older than Tertiary are somewhat higher; for example:—

Rock Type.	*Age.*	*Density.* gm./cc.
Sands, sandstones, conglomerates	General	1·9 – 2·7
	Triassic	2·35
	Various Permian	2·25 – 2·45
Shales	Permian	2·28 – 2·39
	Devonian	2·32

After carefully weighing all the evidence it was decided to assume the following densities, related to depth as shown:—

Depth. feet.	*Density.* gm./cc.	*Age.*
0 – 200	2·00	Tertiary
200 – 500	2·20	Mixed Tertiary and Permian
500 – 1,000	2·25	Permian?
1,000 – 1,500	2·30	Permian?
1,500 – 2,000	2·35	Permian?
2,000+	2·40	Permian?

Basement Rocks.—Samples of the basement rocks were taken from outcrops mainly between Berrigan and Mulwala and to the north of Corowa. In general it was found that the granites had the highest density of those measured. The rocks can be divided roughly thus:—

Type.	*Density.* (average.)
Granite	2·60
Quartzite and Breccia (pre-Permian)	2·55
Sandstone and Slate (pre-Permian)	2·40

The range of densities measured in the basement rocks was greater than might have been expected. The specimens tested were all taken from the surface and therefore had been subjected to weathering to a greater or lesser degree. Weathering generally leads to some reduction in density and consequently it is likely that the values given above are lower than for these rock types in their unweathered states. Even so, there seems to be significant decrease in density between the granite and some of the pre-Permian sediments that constitute the basement.

It may be expected therefore that this difference in density within the basement rocks will lead to anomalies in the gravitational field other than those expected from variations in the thickness of the overlying sediments.

SEISMIC VELOCITIES.

A full description of the velocities determined and a discussion of their significance is given in Part B of this bulletin, which deals with the seismic survey at Oaklands. However, as the seismic results are discussed briefly in their relation to the gravity results in the following sections, it is proposed also to discuss briefly the velocities that were determined.

Velocities observed in the Oaklands area ranged from 2,500 ft/sec. to slightly more than 18,000 ft/sec. and increased progressively with depth, not continuously, but in more or less discrete steps of 2,000 ft/sec.

Tests were made at many places where the geology is known and it was possible to determine the characteristic velocities of the various rock types. The results of these tests are summarized thus:—

Velocity Range ft./sec.	*Geological Equivalent.*
2,500 – 7,500	Tertiary.
7,500 – 8,000	Tertiary or Permian.
8,000 – 10,000	Permian with possibly some pre-Permian among the higher velocities.
10,000 – 13,000	Basement—pre-Permian sediments not very metamorphosed.
13,000 – 20,000	Basement—metamorphic rocks and granite.

METHOD OF SURVEY.

The survey was begun in September 1948, when Mr. G. B. Clarke, geophysicist attached to the Bureau, established field headquarters at Oaklands, New South Wales, and commenced gravity observations from that centre. The work continued until February 1949, when Mr. Clarke returned to Melbourne to examine the results and to permit the gravity instrument to be overhauled.

During this period, gravity observations had been made at about 480 stations, more or less evenly spaced within an area of 900 square miles bounded by lines joining Urana, Daysdale, Savernake, Berrigan, and Jerilderie.

The survey was resumed towards the end of April and the gravity field work was completed by mid-July, 1949. This latter work was carried out by Mr. S. Waterlander who worked from Mulwala and Corowa and covered the southern part of the area surveyed. More than 400 stations were occupied in an area of approximately 550 square miles.

Plate 2 shows all the gravity stations in their relation to the main towns, the railway and roads. The River Murray between Mulwala and Corowa forms the southern boundary.

INSTRUMENTS USED.

In the work that Mr. Clarke carried out, Heiland Gravimeter No. GSC 2, with a sensitivity of 0·089 milligals per scale division, was used. The sensitivity was checked before and on completion of its use at Oaklands.

When Mr. Waterlander resumed the survey, the above meter was not available and it was replaced by a Western Meter (No. 29) of similar design and sensitivity. Its scale factor was compared with Heiland No. GSC 2 by repeating a chain of stations near Savernake and, in the final reduction of results, the station intervals determined by the two meters are strictly comparable.

SURVEY CONTROL.

County and Parish maps covering the whole area are available, as well as Australian military survey 4-mile series (see map I.55/14 Jerilderie).

The area covered included portions of the counties of Urana, Hume, and Denison. That part of the area south of the line joining Berrigan with Coreen is covered by the Australian military survey one-mile maps for Tocumwal and Buraja.

The plan finally prepared for use in plotting the stations, and obtaining their latitude for correction purposes, is on a scale of 2 miles to one inch. It is based on the County plans, with control provided in the southern portion by the one-mile maps of Tocumwal and Buraja and, in the north, by an accurate re-plot of the Mulwala-Urana railway line. The gravity stations were plotted on the Parish plans in their correct relation to the portion boundaries, &c., and were then transferred to the "base plan." It is believed that, in the northern portion of the area surveyed, the station positions are correct in latitude to one-quarter of a mile with a comparable error in longitude; in the southern portion their positions are probably more accurate.

ELEVATION CONTROL.

Accurate levels had previously been run over most of the area by officers of the Water Conservation and Irrigation Commission of New South Wales while investigating the area for potential irrigation development. The Commission kindly made available plans—on a scale of 20 chains to one inch and covering the whole area— on which all bench marks and surface contours, mostly at 1-foot intervals, were shown. Gravity stations were chosen at bench marks; these were so numerous that it was possible to cover a large part of the area with gravity stations at one-mile intervals on north-south lines approximately 2 miles apart. The average density of stations over the whole area is one station per 1·60 square miles.

RESULTS AND INTERPRETATION.

Before an interpretation can be attempted certain corrections must be applied to the gravimeter readings.

Only relative values of gravity are determined by gravimeters and a constant value would need to be added to them to convert them to absolute gravity. However, this addition is seldom made as it is the gravity anomalies, i.e., variations from normal, and not the absolute values that are important and of geological significance. The values are usually expressed in milligals relative to some arbitrarily chosen base station and are subsequently corrected for elevation and latitude effects. The corrected values are generally plotted in the form of contour maps of "observed gravity anomaly."

The area investigated lies between latitudes 35° and 36° south. To facilitate the application of a latitude correction to the gravity readings, the base plan was gridded with north-south and east-west lines, one mile apart, the origin of the grid system being at Oaklands. The correction factor, expressed in milligals per mile, was varied through six equal zones ranging from 1·230 milligals/mile (corresponding to 35°) at the north to 1·243 milligals/mile (36°) at the south.

An elevation correction factor (Bouguer plus Free Air) of 0·068 milligal/foot was used, corresponding to a density of 2·00 gm./cc. for the Tertiary sediments which cover all but an insignificant portion of the area. Gravity values were corrected to a uniform plane 400 feet above sea level. The anomalies are expressed relative to an arbitrarily chosen datum. To convert them to values relative to theoretical values on the International Ellipsoid, a correction—which is a function of the elevation—must be added. This correction is (46·4—0·008h) ± 0·5 milligals, where " h " is the station height above RL 400 feet and, except for 14 stations, ranges from +60 to −32 feet.

Plate 2 shows the position of all the gravity stations and Plate 3 (Observed Gravity Contours) shows gravity contours (interval 1 milligal). This contour plan, covering an area of approximately 1,450 square miles in the area bounded by the towns of Urana, Corowa, Mulwala, Berrigan, and Jerilderie, shows a major depression (approximately 30 milligals) which, if due entirely to light sediments, would be explained by a sedimentary basin of very considerable dimensions extending in a north-south direction from the Murray River to Jerilderie and in an east-west direction from Daysdale to Berrigan. However, a superficial examination of the contour pattern shows that gravity varies considerably over places where basement rocks either crop out or are known to lie at a shallow depth. Over outcrops and shallow basement near Urana and east of Daysdale, i.e. on the north-eastern and eastern edges of the basin, the gravity value ranges from 35 to 37 milligals. Between Berrigan and Mulwala, however, there are several basement outcrops over which reduced gravity ranges from 15 to 33 milligals. Over basement outcrops north-west of Corowa the value is approximately 25 milligals. The basement rocks are mainly granite and metamorphosed sediments near Daysdale and Urana and, as far as can be determined, are of similar types between Berrigan and Mulwala and north-west of Corowa.

It has been shown (p. 13) that there appear to be appreciable differences in density within the basement rocks. However, there is no obvious correlation between the value of gravity and the basement rock type and it seems probable that the variation noted above is due at least in part to some deep-seated cause. The combined gravity effects due to variations in density within the basement rocks and to deep-seated causes (in other words the gravity effect due to causes other than the sediments filling the basin) are called the " regional effects."

It is believed that the " regional effect," or the gravity pattern to which it gives rise, is a reasonably smooth pattern, not subject to rapid or pronounced changes, but changing gradually from place to place. If, therefore, the general form of the regional pattern could be obtained by determining the regional effect at a number of selected points throughout the area, it would seem likely that the effect of the sediments could be separated from the regional effect.

One method of doing this would be by drilling to determine the thickness of the sediments and, after determining their density, calculating the gravity effect produced by them. In this way the gravity effect that would have been observed had there been no sediments present—in other words the true regional effect—could be determined. However such drilling would be very expensive, especially as the holes would in all probability be very deep and perhaps 20 to 30 would be needed to furnish the desired control. In any case the object of the geophysical survey was to delineate the basin so that drilling for coal could be carried out expeditiously.

It was therefore decided to use a different geophysical technique, namely the seismic method, which it was expected would give the required information with sufficient accuracy at relatively small cost. Subsequently five sections, shown on Plate 4 as Sections A-A, B-B, C-C, D-D, and E-E, were observed. Shot points, i.e. points where a depth determination was made, were spread in pairs one mile apart at intervals of 2 to 3 miles along these sections.

The technique of refraction shooting was employed but at certain places in the deeper parts of the basin, notably in the vicinity of shot points 8 to 12, some rather poor reflections were obtained, the deepest appearing to come from depths of 4,000 to 5,000 feet.

From the results of tests it was considered that the basement would be characterized by velocities greater than 10,000 ft./sec. In general, velocities of the order of 15,000 to 18,000 ft./sec. were found at places on the rim of the basin but no evidence was recorded of their presence in the deeper parts. This could have been due either to the corresponding rock type being present but too deeply buried to yield any response at the surface, or to the basement rocks being different in character and having a lower velocity than that recorded near the rims.

In the deeper parts there persists a refraction horizon with a velocity between 10,000 and 12,000 ft./sec., the depth to its upper surface being between 1,000 and 2,500 feet, and this is assumed to be the basement. The Permian Coal Measures have a velocity of 7,500 to 10,000 ft./sec. and rest either on rocks with a velocity of 15,000 to 18,000 ft./sec. (near the rim) or on rocks with the above-mentioned velocity of 10,000 to 12,000 ft./sec. which are believed to be either Ordovician or other sediments older than the Coal Measures.

DETERMINING REGIONAL CORRECTION.

(1) The gravity values obtained on basement outcrops provide one set of data for determining the regional effect.

(2) At each place in the area where the thickness of the sediments is known through drilling, the gravity effect that would have been measured had these sediments not been present has been calculated. This was done by calculating the gravity effect of a layer of thickness equal to the sediments and densities equal to the difference between the sediments and basement. The effect so calculated is the amount by which the gravity field has been reduced by the presence of the sediments, and by adding this to the observed value, the regional effect is obtained.

(3) At each of the seismic shot points a value has been obtained for the thickness of sediments above the assumed basement, and the gravity effect of these sediments has been calculated after the manner described in (2) above, and the " regional effect " determined.

RESIDUAL GRAVITY PATTERN.

To assist in the preparation of the residual gravity pattern, gravity profiles were drawn two miles apart in the east-west direction.

Where these profiles crossed or were near basement outcrops, bores of known depth to basement, or seismic shot holes (i.e. at any of the three controls mentioned above), the regional effect was either plotted on or projected onto the profiles. On the assumption that the regional pattern would be smooth, the regional profiles were completed by drawing smooth lines between the control points. On some of the sections the control data was sufficient to determine fairly accurately the shape of the regional profiles. This shape was matched on adjoining sections where the control data was less complete and in this way the " regional effect," in profile form, was extended throughout most of the area.

Once the regional effect was extended, the residual effect, which is the arithmetical difference between the observed and regional gravity, could be determined.

The east-west profiles provided the data for plotting the regional gravity contour shown on Plate 5 as well as the residual gravity contour pattern (Plate 4).

A comparison of the three contour plans, observed, regional and residual, shows that the regional effect is considerably larger than the residual effect. Nevertheless it is believed that the residual pattern does represent a large sedimentary basin containing Permian Coal Measures and associated sediments and provides a picture of the basinal conditions sufficiently accurately to be used as a basis for testing the Coal Measures by drilling.

It must be remembered that in the deeper and more central parts of the basin, the residual pattern represents the effect of the sediments above an arbitrarily chosen horizon (the 10,000 to 12,000 ft./sec. layer) which itself may be part of the sedimentary sequence. Consequently the regional pattern may include the effect of some sediments that are older than the Permian Coal Measures and that have been considered as part of the basement.

The seismic tests yielded reflections at various places throughout the basin and many of these appear to be coming from depths between 4,000 and 5,000 feet. The reflections were poor and could not be correlated between shot holes. Nevertheless they do provide some evidence of more or less horizontal reflecting layers, presumably sedimentary, at depths at least twice as great as the top of the 10,000 to 12,000 ft./sec. layer, and therefore lying within the supposed basement.

Such deep sub-horizontal sediments could be Lower Permian, perhaps Permian glacial beds similar to those intersected by bores north of Wangaratta in Victoria. They could be Devonian sediments—some sediments of this age have been mapped 50 to 100 miles north of the area—or, in view of the velocity test near Mulwala, they may be Ordovician. It is not suggested that such deeper sediments provide a complete explanation for the regional pattern but they may contribute a significant part. Other contributory causes would be variations in density within the basement rocks, and perhaps deeper causes.

The residual pattern, Plate 4, represents a wide, rather shallow, basin containing a maximum thickness of approximately 2,500 feet of sediments and occupying an area of about 600 square miles. The contour pattern is open to the north and, although gravity observations were made for a considerable distance (10 to 20 miles) to the north of where the residual pattern has terminated, there is no control data on which to base any reduction.

The pattern near Coorabin and Oaklands suggests that the area where coal is now being mined is on the eastern edge of the basin and consequently the coal seams could be expected to extend westwards towards the centre.

The basin appears to have two lobes on its southern boundary. One lobe extends south-east from Oaklands towards Coreen and Lowesdale, with Daysdale lying about two miles east of the eastern rim. The other lobe extends from about the centre of the basin towards the Murray River between Mulwala and Corowa, with Rennie and Savernake lying approximately on its axis.

The basement outcrops north-west of Corowa and constituting the Corowa Goldfield appear to extend as a narrow saddle for about 25 miles towards the north-north-west, separating the two southern lobes of the basin.

One factor of considerable importance in determining the nature of this supposed basin is the relative amounts of Tertiary and Permian sediments it might contain.

As mentioned earlier, present knowledge of the thickness and structure of the Tertiary sediments is very meagre. The widely-scattered water bores that have tapped Tertiary aquifers show that its thickness is seldom less than 150 feet and the greatest proved thickness is 530 feet.

Although it was hoped that the seismic method would show a velocity difference between Permian and Tertiary sediments and thus provide a means of determining the thickness of the Tertiary rocks, this was in fact not established. However, in certain places, for example shot points 14 and 15, a near-surface layer of velocity approximately 6,000 ft./sec. which can be identified with fair certainty as Tertiary is replaced by another with a velocity in excess of 8,000 ft./sec. at depths of 500 to 600 feet. The identity of the deeper layer is not known; it may be Permian or Tertiary but probably is Permian. The above result establishes a minimum thickness of 500 to 600 feet for the Tertiary sediments in this part of the area, although the true thickness may be more. Further west, at shot points 17 and 18 (3 miles east of Berrigan) there appear to be only about 200 feet of Tertiary sediments resting directly on basement rocks.

The thickening of the Tertiary sediments evident at shot points 14 and 15 seems to extend southwards towards the Murray River, as is evidenced by the seismic results at shot points 40 and 41, and 48 to 50. There may in fact be a wide relatively deep Tertiary channel extending north-west to south-east through the south-western part of the supposed basin. Some support for this interpretation is provided by the appearance of the observed gravity pattern (and to a lesser extent in the residual pattern) with its series of low gravity closures stretching from the Murray near Corowa towards Jerilderie. Such a Tertiary channel could be associated with the Tertiary deep leads of Northern Victoria such as those of Chiltern and Rutherglen which have been traced north as far as the Murray in the vicinity of Corowa. The deepest channel was slightly deeper than 400 feet and it was thought to pass under the Murray to New South Wales. As the amount of gold in the channel diminishes towards the north it is unlikely that deep leads in the area covered by the gravity survey would carry payable gold, but nevertheless it is an interesting speculation.

On the eastern side of the area, between Coreen and Coorabin, the most striking feature of the observed gravity pattern is the crowding of the contour lines (25 to 30 milligals) in a relatively narrow zone that strikes roughly north-west. Bores 4, J, and 5, 2 miles north of Oaklands, provide a section across part of this zone and it is significant that, whereas between Bores 4 and J the dip of the Permian strata and the gravity gradient are both low, they both increase substantially between Bores J and 5, which lie within the zone of crowded contours.

Seismic results near shot points 1 and 2 (east of Oaklands) and 19 and 20 (west of Daysdale) show that the edge of the basin is parallel to and coincides with the eastern edge of this zone. Further north at Coorabin, however, the Permian Coal Measures extend well beyond the eastern edge of the zone.

It seems likely that in the eastern part of the field the observed gravity contour pattern will conform generally to the basement topography. The magnitudes of the gravity gradients, however, are greater than would be expected from the basement gradients as measured by the seismic method, and consequently the existence of regional gradients has had to be assumed. In the residual gravity pattern, the gravity gradients in the zone referred to above are considerably less in magnitude than in the observed pattern but the zone can still be recognized as a persistent feature.

It is possible that the eastern edge of the zone marks the axis of a monoclinal fold of post-Permian, but pre-Tertiary, age, and that the Coal Measures are downfolded to the west. Deep faulting could be the underlying cause of such folding as it is, for example, in monoclinal folds in the Tertiary coal deposits of the Latrobe Valley.

A similar crowding of the contour lines occurs in a zone of comparable strike east of Rennie and west of Sangar. This zone also coincides roughly with a basin edge but the gravity gradient is very much greater than could be accounted for by the basement slope as indicated by the seismic results between shot points 29 and 31. Because of this, the residual gravity pattern shows practically no sign of it and the zone shows up strikingly in the regional pattern. One possible explanation would be that this zone also marks a pre-Permian fault with relatively light sediments down-faulted on the west.

RECOMMENDATIONS FOR TESTING.

The object of the survey was to obtain a picture of the sedimentary basin which contains the Permian Coal Measures so that a programme of testing can be laid down.

Such factors as the probable extent of the measures and the depths at which coal seams might occur are of utmost importance in planning a testing campaign.

It is believed that the residual gravity pattern gives a reasonably faithful picture of the extent of the Coal Measures. The chances of Coal Measures occurring in the southern lobe near Rennie are not considered to be as good as they are within the main basinal area. Even omitting the southern lobe, there remains an area of approximately 400 square miles with reasonable prospects of containing valuable coal seams.

Testing may be divided into two categories:—

(1) testing aimed at proving reserves of coal near the known coal-bearing areas—for example, testing might aim at proving, say, 50 square miles of coal in the general vicinity of Coorabin and Oaklands to ensure sufficient reserves for the operation of one or more large collieries;

(2) testing to prove the extent of the Coal Measures within the supposed basin and to prove or disprove the main geophysical contentions.

Naturally from the point of view of the geophysical survey, the second form of testing would be the more satisfactory. The confirmation of the general basinal conditions by drilling would be a major success for the methods. However, the proving of additional coal reserves is equally important and in selecting sites for testing this has been borne in mind.

The residual gravity pattern may be considered very largely as an expression of the seismic results, the trends of the observed gravity pattern being used to extend them. The reliability of the residual pattern is consequently highest at the shot points and decreases as the distance from the shot points increases.

Testing is therefore recommended primarily at or near seismic shot points. It is considered that the maximum value can only be obtained from such testing if it is carried as deep as the seismic information extends. The deepest seismic refractions appear to come from a depth of 2,500 feet and consequently it is considered that testing requires a drill capable of reaching a target at a depth of not less than 3,000 feet.

It is recommended that testing be carried out at the following sites, which are shown on Plate 4—

SITE No. 1. (At shot point 35, approximately 2 miles east-south-east of Oaklands). Velocities recorded from the surface downwards are: 3,000 ft./sec., 5,470 ft./sec., 7,930 ft./sec., 8,830 ft./sec., 10,350 ft./sec., and 17,380 ft./sec. The first two correspond to Tertiary sediments and indicate a total thickness of approximately 100 feet, the third and fourth are believed to correspond to Permian sediments including the Coal Measures and the last two are considered to be basement velocities.

The layer of velocity 10,000 to 12,000 ft./sec., which was considered to be basement in the central part of the basin, appears to be at a depth of 1,180(±) feet. The highest velocity recorded is probably due to granite which it is expected will be intersected at a depth of approximately 2,100 feet.

Deep testing to intersect the various layers mentioned would provide data for interpreting the seismic results. Further, the site is favourably located for proving additional coal reserves. A bore giving a good coal intersection at this site would need to be succeeded, however, by other bores in the region between this site and Bores 4, J and 5 to prove continuity of the seams.

SITE No. 2. (At shot point 9). This site lies about 7½ miles west of Oaklands on the Berrigan-road. It is situated near the centre of the sedimentary basin where it is believed Permian sediments of considerable thickness exist.

The following layers, differentiated by their velocities, are recognized:—

Depth feet	Velocity ft/sec.	Types
0– 140	2,880	Tertiary
140– 410	5,950	Tertiary
410– 900	8,250	Permian
900–1,450	8,720	Permian
1,450–2,600	10,010	Pre-Permian (Basement)
2,600+	12,800	Pre-Permian

It is believed that the coal horizons, if present, will lie above the 10,010 ft./sec. layer, i.e. above a depth of approximately 1,450 feet. There seems to be a good opportunity here to test a thick section of Permian sediments, perhaps 1,000 feet thick.

The information to be gained from this hole should assist materially in interpreting the seismic results. Further, if a good quality coal seam of workable thickness be intersected, the "possible" reserves would become enormous.

SITE No. 3. (At shot point 16). This is close to what is believed to be the western margin of the sedimentary basin. At shot point 37, about three-quarters of a mile further west, the seismic results suggest a very thick Tertiary section (velocity 6,220 ft./sec.) resting more or less directly on granite (?) basement at a depth of 800 feet. At shot point 16, however, no evidence of a granite (?) basement was disclosed, the deepest layer determined being one of velocity 12,130 ft./sec. at a depth of 1,900 feet. Slow velocity layers (up to 6,200 ft./sec.) almost certainly Tertiary, are present to an estimated depth of 400 feet, and underlying them are layers of velocity 8,280 ft./sec., which it is believed include Permian sediments, and 10,850 ft./sec., which is probably basement. The chances of finding coal here will be governed largely by the results of drilling at site No. 2 (shot point 9).

SITE No. 4. (At shot point 41). This site is chosen to test the southern lobe of the basin. It is situated near the railway siding of Rennie on the Oaklands-Mulwala railway.

The seismic results suggest the following section:—

Depth feet	Velocity ft/sec.	Types
0– 90	2,430	Tertiary
90– 480	5,800	Tertiary
480–1,500	9,780	Permian(?)
1,500+	11,400	Pre-Permian(?)

The section contains a thick Tertiary layer which appears to cover most of the western side of the basin and which may be responsible for the major part of the residual gravity effect in the southern lobe. However, at this site, the seismic results suggest a reasonably thick Permian section although the velocity is higher than for Permian sediments near Oaklands. Testing should be continued to a depth of approximately 2,000 feet if still in unidentified sediments or until the Permian section, if any, has been fully tested.

SITE No. 5. (At shot point 21). The seismic results are similar to those at shot point 35 (site No. 1).

The following section is suggested by the seismic results:—

Depth feet	Velocity ft/sec.	Types
0– 160	2,910	Tertiary
160– 550	7,500	Tertiary and/or Permian
550–1,600	9,030	Permian(?)
1,600+	11,100	Pre-Permian (?)

The site is favourably situated to intersect the coal seams if they persist as far south as this. If coal of workable size and quality were proved, very substantial additions to the " possible " coal reserves would be made.

The sites listed above are considered adequate for an initial testing campaign aimed at proving or disproving the main conclusions of the geophysical interpretation. However, much of value will be lost unless further seismic tests are carried out as the sites are drilled. This would consist of measuring vertical velocities in the holes after completion of drilling but while the rig is still in place to be used for lowering and raising special geophones.

To provide satisfactory geological control, core samples should be taken every 50 feet where possible and all coal seams should be cored continuously. Electrical logging of the holes should also be undertaken if equipment is available.

Further drilling will be needed to prove coal reserves and much of this can be done with a smaller rig than would be needed for the testing recommended above, the results of which should indicate the capacity of the rig needed for the more detailed drilling.

A favourable place to begin testing for reserves would be near Bores 4, J and 5 and, as an initial project, it is suggested that the section proved by these bores should be extended westward by drilling two additional bores at mile intervals to the west of No. 5. The residual gravity pattern suggests that the relatively steep gradient that was found between Bores J and 5 does not persist far to the west and consequently the coal seams are expected to flatten west of No. 5. Proposed sites for the bores are shown as G.1 and G.2 on Plate 4.

The residual gravity pattern suggests that, west of the Clear Hill shafts, the floor of the basin—and presumably the Permian Coal Measures—dips to the west. Although the seams intersected by these shafts were thin and of poor quality, it is expected that coal seams comparable with those intersected by Bores 4, J and 5 might be disclosed by drilling on this westerly-dipping portion. A drilling site (G.3) has been selected about 1 mile due west of Clear Hill shaft and its position is shown on Plate 4.

Other sites selected for testing are shown as G.4, which is about half-way between shot points 3 and 5, and G.5 near Wangamong.

The results of drilling at sites 1 to 5 and G.1, G.2, G.3, G.4 and G.5 will be used as a guide to the selection of further drill sites for testing the coal reserves.

PART B—SEISMIC SURVEYS.

INTRODUCTION.

This part of the bulletin describes in detail the results of the seismic surveys at Oaklands and should be read in conjunction with Part A—Gravity Surveys. The history and geology of the field are discussed on pages 9 and 10, and in Part A the gravity results and their relation to the geology of the area are described in detail. The seismic results are also discussed in Part A but only in so far as they affect the interpretation of the gravity results. Conclusions regarding the distribution of the Coal Measures are drawn from the gravity results, and recommendations for a test boring programme have been given.

The seismic results will be discussed in this part of the bulletin in greater detail than in Part A and, because of the close relation between the gravity and seismic results, reference will be made throughout to the gravity results.

As great differences in gravity were observed over basement outcrops at Daysdale, Urana, Berrigan, and Mulwala, it is evident that the observed gravity anomalies are not due entirely to sediments in a basin structure, but are largely an expression of a regional effect. By means of seismic tests carried out at selected places, depths to basement were obtained and it was thereby possible to calculate the gravity effect of the sediments. The sites for these tests were distributed throughout the supposed area of the basin and the tests provided sufficient data to make possible the compilation of a reasonably accurate map of the regional gravity effect and, ultimately, the compilation of a residual gravity map.

The seismic results show that the thickness of the sediments above basement, and hence the gravity effect due to them, is relatively small. It follows therefore that a regional effect is probably the major factor contributing to the observed gravity pattern, but there is associated with this pattern a sedimentary basin—at least 2,000 feet deep and extending over an area of approximately 600 square miles as it is shown in the residual gravity pattern.

ANALYSIS OF OPERATIONS.

Four geophysicists, a surveyor, a driller and six field assistants made up the party, which was engaged on the seismic survey for a period of three months from July to September 1949. The equipment was mounted on motor trucks and comprised a reflection seismograph (12 channels), shot-hole drill, shooting equipment and radio-communication sets. Three other vehicles, including a water tender, were used. In general, it was possible to select straight stretches of road for making observations and only rarely was it necessary for any of the vehicles to enter paddocks. The country is flat and the roads fair, so little time was lost in driving to and from the field even when distances of 20 miles were involved. The party operated from Oaklands during the surveying of the northern section and later moved to Mulwala and Yarrawonga as the work progressed southwards.

SEISMIC METHOD AND APPLICABILITY TO PROBLEM.

The seismic method was used at selected places with the object of determining the depth to basement and the thickness of the Tertiary and Permian sediments and, if possible, the structure of the Permian sediments. The seismic method usually employed for a problem of this nature is the refraction method. The effects due to abrupt discontinuities of velocity of a compressional wave within a sedimentary section are recorded and it is possible to calculate the depth of the discontinuities. It is a necessary condition for the successful use of the method that at any discontinuity the faster velocities be the deeper.

The main contributory factors that determine the velocity of the compressional wave within a rock are the density and elastic modulus of the rock. Because the age of a rock, its depth of burial, and its lithology affect both these factors, an abrupt change in age or lithology—for example, where there is an unconformity—will in many places coincide with an abrupt change in velocity.

A pronounced contrast in velocity between the Tertiary and Permian rocks and between Permian and basement rocks would provide the best theoretical conditions for the application of the refraction method in this area. It was thought that, because of differences in age and/or depth of burial, the velocity of the Tertiary sediments would be appreciably less than the velocity in the Coal Measures and, for similar reasons, that the velocity in the basement rocks would be greater than in either the Tertiary or Permian rocks. It was also thought possible that the Permian Coal Measures may contain some bed or beds with a velocity between the velocities of the average Permian and basement rocks, thus providing a marker bed by means of which the structure of the Permian could be mapped.

All these ideal conditions were not encountered and consequently there remain, in the interpretation of the seismic results, many doubtful points that will need to be checked by boring before a final interpretation can be made. However, the combined results of the seismic and gravity methods have yielded a picture of the sedimentary basin which serves to reduce very considerably the programme of boring necessary to determine the full extent of the coal resources of the basin.

To apply the refraction method two shot holes were drilled approximately 80 feet deep and 5,250 feet apart and geophone stations were spaced at 150-foot intervals away from each shot point on a line towards and beyond the other shot point to a total distance of 8,400 feet—end geophones were thus 11,550 feet apart. Charges of gelignite mostly between 5 lb. and 50 lb.—for near and far geophones respectively—were exploded in the bottoms of the shot holes and groups of twelve geophone stations were occupied for each explosion until sufficient data had been recorded. From this data was plotted a time-distance curve showing when the compressional wave-front would have been received if all geophone stations had been occupied for a single explosion. The time-distance curves for all the shot points and the sub-surface refraction horizons as deduced from these results are shown on Plates 7 to 9.

The equipment used was manufactured by Heiland Research Corporation of U.S.A. and similar equipment is described by Heiland (1940) in his book on Geophysical Prospecting.

METHOD OF INTERPRETATION

The method used for analysing the records is a development of the method devised by O. V. Schmidt. His method, as described by Heiland (1940), deals with only two layers and it has been extended to cover the general problem of any number of layers; the formulae are described in Appendix 1 of this bulletin.

The times shown on the time-distance curves (see Plates 7 to 9) to which the above analysis was applied are not actual recorded times but are the times that would have been recorded if the shot had been fired at the surface of the ground and the elevation of the geophone stations had been the same as the elevation of this hypothetical surface shot.

The analysis assumes that each interface between adjacent layers dips uniformly along the section covered by the geophones and that the velocities within the layers are constant.

VELOCITIES IN KNOWN FORMATIONS

During the course of the survey, experimental shots were fired at about fifteen places to determine the characteristic velocities of the known sedimentary rocks and the basement rocks. A knowledge of these velocities was needed to make a reasonable interpretation.

BASEMENT

Basement rocks crop out near Daysdale, Berrigan and Mulwala and tests were made at each place. Near Daysdale the basement is composed of schists and quartzite; near Berrigan, granite; and at Mulwala, slate. It is believed that the rocks exposed at these three places represent the full range of basement types. Relatively high velocities, which are ascribed to basement rocks, were recorded from shallow depth at some places near the margin of the basin. It has been possible on the basis of their relative proximity to known outcrops, or on the basis of their velocities, to correlate them with one or other of the three basement types with reasonable certainty.

Details of the tests are as follow:—

(*a*) *Daysdale—Shot points A and B,* near outcrops of schists and quartzites. Approximate basement velocity 14,500 ft./sec.

Shot points C and D, thin Tertiary cover over metamorphic basement. Approximate basement velocity 16,000 ft./sec.

(*b*) *Berrigan—Shot points* 27 *and* 28, near granite outcrop. Approximate basement velocity 17,000 ft./sec.

(*c*) *Mulwala—Shot points* 60 *and* 61, over outcropping slate. Velocity near surface approximately 10,600 ft./sec. but increased to 18,400 ft./sec. at a depth of 350 feet (approx.).

(d) Other Places—Shot points 1 *and* 2, three miles east of Oaklands: Approximate basement velocity 17,200 ft./sec.; probably metamorphic rocks similar to those near Daysdale.

Shot points 29 *and* 30, east of Rennie. Approximate basement velocity 16,000 ft./sec.; probably metamorphic rock.

Shot points 52 *and* 53, north-west of Mulwala. Approximate basement velocity 11,840 ft./sec.; probably similar to rocks at Mulwala.

Shot points 42 *and* 43, south of Savernake. Approximate basement velocity 16,300 ft./sec.

Shot points 44 *and* 45: 58 *and* 59, south of Savernake. Approximate basement velocities 18,400 and 18,100 ft./sec. for the respective pairs. These velocities correspond to granite basement.

Shot points 17 *and* 18, east of Berrigan. Approximate basement velocity 17,600 ft./sec., corresponding to a granite basement.

It will be seen that, with the exception of the test at shot points 60 and 61 at Mulwala, and 52 and 53 north-east of Mulwala, the basement velocities ranged from 14,500 to 18,400 ft./sec. The slate at the surface at shot points 60 and 61 is undoubtedly part of the basement complex and its velocity, 10,600 ft./sec., must therefore be considered as a basement velocity. However, at a depth of approximately 350 feet this velocity is replaced by one of 18,400 feet per second and it is possible that some if not all of the change is due to the fact that the rocks below 350 feet are not weathered. The basement velocity of 11,840 ft./sec. recorded at shot points 52 and 53 could correspond to basement rocks similarly weathered. An alternate explanation for the change of basement velocity recorded at shot points 60 and 61 is that the slate is underlain by rocks of a different type, for example, granite, at a depth of 350 feet.

It is possible that velocities slightly lower than any of those mentioned above could be measured in basement elsewhere within the area and for this reason the lower limit of basement velocity is taken as 10,000 ft./sec.

TERTIARY AND PERMIAN

Tests of velocities within the Tertiary and Permian sediments were not as complete as those within the basement rocks. There are no Permian outcrops and there is only one small area where the depth to the Tertiary-Permian contact is known. There is no place where the thickness of the Permian is known. The geological section disclosed by the logs of Bores 4, J, and 5 was considered to be the best available section on which to carry out tests to determine the velocities within the Tertiary and Permian. Shot holes F, E and G were drilled close to Bores 4, J and 5 respectively and the seismic results are shown with the geological section on Plate 7.

The seismic interpretation shows two layers overlying basement. The top layer, which has a velocity of 3,180 ft./sec. and a thickness of approximately 150 feet, corresponds to the Tertiary sediments above ground water level. The second layer has a velocity of approximately 8,000 ft./sec. and corresponds to the sediments below ground water level. No distinction between Tertiary and Permian sediments is apparent. Basement velocities are approximately 17,000 ft./sec. and indicate a basement of metamorphic rocks or granite. The basement is flat between shot points F and E but dips westerly at about 8° between shot points E and G. The dip of the Coal Measures is smaller (approx. 3°). The Coal Measures, if present in the centre of the basin, will, because of their dip, be somewhat deeper than they are at the edge; however the Coal Measures will not necessarily, in the deeper parts, extend to the basement—increased depth to basement should not therefore be taken as necessarily indicating an equal increase in depth of the Coal Measures.

Test shot hole H was drilled to a depth of 430 feet between shot points E and F in order to confirm, by tests of vertical velocities, the interpretation based on the horizontal velocities recorded from shot points G, E and F. These tests confirmed the existence of the two layers with velocities of approximately 3,000 ft./sec. and 8,000 ft./sec. respectively.

Although the above tests failed to show any difference between Tertiary and Permian sediments below the water table, they are not entirely conclusive. Over most of the area covered by the survey there is a layer with a velocity of approximately 6,000 ft./sec. immediately below the water table and this is believed to be composed of Tertiary sediments. This layer is generally underlain by one with a velocity of approximately 8,000 ft./sec. which is believed to be composed largely of Permian sediments including the Coal Measures although it may include some Tertiary sediments.

From the results of the above tests and of the survey in general it is considered that the velocity in the Tertiary sediments will range from 2,500 to slightly more than 8,000 ft./sec. and the velocity in the Permian sediments will range from 7,500 to approximately 10,000 ft./sec.

CONCLUSIONS.

The tests of the velocities in known formations may be summarized as follow:—

	Velocity Range ft./sec.	*Geological Equivalent.*
1.	2,500 – 7,500	Tertiary.
2.	7,500 – 8,000	Tertiary or Permian.
3.	8,000 – 10,000	Permian with possibly some undetermined pre-Permian particularly among the higher velocities.
4.	10,000 – 13,000	Basement—pre-Permian sediments not highly metamorphosed.
5.	13,000 – 16,000	Basement—pre-Permian sediments highly metamorphosed.
6.	16,000 – 17,500	Basement—highly metamorphosed sediments or granite.
7.	17,500 – 20,000	Basement—granite.

RESULTS OF SURVEY.

The seismic survey was confined to five traverses referred to as A-A, B-B, C-C, D-D, and E-E which are shown on Plate 4. The time-distance curves and interpretation showing thicknesses and velocities corresponding to the individual shot points are shown on Plates 7 to 9, and the sections along the traverses showing the correlation of the layers based on the recorded velocities are shown on Plate 6. The results will be described traverse by traverse.

TRAVERSE A-A. (Shot points 1 to 18 inclusive, and 35 to 38 inclusive.)

This traverse followed the Oaklands-Berrigan road for convenience of operation. It is approximately 25 miles long, extending from a point 3 miles east of Oaklands to within 3 miles of Berrigan. It was designed to give information over a part of the area where the observed gravity anomaly was a maximum and also to prove whether or not the extensive sedimentary basin indicated by the gravity anomaly did, in fact, exist.

The traverse shows a wide basin with its eastern rim near shot point 2 and its western rim near shot point 37. Two distinct layers of the Tertiary sediments are indicated by velocities of approximately 3,000 and 6,000 ft./sec.; a layer with a velocity of 8,000 ft./sec. may include both Tertiary and Permian and a layer of velocity 9,000 ft./sec. is probably Permian. Basement velocities on the rims of the basin range from 17,200 to 18,200 ft./sec., but within the basin they range only from 10,000 to 13,000 ft./sec. It is possible that rocks with higher velocities may underlie them but at too great a depth to have been recorded.

At shot point 35 near the eastern rim and 37 near the western rim of the basin, two basement velocities are recorded, the slower one overlying the other. In each place it is believed that granite or highly metamorphosed sediments underlie the slightly metamorphosed types or that there is a weathered zone above unweathered rocks.

From east to west along traverse A-A it can be seen (Plate 6) that at shot point 1 there are about 160 feet of Tertiary (3,070 ft./sec.) overlying 190 feet of Tertiary and/or Permian (7,960 ft./sec.) with a granite or metamorphic basement (17,200 ft./sec.) beneath. This basement dips at about 8° to the west between shot points 1 and 2; plunges sharply at about 20° between shot points 2 and 35 and continues dipping at 8° towards shot point 36. The section at shot points 35 and 36 is more complex than that at shot points 1 and 2. In addition to the layers mentioned above are layers with velocities of 5,470 and 8,830 ft./sec. as well as the two basement velocities already mentioned. This indicates a pronounced change in stratigraphy as the edge of the basin is crossed near shot point 2. The following is the approximate stratigraphic sequence indicated at shot point 35: 100 feet of Tertiary, 420 feet of Tertiary and/or Permian, 660 feet of Permian with possibly some older sediments, and 850 feet of basement sediments overlying granite or highly metamorphosed sediments.

The Tertiary and Permian sediments shown at shot point 35 appear to extend across the entire basin with velocities centering around 3,000, 6,000, 8,000, and 9,000 ft./sec. At shot points 3 and 4 the 6,000 ft./sec. Tertiary layer was not recorded but its effect may have been obscured by the relatively great thickness of the 3,000 ft./sec. layer beneath the crest of a sandhill. The thicknesses of these layers show undulating changes particularly in the Permian sections but generally the thickness of the 3,000 ft./sec. layer is about 150 feet; the 6,000 ft./sec. layer about 250 feet and the Permian layers each about 400 to 600 feet thick. The 9,000 ft./sec. layer seems to be absent to the west of shot point 14, a few miles within the western edge of the basin.

The western edge of the basin is near shot point 37, and therefore shot point 16, about three-quarters of a mile to the east, appears to be in a position comparable to shot point 35 on the eastern side. The results at shot point 37 show velocities of 2,760, 6,220, 10,400, and 18,200 ft./sec. The last two are regarded as basement velocities and the section indicates 780 feet of Tertiary resting on basement. Basement appears to be mainly granite (18,200 ft./sec.) with a comparatively thin layer of basement sediments overlying it. The thickness of the basement-type sediments could not be calculated because of confusion of the refraction times with those from other layers. The results at shot point 16 show velocities of 2,830, 6,200, 8,280, 10,850, and 12,130 ft./sec. and indicate 430 feet of Tertiary, 770 feet of Permian which may include some Tertiary near the top, and 720 feet of sedimentary-type basement or metamorphic-type basement rocks.

TRAVERSE B-B. (Shot points 19 to 26 inclusive.)

This traverse extends from a point near Daysdale, westward through Wangamong, for a total distance of approximately 11 miles. The results differ in one main respect from those on traverse A-A. Within the lower velocity range there were three distinct layers in traverse A-A with characteristic velocities of approximately 3,000, 6,000, and 8,000 ft./sec. respectively, but in traverse B-B the layer with a velocity of 6,000 ft./sec. was not recorded. Apart from this difference, the velocities are similar to those for traverse A-A. Shot points 19 and 20 are near the eastern rim of the basin—any coal seams in this part of the area would probably be partly eroded. The western rim appears to be some distance west of shot point 26, which records the thickest Tertiary and Permian section recorded within the basin and indicates 115 feet of Tertiary (2,370 ft./sec.), 555 feet of Tertiary and/or Permian (7,450 ft./sec.) and 1,080 feet of Permian (9,180 ft./sec.). Basement velocity is 11,630 ft./sec.

The basement beneath the section shows similar changes in velocities to the basement beneath traverse A-A. Granite (18,360 ft./sec.) is recorded at quite shallow depths, namely, 295 and 985 feet beneath shot points 19 and 20 respectively, but the data indicates a relatively low velocity (sedimentary-type) basement for the rest of the traverse. The results at shot points 23 and 24 indicate two basement velocities similar to those recorded at shot point 16, traverse A-A.

TRAVERSE C-C. (Shot points 6, 26, and 54 to 59 inclusive.)

This traverse runs approximately south from shot point 6, which lies 3 miles west of Oaklands, to shot point 59 which is 4 miles south of Savernake. Its total length is approximately 18 miles. Shot points 6 and 26 fall also on traverses A-A and B-B, respectively, which have already been described. Apart from the absence of the 6,000 ft./sec. Tertiary at shot point 26, the section between shot point 6 and shot point 57 is similar to that of traverse A-A. Velocities of 8,750 and 9,980 ft./sec. at shot points 56 and 57 are correlated with velocities of 8,000 and 9,000 ft./sec. on traverse A-A. This correlation, however, may be incorrect and the 9,980 ft./sec. layer may be part of the basement. However, there is undoubtedly a thick sedimentary section at shot points 56 and 57 and the test boring programme to be carried out later will give further evidence on what the correct correlation should be. Shot points 58 and 59 appear to be over granite (18,100 ft./sec.) basement with a cover of approximately 200 feet of Tertiary (2,830 ft./sec.).

TRAVERSE D-D. (Shot points 29 to 34 inclusive and 39 to 45 inclusive.)

This traverse runs east and west from Rennie for distances of approximately 7 miles to the east and 7 miles to the west of the township. The result shows the basin to be considerably narrower and shallower than it is further north. The eastern rim is at shot point 39 and the western rim at shot point 42. The section shown by the traverse has Tertiary layers with velocities of 3,000 and 6,000 ft./sec. respectively. The remainder of the sedimentary section is different from that recorded further north. The layer with a velocity of approximately 8,000 ft./sec. is absent except between shot points 31 and 32. At other shot points a velocity of approximately 9,000 ft./sec. or higher is recorded but at no place is there any indication of the velocities of 8,000 and 9,000 ft./sec. occurring together. The thickest recorded section along the traverse is at shot point 41 but here, however, the assumed Permian layer has recorded a velocity of 9,780 ft./sec. and this is underlain by basement of velocity 11,400 ft./sec. These velocities are very similar to, and probably correlate with, the velocities in the lower Permian layer and basement at shot points 56 and 57. The section at shot point 41, as shown on Plate 6, is 480 feet of Tertiary and 1,030 feet of Permian lying on a sedimentary-type basement. The section at shot point 32 contains velocities of 3,100, 5,690, 7,950, and 11,200 ft./sec., and indicates 350 feet of Tertiary and 350 feet of Permian on a sedimentary-type basement. Apart from the variations in Permian velocities these velocities are fairly typical of the section between shot points 31 and 40.

Basement on the eastern and western rims of the basin appears to be granite and/or highly metamorphosed sediments. No indication of its dip was obtained on the western side but on the eastern side (east of shot point 39) the dip in the line of traverse appears to be approximately 20° and the high velocity basement probably extends westwards for some distance beneath the relatively low velocity (sedimentary) type.

TRAVERSE E-E. (Shot points 34, 40, and 48 to 53 inclusive.)

This traverse extends approximately southwards from Rennie along the Mulwala road for a distance of 10 miles. Shot points 34 and 40 also appear on traverse D. The 3,000 and 6,000 ft./sec. Tertiary layers are present over the entire traverse. The 8,000 ft./sec. Permian layer is absent from the whole traverse but the 9,000 ft./sec. (or higher) layer extends from shot point 34 to south of shot point 49. Basement velocities range between 10,250 and 11,840 ft./sec., thus indicating a sedimentary-type basement. Shot point 49 is a good example of the section. Velocities of 3,460, 5,750, 9,450, and 11,350 ft./sec. were recorded, indicating 540 feet of Tertiary and 430 feet of Permian sediments lying on a sedimentary-type basement. This section is typical of the section north to shot point 34. Omitting the Permian layer it is also typical of the section south of shot point 50 to shot point 53.

TEST BORING IN RELATION TO SEISMIC SURVEY.

The test boring programme has already been discussed in some detail in Part A of this bulletin, but special reasons associated with the seismic survey for selecting sites 1 to 5 will now be discussed.

Test bore sites 1, 2, and 3 have been selected at shot points 35, 9, and 16 to test the main contentions of the geophysical interpretation near the eastern rim, the centre and the western rim of the basin. They have been selected to show the width of the basin and to show broadly the extent of the Permian rocks and, therefore, possibly the Coal Measures. The results should enable further correlation of geophysical results with known geological conditions, and thus provide a key for a more precise geophysical interpretation.

Test bore site 4 has been selected at shot point 41 which was described when discussing traverse D-D. The results of this test will permit a clearer understanding of shot points 56 and 57 and of the area represented by traverse E-E. At present it is thought unlikely that coal will be intersected because of the absence of the 8,000 ft./sec. layer in which the coal occurs near Oaklands.

Test bore site 5 has been selected at shot point 21 to test whether various layers on section B-B are geologically comparable with layers of similar velocity on section A-A.

Test bores 1 to 4, at least, should be drilled to basement and cored sufficiently to provide a good geological correlation with the seismic velocities. They should be tested for vertical seismic velocity to provide further data on correlation between velocity and rock formation.

CONCLUSIONS.

The seismic survey of the Oaklands-Coorabin coalfield has made it possible to correct the observed gravity values of the gravity survey in order to arrive at a residual gravity map to form a basis for planning a preliminary test-boring programme. Five bores drilled to basement will permit a more exact interpretation of the geophysical results so that a more detailed test-boring programme can be laid out to determine the extent of the coalfield, its reserves, and its possibilities for economic working south of an east-west line through Coorabin. When the recommended boring is completed, further seismic work will be warranted to determine more accurately the rim of the basin in the areas of economic importance.

It is possible that the coal occurs only within the 8,000 ft./sec. Permian layer; the limited evidence available at present supports this. If this is proved to be correct, future seismic work can be confined to testing for the existence of, and calculating the approximate depth of, this particular layer. Such a problem would be comparatively simple to solve and the survey could be made with 6-channel portable equipment. There will always, however, be some doubt as to whether such a seismic layer is Permian or Tertiary and any recommendations based on seismic information alone must always be subject to some confirmatory test boring.

Results to date indicate that the basin is open to the north-west and an extensive programme of gravity and seismic work, with associated test boring, is warranted to determine the extent and resources of the basin in this direction. It is believed that the likelihood of finding coal at depths shallow enough to enable open-cutting may be greatest in the area to the north-west. The Tertiary cover is known to thin towards the north and, if thick coal seams persist in that direction, favourable overburden-to-coal ratios are possible.

Altogether, it may be stated that a sedimentary basin of some 600 square miles in area has been proved. Its maximum depth has been proved to be at least in the vicinity of 1,500 to 2,000 feet and some 400 square miles may contain Coal Measures.

PART C—TESTING.

In addition to the five test sites recommended in Parts A and B, some sites were selected in the vicinity of Oaklands with a view to proving extensions of the known seams and thus adding to the proved reserves. Use was made of the residual gravity pattern in selecting the additional sites, some of which are close to the eastern edge of the basin.

The testing programme was begun during the first week of July 1950, and continued until December 1950. Because the drilling plants were required for urgent work elsewhere, the programme was suspended indefinitely.

The testing was carried out by the Bureau under the supervision of the Chief Petroleum Technologist (Mr. H. Temple-Watts) and his staff. The equipment consisted of a Failing 2,500 portable unit capable of drilling to 4,000 feet and a Failing 750 (shot-hole drill) capable of drilling to 750 feet.

A comprehensive report on the results of the drilling will be issued later but meanwhile it is considered desirable to describe the results briefly and to comment on the way in which they may be correlated with gravity and seismic results.

Seven holes were drilled and their positions are shown on Plate 2. They have been named CH.S1, CH.S2, CH.S3, CH.S4, and CH.S5 in the Parish of Clear Hill and G.S1 and G.S2 in the Parish of Gunambil. Some were drilled at sites recommended in Parts A and B.

The table below summarizes the results of the drilling:—

SUMMARY OF TEST BORES IN PARISHES OF CLEAR HILL AND GUNAMBIL, NEAR OAKLANDS, N.S.W. [MODIFIED AFTER REES (1951).]

Bore No.	Base of Tertiary. ?	Zone Containing some Carbonaceous Matter.	Main Coal Seam.		Coal Thickness.
			Top.	Bottom	
	feet.	feet.	feet.	feet.	feet.
CH.S1 ..	202	118–132	214	276	62
CH.S2 ..	210 or higher	114–133	214	275	61
CH.S3 ..	307	251–270	340	396	56
CH.S4 ..	506	450–485	564	611	28 ; plus 19 feet of carbonaceous matter
CH.S5 ..	335 or 369	297–318 ; contains Coal with Cal. val. 9,600 B.T.U.	369	389	20
G.S1 ..	182	..	186	230	44
G.S2 ..	231	170–189	277	331	52 ; plus 2 feet gravel

The main coal horizon is a persistent feature of all bores, and this indicates that the selection of sites was soundly based. Attention is drawn to a carbonaceous zone that is present in all bores (except G.S1 where it may have been removed by pre-Tertiary erosion) and lies at 50 to 80 feet above the main seam. In Bore CH.S5 the zone contains a coal seam which on analysis was found to be almost identical with the Permian coal of the main seam. This, combined with the fact that the upper carbonaceous zone is conformable with the main coal seam, strongly suggests that the upper carbonaceous zone is Permian and that the base of the Tertiary rocks lies above this zone. This interpretation differs from that given in the table which doubtfully places the base of the Tertiary sediments below the upper carbonaceous zone. However, the interpretation shown in the table is based on lithology and not on palaeontological evidence, and clay and other unconsolidated sediments could be the product of pre-Tertiary weathering of the Permian Coal Measures in situ, that is, they may not necessarily be Tertiary deposits.

This difficulty in establishing the thickness of the Tertiary sediments is stressed because it has an important bearing on the interpretation of the seismic evidence. For example, sediments in the upper part of Bores 4, 5, and J—with a seismic velocity approaching 8,000 ft./sec.—previously thought to be Tertiary could possibly be predominantly Permian. There may in fact be no real evidence that Tertiary deposits can have velocities as high as 8,000 ft./sec. Indeed, on other evidence it seems possible that the Tertiary sediments below ground water level have a velocity of 5,000 to 6,000 ft./sec., and sediments with this range of velocity are a persistent feature over most of the area.

Drill holes CH.S1 and CH.S2 are within a few chains of seismic shot point No. 35, Traverse A-A (site No. 1). CH.S1 was drilled to a total depth of 1,199 feet. Coal was intersected between 216 and 280 feet, and continuous coring was attempted. However, core recovery was low and subsequently a second hole, CH.S2, was drilled alongside for the express purpose of obtaining a more complete core sample of the coal.

As these two holes are the only ones drilled near a seismic shot point and therefore afford the only real comparison between the drilling and the seismic results, the results from them will be described in some detail.

As stated above it is difficult to determine the thickness of the Tertiary deposits from the drilling logs. Clay is commonly recorded to about 150 feet and a boulder conglomerate noted in CH.S2 between 143 and 163 feet could possibly mark the base of the Tertiary. However, from what has been discussed above, it seems likely that the carbonaceous material intersected between 114 and 133 feet in CH.S2 is Permian, and therefore the depth of the base of the Tertiary may be less than 114 feet. The coal intersected between 216 and 279 feet is Permian in age, and it is tentatively assumed that the remainder of the section between coal and basement, which was reached at 1,197 feet, is also Permian.

The section underlying the coal is composed mostly of sandstone and shale to a depth of approximately 660 feet; sandstone, calcareous sandstone and some limestone from 660 to 730 feet; shale, sandstone and some conglomerate from 730 to 750 feet; and mainly conglomerate ranging from fine to cobblestone from 750 feet to where the basement is entered at 1,197 feet. The basement is quartz-mica schist and is very hard.

In the seismic results at this site velocity changes were recorded at depths of 70, 101, 523, 1,185, and 2,040 feet. The first (from 3,000 to 5,470 ft./sec.) is assumed to coincide with water level. However, the depth to the water table was not determined, and it is not possible to check this assumption. The second change (from 5,470 to 7,930 ft./sec.) occurs near the top of the carbonaceous zone referred to above and may therefore coincide with the top of the Permian Coal Measures.

It will be noted that the coal occurs within the layer between 101 and 523 feet which has a velocity of approximately 8,000 ft./sec. as was the case at Bores 4, 5, and J, and there is reason to believe therefore that the coal seams may be restricted to layers that range in velocity from 8,000 to 9,000 ft./sec.

At 523 feet there is no abrupt change in lithology corresponding to the change in velocity from 7,930 to 8,830 ft./sec. Marine foraminifera were found at 560 feet and limestone and calcareous sandstone were noted between 660 and 730 feet. The change from fresh water to marine rocks may possibly explain the change in velocity from 7,930 to 8,830 ft./sec. It is considered significant that in the bore the bottom part, which is mainly in conglomerate, is confined to that section which has a velocity of 8,830 ft./sec. The change in velocity from 8,830 to 10,350 ft./sec at a depth of 1,185 feet coincides with the reported change from conglomerate (presumably Permian) to basement which is hard quartz-mica schist, but it is surprising that such a hard basement should have a velocity as low as 10,350 ft./sec. It should be noted, however, that the evidence for basement at 1,197 feet is not conclusive. The chippings in the return water from drilling the last 3 feet contained an abundant amount of quartz-mica schist and a 4-inch core of this material was obtained from the bottom of the hole. The possibility of a large boulder of this material having been encountered in the conglomerate cannot be overlooked.

The bore hole being only 1,197 feet deep, provides no explanation for the change in velocity from 10,350 to 17,380 ft./sec. which was recorded at a depth of 2,040 feet.

TEST BORE CH.S3. This bore is about midway between CH.S1 and the pre-existing Bore J and was drilled to test for the continuity of the coal seam between them. Approximately 56 feet of coal was intersected between 345 and 401 feet.

TEST BORE CH.S4 was drilled near recommended site G2 about 2 miles west of the pre-existing Bore 5 (see Plate 4). Forty-seven feet of coal was intersected between 569 and 616 feet; about 19 feet was poor quality coal containing shale bands. The occurrence of clay to a depth of 530 feet might suggest that the Tertiary sediments occur to at least this depth, but there is no palaeontological evidence to support this suggestion. As stated previously, there is some evidence that the carbonaceous zone encountered between 450 and 485 feet in this bore may be Permian and therefore the base of the Tertiary may be less than 450 feet. There are no seismic results at this site to compare with the drilling results.

The residual gravity pattern in this area clearly shows the relatively steep basement gradient between Bores J and 5 and this was also indicated by the seismic results. To the west of Bore 5 and towards Bore CH.S4, however, the residual gravity gradient is small and this suggests that the basement is relatively flat between Bores 5 and CH.S4. The drilling results at CH.S4 confirm this interpretation.

TEST BORE CH.S5 is near recommended site G4. Approximately 4 feet of coal was intersected between 303 and 318 feet (analysis indicates that this is Permian) and Permian coal from 374 to 400 feet. The main seam is somewhat shallower than might have been expected from the seismic results on Section A-A. However, on examining the seismic Section A-A on Plate 6, it will be noted that the basement is rising towards the west between shot points 36 and 3, and the depth to the coal found at CH.S5 is consistent with the seismic results if it is assumed that this rise persists to the west of shot point 3 as far as bore CH.S5. Faulting may also explain the presence of coal at relatively shallow depth in this bore, but neither the gravity nor seismic results provide any evidence of such faulting.

BORES G.S1 and G.S2 are in the Parish of Gunambil and lie south-east of Bores CH.S1 and CH.S2. They were drilled to test the continuity of the coal seams towards Daysdale. G.S1 is approximately 1 mile south-east of CH.S1, and G.S2 is 1 mile south of G.S1. Coal was intersected between 190 and 234 feet at G.S1 and between 288 and 330 feet at G.S2.

CONCLUSIONS.

In selecting the bore sites, the residual gravity pattern was used to indicate where the eastern edge of the basin lay and the drilling results amply confirm the selection.

It was unfortunate that the drilling programme had to be interrupted at this stage. Much remains to be done before the potentialities of the area are fully tested. The limited evidence provided by drill holes CH.S1 and CH.S2, which are the only ones close to a seismic shot hole, suggests that the Tertiary rocks have a velocity of 6,000 ft./sec. or less and that the Permian Coal Measures are confined to the layer with a velocity of 8,000 to 9,000 ft./sec. If this is so, then future prospecting—for example in the area north-west of that already covered—would consist of a gravity reconnaissance to locate the edges of the basin, then refraction surveys to test for the presence of the 8,000 to 9,000 ft./sec. layer. Such refraction work could be carried out with light-weight portable equipment, and deep shot holes requiring the use of a drill would not be necessary.

Melbourne, February, 1952.

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APPENDIX 1.

CALCULATION OF DEPTH AND DIP OF SEVERAL LAYERS BY REFRACTION SEISMIC METHOD

by J. C. Dooley

Consider a formation of (n+1) layers (see fig. 1; n=4 in diagram) with plane interfaces dipping at angles $\theta_1, \theta_2,$ ------$\theta_n,$ to the horizontal in the plane of the diagram. Let the velocities of the seismic waves in the various layers be $v_1, v_2, v_3,$ -------v_n, v_{n+1}. (The layers shown in fig. 1 are dipping to the left corresponding to positive values of θ. The left of the diagram will be referred to as down-dip, and the right as up-dip, in the following discussion. If one or more layers dip in the opposite direction, θ has a negative value; separate treatment is not necessary for such a case).

From two shot-points at the surface, travel-time curves are obtained for up-dip and down-dip directions. Let the apparent velocities recorded at the surface for the seismic waves refracted along the top of the m^{th} layer be v_{mu} and v_{md} respectively. Let the sections of the travel-time curves representing v_{mu} and v_{md} be produced to intersect the time-ordinates through the respective shot-points at the intercept times T_{mu} and T_{md}. T_{mu} and T_{md} will be known as delay times.

Then for the up-dip time we have (using the notation illustrated in fig. 1):

$$t_{mu} = T_{mu} + \frac{x_{1u}}{v_{mu}} \qquad \text{-----------------} \qquad (1)$$

and for the down-dip time

$$t_{md} = T_{md} + \frac{x_{1d}}{v_{md}} \qquad \text{-----------------}$$

We have also the following equations for the section of the travel-time curves representing the $(n+1)^{th}$ layer:

$$t_{(n+1)u} = \sum_{m=1}^{m=n_S} \frac{\;_{mo}}{v_m} + \sum_{m=1}^{m=n_{S'}} \frac{\;_{m}}{v_m} + \frac{x_{(n+1)u}}{v_{n+1}} \text{---} \qquad (2)$$

$$t_{(n+1)d} = \sum_{m=1}^{m=n_{S'}} \frac{\;_{mo}}{v_m} + \sum_{m=1}^{m=n_S} \frac{\;_{m}}{v_m} + \frac{x_{(n+1)d}}{v_{n+1}} \text{---}$$

As the refracted wave travels along the top of the $(n+1)^{th}$ layer, it gives rise to further refracted rays S'_n -------S'_1, from each successive point. All such rays between two interfaces are parallel, but the lengths of the rays vary as the wave travels along the interface. Let the intersection of the rays with the top of the $(m+1)^{th}$ layer travel with an apparent velocity V_{mu}.

Considering the up-dip paths of rays from the shot-point through the n layers, refracted along the top of the $(n+1)^{th}$ layer, and refracted again to the surface, it can be seen that the segments S_{1o} ----S_{no} of the path SQ remain the same for all rays, but the lengths of the segments S'_n -----S'_1 of the return path vary linearly with respect to $x_{(n+1)u}$. Equation (2) thus can be written:

$$t_{(n+1)u} = \sum \frac{S_{mo}}{v_m} + A + Bx_{(n+1)u} \quad \text{--------} \quad (3)$$

where A and B are constants for a particular formation.

Although negative values of $x_{(n+1)u}$ are physically impossible, we can assume such negative values to facilitate the study of equation (3) and to derive an expression for $T_{(n+1)u}$.

Let us study the equation when $t_{(n+1)u} = T_{(n+1)u}$. $x_{(n+1)u}$ will be equal to -RQ, and the general ray with segments S'_m becomes the particular ray with segments S'_{m1}. Substituting these values in equation (2) we have:

$$T_{(n+1)u} = \sum \frac{S_{mo}}{v_m} + \sum \frac{S'_{m1}}{v_m} - \frac{RQ}{v_{n+1}}$$

$$= \left\{ \sum \frac{S'_{m1}}{v_m} - \frac{RP_n}{v_{n+1}} \right\} + \left\{ \sum \frac{S_{mo}}{v_m} - \frac{P_nQ}{v_{n+1}} \right\} \quad \text{---} (4)$$

Consider each bracket separately. Let the point P_m lie vertically under P on the m^{th} interface. Consider the ray segments passing through P_1, P_2, ---- P_{n-1}, and parallel to S'_{21}, S'_{31} ------ S'_{n1}. Let the ray through P_{m-1} cut the m^{th} interface at N'_m; let the ray S'_{m1} cut the m^{th} interface at L_m. Let $P_mN'_m = Y'_m$, and $N'_mL_m = Z'_m$. Let the ray segment N'_mP_{m-1} be S'_{mm}.

If we study the wave front striking successive interfaces, then the time interval between the wave front reaching L_m and P_{m-1} may be calculated as either:

$$\frac{Z'_m}{V_{mu}} + \frac{S'_{mm}}{v_m}$$

or

$$\frac{S'_{m1}}{v_m} + \frac{Y_{m-1} + Z_{m-1}}{V_{(m-1)u}}$$

Equating these two expressions, we get:

$$\frac{Z'_m}{V_{mu}} + \frac{S'_{mm}}{v_m} = \frac{S'_{m1}}{v_m} + \frac{Y_{m-1} + Z_{m-1}}{V_{(m-1)u}} \quad \text{-----(5)}$$

Writing out equation (5) for the various layers, we get:

$$\left.\begin{array}{l}
\frac{S'_{21}}{v_2} + \frac{Y'_1}{V_{1u}} = \frac{Z'_2}{V_{2u}} + \frac{S'_{22}}{v_2} \\
\frac{S'_{31}}{v_3} + \frac{Z'_2}{V_{2u}} + \frac{Y'_2}{V_{2u}} = \frac{Z'_3}{V_{3u}} + \frac{S'_{33}}{v_3} \\
\text{------------------------------------} \\
\frac{S'_{m1}}{v_m} + \frac{Z'_{m-1}}{V_{(m-1)u}} + \frac{Y'_{m-1}}{V_{(m-1)u}} = \frac{Z'_m}{V_{mu}} + \frac{S'_{mm}}{v_m} \\
\text{------------------------------------} \\
\frac{S'_{n1}}{v_n} + \frac{Z'_{n-1}}{V_{(n-1)u}} + \frac{Y'_{n-1}}{V_{(n-1)u}} = \frac{Z'_n}{V_{nu}} + \frac{S'_{nn}}{v_n}
\end{array}\right\} \quad (6)$$

Adding these equations, the terms $\frac{Z'_m}{V_{mu}}$ (m=2----(n-1)) cancel out. Add $\frac{S'_{11}}{v_1} + \frac{Y'_n}{V_{nu}}$ to each side of the summed equation. We now have:

$$\sum \frac{S'_{m1}}{v_m} + \sum \frac{Y'_m}{V_{mu}} = \sum \frac{S'_{mm}}{v_m} + \frac{Z'_n + Y'_n}{V_{nu}} \quad \text{--- (7)}$$

As we are considering the wave front that travels along the top of the $(n+1)^{th}$ layer and is refracted up to the surface from there, we have:

$$V_{nu} = v_{n+1}$$

Thus equation (7) can be re-written:

$$\sum \frac{S'_{m1}}{v_m} - \frac{RP_n}{v_{n+1}} = \sum \left\{ \frac{S'_{mm}}{v_m} - \frac{Y'_m}{V_{mu}} \right\} \text{---(8)}$$

By a similar treatment for the ray S_{1o} ---- S_{no} we get:

$$\sum \frac{S_{mo}}{v_m} - \frac{QP_n}{v_{n+1}} = \sum \left\{ \frac{S_{mm}}{v_m} - \frac{Y_m}{V_{md}} \right\} \text{----(9)}$$

Substituting equations (8) and (9) in equation (4) we get:

$$T_{(n+1)u} = \sum \left\{ \frac{S'_{mm} + S_{mm}}{v_m} - \frac{Y'_m}{V_{mu}} - \frac{Y_m}{V_{md}} \right\} \text{-(10)}$$

Thus a delay D_m can be calculated for each layer, where

$$D_m = \frac{S'_{mm} + S_{mm}}{v_m} - \frac{Y'_m}{V_{mu}} - \frac{Y_m}{V_{md}} \text{---------(11)}$$

and then

$$T_{(n+1)u} = \sum D_m \text{-------------------------(12)}$$

Consider the delay for the m^{th} layer (see fig. 2). Drop perpendiculars from P_m to M'_m and M_m on the ray segments S'_{mm} and S_{mm} respectively. These perpendiculars are parallel to the wave-fronts corresponding to the rays. Therefore we have:

$$\frac{N'_m M'_m}{v_m} = \frac{N'_m P_m}{V_{mu}} = \frac{Y'_m}{V_{mu}} \text{---------------(13)}$$

$$\frac{N_m M_m}{v_m} = \frac{Y_m}{V_{md}} \text{---------------------------(14)}$$

Substituting equations (13) and (14) in equation (11) we get:

$$D_m = \frac{(S'_{mm} - N'_m M'_m) + (S_{mn} - N_m M_m)}{v_m}$$

$$= \frac{H_m}{v_m} \left\{ \cos(b_{mn} - \theta_m) + \cos(a_{mn} + \theta_m) \right\} \text{ -------(15)}$$

where a_{mn} and b_{mn} are the angles of incidence of the ray segments S_{mm} and S'_{mm} respectively at the m^{th} interface, for the ray refracted from the n^{th} interface (see fig. 4.).

For the n^{th} interface, $a_{nn} = b_{nn} = i_n$, the critical angle. Thus we have:

$$D_n = \frac{H_n}{v_n} \left\{ \cos(i_n - \theta_n) + \cos(i_n + \theta_n) \right\}$$

$$= \frac{2H_n}{v_n} \cos \theta_n \cos i_n \text{ ------------------------ (16)}$$

Thus substituting equations (15) and (16) in equation (12) and writing $C_{mn} = \cos(b_{mn} - \theta_m) + \cos(a_{mn} + \theta_m)$--(17) we have:

$$\left.\begin{aligned} T_{(n+1)u} &= \sum_{m=1}^{n-1} \frac{H_m}{v_m} \cdot C_{mn} + \frac{2H_n}{v_n} \cos \theta_n \cos i_n \\ \text{Similarly} & \\ T_{(n+1)d} &= \sum_{m=1}^{n-1} \frac{h_m}{v_m} C_{mn} + \frac{2h_n}{v_n} \cos \theta_n \cos i_n \end{aligned}\right\} \text{ ----(18)}$$

In fig. 3, let KX be a ray parallel to S'_{11}, with PK perpendicular to KX. As PK is parallel to the wave-front in the first layer, we have:

$$\frac{KX}{v_1} = \frac{PX}{v_{(n+1)u}}$$

$$\frac{v_1}{v_{(n+1)u}} = \frac{KX}{PX} = \sin(b_{1n} - \theta_1) \text{ ----------------(19)}$$

Similarly

$$\frac{v_1}{v_{(n+1)d}} = \sin(a_{1n} + \theta_1) \text{ --- ------------------(20)}$$

In calculating the depth and dip of several layers from a pair of travel-time curves, certain assumptions must be made:

(1) All interfaces are continuous plane surfaces.

(2) The seismic velocity does not vary within each layer.

(3) Each layer has a higher velocity than the layers above it.

(4) All layers have enough thickness and velocity contrast to be recorded.

(5) The traverse lies approximately in the direction of maximum dip of all interfaces.

The foregoing discussion was based on these assumptions. They are not always fully justified in practice, but conditions usually are such that the formulae arrived at give a reasonable representation of sub-surface structure. As variations from the basic assumptions cannot always be recognized, for a complete sub-surface picture the seismic results must be checked by boring, and if possible the seismic horizons must be correlated with geological horizons revealed by the boring.

Having due regard to these considerations, the procedure for calculation is as follows:-

Calculate for each layer in turn from the surface downwards. The information gained about each layer is required as data for the calculations for the next layer.

Extend the various sections of the travel-time curves to the shot-points, and determine the delay times T_{2u}, T_{3u}, ----, $T_{(n+1)u}$, T_{2d}, T_{3d}, ----, $T_{(n+1)d}$. Values for v_1, v_{2u}, v_{3u}, ----, $v_{(n+1)u}$, v_{2d}, v_{3d}, ----, $v_{(n+1)d}$, are also determined from the travel-time curves (see fig.4).

<u>1st Layer</u>

From equations (19) and (20)

$$\frac{v_1}{v_{2u}} = \sin (i_1 - \theta_1)$$

$$\frac{v_1}{v_{2d}} = \sin (i_1 + \theta_1)$$

Solve for i_1 and θ_1. Then

$$v_2 = \frac{v_1}{\sin i_1}$$

For n=1, equation (18) becomes

$$T_{2u} = \frac{2H_1}{v_1} \cos \theta_1 \cos i_1$$

$$T_{2d} = \frac{2h_1}{v_1} \cos \theta_1 \cos i_1$$

From these calculate H_1 and h_1.

We have now calculated

$i_1, \theta_1, v_2, H_1, h_1$.

<u>2nd Layer</u>

From equations (19)and (20)

$$\frac{v_1}{v_{3u}} = \sin (b_{12} - \theta_1)$$

$$\frac{v_1}{v_{3d}} = \sin (a_{12} + \theta_1)$$

Solve for a_{12}, b_{12}.

By Snell's Law,

$$\sin b'_{12} = \frac{v_2}{v_1} \sin b_{12} = \frac{\sin b_{12}}{\sin i_1}$$

$$\sin a'_{12} = \frac{v_2}{v_1} \sin a_{12} = \frac{\sin a_{12}}{\sin i_1}$$

Now $b'_{12} = i_2 - (\theta_2 - \theta_1)$

$a'_{12} = i_2 + (\theta_2 - \theta_1)$

Hence solve for i_2, θ_2. Then $v_3 = \dfrac{v_2}{\sin i_2}$

From equation (17) calculate C_{12}. Then from equation (18)

$$T_{3u} = \frac{H_1}{v_1} C_{12} + \frac{2H_2}{v_2} \cos \theta_2 \cos i_2$$

$$T_{3d} = \frac{h_1}{v_1} C_{12} + \frac{2h_2}{v_2} \cos \theta_2 \cos i_2$$

Solve these for H_2 and h_2

We have now calculated i_2, θ_2, v_3, H_2, h_2.

3rd, 4th and later layers

The procedure is similar to that for two layers but naturally becomes more complicated as n increases. The method of calculation is outlined for the general case of the m^{th} layer.

Assuming that the $(m-1)^{th}$ layer calculations have been made, we know

i_{m-1}, θ_{m-1}, v_m, H_{m-1}, h_{m-1}

From equation (19) and (20)

$$\frac{v_1}{v_{(m+1)u}} = \sin (b_{1m} - \theta_1); \quad \frac{v_1}{v_{(m+1)d}} = \sin (a_{1m} + \theta_1)$$

Solve for b_{1m}, a_{1m}.

Then similarly to the two-layer case, we have,

$$\sin\left\{ b_{2m} - (\theta_2 - \theta_1) \right\} = \frac{\sin b_{1m}}{\sin i_1}$$

$$\sin\left\{ a_{2m} + (\theta_2 - \theta_1) \right\} = \frac{\sin a_{1m}}{\sin i_1}$$

Solve for b_{2m}, a_{2m}.

This process is repeated; in general

$$\left.\begin{aligned} \sin\left\{ b_{pm} - (\theta_p - \theta_{p-1}) \right\} &= \frac{\sin b_{(p-1)m}}{\sin i_{p-1}} \\ \sin\left\{ a_{pm} + (\theta_p - \theta_{p-1}) \right\} &= \frac{\sin a_{(p-1)m}}{\sin i_{p-1}} \end{aligned}\right\} \quad p = 2, 3, \text{-- -------} m-1$$

These can be solved successively for a_{pm}, b_{pm} up till $a_{(m-1)m}$, $b_{(m-1)m}$. For the last layer, the equations become:-

$$\sin\left\{ i_m - (\theta_m - \theta_{m-1}) \right\} = \frac{\sin b_{(m-1)m}}{\sin i_{m-1}}$$

$$\sin\left\{ i_m + (\theta_m - \theta_{m-1}) \right\} = \frac{\sin a_{(m-1)m}}{\sin i_{m-1}}$$

Solve these for i_m, θ_m. Then

$$v_{m+1} = \frac{v_m}{\sin i_m}$$

Calculate C_{pm}, from equation (17) for p=1, 2,--- -----m-1. Then from equation (18) we have

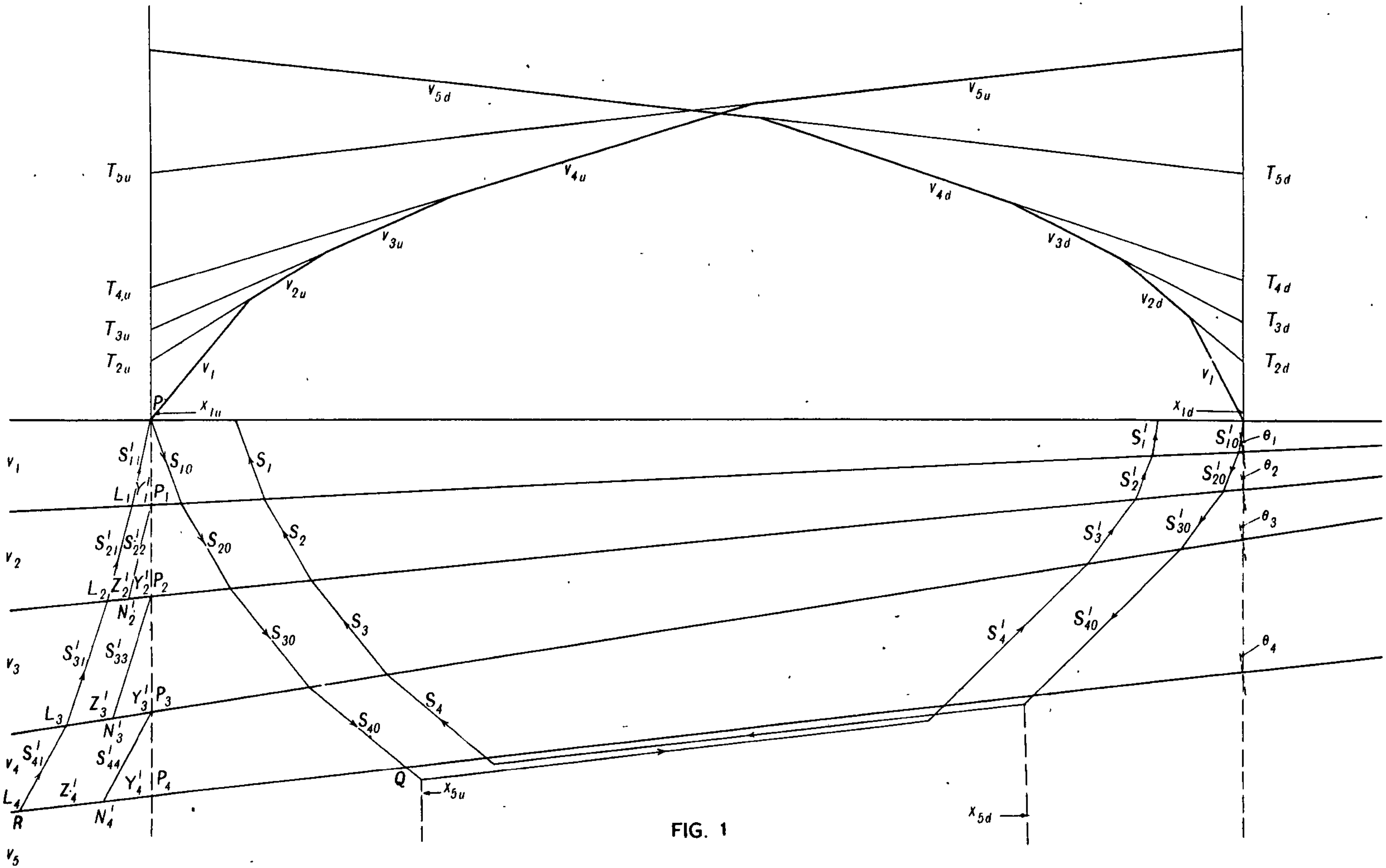
$$T_{(m+1)u} = \sum_{p=1}^{m-1} \frac{H_p}{v_p} C_{pm} + \frac{2H_m}{v_m} \cos\theta_m \cos i_m$$

$$T_{(m+1)d} = \sum_{p=1}^{m-1} \frac{h_p}{v_p} C_{pm} + \frac{2h_m}{v_m} \cos\theta_m \cos i_m$$

Solve these for H_m, h_m.

We know now i_m, θ_m, v_{m+1}, h_m, H_m

This enables calculations for the $(m+1)^{th}$ layer to proceed.



T5u
T4u
T3u
T2u
T5d
T4d
T3d
T2d
v5d
v5u
v4u
v4d
v3u
v3d
v2u
v2d
v1
P
x1u
x1d
Q
R
x5u
x5d

FIG. 1

G46-15

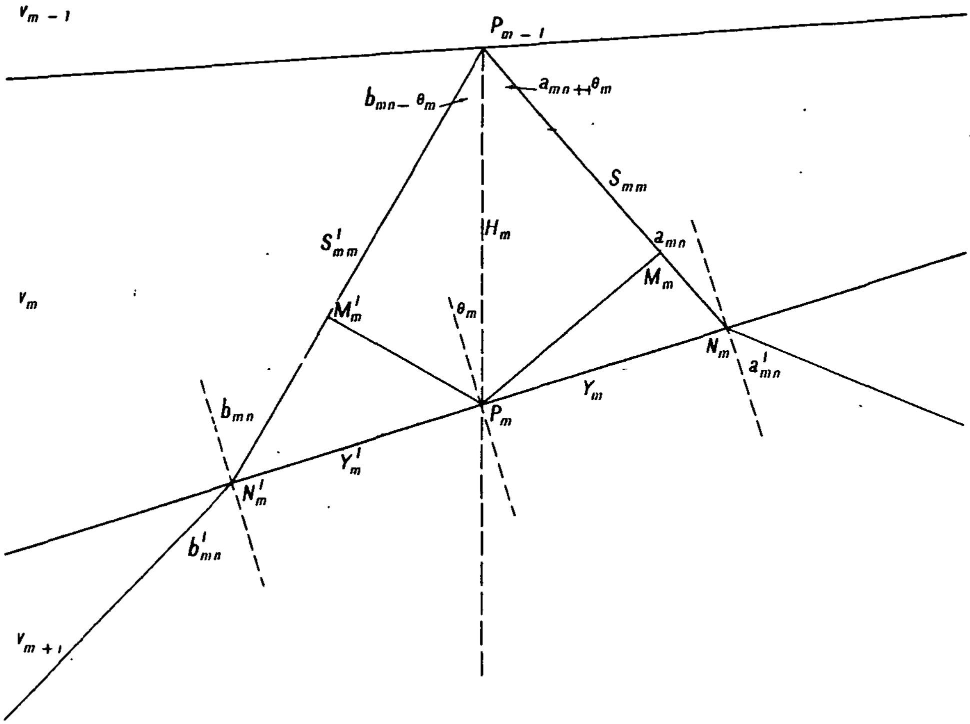


FIG. 2

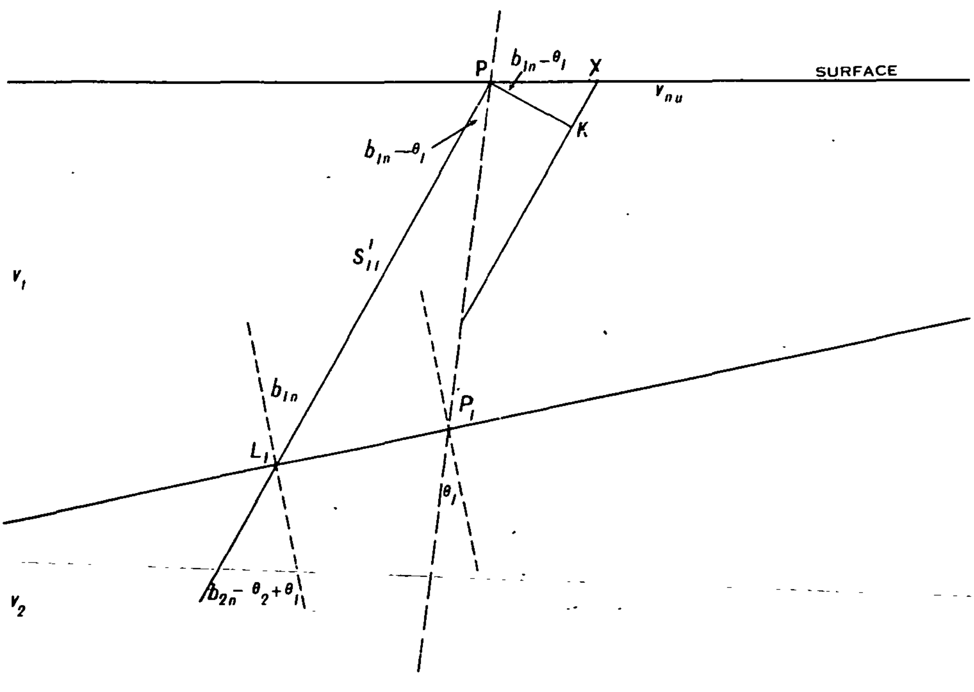


FIG. 3

G46-16

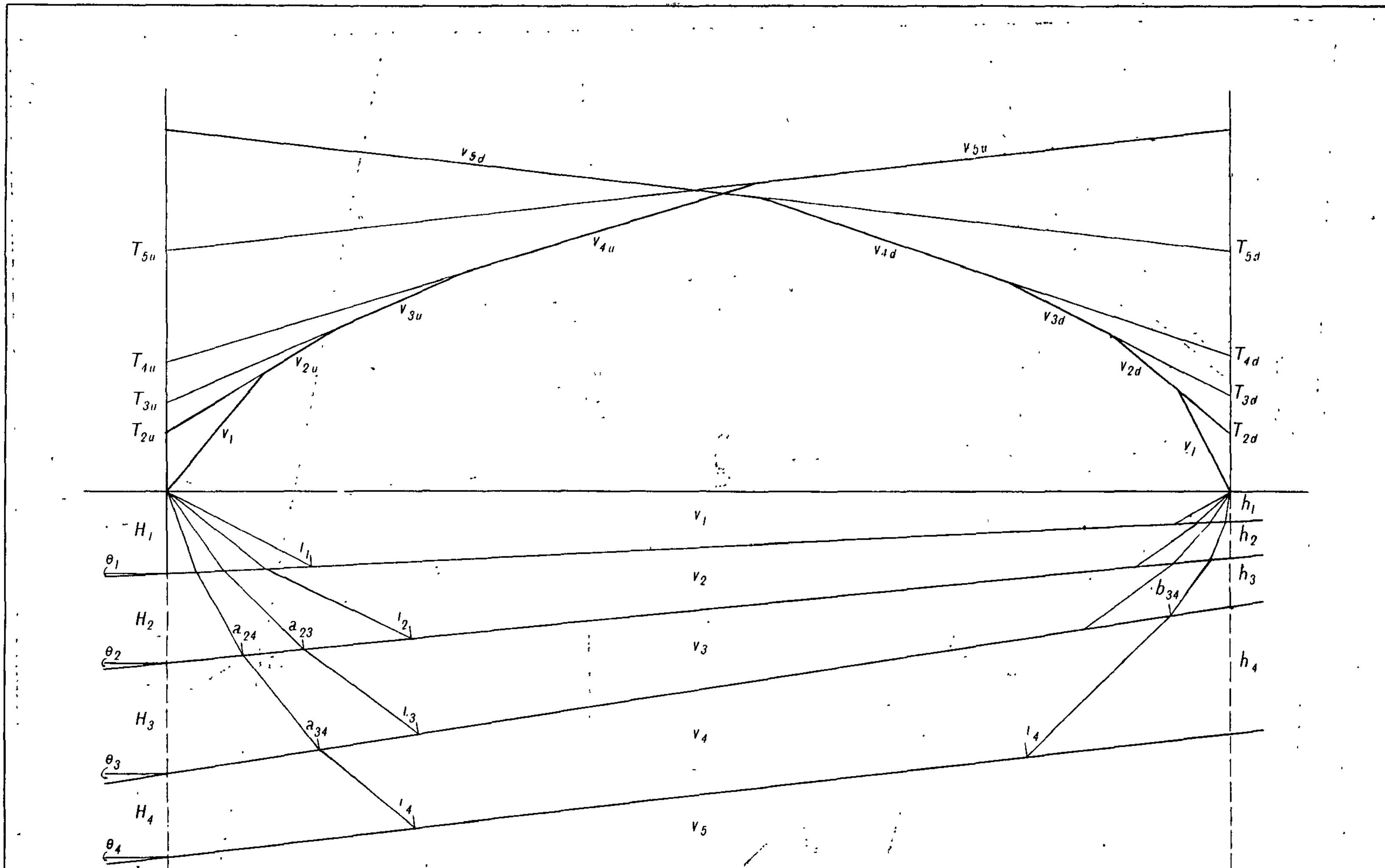
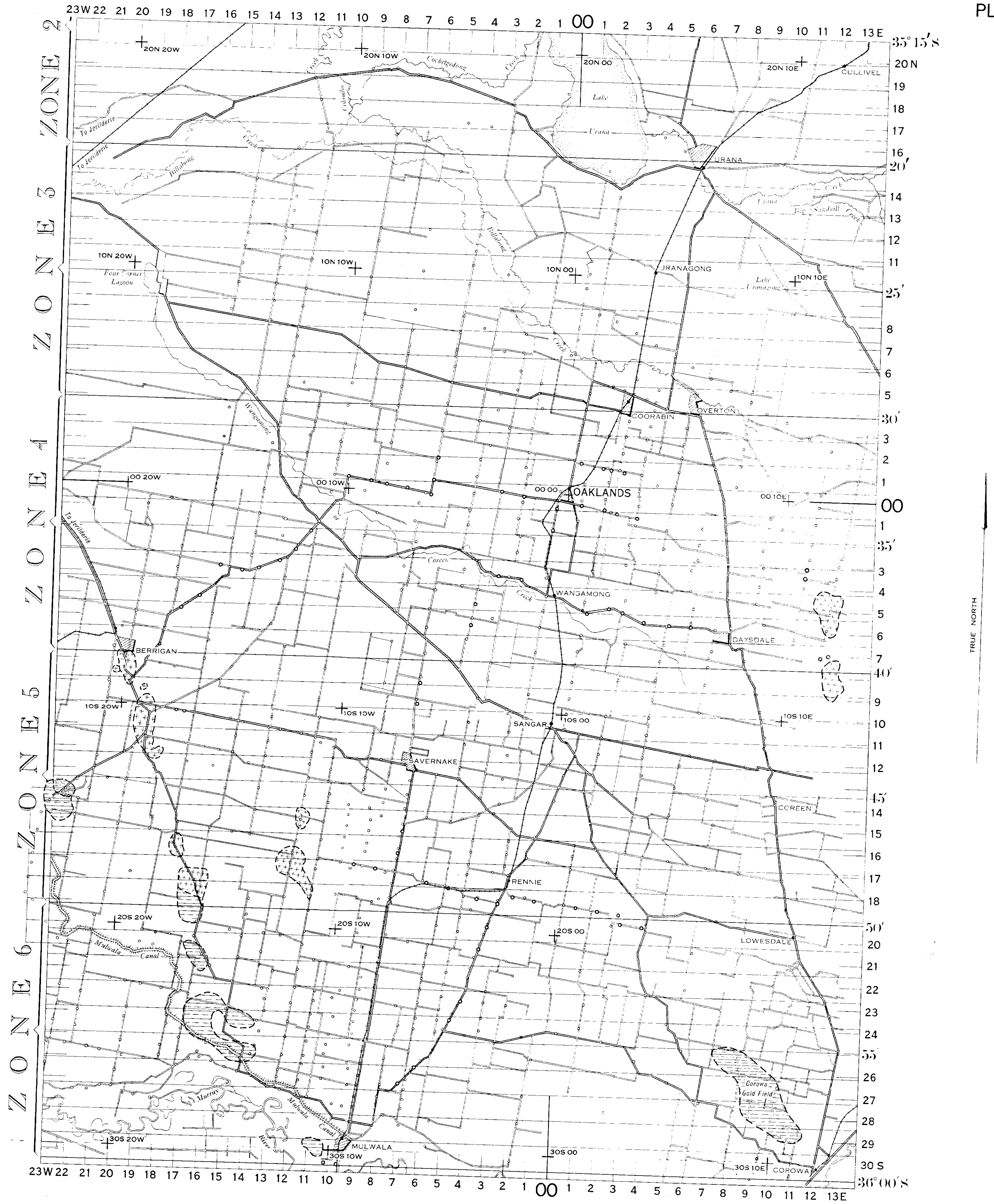

v5d
v5u
T5u
T5d
v4u
v4d
v3u
v3d
T4u
T4d
v2u
v2d
T3u
T3d
T2u
T2d
v1
v1
H1
h1
v1
i1
h2
θ1
v2
h3
H2
i2
b34
a24
a23
θ2
v3
h4
H3
i3
a34
v4
i4
θ3
H4
i4
v5
θ4

FIG. 4

G46-17



LEGEND

Recent and Pleistocene alluvial deposits.

Granite

Slates and sandstones with quartzite

Slates and sandstones with quartzite and breccia

Gravity station

LOCALITY MAP

REFERENCE

REFERENCE: I/55 - 14 - 750, 751, 760, 761, 770, 771

CONTROL: Nil.

SURVEY: Based on existing Aust. Svy. Cps. 1 mile sheets 770 and 771, with an extended plot of railway surveys and one interconnecting main road.

DETAIL: Parish maps adjusted around control framework, with 1 mile rectangular grid and every one minute of arc of Latitude superimposed.

RELIABILITY: Controlled sketch.

SCALE

MILES 2 1 0 2 4 6 8 10 MILES

YARDS 2000 0 2 4 6 8 10 12 14 16000 YARDS

GEOPHYSICAL SURVEY AT OAKLANDS - COORABIN COALFIELD, N.S.W.

AREA COVERED BY GEOPHYSICAL SURVEY

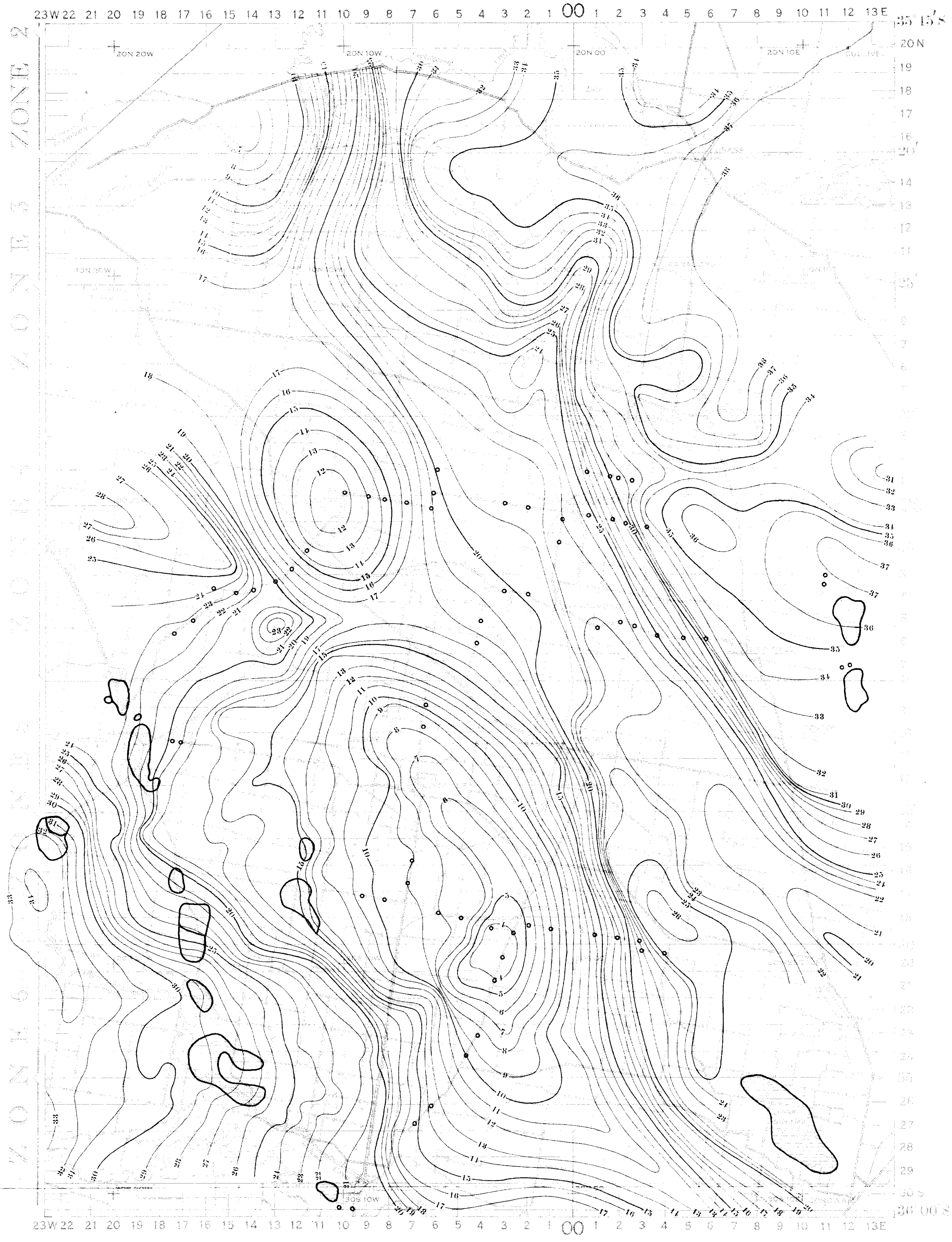
R. F. Thyer

Superintending Geophysicist

December, 1951

G46-7

Compiled and drawn by Geophysical Section, Bureau of Mineral Resources, Geology & Geophysics.



LEGEND

Recent and Pleistocene alluvial deposits.

Granite

Slates and sandstones with quartzite

Slates and sandstones with quartzite and breccia

Gravity station

Seismic Shot Point

Observed Gravity Contours

SCALE

MILES 2 1 0 2 4 6 8 10 MILES

YARDS 2000 0 2 4 6 8 10 12 14 16000 YARDS

NOTE: *To convert to BOUGUER ANOMALIES (density 2·67) relative to theoretical values on International Ellipsoid add (46·4 − 0·008 h) ± 0·5 Milligals, where 'h' is the station height above R.L. 400 feet, and (except for 14 stations) ranges between +60 feet and −32 feet.*

R. F. Thyer (signature)

Superintending Geophysicist

December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS-COORABIN COALFIELD, N.S.W.

OBSERVED GRAVITY CONTOURS

CONTOUR INTERVAL 1.0 MILLIGALS

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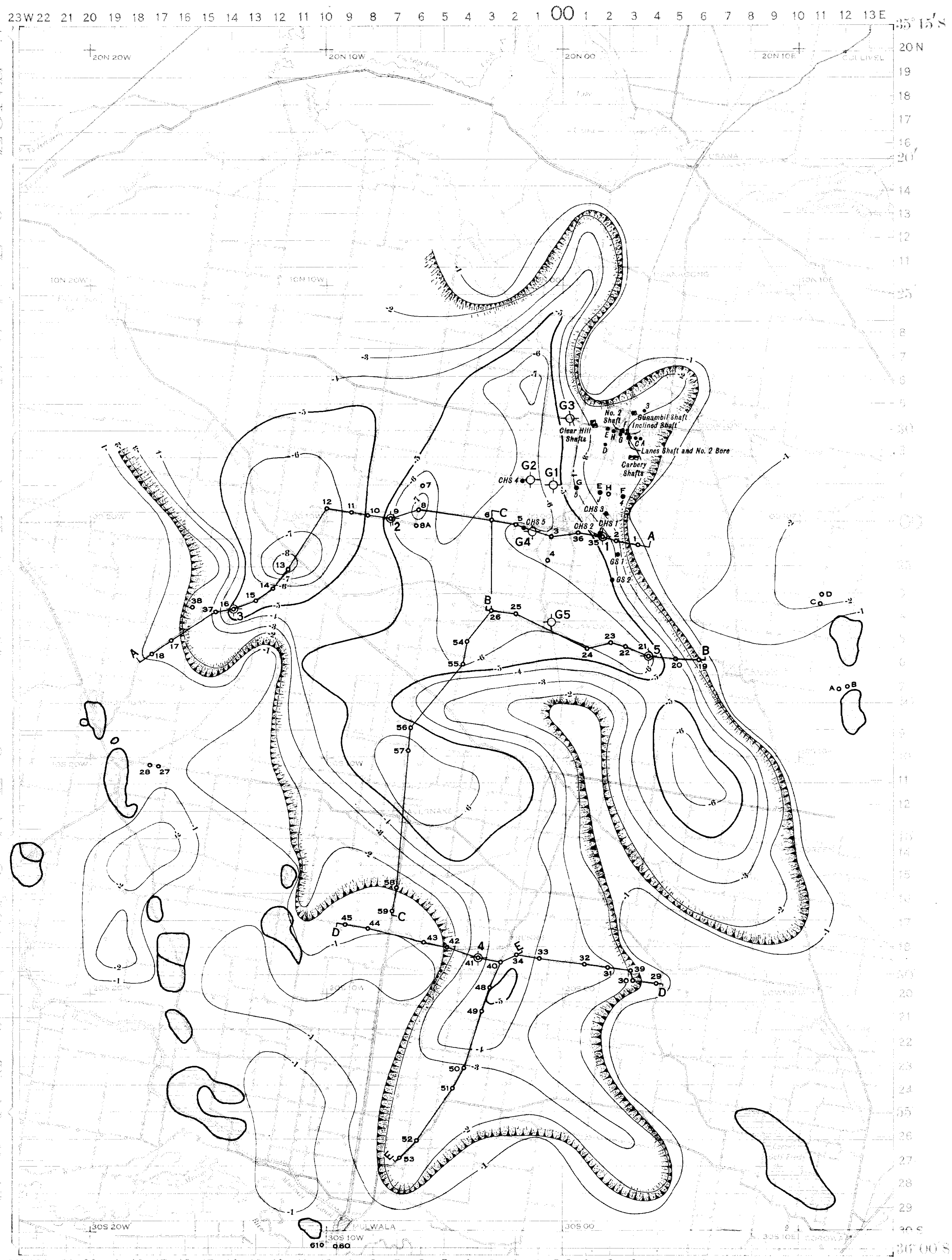
PLATE 4



LEGEND

Recent and Pleistocene alluvial deposits.	Residual Gravity Contours
Granite	Seismic Profile
Slates and sandstones with quartzite	Recommended Test Sites
Slates and sandstones with quartzite and breccia	Bores
Gravity station	Approximate rim of Sedimentary Basin
Seismic Shot Points	Shaft

SCALE

MILES 2 1 0 2 4 6 8 10 MILES

YARDS 2000 0 2 4 6 8 10 12 14 16000 YARDS

Superintending Geophysicist
December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS - COORABIN COALFIELD, N.S.W.

RESIDUAL GRAVITY CONTOURS

CONTOUR INTERVAL 1.0 MILLIGAL

G46-9

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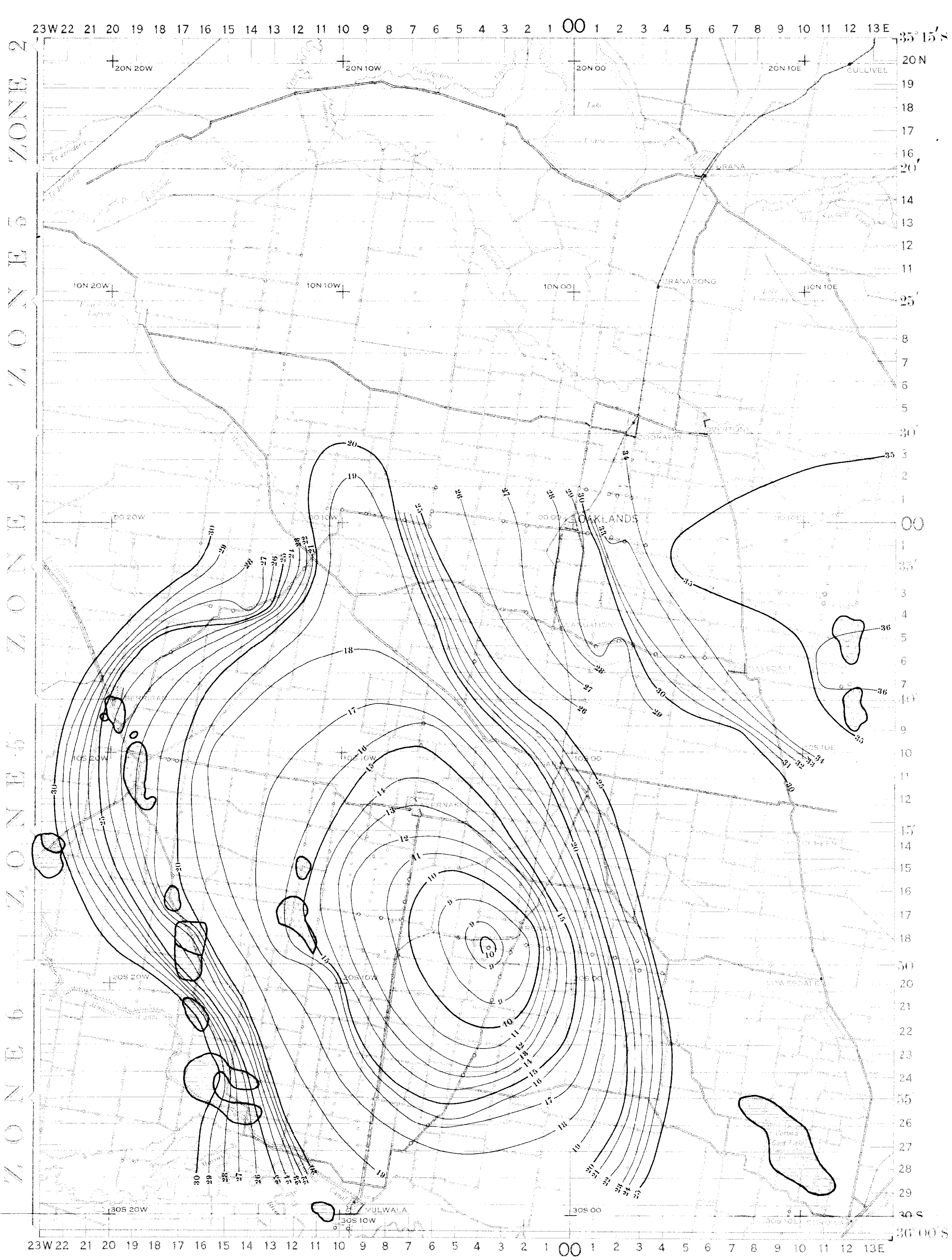

LEGEND

Recent and Pleistocene alluvial deposits.

Granite

Slates and sandstones with quartzite

Slates and sandstones with quartzite beds and breccia

Gravity station

Regional Gravity Contours

SCALE

MILES 2 1 0 2 4 6 8 10 MILES

YARDS 2000 0 2 4 6 8 10 12 14 16000 YARDS

Superintending Geophysicist

December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS-COORABIN COALFIELD, N.S.W.

REGIONAL GRAVITY CONTOURS

CONTOUR INTERVAL 1.0 MILLIGAL

G46-10

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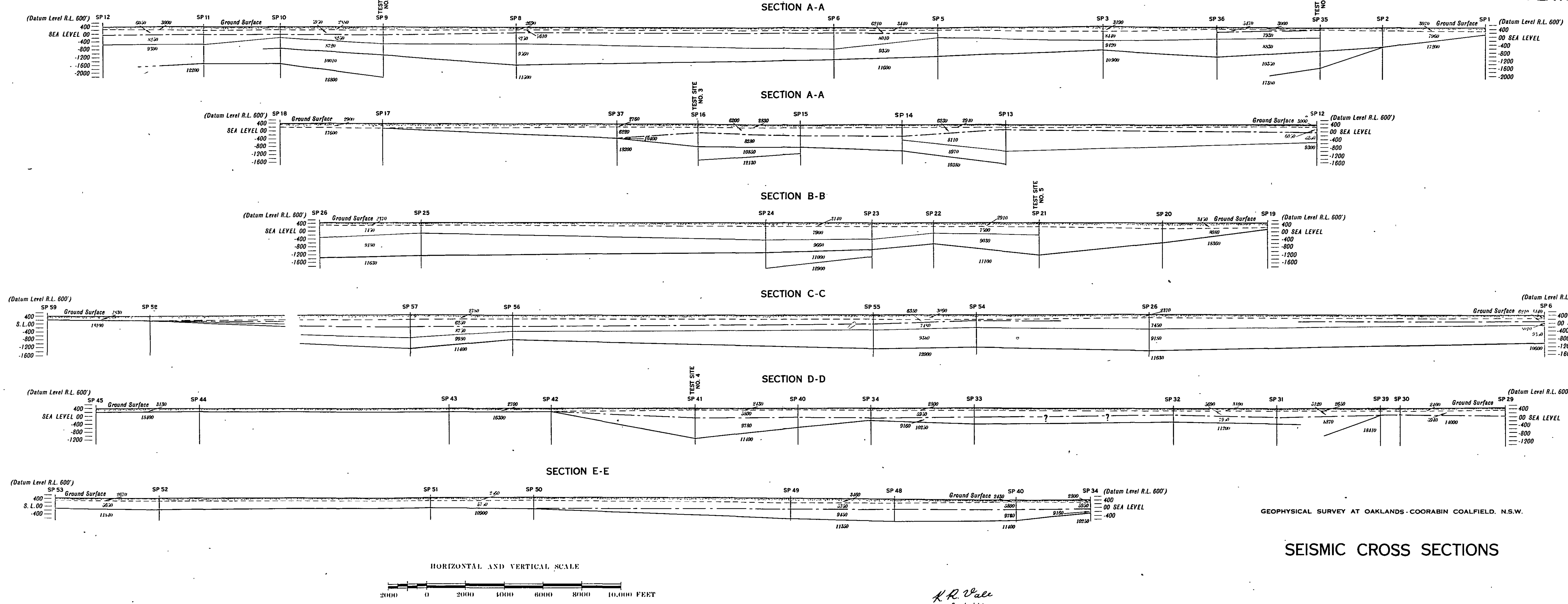

GEOPHYSICAL SURVEY AT OAKLANDS - COORABIN COALFIELD, N.S.W.

SEISMIC CROSS SECTIONS

K. R. Vale
Geophysicist
December, 1951

G46-11

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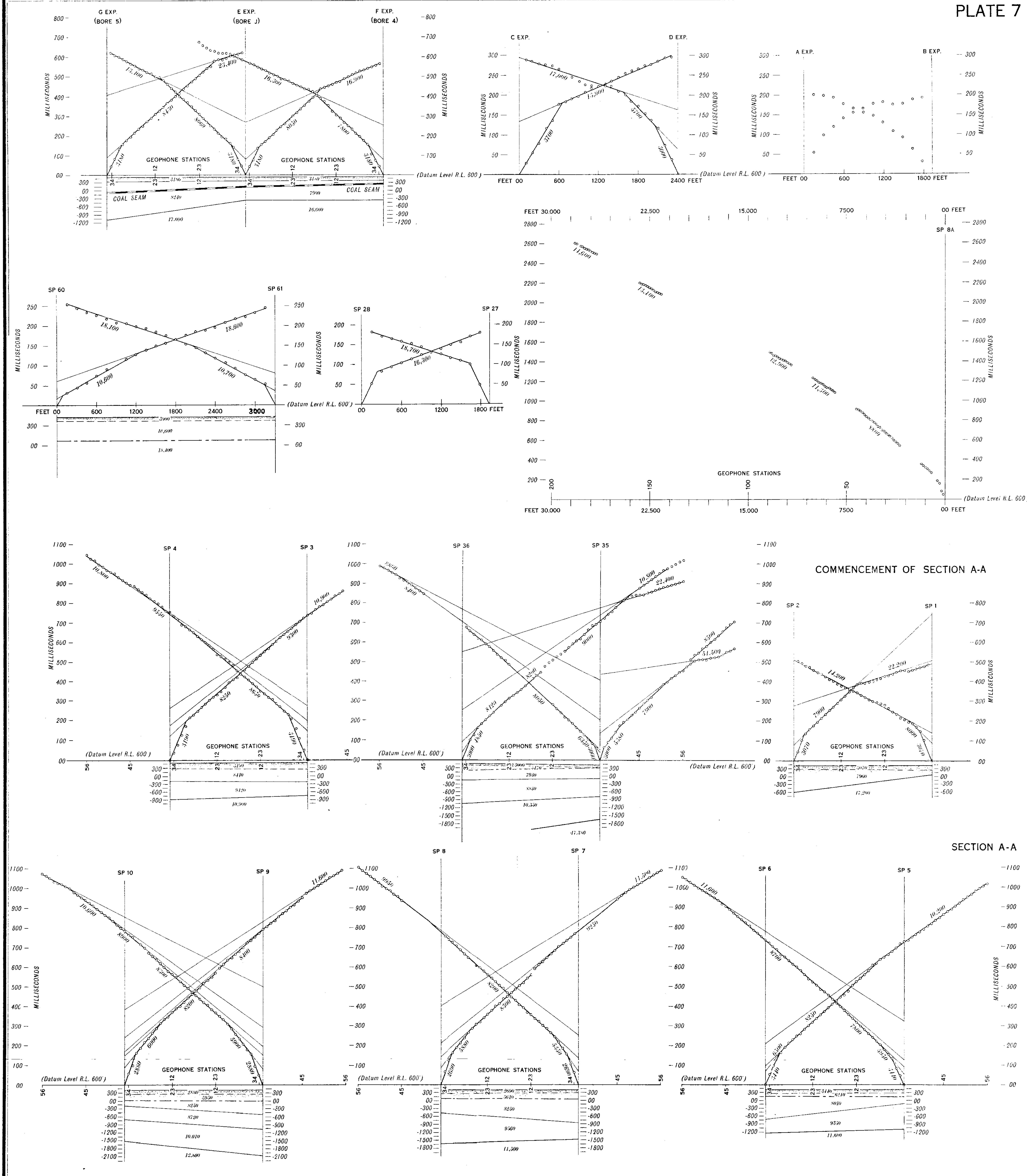

FOR CONTINUATION OF SECTION A-A SEE PLATE 8

HORIZONTAL AND VERTICAL SCALE

1500 0 1500 3000 4500 6000 7500 FEET

Except for Shot Points A to D, 8A, 27 and 28, 60 and 61.

K.R. Vale
Geophysicist
December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS - COORABIN COALFIELD, N.S.W.

TIME VERSUS DISTANCE GRAPHS OF SEISMIC RECORDINGS

G 46-12

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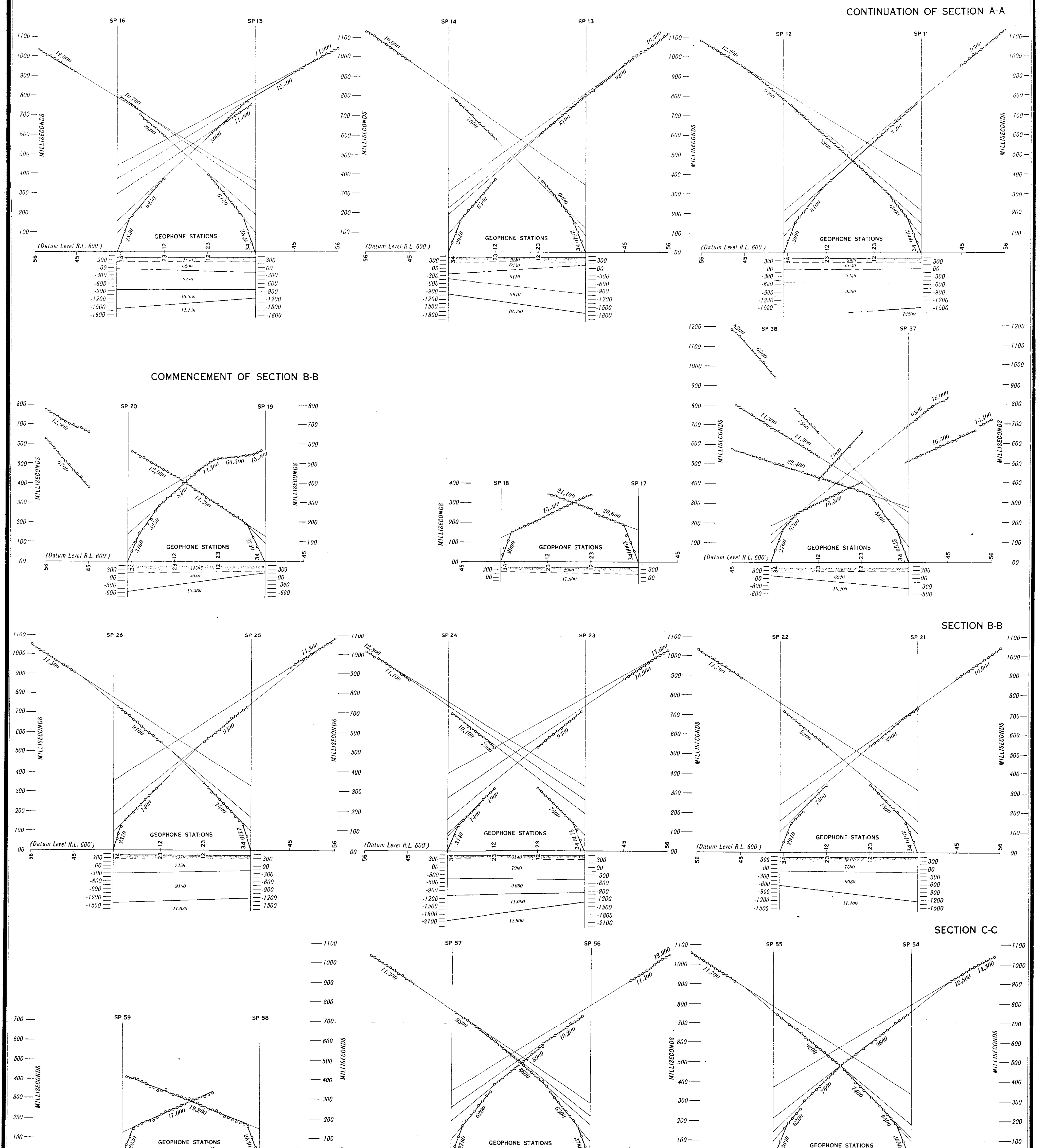
PLATE 8



HORIZONTAL AND VERTICAL SCALE

1500 0 1500 3000 4500 6000 7500 FEET

K. R. Vale
Geophysicist
December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS-COORABIN COALFIELD, N.S.W.

TIME VERSUS DISTANCE GRAPHS OF SEISMIC RECORDINGS

G 46-13

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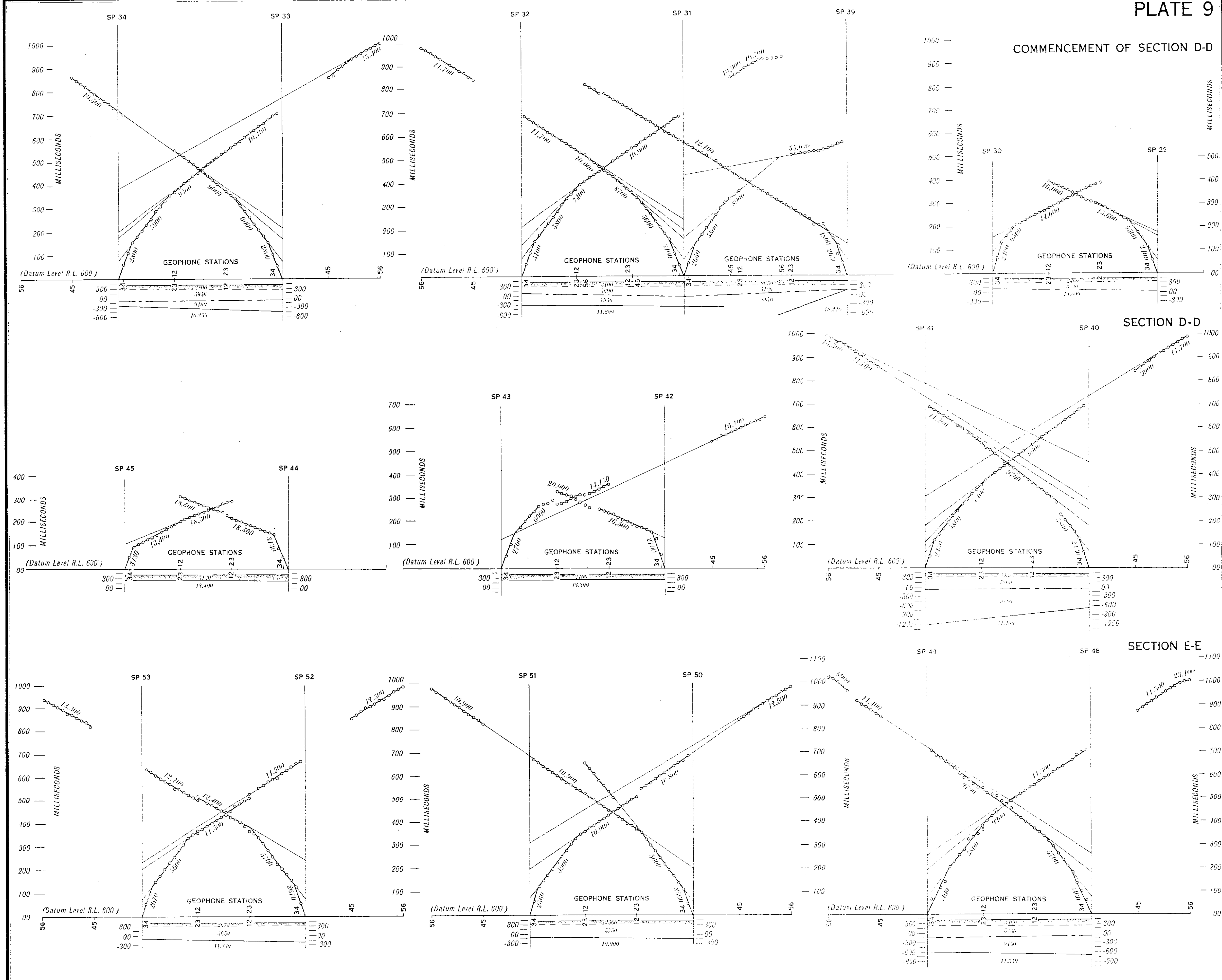
PLATE 9



HORIZONTAL AND VERTICAL SCALE

1500 0 1500 3000 4500 6000 7500 FEET

K.R. Vale
Geophysicist
December, 1951

GEOPHYSICAL SURVEY AT OAKLANDS-COORABIN COALFIELD, N.S.W.

TIME VERSUS DISTANCE GRAPHS OF SEISMIC RECORDINGS

G 46-14

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