DEPARTMENT OF NATIONAL RESOURCES

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

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CHRISTMAS ISLAND (INDIAN OCEAN) GEOPHYSICAL SURVEY FOR GROUNDWATER, 1973

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SUMMARY

A geophysical survey was conducted on Christmas Island in the Indian Ocean by the Engineering Geophysics Group of the Bureau of Mineral Resources, Geology and Geophysics in September/October 1973. The purpose of the survey was to locate additional supplies of water, to be used to upgrade phosphate mined on the island.

Christmas Island has a basalt volcanic core covered by a sequence of Tertiary to Recent coral limestones overlain by a superficial layer of phosphate. The phosphate is permeable and there is no surface runoff. Rainwater drains underground through the karstic limestone, although some drainage may be through volcanic vents.

Four geophysical methods were used:

The gravity method suggests that three rift zones radiate from the central volcano core, although more work is required to confirm this. The gravity method also indicated cavities in limestone as local minima.

The magnetic method indicated the major structures, faults, and shear zones which control the directions of caverns in the limestone.

The resistivity investigation - using wenner depth-probing and traversing, potential gradient, and dipole-dipole traversing - indicated the thickness of the phosphate, the depth to the basalt, and the existence of cavities in the limestone.

Overall the survey indicated that the main system of cavities changes the direction of water flow twice. Drilling targets have been located on the predicted continuation of existing cavities and a possible cavity draining in a southeasterly direction.

The seismic method indicated the depth of weathering in limestone, but did not contribute to the location of groundwater.

Results of laboratory measurements of seismic velocities, magnetic susceptibility, and remanent magnetization direction on rock samples, and chemical analyses of water samples, are given.

A proposal for future work is considered.

1. INTRODUCTION

Christmas Island, in the southeast Indian Ocean (Plate 1), is a raised atoll comprising a volcanic core covered by a sequence of Tertiary to Recent limestones overlain by a superficial layer of phosphate.

The Christmas Island Phosphate Commission (CIPC) works the phosphate deposits on behalf of the British Phosphate Commissioners (BPC), jointly owned by the Australian and New Zealand Governments. The production is limited by the availability of white (grade A) phosphate and could be increased by 450 000 tons per year if an additional water supply was secured to wash less pure (grade B) phosphate.

The Bureau of Mineral Resources, Geology and Geophysics (BMR) has been involved in the geological investigation on the island since 1964. The results of the work are included in BMR Records (Barrie, 1967; Rivereau, 1965). Other BMR publications dealing with phosphate (not necessarily with Christmas Island deposits) are: Kaulback, 1965; White & Warin, 1964; Jones, 1966; Sheldon, 1966).

The Geophysical Branch of BMR became involved in the water search in 1967, when it agreed to lend to BPC magnetic and resistivity geophysical equipment and to interpret BPC geophysical data. The data were interpreted by the BMR Engineering Geophysics Group, and as a result BPC was advised where to put down bores. One of these produced water but not in sufficient quantities. A reinterpretation of the data is included in this report.

The complexity of the data prompted BPC to invite a BMR geophysical party to the island to investigate the possibilities of using geophysics to find water in cavities in the limestone. The survey took place between 1 September 1973 and 17 October 1973. The geophysical party consisted of E.J. Polak (Geophysicist) and M. Dickson (Technical Assistant). Seismic refraction, magnetic, gravity, and electrical methods were used. The opportunity was taken to collect oriented samples of basalt from all accessible outcrops of basalt for palaeomagnetic determination, in an attempt to differentiate the lava flows. All the stations of the 1973 survey are identified in the text by letter G, but the letter is not shown in the plates. Not all the data obtained in the survey are shown in detail.

BPC provided the field hands and topographical surveyors; transport on the island and to and from Canberra; and accommodation and food for the BMR personnel.

The help of BPC is acknowledged.

2. GEOLOGY AND HYDROLOGY

2.1 Geology

Christmas Island (Plate 2) is an atoll that rose in several stages, starting probably in the Tertiary. After each uplift the basaltic core was covered by limestone to form several terraces. On the terraces a superficial layer of phosphate formed. (Barrie, 1967).

Basalt crops out in several places on the island; it has been exposed by localized landslides removing the limestone into the deep water around the island (Plate 2). The theory that such landslides are responsible for the three-pronged shape of the island is disputed in this Record.

Limestone on the island is of organic and detrital origin, and in places is dolomitized, especially in the pinnacles immediately below the phosphate horizon. It is generally very porous and vuggy, but in some places the vugs are filled with calcite crystals, forming dense crystalline limestone.

The phosphate overlying the limestone consists of three separate layers. The top layer consists of brown earthy phosphate containing iron and aluminium phosphate minerals (grade C). The middle layer consists of the same material with pellets of oolites and fragments of apatite (grade B). The lowest layer contains white apatite (grade A).

The limestone is generally flat-lying, but in several places dips are evident, of which some are depositional and the others have resulted from faults. Several lineations - evident on aerial photographs and on the ground - represent faults, fractures, and joints; these features are discussed by Rivereau (1965).

2.2 Hydrology

In time of heavy rain some runoff occurs, but large quantities of water permeate the phosphate deposits and flow into open sinkholes and vertical shafts. The scarcity of surface streams indicates a fully developed karst and the surface appears more dry than it is (Le Grand & Stringfield, 1973). As a result of the increased permeability by solution of the limestone the water-table is lowered. Caverns that were once air-filled may collapse, lowering the land surface; the water-table then comes nearer the surface.

The water in the limestone travels outwards towards the sea, and downwards to the basalt, to reappear as springs at the limestone/basalt contacts on the cliffs of the island. However, the possibility of water entering basalt should not be overlooked. Some of the outflows are in the form of caves, others as wide seepages.

The water-supply for the island comes from a spring at Waterfall (Plate 1) at sea level, and from a cave system at Grants Well, Jedda Cave, and Jane Up. The system of underground flow may be controlled by a fault (Rivereau, 1965).

The supply from Grants Well and Jedda Cave, which form part of the main cave on the island, comes from the limestone/basalt contact, but the supply at the bottom of Jane Up cavity is within the limestone, above the contact. The development of underground flow in limestone is fully discussed by Davis (1930).

3. GEOPHYSICAL SURVEY OF 1941

A resistivity survey was carried out in 1941 by the Geophysical Prospecting Company of London. Unfortunately the records and field geophysicist were lost in Singapore on the entry of Japan into the Second World War. However, from the available monthly reports it is possible to build up a picture as to what was achieved in the survey.

The survey used a four-electrode (probably Wenner) arrangement. It indicated water-bearing rocks at a depth of 25 m (80 feet) and 107 m (350 ft) in the Grants Well area. The upper level coincides with the level of supply at Grants Well. The lower level is in the basalt, and some explanation must be found to account for its existence. Several other areas were briefly investigated in 1941, but they are outside the area of the 1973 survey.

4. METHODS, EQUIPMENT, AND RESULTS

Magnetic and resistivity measurements were taken by BPC staff, N. Hill and P. Barrett, in 1967-69. Some of these measure ments were repeated by the BMR party in 1973.

In 1973 the BMR geophysical party used magnetic, electrical, gravity, and seismic methods. The arrangement of traverses for the 1973 survey are shown in Plate 3.

The data from both surveys are discussed in this Record.

4.1 Magnetic method

The magnetic effect of a subterranean rock structure measured at any point on the Earth's surface is the resultant of two vectors: an induced magnetic intensity vector in the direction of the Earth's magnetic field, and a remanent magnetic intensity vector which may lie in any direction. Magnetic measurements may indicate, in certain areas, such features as faults and boundaries between near-surface formations, and depths to magnetic bodies below the non-magnetic rocks.

In basaltic rocks the anomaly component due to remanent magnetization is generally greater than that due to induced magnetization. This is so on Christmas Island (See 4.1.5). When the magnetite weathers to hematite or limonite, for example, in shear zones, the intensity of magnetization is reduced.

The values of magnetic susceptibility of samples of basalt and limestone from Christmas Island are shown in Table 1, and Table 2 shows the complete set of magnetic data from basalt samples collected on the island.

During the 1967-69 survey, traverses were spaced 122 m (400 ft) apart and the stations 61 m (200 ft) apart along the traverse lines. Note that the north-south base line of the survey grid is on a bearing N45^{o}E (Plate 4). Plate 4 is a contour map of the vertical component of the magnetic field of the area surveyed; it is based on measurements by BPC staff. The data were interpreted by Mr H.D. Hsu, a geophysicist from the Airborne Reduction Group of BMR. Plate 5 shows a second derivative contour plan of the same area; it was prepared using the method developed by Henderson & Zietz (1949).

For the 1973 survey, the positions of the stations and of the continuous traverses are shown in Plate 3. Plate 6 shows total magnetic field profiles along the south-north grid lines, and Plate 7 shows the profiles along the east-west grid lines; the profiles shown in the plates were selected from a large number recorded.

4.1.1. Instruments Used

At the beginning of the investigation in 1967 an Askania magnetic variometer was used. This is a Schmidt-type magnetic balance which provides a measurement of the vertical or horizontal components of the Earth's magnetic field. This instrument was replaced by another of the same type but manufactured by the Hilger and Watts Company, London. This instrument was replaced in 1969 by a vertical-component fluxgate magnetometer manufactured by E.J. Sharpe Instruments of Canada. The sensitivity of this instrument is 10 gammas per scale division, and the accuracy is estimated as $\pm$ 5 gammas.

In 1973 the BMR party used a proton precession magnetometer manufactured by Geo-Metrics, Palo Alto, California, USA. The instrument, which measures total field intensity, was mounted on a Landrover, and the sensing head of the magnetometer was carried about 20 m behind the vehicle. Values of the magnetic field at about 2-m intervals were plotted automatically on a continuous recording chart.

4.1.2 Magnetic data and rift zone theory of origin of Christmas Island

The interpretation of the magnetic contours, the known geology, and the shape of the island are consistent with a central volcanic zone and the three-rift zone theory of origin of the island. Gravity data presented in section 4.3 is also consistent with this theory.

The area of low magnetic relief surrounding Grants Well (Plate 4) forms part of the central zone, which is shown as zone 1 on the geological map (Plate 2). From this zone three rift zones radiate along the axes of the island; they are indicated by II, III and IV in Plate 2. The boundaries between the zones are not clearly defined. Such a pattern of a central cone and rift zones is not uncommon, one example being the island of Maui, Hawaii (Kinoshita & Okamura, 1965). It is suggested that before the island emerged, deep erosion channels were partly or completely cut through the rift zones and divided the volcanic plateaus into four sections. The resulting valleys were subsequently filled with coral limestone. The evidence for the four zones is as follows:

Zone 1: This is an area of shallow, low-intensity magnetic anomalies assumed to correspond to the central cone. The station intervals of 200 feet are too great to permit depth estimates, but borehole evidence, and basalt encountered in Grants Well, suggest that the depth to basalt is generally less than 30 m. The zone is outlined roughly by the magnetic discontinuity boundary shown in Plate 4 but is very indefinite to the north and may continue into zone 2.

West of Jane Up (Plate 4), data from a line of water-bores drilled along line 250N indicate that the upper surface of the basalt deepens. Basalt is deepest in the most northerly bores (see also Plate 10). Magnetic anomaly depth calculations suggest that the basalt deepens to the northwest, west, and south, and that the depths to basalt are over 100 m. Thus the picture emerges of a large limestone-filled erosion valley in the basalt occupying most of the area west of the railway line in Plate 4. The magnetic province to the west of zone 1 and outlined by the doubtful magnetic discontinuity boundary is an area of significantly higher magnetic intensity but relatively deep anomalies. If it is separated from zone 1 by a fault, as seems probable from geological and magnetic data, the magnetic data suggests that the downthrow is on the zone 1 side.

Zone II. This zone is assumed to link with zone 1 via the zone of low magnetic relief northeast of zone 1 - that is, the right-hand centre of Plate 4.

Zone III. This zone is off the magnetic map southeast of Zone 1. A valley of moderate to deep magnetic sources trends northeast (bottom right-hand quadrant (Plate 4) from the south-eastern magnetic boundary of zone 1. South of this valley and southeast of Zone 1 is an area of low magnetic relief with little or no depth information. It is separated by a steep magnetic gradient from the steep limestone-filled valley postulated in the discussion of zone 1. Zone III may be linked to zone 1 by relatively shallow basalt.

Zone IV. In the western corner of the magnetic map (Plate 4) a zone of low-intensity anomalies from relatively shallow sources may be associated with zone IV (Plate 2), where outcropping basalt at an elevation of 300 m is direct evidence of a high basalt plateau.

4.1.3. Magnetics as related to Grants Well/Jane Up cave system

From a considerable number of local magnetic anomalies, the most important in water search is the elongated magnetic feature along the north-south grid line along 392E. This feature, which probably represents a dyke, seems to control the major drainage of the area, since Jane Up and Jedda Cave are close to it. Northwest of Jane Up, this feature turns sharply to the northwest and disappears across a postulated fault into the broad old erosion valley. Some time ago the Grants Well/Jane Up system may have continued straight across the fault, but the collapse of the roof of the cavity blocked the way, and one of the main problems facing geophysics will be to determine whether a new well developed system of caves exists farther northwest near a fault postulated from magnetic, gravity, and resistivity data to pass between bores WB 67 and WB 68 (see Plate 10).

An additional supply of water may come from the south-east end of the central plateau and possibly from a part of rift zone III along the elongated magnetic feature between grid lines 258N and 262N.

4.1.4 Second Derivative Map

Plate 5 shows a second derivative contour plan of the same area as Plate 4. The second derivative method is used to aid interpretation of the data by measuring the curvature of the features of the magnetic contour map. The method requires a complete coverage of the area with magnetic stations spaced on a regular grid. The spacing of the grid on Christmas Island, 122 m (400 ft), is too large to investigate shallow features and to delineate the long narrow magnetic features interpreted on the vertical-field contour map (Plate 4). The data from the contour plan (Plate 4) were fed into a CDC 3600 computer using the BMR program developed by E.P. Shelley. The formula used is given in Plate 5. From the values obtained, the approximate zero contour was plotted.

At high magnetic latitudes the zero contour of second derivative maps tends to outline the boundary of an anomalous feature and negative troughs surround it. At an inclination of 41°S (that of Christmas Island) the zero contour is still useful, but the negative troughs on the eastern and western margins are less pronounced and a positive anomaly appears near the northern margin of the anomaly-producing holes. However, an examination of the magnetic properties of the basalt samples from the island (Table 2) shows that the dominant component of the anomalies must be due to remanent magnetization and that the variability in intensity of magnetization of adjacent flows could easily produce anomalies of the order of a 1000 or thousands of gammas. By contrast anomalies due to susceptibility differences would be of the order of several hundred gammas at most. In addition, magnetic inclination is highly variable ranging from $+65^{\circ}$ to -31° - that is, both normal and reverse magnetization occur. These magnetic variables make interpretation difficult, and many anomalies cannot be confidently resolved from either the vertical intensity map or the second derivative map. However, in the second derivative map, negative troughs should always be on southern, eastern, and western margins, and frequently on the northern margin, of the anomalous body. Therefore, if the anomalous bodies are deeply weathered and faulted or jointly based, then the zones of deep weathering are most likely to occur in the negative troughs of the second derivative map. Water-bore WB 30, located partly from the negative values of the second derivative map, produced water, but not in the required quantity.

The pronounced east-west and lesser north-south lineations have some geological significance. They are most pronounced in the postulated cone area and southwest of zone 1 - that is, the central part of Plate 5. If they reflect the directions of weathering on joints or faults in the basalt and if this has any control at all on the development of the cave systems, then an easterly trending cave system would be most probable. Although there is no evidence of such a system, and its direction would be contrary to that of the Grants Well/Jane Up system, the possibility should be considered.

The lineation pattern is not so pronounced over the deep limestone-filled valley to the southwest of zone 1, and changes appreciably in character in other parts of the map.

TABLE 1. PROPERTIES OF ROCKS ON CHRISTMAS ISLAND

Registered number of sample	Rock type	Sample type	Locality	Magnetic suscept. x 10^{0} e.m.u./cc	Sp.G.	Porosity %	Resistivity ohm-m at 100 Hz	Long velo. m/sec.
G884-73/117	Basalt	lump	Surface	410	2.94	2	6500	5850
G885-73/118		"	Surface	220	1.97	2	8800	5800
73/139		chips	BH 3-160'-203'	50	2.30			
73/140			BH65-120'-125'	220	2.56			
			125'-130'	230	2.50			
			130'-135'	200	2.69			
			140'-145'	300	2.61			
			145'-150'	80	2.47			
			150'-155'	90	2.42			
			155'-160'	6	2.48			
			175'-180'	450	2.23			
G888-73/119	Limestone	lump	Surface	0	2.64	3	9600	6410
STI-73/120		core	depth 69 ft	0	2.54	6	4900	5770

TABLE 2. REMANENCE, SUSCEPTIBILITY, AND KOENIGSBERGER Q OF CHRISTMAS ISLAND BASALT SAMPLES

Sample	Susceptibility e.m.u./cc x 10^{-6}	Remanence e.m.u./cc x 10^{-6}	Q *	Declination (deg)	Inclination (deg)	Geochronological Sample no.
A2	207	363	17.5	295	-16	74.95.0011
B3	185	(1220 (685	(6.6 (3.7	(294 (178	(-25 (+28	74.95.0012
C2	296	9170	31.0	109	-18	74.95.0013
D3	127	(685 (1770	(13.9 (-	(178 (358	(+28 (-31	74.95.0014
E2	164	1070	6.5	271	0	74.95.0015
F1	-	426	-	208	+48	74.95.0016
G1	247	-	-	-	-	74.95.0017
G3	-	25 000	-	125	+65	

* The Earth's magnetic field is taken as 1 oersted

4.2 Electrical methods

4.2.1 Introduction

The resistivity of a rock depends on the resistivity of the rock matrix and on that of the fluid that occupies the pore spaces within the rock matrix; the interstitial fluid lowers the resistivity of a rock. If the resistivity of the interstitial fluid is constant, the resistivity that is measured depends mainly on the porosity of the material. The porosity of unconsolidated material (phosphate on Christmas Island) is about 40 percent. Even above the water-table sufficient moisture is normally present in the rock to substantially lower its resistivity. Below the water-table the resistivity of the unconsolidated material will be even lower in areas where the water is saturated with salts.

The resistivities of basalt and limestone from Christmas Island are high (see Table 1), and their porosities low. Resistivities were measured in the laboratory on samples saturated with water with an electrical resistivity of 25 ohm-m. The resistivity of water from Jedda Cave is roughly three times higher, and therefore the resistivity of the basalt and solid limestone in situ on the island will be higher than in Table 1.

While the porosity of the unweathered basalt varies within very small limits, the porosity of limestone depends on the number of vugs and cavities, and so the resistivity of the rock will be influenced more by the resistivity of the water. The effect of a cavity in limestone is shown as a low-resistivity zone when containing water, and a higher-resistivity zone when dry. There may be a wide low-resistivity zone around the cavity where the joints have been enlarged by water and contain mud and soil.

4.2.2. Resistivity techniques

Two types of resistivity work were done: traversing and depth-probing. The purpose of resistivity traversing is to measure lateral variations in electrical resistivity; the purpose of depth-probing is to measure the vertical distribution of electrical resistivity. There are several arrangements of electrodes (Heiland, 1946):

a) In the Wenner arrangement (Plate 8, fig. 1) all four electrodes are moved for each reading. The separation between the electrodes is a distance 'a' for a total spread of 3a.

b) In the Lee configuration (Plate 8, fig. 2) electrode P_2 is fixed in the centre, and the other three electrodes are moved, so that for any spread length 3a, $C_1P_1 = a$, $P_1P_2 = a/2$ and $P_2C_2 = 3a/2$.

c) In the Schlumberger arrangement (Plate 8, fig. 3) the separation of the potential electrodes P_1P_2 is kept small compared with the separation of the current electrodes C_1C_2, which are moved progressively outwards until the reading between the potential electrodes becomes too small to give the accuracy required. Then the distance between the potential electrodes is extended and the outward movement of the current electrodes is continued.

d) In the dipole-dipole arrangement (Plate 8, fig. 4) the electrodes are placed relatively close together (a = 10 m). The potential electrodes are then moved away in 'n' steps, where n is the number of units of distance a between centres of current and potential dipoles (from n-2 to n-12 for the survey on Christmas Island). The apparent resistivity is plotted midway between the centres of the dipoles at a depth equal to half the distance between centres (inset Plate 16).

e) In the potential gradient arrangement (Plate 8, fig. 5) two current electrodes are placed far apart (1200 m on Christmas island); the two closely spaced potential electrodes (10 m apart) are moved in the central one-third of the distance between the current electrodes.

f) In the combined arrangement (Plate 8, fig. 6) only one electrode is moved during the investigation: the potential electrode is moved away from a fixed current electrode; the two other electrodes are placed far away, so that they do not influence the readings.

The choice of the electrode arrangement depends on local conditions: for example, at one site the gradient was used to lower the influence on the data of a steel pipeline parallel to the traverse; at another the combined arrangement was used where dense jungle made the use of any symmetrical arrangement impossible.

All the above methods can be used for traversing, and all of them, except for the potential gradient method, can be used for depth-probing. The depth of penetration of the current, and therefore the depth of investigation, depends on the electrode arrangement, the electrode spacing, and the resistivity of the strata.

4.2.3. Resistivity equipment

The Geophysical Megger manufactured by Evershed and Vignoles, London, England, uses a commutated direct current generated in the instrument (a square-wave a.c.). The instrument has enough power for the Wenner, Lee, and Schlumberger arrangements to be used to a limited depth. For other electrode arrangements and for greater depths a more powerful source is required, and during the 1973 survey an induced polarization transmitter manufactured by Geotronics Pty Ltd was used.

The Geotronics transmitter was used to send a pulse of up to 2.0 amp at a frequency of 0.1 Hz and at a potential difference of up to 800 volts. The layout of the receiving unit assembled by BMR is shown in Plate 9. The receiving unit included a telluric current compensator designed to compensate for potentials due to Earth currents up to 0.5 volts. In the combination electrode arrangement a compensation of up to 1.2 volts was required.

4.2.4. Traverse along Grid Line 250 N

Plate 10 shows the profile of a resistivity traverse using a Wenner constant-spacing arrangement of 15 m along the EW grid line 250 N. The geological section is based on drilling. Bores WB 66 to 68 were drilled after the 1973 survey. The apparent resistivity measured along the surface correlates well with the shape of the limestone/phosphate interface but does not give any indication of the depth to basalt under the limestone. Increasing the spacing between electrodes to about 60 m would enable investigation to penetrate to the basalt layer, but would not give good data since the total length of the arrangement (180 m) would be affected by vertical changes in resistivity, which are prominent along traverse 250N.

4.2.5. Resistivity depth probes

4.2.5.1 Grants Well

Plate 11 shows a resistivity depth probe using a Wenner configuration of electrodes (Plate 8, fig. 1) close to Grants Well. The field curve was interpreted using the method of successive superimposition of two-layer curves. The vertical distribution of resistivities is shown in the computer interpretation (Plate 11). The interpretation was checked using a computer program developed by the BMR Engineering Group for the Wang 600 computer. The field curve and the computer-modelled curve are quite similar. A comparison of the computer interpretation with a geological section of Grants Well shown in Plate 11 shows that the computer-interpreted depth to the base of the limestone layer is 20 percent less than the drilled depth.

Plate 11 represents a three-layer section: low-resistivity phosphate overlies high-resistivity limestone, and the deepest interpreted layer is the weathered basalt. Unfortunately only a small proportion of the depth probes on the island indicated this sequence clearly; some depth probes were distorted either by a lateral variation in the resistivity and thickness of the phosphate layer, or by the lack of power of the resistivity equipment. For this reason the resistivity depth probes provide little additional information on the depth to basalt, although the probes are scattered over a large proportion of the magnetic survey grid. However, for locating near-surface water, a classification into curve types is more useful than layered-model interpretation, and this approach has been adopted.

4.2.5.2. Curve types from depth probes

The curves derived from depth probes on Christmas Island may be grouped into three types (inset on Plate 5). Type 1 represents an area where the lower-resistivity bed of phosphate is overlying a higher-resistivity bed of limestone resting on a low-resistivity bed of weathered basalt. Type 2 indicates a similar bed of phosphate over limestone underlain by a higher-resistivity bed, probably dry, fresh basalt. Type 3 represents a depth probe in an area where the resistivity layering of the phosphate, limestone, and basalt as shown in Plate 11 is completely destroyed either by a fault or by a collapse of a cavity; this type of curve may indicate water, but probably not in the required quantity. Therefore the type 1 resistivity curve is most promising as an indicator of water-supply. Plate 5 shows the locations of resistivity depth probes.

4.2.6. Potential gradient - Grants Well to Camp 4

Plate 12 shows potential gradient (Plate 8, fig. 5) measurements. As mentioned before, this arrangement was used to minimize the influence of the steel water-pipe along the road from Grants Well to the railway line near Camp No. 4 (Plate 3). The spacing between the moving potential electrodes was 10 m, and the spacing between the stationary current electrodes was about 300 m, giving an effective depth of investigation of about 40 m. Where the potential gradient is high, high-resistivity limestone overlies high-resistivity basalt; low potential gradients may indicate water-bearing cavities. Gravity results along this traverse are discussed in 4.3.

4.2.7. Dipole-dipole traversing

Because many depth probes were distorted by the near-surface non-uniformity of resistivities, the dipole-dipole arrangement of electrodes (Plate 8 fig. 4), which helps to indicate near-surface changes, was adopted. Locations of traverses measured with the dipole-dipole method are shown in Plate 3; their profiles are shown in Plates 13 to 16.

4.2.7.1 Grants Well and Jedda Cave traverses

Plate 13 shows the dipole-dipole profile across the Grants Well cavity, about 30 m west of the pumping station. The cavity is clearly indicated by the low-resistivity area in the section. The area of low resistivity is much larger than would be expected from the size of the cavity, but all enlarged joints leading to the cavity lower the resistivity. The joints are generally infilled with terra rossa.

Measurements across the cavity at Jedda Cave were not possible owing to the dense jungle there, but a decrease in resistivity towards the cavity is indicated. A possible cavity 60 m to the east of Jedda Cave is also indicated.

4.2.7.2 Line 250N

Plate 14 shows a dipole-dipole profile along grid line 250N northwest of bore WB 54. The results indicate clearly that the characteristic structure of layered limestone has been completely destroyed, perhaps by a fault (forming the edge of the central plateau) roughly parallel to traverse 250N. The remnants of the original limestone are shown as bodies of high resistivity surrounded by low-resistivity phosphate and cavernous limestone. Bore WB 66, drilled on station G113, encountered water, but as no pumping test was done the capacity of the bore cannot be determined. Bore WB 67 was drilled on station G132, beneath which is the most likely evidence along grid line 250N of a water-bearing cavity; however, the bore was abandoned after continuous loss of circulation. Bore WB 68 was drilled to prove the upthrown side of a fault interpreted from gravity and magnetic data.

4.2.7.3 Line 298N

Plates 15 and 16 show dipole-dipole profiles along grid line 298N. The northwestern part of the profile (Plate 15) seems to be more affected by the karst process than the southeastern part (Plate 16), which still shows the layering. In both profiles there are some indications of cavities. In Plate 15, possible cavities are indicated near stations G712 and G719. A magnetic feature shown in Plate 4 cuts the profile close to station G719. In the southeastern section of grid line 298N, a possible cavity is indicated near station G774. This cavity may be a continuation of the cavity indicated in the potential gradient profile near station G320 (Plates 3 and 12), and may join the main cavity system near Jedda Cave.

4.2.8. <u>Combined electrode method - line 376E</u>

The combined electrode arrangement (Plate 8, fig. 6) was used on a short traverse along grid line 376E between stations

G183 and G211 (northeast from WB 30, Plate 3). Near station G200, the profile indicates a possible cavity, which may be correlated with the elongated magnetic feature northeast of WB 30 (Plate 4).

4.2.9. Spontaneous potential method

In the spontaneous potential (SP) method, the difference of potential between two points on the ground surface is measured. The difference of potential may be due to three factors: the flow of current generated by the changes in the Earth's magnetic field, the chemical action between different minerals in the rocks, and the flow of water carrying ions through the pores of a rock (streaming potential). Two test profiles were made along traverse 298N, using a spontaneous potential meter - manufactured by the Austral Geophysical Instrument Co., Adelaide - to determine the presence of any pronounced streaming potential. The profiles correlate well with those derived from the dipole-dipole resistivity measurements, but there was no evidence of any streaming potentials.

4.3 Gravity method

4.3.1. Introduction

The gravity method depends on density contrast. Non-porous limestone has a high density, whereas porous limestone has a much lower density. The presence of a cavity will affect the bulk density considerably, and should influence gravity readings taken on the surface. The specific gravity of basalt is higher than that of limestone (see Table 1).

A gravity survey was conducted to locate cavities within the limestone and to delineate major structural features. The gravity observations were made with a La Coste-Romberg gravity meter G20. The instrument, which is temperature controlled and has a very low drift, gives the relative value of gravity at the location of measurement.

A total of 611 gravity readings was taken. The spacing between readings on selected traverses was 10 m. Thirty-five readings were placed on bench-marks over the island to obtain the Bouguer map of the island (Plate 18). The elevations of the gravity readings were measured by the surveying staff of BPC.

Four base stations were established; these are shown in Plate 17. They were located:

at the Government offices (brass plate)	no. 7392.9501
at the flagpole, Government House	no. 7309.0612
at the Engineering Office (brass plate)	no. 7309.0002
on S 9A bench-mark, BPC staff mess	no. 7309.0001

These stations were connected to the Australian National Gravity Network at Perth Airport no. 6500.0117 and Fremantle no. 6491.0517.

4.3.2. Gravity corrections

The observed gravity values on detailed traverses were corrected to a common elevation - the highest elevation in the area of investigation. The combined elevation factor is a combination of the free-air correction factor and the Bouguer correction factor. The latter is proportional to the density of near-surface rocks. To find this density Nettleton's 'density profile' method was used (Nettleton, 1940, p. 48). The density obtained was 1.8 $gram^{-3}$. A latitudinal correction for $10^{o}30'$S latitude was also made.

The accuracy of Bouguer anomalies is affected by:

1) Random error in observed gravity
   $\Delta g = \pm 0.02$ mGal

2) Error in elevation
   $\Delta h = \pm 0.003$ mGal

3) Error in latitude

$$\Delta l = \pm\ 0.006 \text{ mGal.}$$

Computing the square root of the sum of the squares gives the random error in Bouguer anomalies equal to:

$$\sqrt{0.02^2 + 0.003^2 + 0.006^2} = 0.0209 \text{ mGal.}$$

A systematic error is introduced by the error in density used in the elevation correction. The magnitude of this systematic error equals:

$$2\pi G h \Delta\sigma$$

where G = gravitational constant

h = elevation

$\Delta\sigma$ = error in density

for $\Delta\sigma = \pm\ 0.1$ this systematic error is 0.00417 mGal/m

For a maximum elevation difference of 17 m observed over the whole area this amounts to ± 0.07 mGal. On short traverses the difference in elevation was much smaller, so that the maximum error in Bouguer anomalies was less than 0.1 milligals.

The gravity effect, Δg, over the centre of an infinitely long cylinder or other elongated body is:

$$\Delta g = 2\pi \Delta\sigma G (R^2 / d)$$

where G = universal constant of gravitation (6.67×10^{-8} cgs units)

R = radius of a body

d = depth from surface to axis of cylinder

$\Delta \sigma$ = density contrast.

Assuming:

R = 8 m (26 ft)

d = 20 m (66 ft)

$\Delta \sigma = -1.8\ g/cm^{-3}$

the gravity effect is 0.24 milligal

The effect is well above the errors of measurement, and thus the gravity technique can detect cavities in the limestone that can be regarded as roughly cylindrical bodies with the density contrast used in the calculation above.

The gravity effect of a cavity in limestone over basalt may be enhanced by factors:

1) enlarged joints around the cavity effectively increase its diameter

2) cavities may be located in the depression in underlying basalt

3) the cavities may be located over shear zones in basalt.

The results of gravity measurements are shown on plates 12 to 19.

4.3.3. Traverse across Jedda Cave/Jane Up cavity

Plate 19 shows a gravity profile across a cavity joining Jedda Cave and Jane Up. As the cavity is accessible, its location is well defined. The decrease of the Bouguer anomaly due to the deficiency of mass is clearly shown and 'the half-width' of the anomaly measured at the half-amplitude is 50 m, indicating the depth to the centre of the cavity. The actual depth is about 30 m; the greater indicated depth is due to either the existence of a shear zone there or the deflection of the surface of the basalt, or both. Magnetic and resistivity methods were not possible along the same traverse, which was along a railway line.

4.3.4. Other gravity profiles

Plate 12 shows a Bouguer profile from Grants Well to the railway line. The profile indicates a gradient of 4 mGal/km which conceals the minimum that is due to a proved cavity below survey station 385; consequently, the section between survey stations 365 and 395 was replotted after subtracting the gravity gradient. Here the traverse follows the cavity, whose effect is therefore evident along the greater part of the profile (right hand side of Plate 12). On the other hand, in Plate 13, which shows a gravity profile crossing the Grants Well cavity, the gravity effect of the cavity is not recognisable though the main underground channel may be between station 407 and 408.

Plate 14 shows gravity results over the western part of grid line 250. In places the gravity correlates with the structure, but some deflections have no relation to the structure revealed by the dipole-dipole measurements. A gravity deflection at station G624 may be the result of a slip zone parallel to a postulated fault at G618, where the dipole-dipole profile indicates low resistivity - possibly caused by a cavity.

Plate 15 shows the gravity profile along the part of the western section of grid line 298N that intersects the magnetic feature along grid line 392E (Plate 4). The gravity deflections correlate with the resistivity results, suggesting cavities close to 711/712 and G719/722. A similar conclusion can be reached from the gravity effect near G773 in Plate 16.

4.3.5. Gravity map of Christmas Island

Plate 18 shows the Bouguer gravity map of Christmas Island, and the inset depicts the free-air gravity map of adjacent part of the Indian Ocean

The gravity map produced after the application of latitude, free-air, and Bouguer corrections is the Bouguer map - the usual map on which structure is interpreted. Gravity over ocean areas is usually shown on free-air map.

The triangular shape of the gravity contours suggests that the core of the island consists of a cone and three rift zones. Bathymetric contours have been added to the plate to show that the shape of the island is constant to a depth of at least 2000 m, and there is no evidence of slumped material at depth.

4.4 Seismic method

4.1.1. Introduction - laboratory velocity measurements

The seismic refraction method depends on the sound velocity contrast between formations. Unconsolidated rock is characterized by low seismic velocities, weathered rock shows higher velocities, and the velocity of unweathered rock depends on the constitution of the rock and its porosity. Table 1 includes the results of the laboratory measurements of seismic velocities of basalt and limestone samples from Christmas Island. The velocities are exceedingly high; but generally laboratory measurements give higher velocities than the rocks in situ.

The velocities in situ depend on many factors which do not affect the laboratory specimen - for example, joints, weathering on joints, and the water content. In basaltic rocks there is a linear relation between velocities and other factors. The same does not apply to limestone, through which the energy is transmitted by the frame, and in which the influence of other factors is negligible (Wylie, Gregory, & Gardner, 1956). This fact puts severe restrictions on the use of the seismic refraction method in limestone terrain.

4.2.2. Seismic traverses

During the Christmas Island survey, seismic refraction work was carried out along the railway line and along grid line 250N. SIE 24-channel seismic refraction equipment with the GSL-20D-geophones of natural frequency of 8H_z were used.

Geophones 5 m apart were laid out in a straight line on the ground. Shots were fired at distances of 1 m and 55 m from each end of the geophone spread; to obtain more details, shots were fired at the centres of some spreads. The arrivals of the refracted waves at each geophone were photographically recorded.

4.4.3. Interpretation

Plate 20 shows the data and the results from three spreads covering 300 m recorded on line 250N near the expected line of continuation of the Jedda/Jane Up system. The plotting and the calculations were done on a Wang 600 desk calculator and plotter, with a program developed by F.J. Taylor from the Engineering Geophysics Group.

The arrival times at each geophone are plotted against the distance from a shot to form a time/distance (T/D) curve. The apparent seismic velocity is equal to the reciprocal of the gradient of the best-fitting straight line plotted through the arrival times. The measured apparent velocity depends on the slope of the interface; it is lower than the true velocity when the interface is sloping away from a shot to the geophones, and vice versa. The true velocity is then calculated.

The depth to a seismic interface at each end of a seismic spread is determined from the intercept times of the different velocities at the shot-point. The depth to the interface under each geophone is obtained using the reciprocal geophone method (Heiland, 1946, p. 548). The time-depth profile obtained using the above method is plotted near the top of Plate 20.

The time-distance curve indicates a three-layer structure:

(1) the top layer, with a velocity between 300 and 800 m/s, represents dry phosphate

(2) the second layer, with a velocity between 1200 and 1700 m/s, is a layer of moist phosphate, probably below the water-table

(3) the third layer is bedrock, with velocities of about 1800 m/s.

Stratigraphic boundaries observed in water-bores have been superimposed on the time-depth profile. The depth to the limestone calculated from the seismic data compares well with the depth to the phosphate/limestone interface observed in the two westernmost bores of the section (WB 30, WB 54), the difference being only 2 m or 6 percent. In the next two bores, WB 55 and WB 65, the difference is up to 34 percent. Bore WB 62 shows the smallest difference of only 4 percent, whereas in bore WB 56 the depth from drilling is only 4 m compared with a seismic depth of 19 m. In the seismic method, the waves may follow some horizon, whereas the drilling may prove the top of a local pinnacle (WB 56) or a small local vertical shaft (WB 55, WB 65).

On all traverses on Christmas Island, no seismic refraction was obtained from the basalt underneath the limestone. Table 1 indicates that the seismic velocity in the unweathered basalt is the same as in the limestone. The refraction from the top of limestone would therefore arrive ahead of any refractions from the basalt, especially as the weathered basalt has a lower velocity than that of both limestone and fresh basalt. This would provide additional theoretical complications to the application of the seismic refraction method.

Considering the above points it was decided to discontinue further seismic work after 13 spreads were shot.

5. OTHER INVESTIGATIONS

During the geophysical survey several samples of water and different rocks were collected for future examinations. Table 1 gives the magnetic susceptibility, specific gravity, porosity, resistivity, and longitudinal velocity of several samples of basalt and limestone. Plate 2 shows seven locations from where samples of basalt were collected especially for palaeomagnetic determination.

5.1 Water samples

Four water samples were analysed by the AMDEL Laboratories in Adelaide, and the BMR Spectrographic Laboratory in Canberra. The AMDEL analyses are shown in Plates 21 to 24.

Rainwater on the island was not analysed, but its total dissolved solids is probably not more than 40 ppm (Stearn & Vaksvik, 1935). During the travel downwards to the cavities in the Grants Well area the increase in the total dissolved solids is 450 percent to 195 ppm. The water continuing along the cavity dissolves additional quantities of calcium carbonate, and contains 225 ppm at Jedda Cave (an increase of 15 percent, or 14 percent per kilometre) and 239 ppm at Jane Up (an increase of 6 percent over Jedda Cave, or 26 percent per kilometre). The difference in percent dissolved solids per kilometre will be influenced by mixing of other water coming into the main cavity. The water at Waterfall contains 280 ppm total dissolved solids; this water had to travel further than waters mentioned above. The Waterfall water also indicates admixture of sea water by the increase in sodium and magnesium salts content.

Spectrographic analysis was also done by BMR, to determine if any trace minerals could help in the identification of water. The following tests were done (detectability limits in ppm are shown in brackets): iridium (0.15), copper (0.04), iron (0.05), manganese (0.02), nickel (0.05), lead (0.09), and zinc (0.01). No traces were found.

5.2.1. Remanent magnetization measurements by Dr M. Idnurm

The purpose of the palaeomagnetic work is to determine the orientation of remanent magnetization. From the remanent magnetization it is possible to determine the location of the magnetic pole during the time when the temperature of the volcanic material was lowered below Currie Point. (585°C for magnetite contained in basalt). In turn, the relative ages of separate lava flows, can be determined.

Remanence measurements were carried out on one sample from each of the 7 sites, A to G (Plate 2), in order to determine their suitabilities for palaeomagnetic work.

The stabilities of remanence were tested by alternating field demagnetization of one pilot specimen from each sample. Two additional specimens from the stable samples were then magnetically cleaned and measured. The within-sample scatters were acceptably small. The results are summarized in Table 2.

Site	Stability	Mean Remanence Direction	
		Declination	Inclination
A	good	356.1	-65.5
B	poor	-	-
C	"	-	-
D	"	-	-
E	"	-	-
F	fair	151.8	+16.1
G	good	034.0	+67.9

The negative sign of inclination denotes normal (i.e., present) polarity the positive sign denotes reversed polarity.

Sites A and G, and to a lesser extent F, appear sufficiently stable for palaeomagnetic work. The samples from sites B to E are magnetically unstable presumably because of chemical alteration. Fresh rock from sites B to E can perhaps be recovered by drilling or blasting.

5.3. Geochronology tests by Dr R.W. Page

Seven thin sections of basalt from Christmas Island were estimated for their suitability for K-Ar dating. All the land-specimens are from surface outcrop, and show marked weathering of the rock surface; ironstaining is apparent.

All seven rocks contain the same primary minerals of plagioclase, clinopyroxene, olivine, and an opaque mineral. Olivine is serpentinized in all samples. In 5 samples, 74.95.0012 -0016 (Table 2), the groundmass is largely chloritized and partly epidotized, rendering the samples unsuitable for dating. In 74.95.0011, the groundmass is not quite as altered, but this sample too must be considered inferior for dating. Sample 74.95.0017 is the freshest of the group, but is unfortunately ironstained (probably a weathering effect).

The amygdaloidal nature of some of the samples, and the ubiquitous groundmass alteration in all samples (at least 10% chlorite in best) does not make them suitable for geochronology.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions from the previous and present geophysical work and the supporting drilling evidence are compiled here. Recommendations are given to continue investigation, and a sequence of work is proposed.

6.1. Conclusions

6.1.1.

The island consists of a basaltic volcanic core capped by exposed prograding fringing coral reefs formed when the island emerged. The shape of the island is primarily controlled by three rift zones about the core volcano (4.3.5) - not by the major slips as suggested in (2.1).

6.1.2.

The island is divided into four zones, I-IV (Plate 4) as indicated by the interpretation of the magnetic data. These zones are separated by steep erosional features. The erosion occurred before coral limestone was deposited (4.1.2).

6.1.3.

The water regime in each of zones I-IV must be studied separately. During the present survey only the central plateau was investigated.

6.1.4.

On the central plateau magnetic interpretation indicates a major feature (4.1.3), probably a dyke, roughly along line 392E. This feature partly controls the drainage from the central plateau as shown by the existence of Jane Up and Jedda Cave and by the geophysical indications from resistivity (4.2.7.3) and gravity data (4.3.4).

Several branch cavities may exist: one crosses Grants Well, and another is suggested farther east (4.2.7.1).

6.1.5.

Downstream of Jane Up the cavity system is inferred to take a turn to the west, probably along a fault roughly between grid lines 258N and 262N, along which the limestone is brecciated (see resistivity profile, Plate 14). The cavity system must cross grid line 250N southwards probably close to bore WB 67. Farther south, the water descends, following the erosional feature (4.1.2).

6.1.6

No other major drainage from the central plateau is suggested by present geophysical work, but water may drain through a volcanic vent (or vents). In the report of the 1941 survey (Section 3), fresh water is indicated in basalt at a depth of 107 m, and in a cavity at sea level and stretching to the centre of the west rift zone. Drainage through a volcanic vent is quite common on many islands.

6.1.7.

Three geophysical methods - electrical, magnetic, and gravity - may contribute to the location of the cavities in the limestone. The seismic refraction method gives the depth to a layer within the limestone, and therefore does not contribute to the location of water in the limestone in conditions encountered on Christmas Island.

6.2 Recommendations

6.2.1.

A search should be made for any sinkholes along the magnetic feature (Plate 4) and the electrical indications on grid lines 250N and 298N. An attempt should be made to dig out the sinkholes to reach the underlying basalt. An area close to the abandoned bore WB 67 should be closely investigated, for a branch cavity along the fault between bores WB 67 and WB 68 may bring an additional supply of water to the main system.

6.2.2.

All igneous rocks recovered from any sinkholes in the central plateau area should be examined to find whether there is any geological evidence for the existence of a vent.

6.2.3.

Samples of water should be collected and analysed. Two samples of rainwater should be collected: one at the onset of a rainfall, and the second later during the same rainfall. Additional samples of water should be collected from springs and caverns other than those included in this Record, and analysed to provide guidance of the distance travelled by water.

6.2.4.

When a drilling rig is available:

a) Water-bore WB 67 (Plate 14) should be deepened to reach basalt. The bore should be left open for the geophysical party to investigate around the bore. A pumping test should be done on the bore. If the bore does not prove a cavity a new bore should be drilled close to station G134.

b) A bore could be drilled at station G624 (Plate 14) to check whether the low-resistivity zone represents a cavity bringing water from the area west of the fault mentioned in 6.2.1.

c) A bore could be drilled at the junction of grid lines 270N and 440E (Plate 4) to test the possibility of an additional cavity taking water in a southeasterly direction. If a channel is proved there, it would carry water different from that in the Jedda Cave/Jane Up system (see end of paragraph 4.1.4). This bore site, selected mostly on geological and geophysical evidence, could serve as a starting point for geophysical investigations.

6.2.5.

If additional geophysical work is done:

a) An attempt should be made to investigate the possible existence of a drainage system through the vent of the central plateau. It should be made by detailed gravity, magnetic, and deep resistivity-sounding followed by drilling. The porous lava and volcanic ashes may provide an underground reservoir which could be tapped by a deep bore and pumped during the dry season.

b) Additional gravity stations should be located in zones III and IV (Plate 18) to obtain supporting evidence for the theory of the origin of the island.

c) A continuous salinity/temperature traverse should be run around the island from a boat to locate areas of entry of fresh water into the ocean.

d) Infrared photographs of cliffs should be taken from a boat to locate areas of higher chlorophyll content in bushes over freshwater seepage.

e) Several geophysical methods should be used to determine whether the Grants Well/Jane Up system crosses the bore line in the form of well defined cavities or as a soak. The quantity of water in the system is assumed to increase with distance from the Jane Up cavity, and at the place where the water descends from the plateau into the erosional valley the quantity of water may be enough for washing phosphate. The methods which should be tested are electrical (mise-a-la-masse seems to be the most appropriate), seismic (recording the noise of water flowing down the cavity or of a detonator blast), and gravity.

f) If insufficient water is found in this system, the erosional features between rift zones II and III should be investigated.

g) Detailed geophysical investigation of the three rift zones should offer good prospects of locating additional sources of underground water. The methods to be used would be magnetic, electrical, and seismic listening.

h) An attempt should be made to recover oriented samples of unweathered basalt for palaeomagnetic investigation, which - though it will not help directly to find water - it will give evidence of the theory of the origin of the island. If the rift zone theory of origin applies to Christmas Island, the cone would consist of the oldest flow, and in the rift zones the age of the flow would decrease with the increase of distance from the cone.

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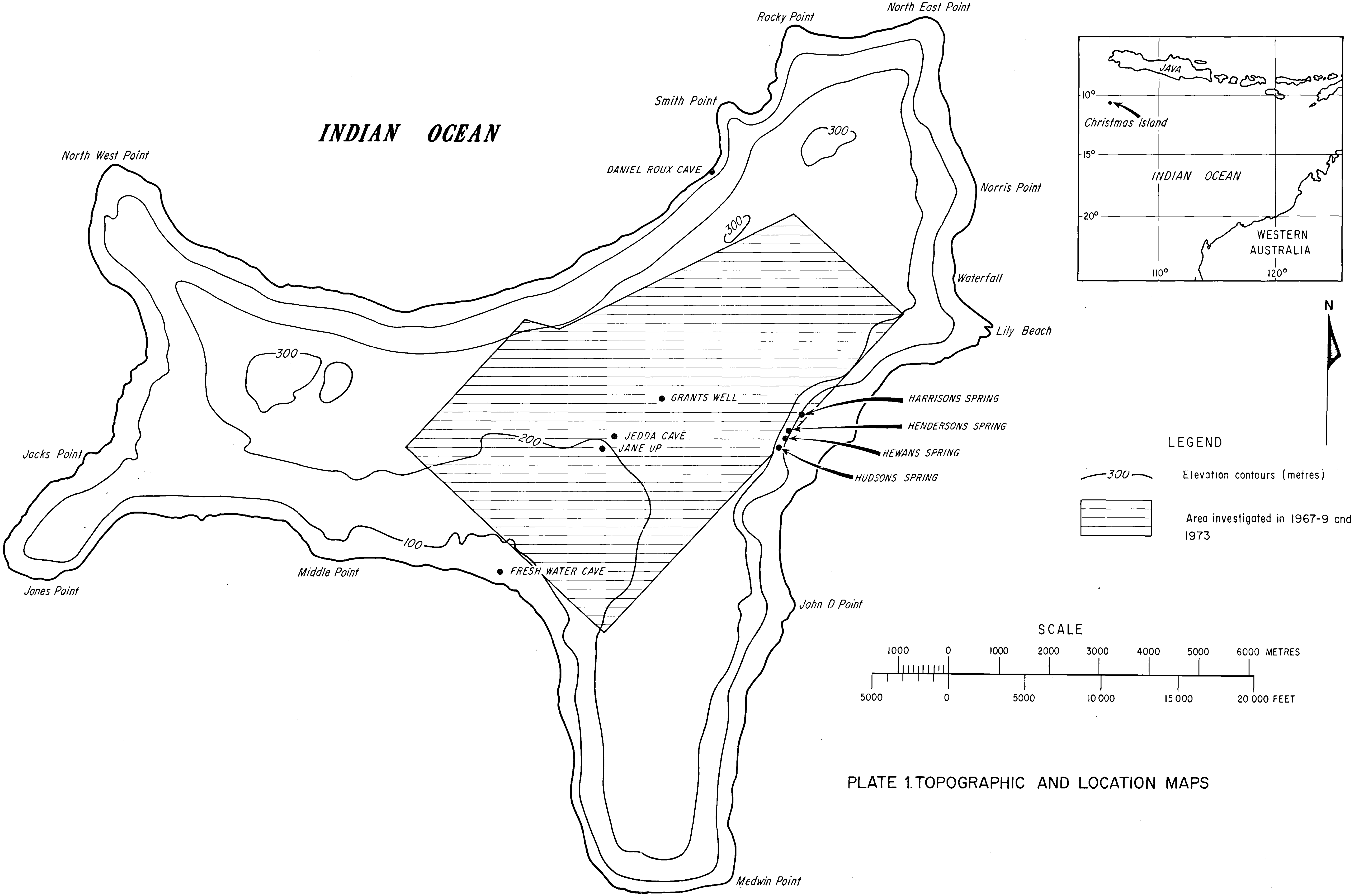


PLATE 1. TOPOGRAPHIC AND LOCATION MAPS

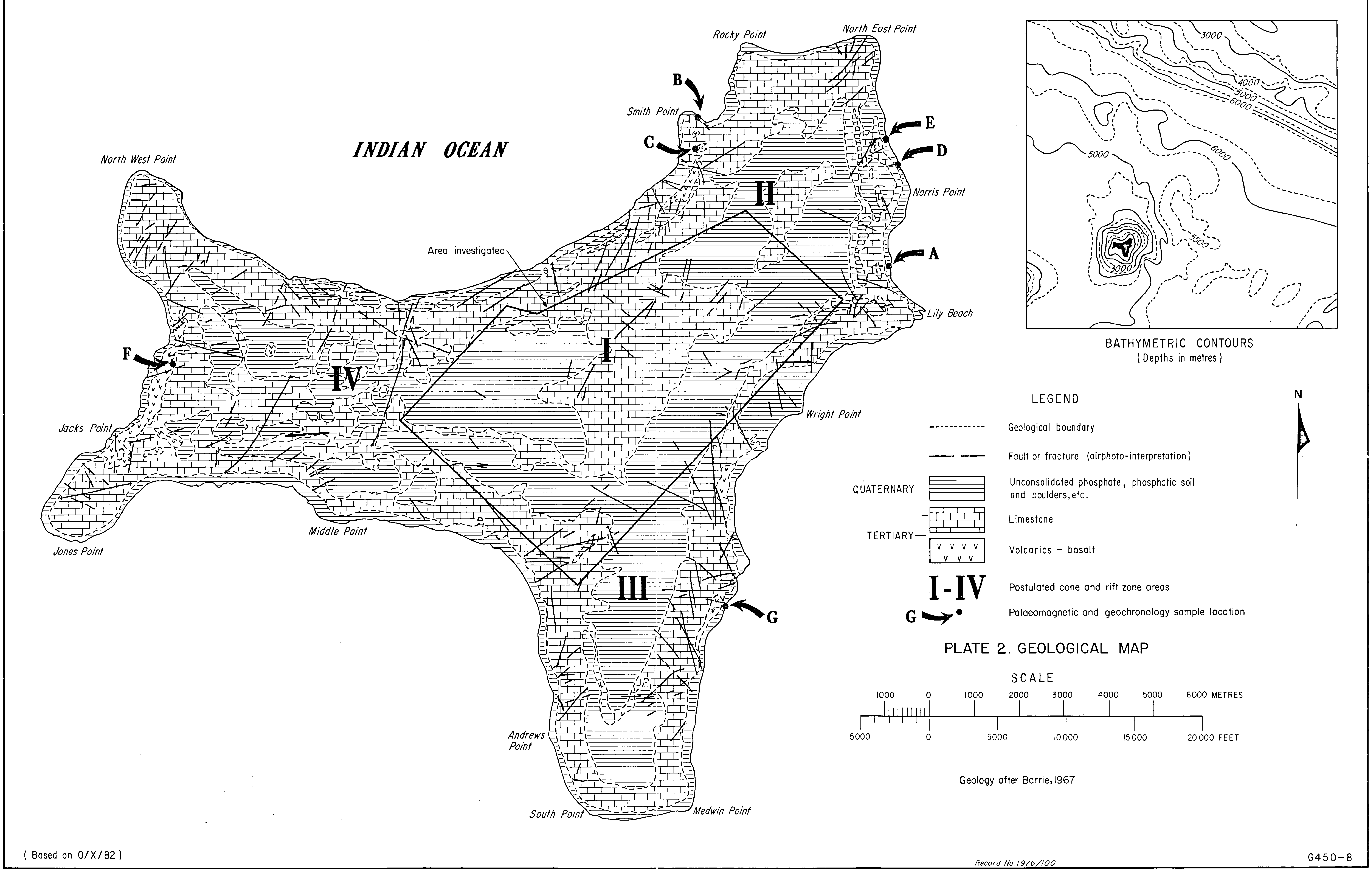


PLATE 2. GEOLOGICAL MAP

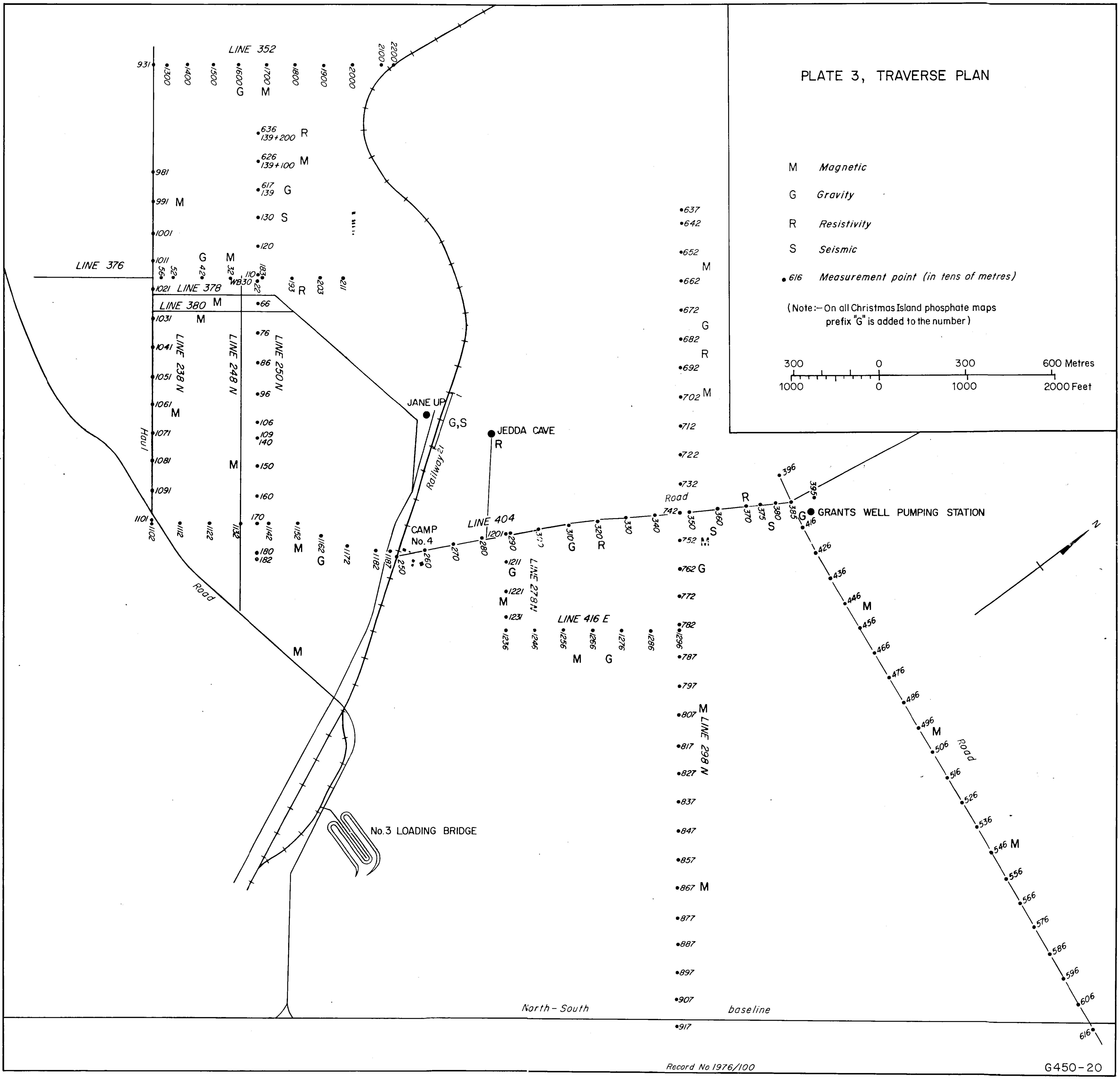


PLATE 3, TRAVERSE PLAN
M Magnetic
G Gravity
R Resistivity
S Seismic
616 Measurement point (in tens of metres)
(Note:— On all Christmas Island phosphate maps prefix "G" is added to the number)
300 0 300 600 Metres
1000 0 1000 2000 Feet
N
LINE 352
LINE 376
LINE 378
LINE 380
LINE 238 N
LINE 248 N
LINE 250 N
LINE 404
LINE 278 N
LINE 416 E
LINE 298 N
JANE UP
G,S
JEDDA CAVE
CAMP No. 4
Railway
Haul
Road
GRANTS WELL PUMPING STATION
No.3 LOADING BRIDGE
North - South baseline
Record No 1976/100
G450-20


PLATE 4
Traverse with magnetic stations
Railway
MODERATE >300 gammas
LOW 100-300 gammas
V. LOW <100 gammas
Magnetic low
Discontinuity interpreted from magnetic data
(doubtful)
Near surface point source
Outline of significant magnetic unit
300'—500' Depth to magnetic source (approximate)
PLATE 4. MAGNETIC CONTOUR MAP
METRES
300 0 300 600
1000 0 1000 2000
FEET
N
MODERATE
100'-400'
LOW
V. LOW
>500'
100'-300'
300'-500'
~75
JANE UP
JEDDA CAVE
GRANTS WELL
CAMP No 4
WB 68
WB 67
WB 69
WB 70
WB 71
WB 66
WB 30
WB 54
WB 55
WB 65
WB 62
WB 56
WB 57
WB 58
WB 59
WB 60
NORTH-SOUTH BASE LINE
EAST-WEST BASE LINE
Record No.1976/100
G450-26

Record No. 1976/100

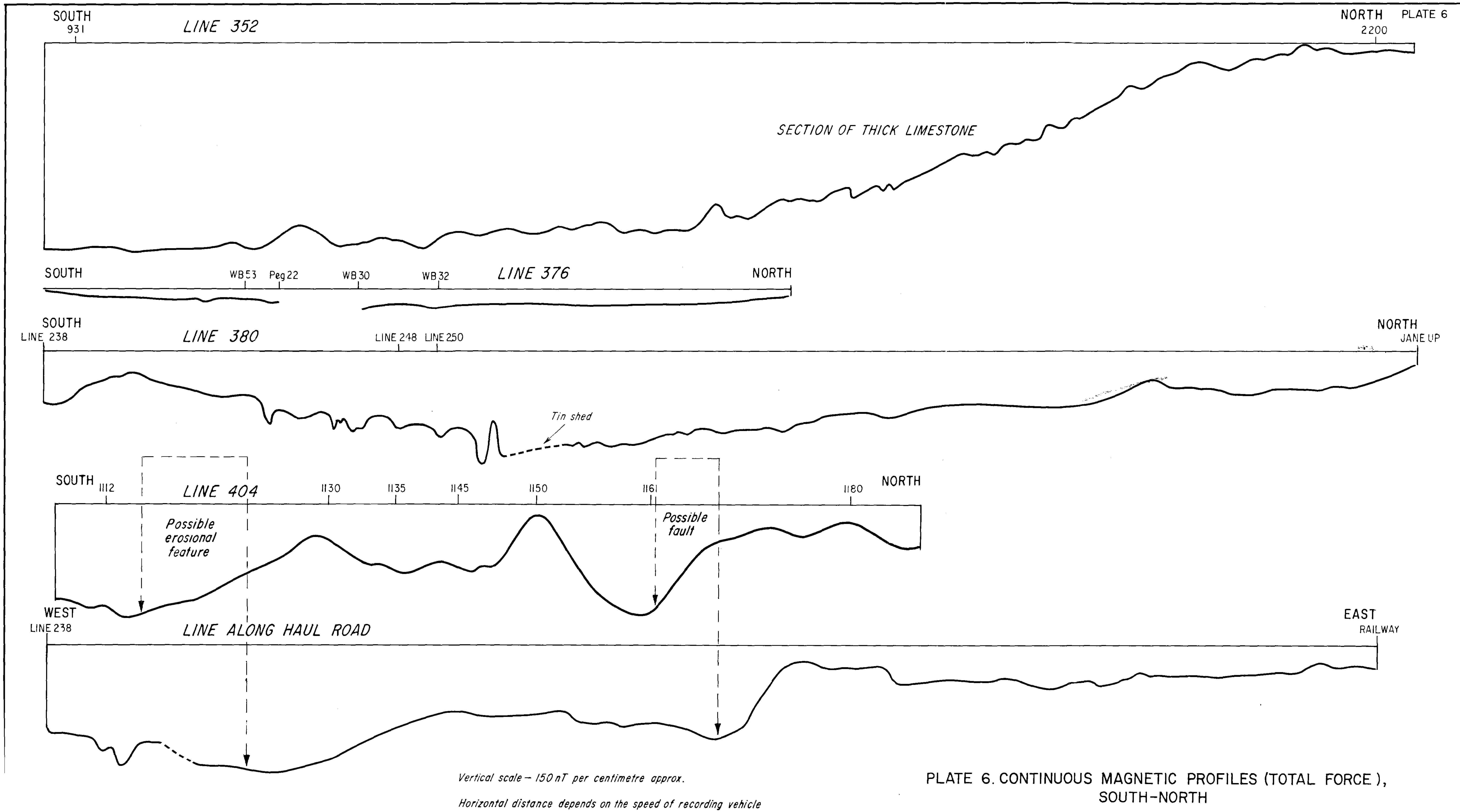
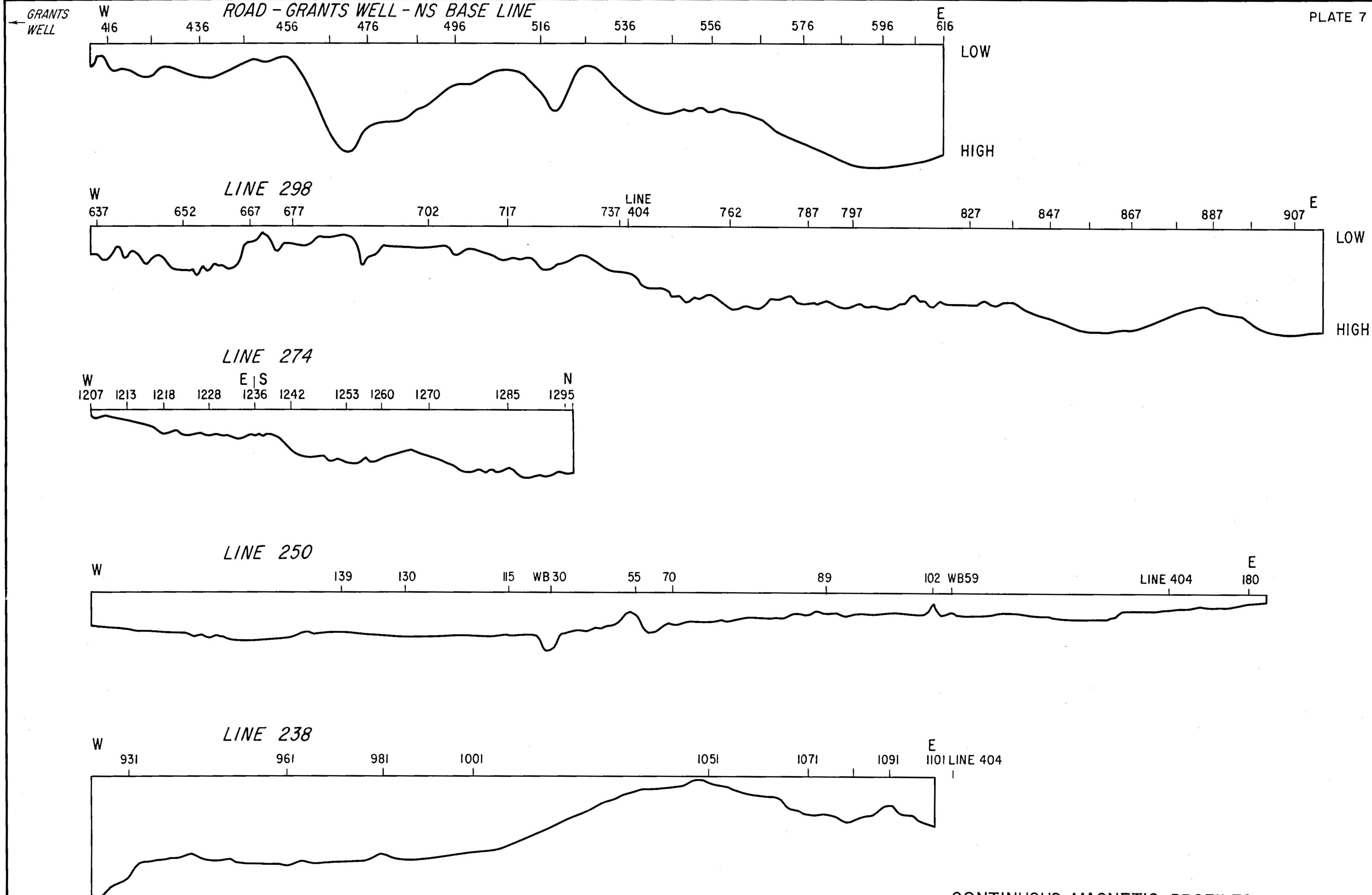


PLATE 6. CONTINUOUS MAGNETIC PROFILES (TOTAL FORCE), SOUTH–NORTH

Record No 1976/100

G450-21



Vertical scale – 150 nT per centimetre approx.

Horizontal distance depends on the speed of recording vehicle

CONTINUOUS MAGNETIC PROFILES, WEST-EAST

Fig. 1 · WENNER

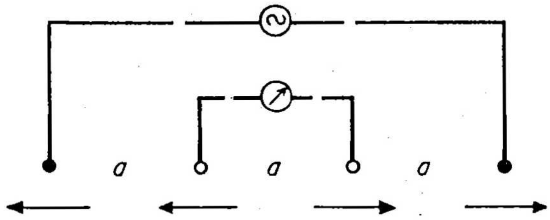


Fig. 2 LEE

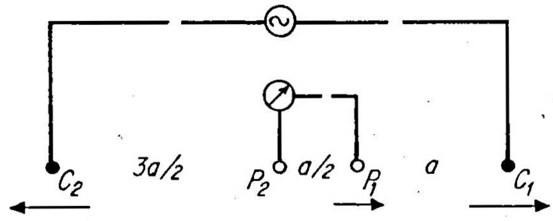


Fig. 3 SCHLUMBERGER

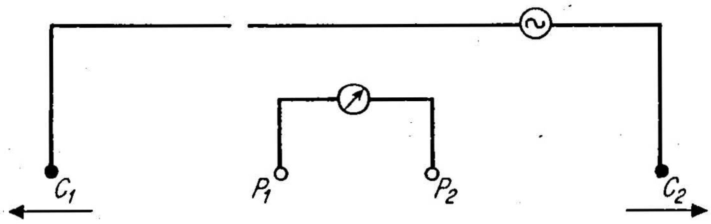


Fig. 4 DIPOLE - DIPOLE

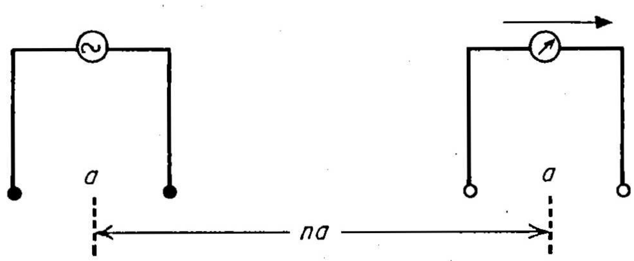


Fig. 5 POTENTIAL GRADIENT

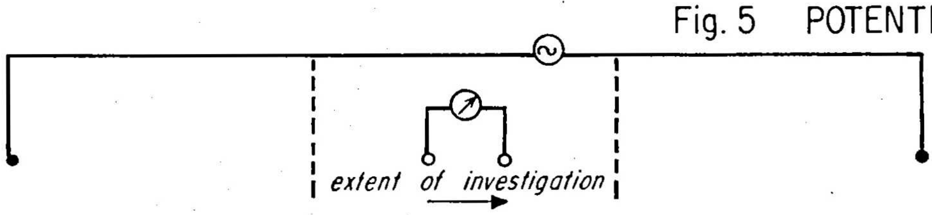
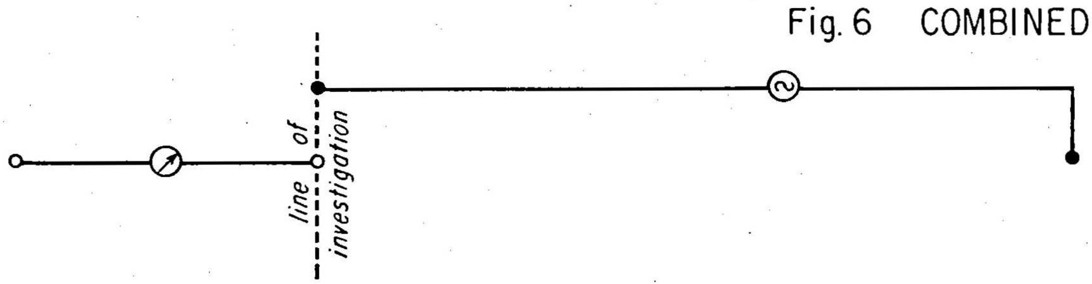


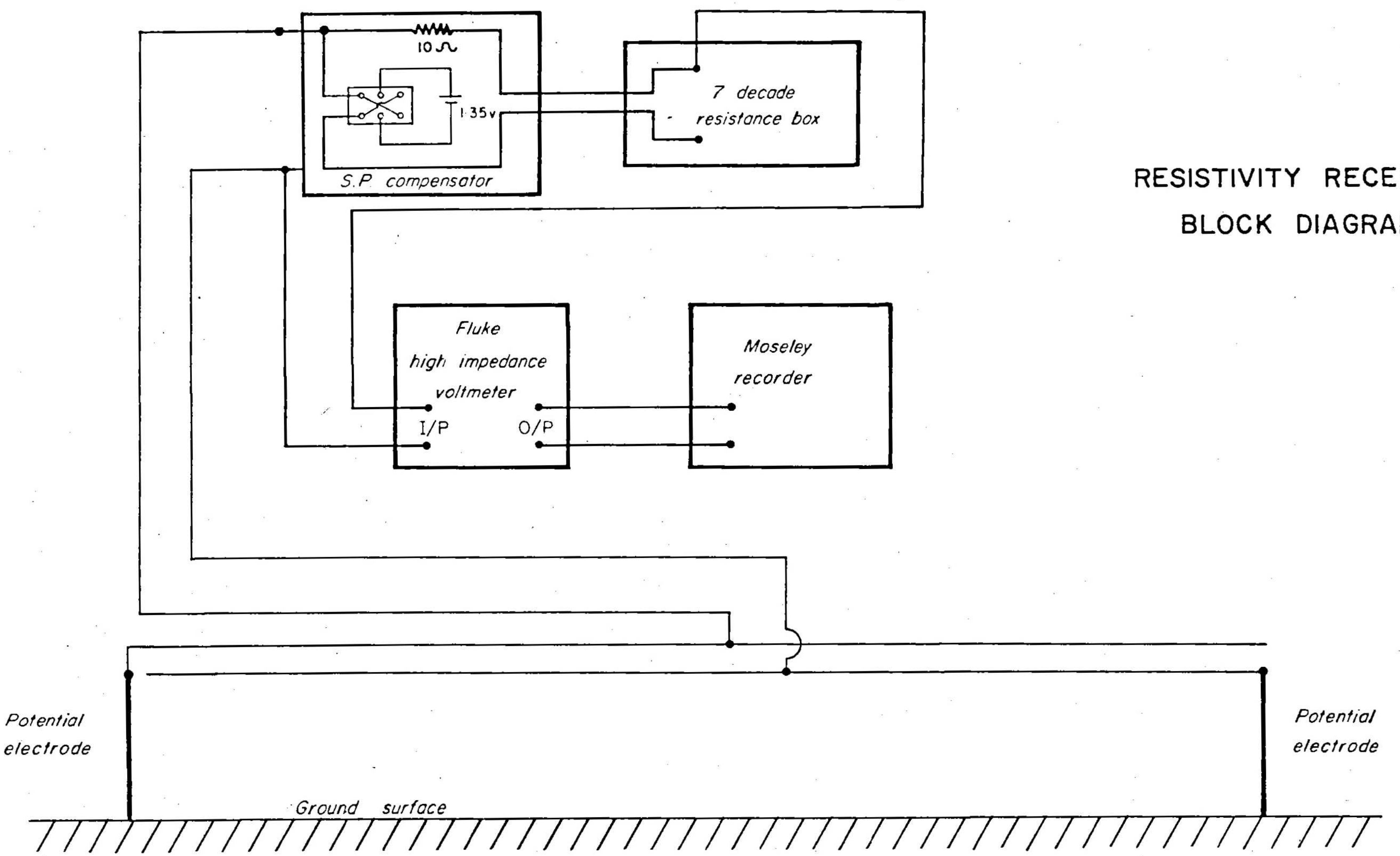
Fig. 6 COMBINED METHOD



- ● *Current electrode*
- ○ *Potential electrode*
- ⊘ *Potentiometer*
- ⊚ *Current source: ammeter*

ELECTRODE ARRANGEMENTS

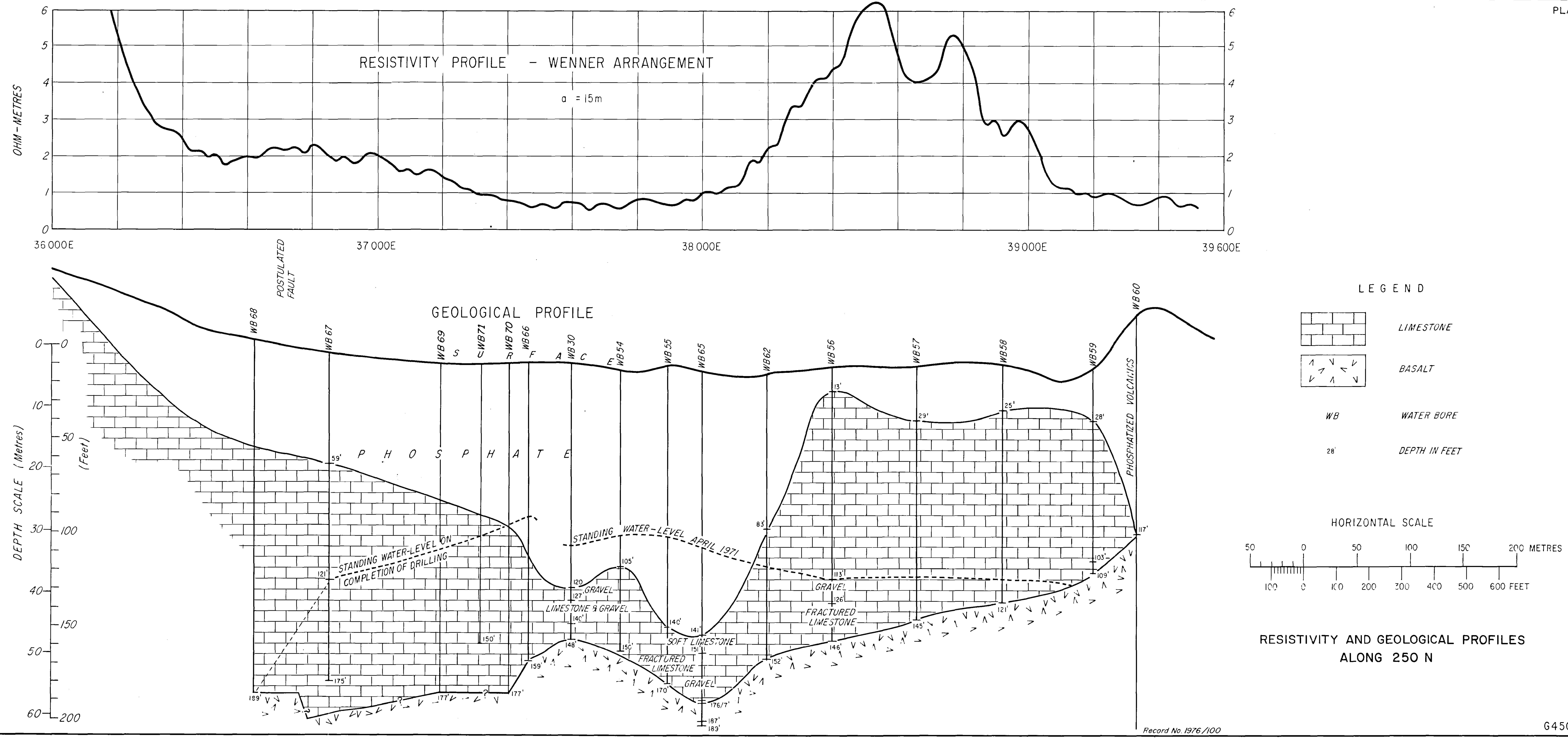
RESISTIVITY RECEIVER BLOCK DIAGRAM



Record No. 1975/25, 1976/100

G450-19A

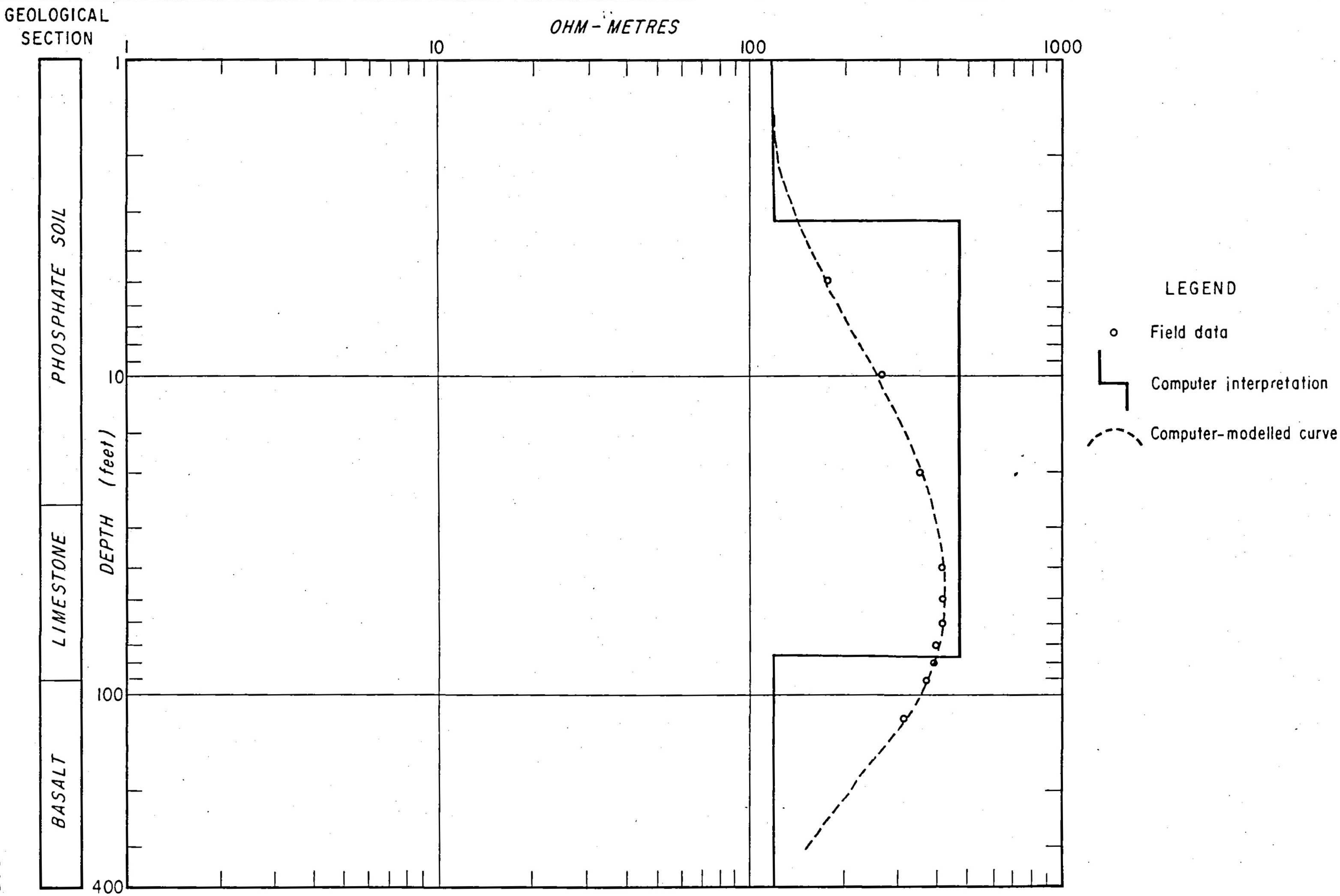
PLATE 9



RESISTIVITY AND GEOLOGICAL PROFILES
ALONG 250 N

Record No. 1976/100

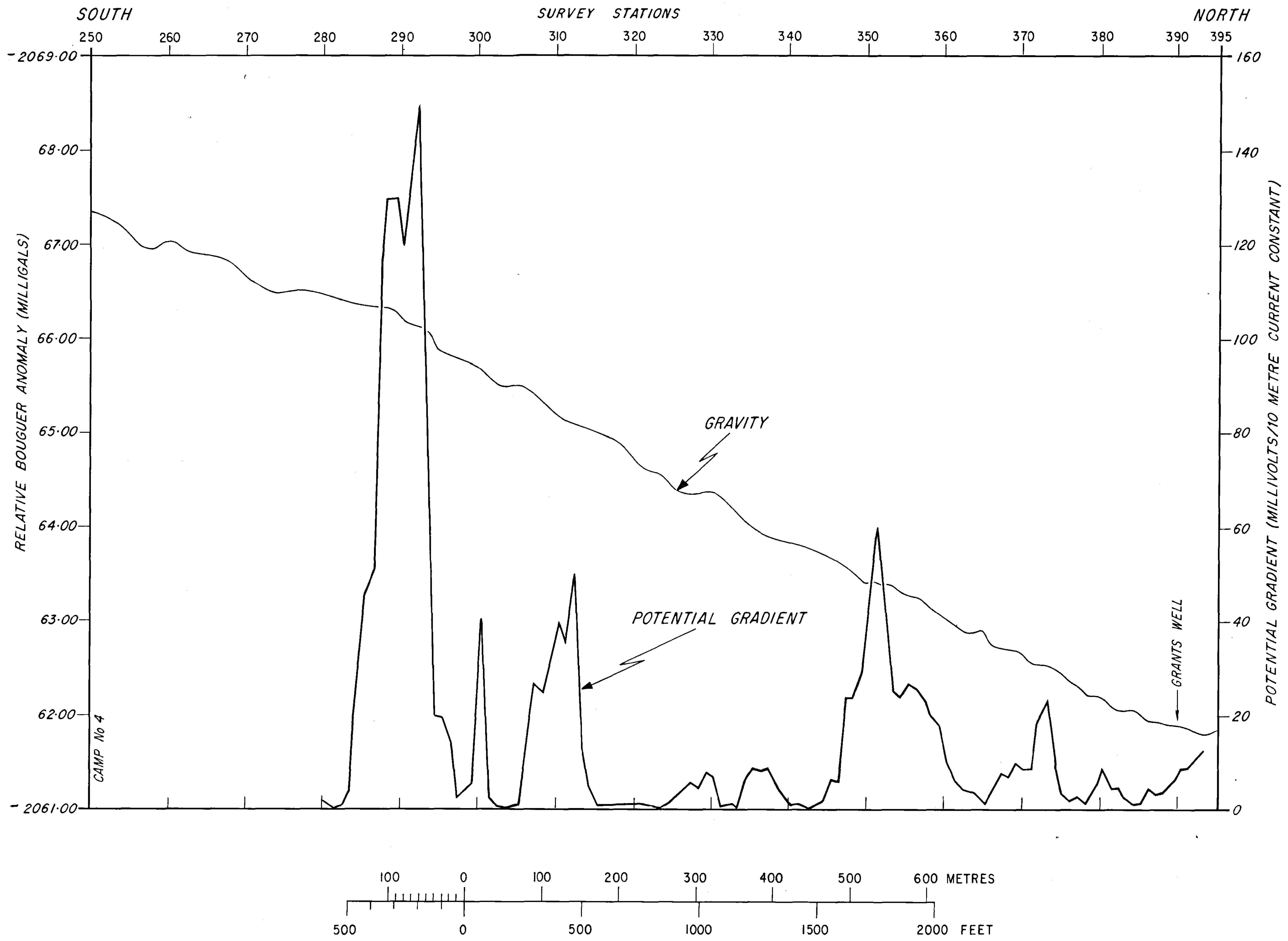
G450-10

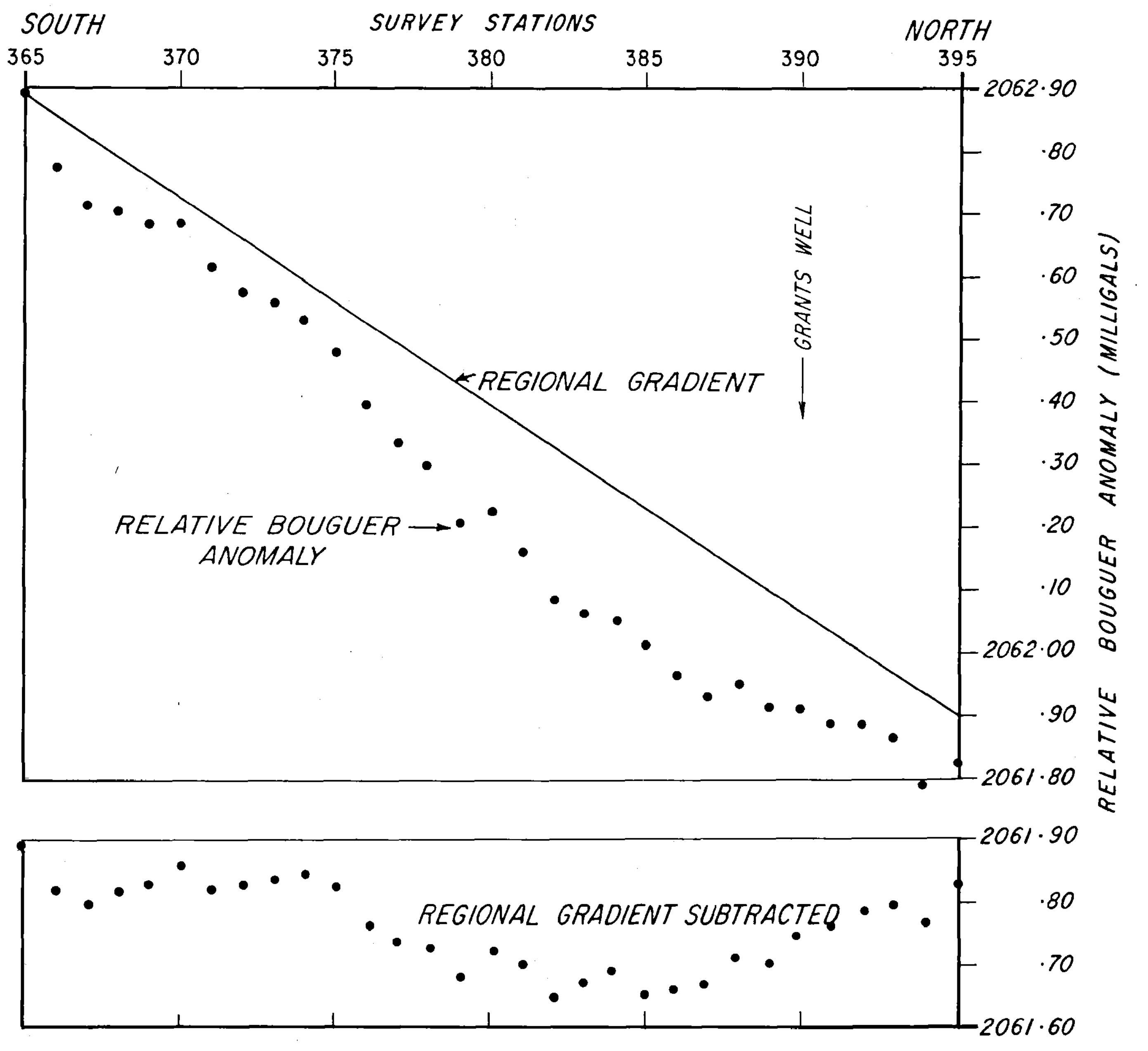


NO.1 GRANTS WELL RESISTIVITY DEPTH PROBE

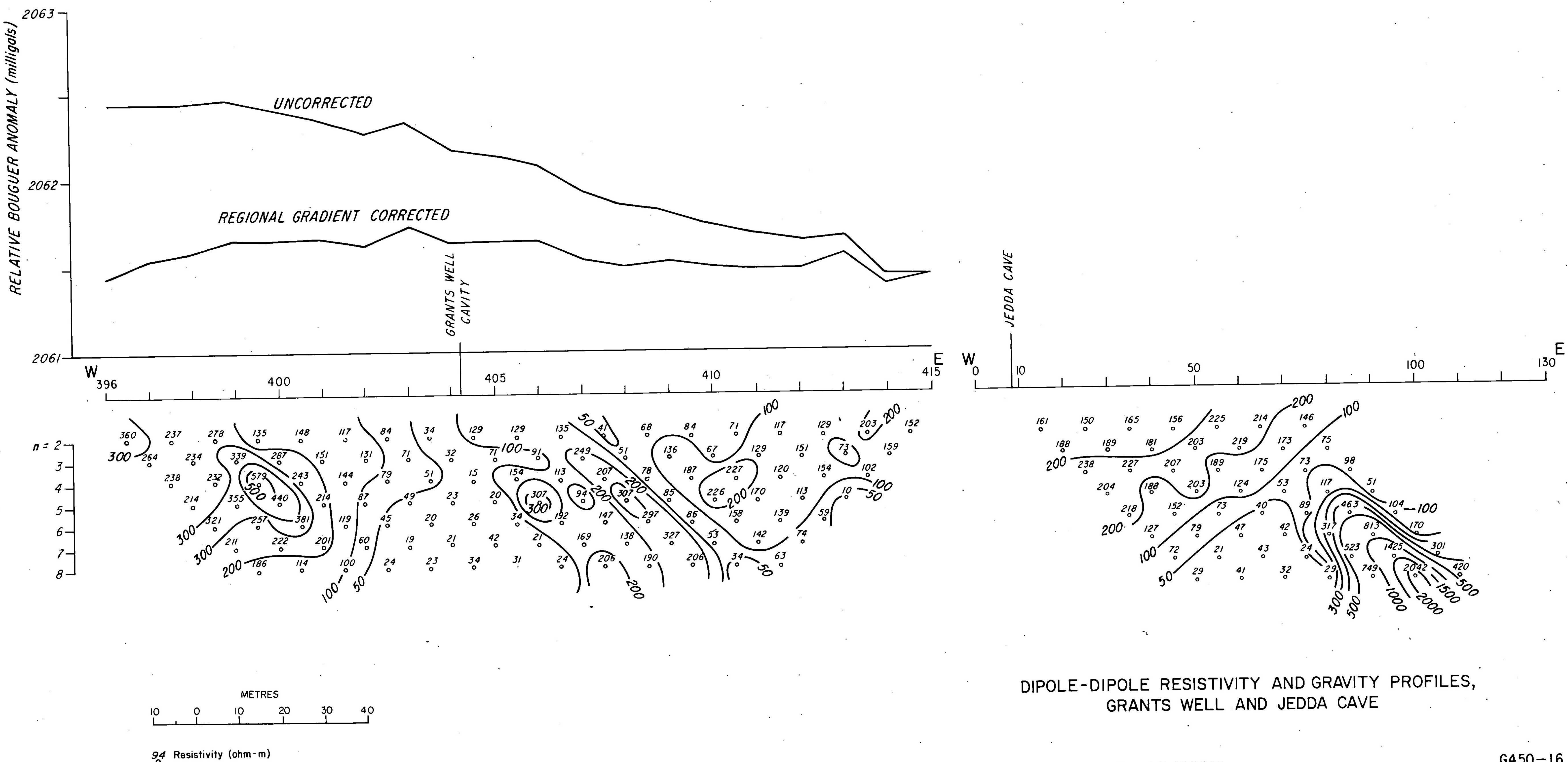
G450-13A

PLATE 11





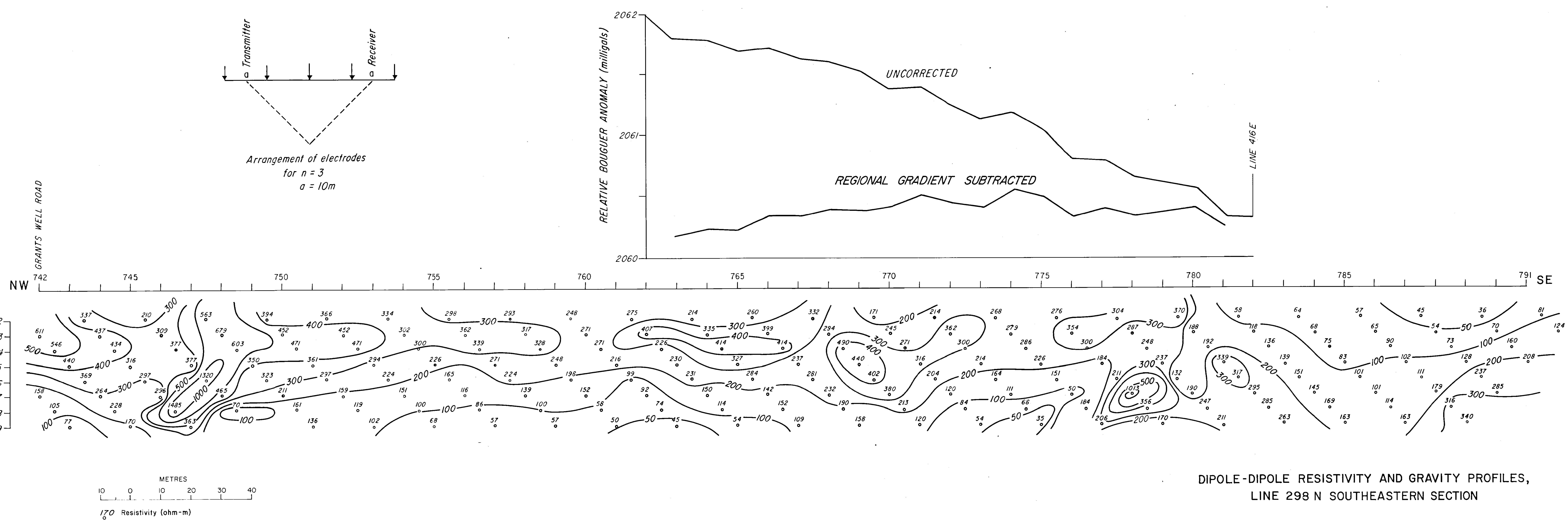
GRAVITY AND POTENTIAL GRADIENT,
TRAVERSE CAMP NO.4 TO GRANTS WELL



DIPOLE-DIPOLE RESISTIVITY AND GRAVITY PROFILES, GRANTS WELL AND JEDDA CAVE

DIPOLE-DIPOLE RESISTIVITY GRAVITY PROFILES,
LINE 250N

DIPOLE-DIPOLE RESISTIVITY AND GRAVITY PROFILES,
LINE 298N NORTHWESTERN SECTION

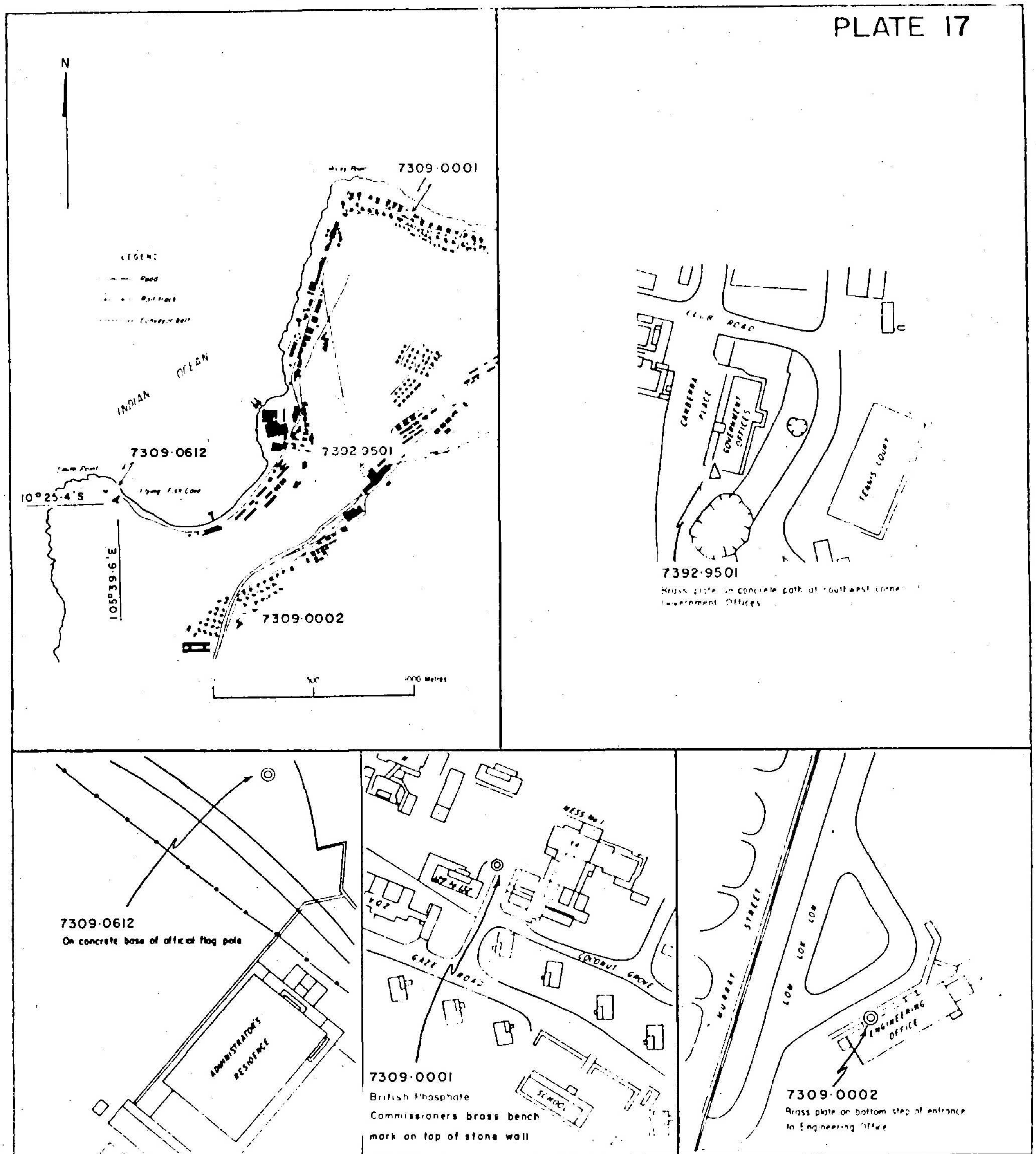


DIPOLE-DIPOLE RESISTIVITY AND GRAVITY PROFILES,
LINE 298 N SOUTHEASTERN SECTION

Record No.1976/100

G450-15

PLATE 17



△ Secondary base

◎ Excentre

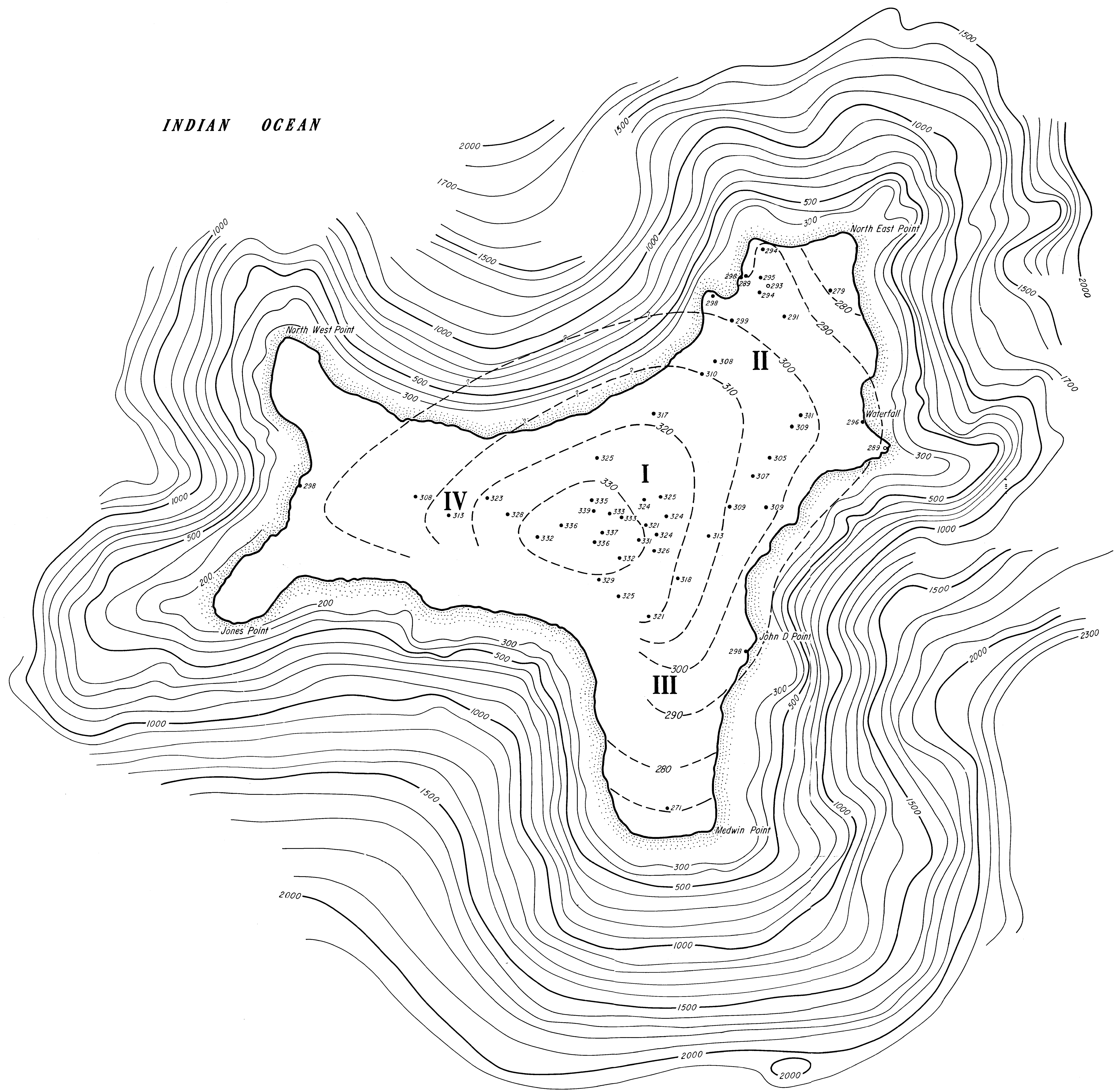
CHRISTMAS ISLAND

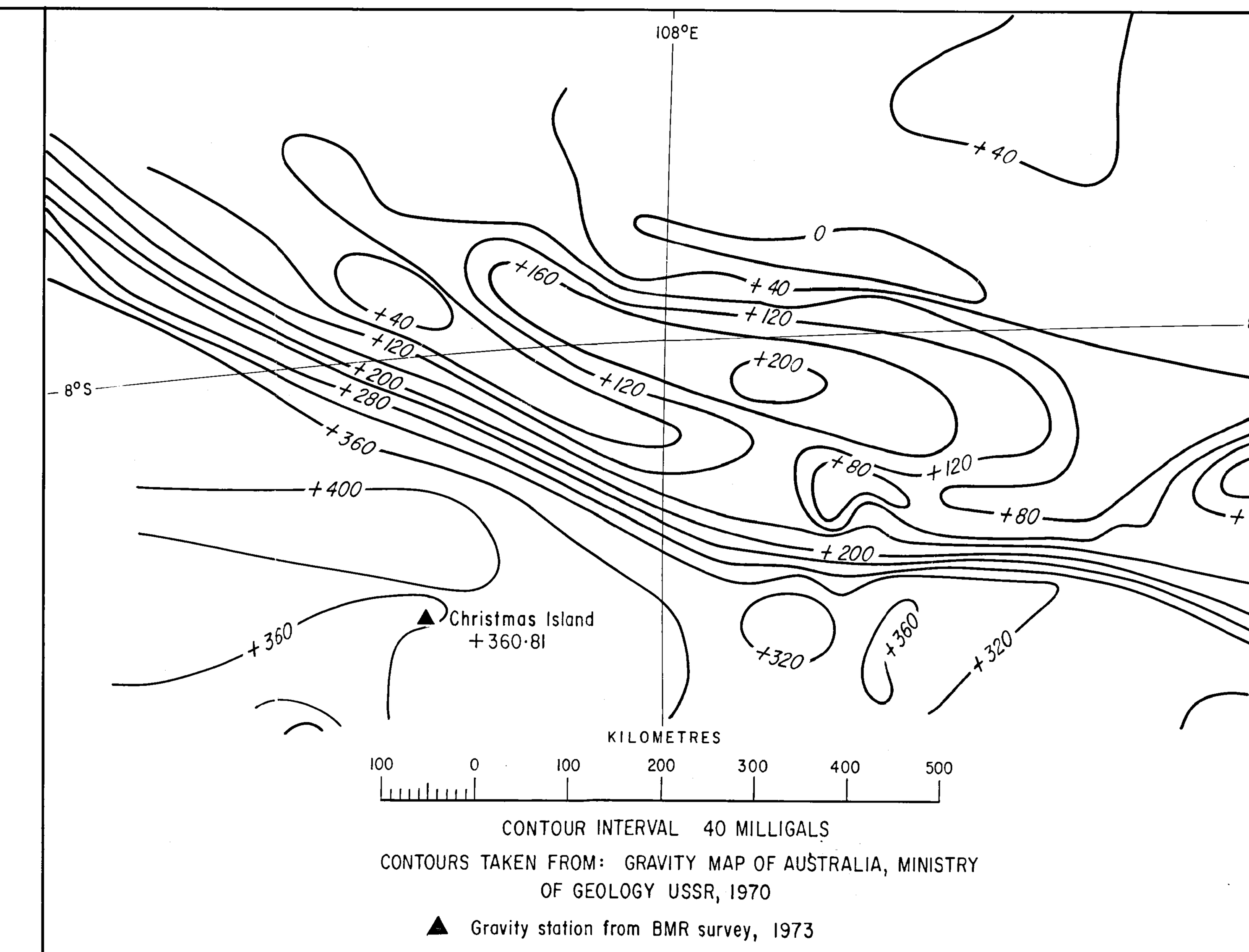
G450-31A

GRAVITY STATIONS
AUSTRALIAN NATIONAL GRAVITY NETWORK

Record No. 1976/11, 1976/100

Geophysical Branch, Bureau of Mineral Resources, Geology and Geophysics

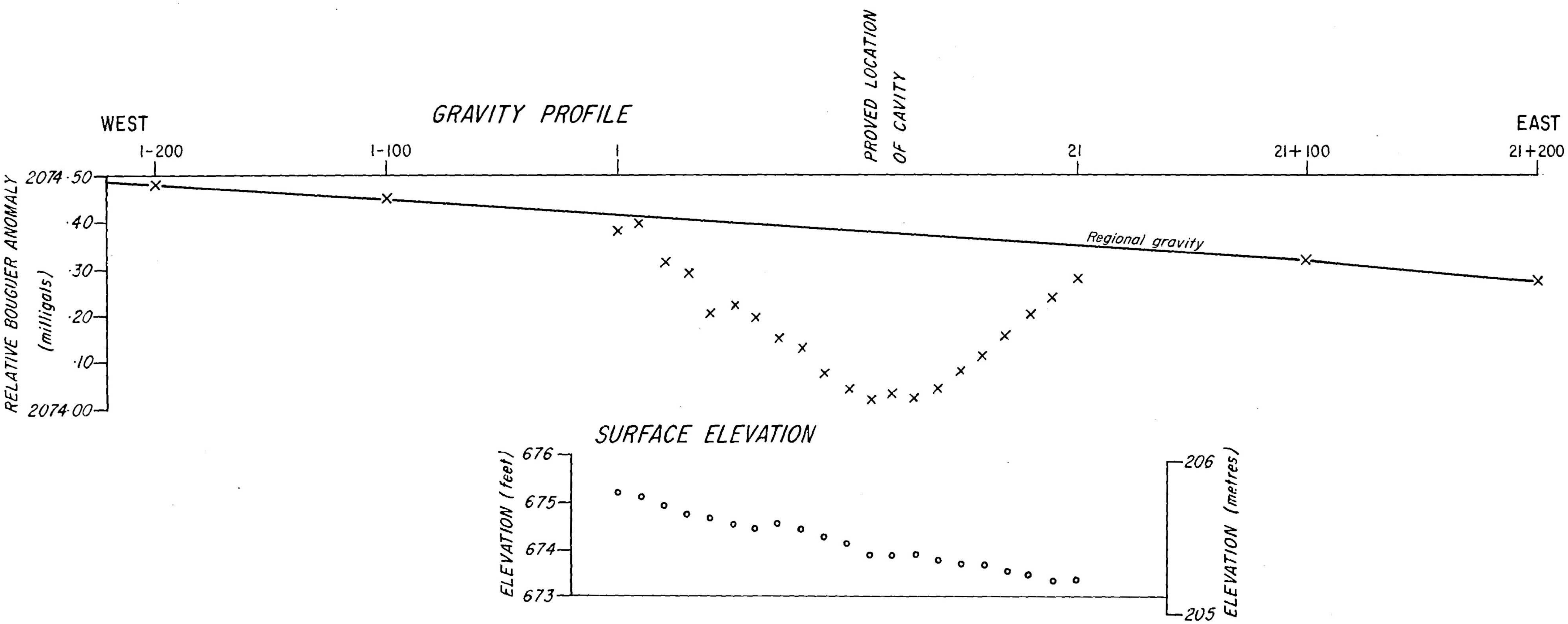




FREE-AIR GRAVITY ANOMALIES

PLATE 18. BATHYMETRY, PRELIMINARY BOUGUER AND FREE AIR ANOMALIES

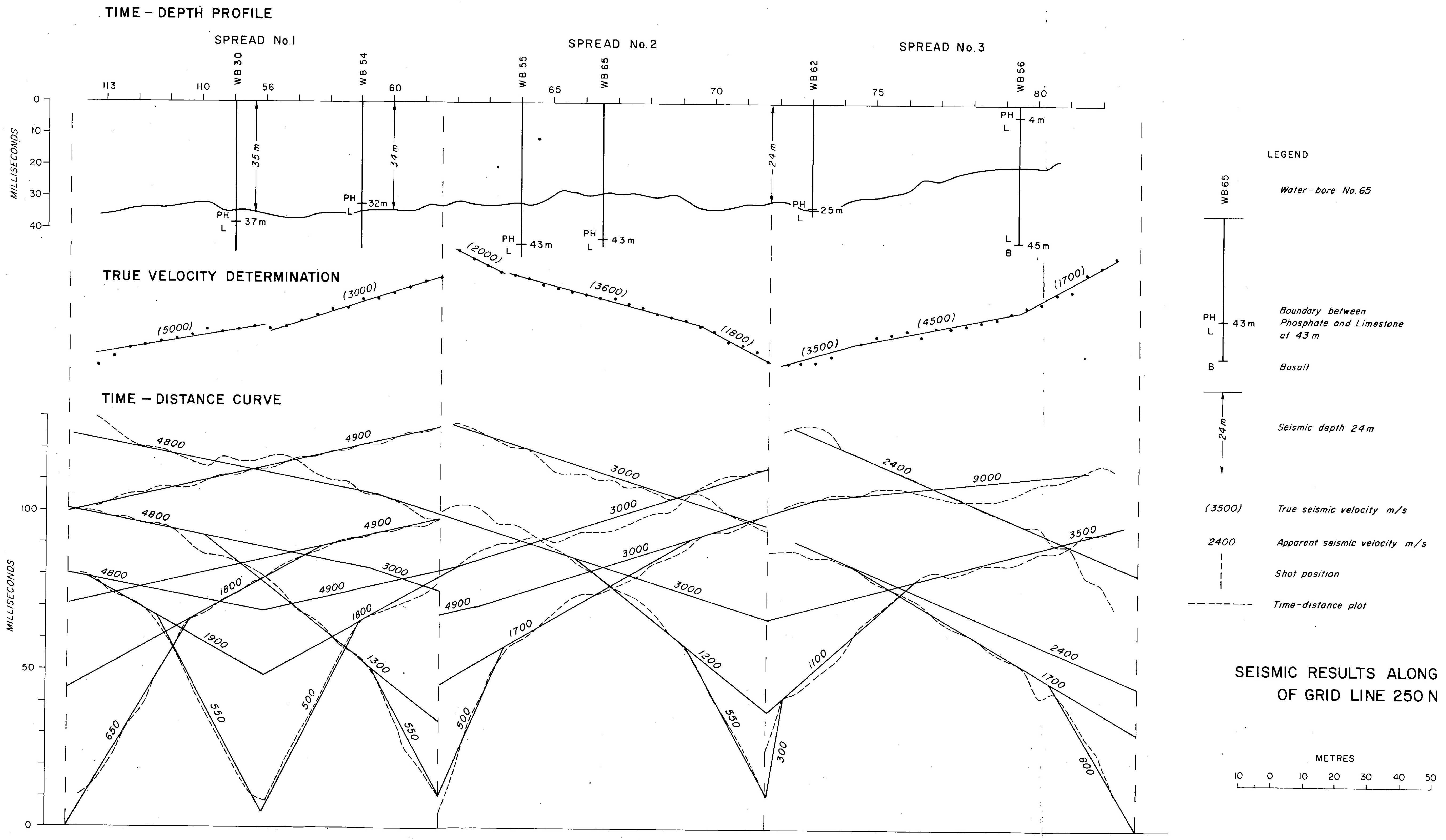
PLATE 19



GRAVITY PROFILE ALONG RAILWAY LINE NEAR JANE-UP.

Record No.1976/100

G450-24



SEISMIC RESULTS ALONG PART OF GRID LINE 250 N

Record No. 1976/100

G450-32

WATER ANALYSIS REPORT, GRANTS WELL — AMDEL COMPUTER SERVICES

SAMPLE NO. 74140001 — JOB NO. 4043-74

CHEMICAL COMPOSITION

		MILLIGRAMS PER LITRE MG/L	MILLIEQUIVS. PER LITRE ME/L
CATIONS			
CALCIUM	(CA)	64.	3.2
MAGNESIUM	(MG)	2.	.2
SODIUM	(NA)	9.	.4
POTASSIUM	(K)	<1.	.0
ANIONS			
HYDROXIDE	(OH)	.	.0
CARBONATE	(CO3)	.	.0
BICARBONATE	(HCO3)	212.	3.5
SULPHATE	(SO4)	4.	.1
CHLORIDE	(CL)	12.	.3
NITRATE	(NO3)	<1	.0
PHOSPHATE	(PO4)	.	.0

TOTALS AND BALANCE

CATIONS (ME/L) 3.7 DIFF = .1
ANIONS (ME/L) 3.9 SUM = 7.6

DIFF*100. / SUM = 1.7 %

DERIVED AND OTHER DATA

CONDUCTIVITY (E.C.) MICRO-S/CM AT 25 DEG. C 356.

	MILLIGRAMS PER LITRE MG/L
TOTAL DISSOLVED SOLIDS	
A. BASED ON E.C.	
B. CALCULATED (HCO3=CO3)	195.
C. RESIDUE ON EVAP. AT 180 DEG. C	194
TOTAL HARDNESS AS CACO3	168.
CARBONATE HARDNESS AS CACO3	168.
NON-CARBONATE HARDNESS AS CACO3	<5
TOTAL ALKALINITY AS CACO3	173.
FREE CARBON DIOXIDE (CO2)	
SUSPENDED SOLIDS	
SILICA (SIO2)	
BORON (B)	

	UNITS
REACTION - PH	8.0
TURBIDITY (JACKSON)	
COLOUR (HAZEN)	
SODIUM TO TOTAL CATION RATIO (ME/L)	10.4 %

REMARKS

PHOSPHATE PO4 0.01 MG/L

NAME-
ADDRESS-
DATE COLLECTED-26-10-73
DATE RECEIVED-

HUNDRED-
SECTION-
HOLE NO-GRANTS WELL
SUPPLY-
SAMPLE COLLECTED BY-

WATER CUT-
WATER LEVEL-
DEPTH HOLE-

Record No.1976/100

WATER ANALYSIS REPORT,JEDDA AMDEL COMPUTER SERVICES

SAMPLE NO. 74140002 JOB NO. 4043-74

CHEMICAL COMPOSITION

		MILLIGRAMS PER LITRE MG/L	MILLIEQUIVS. PER LITRE ME/L
CATIONS			
CALCIUM	(CA)	73.	3.6
MAGNESIUM	(MG)	3.	.2
SODIUM	(NA)	10.	.4
POTASSIUM	(K)	2.	.1
ANIONS			
HYDROXIDE	(OH)	.	.0
CARBONATE	(CO3)	.	.0
BICARBONATE	(HCO3)	242.	4.0
SULPHATE	(SO4)	4.	.1
CHLORIDE	(CL)	14.	.4
NITRATE	(NO3)	<1	.0
PHOSPHATE	(PO4)	.	.0

TOTALS AND BALANCE

CATIONS (ME/L)	4.4	DIFF =	.1
ANIONS (ME/L)	4.4	SUM =	8.8

DIFF*100. / SUM = .6 %

DERIVED AND OTHER DATA

CONDUCTIVITY (E.C.) MICRO-S/CM AT 25 DEG. C 366.

TOTAL DISSOLVED SOLIDS	MILLIGRAMS PER LITRE MG/L
A. BASED ON E.C.	
B. CALCULATED (HCO3=CO3)	225.
C. RESIDUE ON EVAP. AT 180 DEG. C	235
TOTAL HARDNESS AS CACO3	195.
CARBONATE HARDNESS AS CACO3	195.
NON-CARBONATE HARDNESS AS CACO3	<5
TOTAL ALKALINITY AS CACO3	198.
FREE CARBON DIOXIDE (CO2)	
SUSPENDED SOLIDS	
SILICA (SIO2)	
BORON (B)	

	UNITS
REACTION - PH	7.7
TURBIDITY (JACKSON)	
COLOUR (HAZEN)	
SODIUM TO TOTAL CATION RATIO (ME/L)	9.9 %

REMARKS

PHOSPHATE PO4 <0.01 MG/L

NAME-
ADDRESS-

DATE COLLECTED-27-10-73
DATE RECEIVED-

HUNDRED-
SECTION-
HOLE NO-JEDDA
SUPPLY-
SAMPLE COLLECTED BY-

WATER CUT-
WATER LEVEL-
DEPTH HOLE-

G450-29A

PLATE 22

Record No.1976/100

WATER ANALYSIS REPORT, JANE UP — AMDEL COMPUTER SERVICES

SAMPLE NO. 74140003 — JOB NO. 4043-74

CHEMICAL COMPOSITION

		MILLIGRAMS PER LITRE MG/L	MILLIEQUIVS. PER LITRE ME/L
CATIONS			
CALCIUM	(CA)	80.	4.0
MAGNESIUM	(MG)	2.	.2
SODIUM	(NA)	10.	.4
POTASSIUM	(K)	1.	.0
ANIONS			
HYDROXIDE	(OH)	.	.0
CARBONATE	(CO3)	.	.0
BICARBONATE	(HCO3)	261.	4.3
SULPHATE	(SO4)	3.	.1
CHLORIDE	(CL)	14.	.4
NITRATE	(NO3)	<1	.0
PHOSPHATE	(PO4)	.	.0

TOTALS AND BALANCE

CATIONS (ME/L) 4.6 DIFF = .1
ANIONS (ME/L) 4.7 SUM = 9.4

DIFF*100. / SUM = 1.3 %

DERIVED AND OTHER DATA

CONDUCTIVITY (E.C.) MICRO-S/CM AT 25 DEG. C 431.

	MILLIGRAMS PER LITRE MG/L
TOTAL DISSOLVED SOLIDS	
A. BASED ON E.C.	
B. CALCULATED (HCO3=CO3)	239.
C. RESIDUE ON EVAP. AT 180 DEG. C	245
TOTAL HARDNESS AS CACO3	208.
CARBONATE HARDNESS AS CACO3	208.
NON-CARBONATE HARDNESS AS CACO3	<5
TOTAL ALKALINITY AS CACO3	214.
FREE CARBON DIOXIDE (CO2)	
SUSPENDED SOLIDS	
SILICA (SIO2)	
BORON (B)	

	UNITS
REACTION - PH	7.6
TURBIDITY (JACKSON)	
COLOUR (HAZEN)	
SODIUM TO TOTAL CATION RATIO (ME/L)	9.4 %

REMARKS

PHOSPHATE PO4 0.01 MG/L

NAME-
ADDRESS-
DATE COLLECTED-26-10-73
DATE RECEIVED-

HUNDRED-
SECTION-
HOLE NO-JANE-UP
SUPPLY-
SAMPLE COLLECTED BY-

WATER CUT-
WATER LEVEL-
DEPTH HOLE-

G450-28A

PLATE 23

Record No.1976/100

WATER ANALYSIS REPORT,WATERFALL   AMDEL COMPUTER SERVICES

SAMPLE NO. 74140004   JOB NO. 4043-74

CHEMICAL COMPOSITION		MILLIGRAMS PER LITRE MG/L	MILLIEQUIVS. PER LITRE ME/L
CATIONS			
CALCIUM	(CA)	81.	4.0
MAGNESIUM	(MG)	7.	.6
SODIUM	(NA)	17.	.7
POTASSIUM	(K)	2.	.1
ANIONS			
HYDROXIDE	(OH)	.	.0
CARBONATE	(CO3)	.	.0
BICARBONATE	(HCO3)	277.	4.5
SULPHATE	(SO4)	3.	.1
CHLORIDE	(CL)	26.	.7
NITRATE	(NO3)	8.	.1
PHOSPHATE	(PO4)	.	.0

TOTALS AND BALANCE

CATIONS (ME/L)	5.4	DIFF =	.1
ANIONS (ME/L)	5.5	SUM =	10.9

DIFF*100. / SUM = .6 %

DERIVED AND OTHER DATA	MILLIGRAMS PER LITRE MG/L
CONDUCTIVITY (E.C.) MICRO-S/CM AT 25 DEG. C	457.
TOTAL DISSOLVED SOLIDS	
A. BASED ON E.C.	
B. CALCULATED (HCO3=CO3)	281.
C. RESIDUE ON EVAP. AT 180 DEG. C	280
TOTAL HARDNESS AS CACO3	231.
CARBONATE HARDNESS AS CACO3	228.
NON-CARBONATE HARDNESS AS CACO3	<5
TOTAL ALKALINITY AS CACO3	228.
FREE CARBON DIOXIDE (CO2)	
SUSPENDED SOLIDS	
SILICA (SIO2)	
BORON (B)	

	UNITS
REACTION - PH	7.7
TURBIDITY (JACKSON)	
COLOUR (HAZEN)	
SODIUM TO TOTAL CATION RATIO (ME/L)	13.7 %

REMARKS

PHOSPHATE PO4 0.01 MG/L

NAME-
ADDRESS-

DATE COLLECTED-29-10-73
DATE RECEIVED-

HUNDRED-
SECTION-
HOLE NO-WATER FALL
SUPPLY-
SAMPLE COLLECTED BY-

WATER CUT-
WATER LEVEL-
DEPTH HOLE-

G450-27A

PLATE 24