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TRANSIENT ELECTROMAGNETIC FIELD TESTS, NORTHERN TERRITORY AND QUEENSLAND, 1973

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SUMMARY

In 1973 the Bureau of Mineral Resources continued field tests started in 1972 of the Russian built MPPO-1 transient electromagnetic equipment. Data were acquired so that results could be compared with results from other geophysical methods as a basis for an evaluation of the transient electromagnetic method. The tests were made in selected parts of the Rum Jungle area, NT, and of the Mount Isa/Cloncurry area, Qld.

The transient electromagnetic fieldwork was at times slower than other types of electromagnetic fieldwork, but more information was available per reading. One set of transient electromagnetic readings at a station is equivalent to a set of a large number of variable-frequency readings.

Experiments with a dual-loop configuration demonstrated advantages of a dual loop over a single loop for steeply dipping narrow conductors. Other experiments showed that the transient electromagnetic method can be used for resistivity profiling and depth-sounding in appropriate circumstances. The depth-sounding experiments showed reasonable correlation between results from large loops and theoretical results. Further work is recommended to study the response from small loops.

In one area surveyed in the Mount Isa Cloncurry area, anomalously low and negative transient electromagnetic values were obtained over parts of a conducting shale which should have given high values throughout, and field and laboratory work are recommended to investigate this phenomenon.

1. INTRODUCTION

In 1973 the Bureau of Mineral Resources (BMR) continued field tests, started in 1972, of the Russian built MPPO-1 transient electromagnetic TEM equipment. Data were acquired so that results could be compared with results from other geophysical methods as a basis for an evaluation of the TEM method. The 1972 field tests are described by Spies (1974b). In 1973 the field tests were made in the Rum Jungle area, Northern Territory, and in the Mount Isa/Cloncurry area, Queensland.

In the Rum Jungle area (Plate 1), the field tests were made over a well defined conducting shale bed in the Mount Minza area, and over conducting shale and sulphide mineralization in the Woodcutters area; both these areas have had geophysical surveys made in them in previous years, and are areas where TEM field tests were made in 1972. Traverses were surveyed between stratigraphic drill holes in the Gould and Crater Lake areas. The holes were drilled in 1973 to obtain information regarding the boundary between the Coomalie Dolomite and the Golden Dyke Formation and the TEM surveys were made to determine if the method can be used to locate the boundary.

In the Mount Isa/Cloncurry area (Plate 7), the field tests were made in an area of black shale in the Corella Formation about 15 km west of Mary Kathleen; in the Dobbyn area; and in two areas of Mesozoic sediments east of Cloncurry. Other geophysical results were available in each of these areas.

The Rum Jungle area TEM surveys were made in early July and early August 1973 by I. Hone; the Mount Isa/Cloncurry area TEM surveys were made in September and October by B Spies. Other personnel were J.W. Williams (Technical Officer) and two field hands.

In 1973 the TEM method was also used in the Mary River area, Northern Territory (Hone & Major, in prep.) and in areas in the Mount Isa/Cloncurry area, Queensland (Sampath, in prep.).

2. TRANSIENT ELECTROMAGNETIC METHOD

The TEM method is described in detail by Spies (1974b). It operates on the principle of inducing eddy currents in the ground and analysing their decay; this provides information on subsurface conductors. A single ungrounded loop both transmits the primary energizing field and senses any secondary currents set up by subsurface conductors. The equipment consists essentially of a voltage pulse generator/secondary signal measuring unit, power supply unit, and various size transmitter/receiver loops.

The generator produces periodic rectangular current pulses in the loop laid out on the ground surface. If a conductor is present in the vicinity of the loop, the sudden change in magnetic field at the edge of a current pulse will induce eddy currents in the conductor which will tend to oppose the decay of the field. Such eddy currents produce a secondary electromagnetic field which will decay with time in the same manner as the eddy currents. A time dependent emf, e(t), is induced in the loop in the interval between the current pulses, and is proportional to the time derivative of the secondary magnetic field.

The measuring unit averages the signal received from a loop over several hundred cycles at a particular time, t, after the transmitting pulse terminates, and gives a voltage, e(t). With the MPPO-1 equipment used the voltage is obtained at twelve separate sample times between $\frac{1}{2}$ ms and 15 ms.

The results are shown as decay curves or as profiles or contours of e(t) at different sample times. In practice e(t)/I is used rather than e(t), where I is the current in the loop.

In general, strong conductors induce emfs which decay more slowly than those from weak conductors and a comparison of an anomaly recorded at different sample times should indicate the conductivity of the source.

3. RESULTS FROM THE RUM JUNGLE AREA, NORTHERN TERRITORY

Geology

The geology of the area is described by Walpole et al. (1968). Two granitic complexes occur in the area, the Rum Jungle and Waterhouse Complexes. These are overlain by rocks of the Batchelor Group (Beestons Formation, Celia Dolomite, Crater Formation, and Coomalie Dolomite), which in turn are overlain by rocks of the Golden Dyke Formation of the Goodparla Group. All the sedimentary rocks are Lower Proterozoic; the complexes are Proterozoic to Archaean.

The surveys were made over Coomalie Dolomite and the Golden Dyke Formation. The Golden Dyke Formation consists dominantly of dolomitic and carbonaceous siltstone; pyrite is a common constituent of the carbonaceous rocks. The Formation is intruded by amphibolite. The Coomalie Dolomite consists of algal dolomite, silificied dolomite, marl and slump breccia, black calcilutite and siltstone, tremolite schist, and coarse marble (Walpole et al., 1968).

Much of the mineralization in the Rum Jungle area occurs in the basal beds of the Golden Dyke Formation. East of the Waterhouse Complex (for example, in the Gould area) these beds consist of weakly pyritic, calcareous pale green siltstone; east and southeast of the Rum

Jungle Complex (including the Crater Lake traverse) they consist of pyritic, graphitic, calcareous shale (Johnson, 1974).

Woodcutters area

The TEM method in the Woodcutters area was used over black shale of the Golden Dyke Formation known to produce Slingram and Turam electromagnetic anomalies and over sulphide mineralization so that the results could be compared with the previous geophysical work and with the mapped geology. The old survey grid was reconstructed from 201S to 230S using drill-collars for reference. The area was surveyed with 60-m loops, and traverse 220S was surveyed in detail with 200-m, 100-m, 60-m, and 30-m loops to define the anomalies more exactly. The area is immediately south of the area surveyed in 1972 (Plate 1).

Spies (1974b) summarizes previous investigations in the Woodcutters area; Crohn Langron, & Prichard (1967) stated that no electromagnetic anomaly is likely to be obtained over the mineralization in the area because of lack of conductivity contrast between the mineralization and the surrounding highly conducting slate.

Contour maps of the TEM response over the grid for delay times of 1.1, 3.2, and 8.2 ms, together with geology from Shatwell (1966) and Slingram anomaly axes from Duckworth (1966), are shown in Plate 2. In the west of the area surveyed there is correlation between the TEM high and the westernmost Slingram anomaly. The Slingram anomaly immediately east correlates only with TEM highs at early delay times suggesting a superficial conductor. A TEM high runs through the centre of the area surveyed and correlates with another Slingram anomaly; this is an extension of the high found by Spies in 1972.

Correlation of the TEM results with the geology mapped by Shatwell (1966) is not good. The eastern black shale did not produce a response, and no distinct rock type has been recognized for the conducting horizon which runs through the centre of the area surveyed. The amphibolite and chloritic schist have no characteristic response. The mineralization lies in the eastern region of low TEM response and, as predicted, has no characteristic response.

In general, the rocks in the area surveyed are completely weathered to 35 m and partly weathered to 60 m (Crohn et al., 1967). The Slingram results indicate a subsurface horizontal conductor in most of the Woodcutters area at 45 m (Duckworth, Farrow, & Gardener, 1968) within the partly weathered zone. This conductor was detected at all stations with the 60-m loops at early delay times, indicating the total depth penetration was more than 45 m.

Traverse 220S was surveyed with 200-m, 100-m, 60-m, and 30-m loops. No loop overlap was used with the 200-m loops and as only a few stations were read the results are not shown. The strongest TEM anomaly is in the centre of the survey area and corresponds to Slingram and gravity anomalies interpreted to be caused by a high in the unweathered slate (Gardener, 1968b). The TEM profiles (Plate 3) show that all loop sizes produced anomalies at all delay times, and so the top of the conductor must be fairly close to the surface. The western conducting zone was only surveyed adequately with 60-m loops. The results show anomalies at early delay times; small responses were obtained at late delay times. The results indicate near-surface conducting zones, possibly due to products of weathering. The unweathered zone is fairly shallow in the centre of the area, but in the western part of the area it is probably at a depth where it is at the limit of detection using 60-m loops.

Mount Minza area

In the Mount Minza area an 1800-m-long highly conducting carbonaceous shale bed occurs as a 30-m thick tabular body dipping west and striking north. A less conducting black shale bed occurs 90 m east. The rocks in the area are part of the Golden Dyke Formation; weathering depth of is about 15 m.

Geophysical surveys in the area using Slingram, Turam, S-P, and IP methods revealed strong anomalies over the highly conducting shale bed (Shatwell & Duckworth, 1966; Farrow, 1967; Duckworth, 1968). In 1972, Spies (1974b) used the TEM method on traverse 201S with 60-m loops in a reconnaissance mode, and obtained a strong anomaly over the conducting shale.

In 1973, traverse 201S was surveyed with 100-m, 50-m, 25-m, and 10-m loops with loop overlap to provide more detailed information to assist the interpretation of the anomaly. Plate 4 shows TEM profiles along the traverse and the inferred geological section after Duckworth (1968). The conducting shale was detected with all loop sizes.

Profiles at early delay times are mainly from the near-surface weathered zone, and those at late delay times are from the deeper unweathered zone. The westerly dip of the conductor causes asymmetry in profiles, particularly at late delay times, owing to the deeper western part of the conductor being detected.

The eastern, less conducting, black shale was detected with the 25-m, 50-m, and 100-m loops. The profiles for the 100-m loops indicate overlap of anomalies from the two conductors, particularly at late delay times. The anomalies from the conducting shale are larger with larger loops, indicating deeper penetration into more-conducting unweathered rock. In particular, the small amplitudes obtained with the 10 m loops indicate that the response is probably entirely from the weathered zone.

Gould area

A TEM traverse was surveyed with 60-m loops between three stratigraphic drill holes in the Gould area (Plate 1) to determine if the Coomalie Dolomite and the Golden Dyke Formation give responses sufficiently different for the boundary between them to be mapped.

TEM profiles are shown in Plate 5 with the approximate locations of geological and electromagnetic boundaries mapped by Shatwell & Duckworth (1966). The electromagnetic boundaries are based on a Slingram survey and are between, from west to east, an undisturbed Slingram area over Golden Dyke Formation, an area of disturbed Slingram real and imaginary components over amphibolite, and an area of large Slingram real component anomalies generally over Golden Dyke Formation, found east of the section in Plate 5. This Formation gave two types of response in the Gould area. Plate 5 also shows the drill-hole positions and the formations they penetrated.

The TEM results correlate well with the Slingram results. A high TEM response was obtained over the area of disturbed Slingram response. The western area has virtually no TEM response. Drill holes R2 and R3 passed through very weathered rock of the Golden Dyke Formation. Drill hole R3 intersected Coomalie Dolomite at about 40 m. The results indicate that the TEM method is unlikely to be able to detect the boundary between the Coomalie Dolomite and the Golden Dyke Formation in the Gould area since the western part of the Golden Dyke Formation does not contain zones of sufficient conductivity.

Crater Lake area

The Crater Lake area is in the Coomalie Creek area. A TEM traverse using 30-m loops was surveyed between three stratigraphic drill holes to determine if the boundary between Coomalie Dolomite and the

Golden Dyke Formation can be mapped.

The drill-hole positions and the geology mapped by Willis (1969) are shown in Plate 6. Drill hole R6 intersected Coomalie Dolomite, and the TEM response here was small and decayed quickly. Holes R4 and R5 intersected black calcareous graphitic pyritic shale of the Golden Dyke Formation, which produced a higher TEM response with a slower decay.

The results indicate that a conductivity contrast between the Coomalie Dolomite and the Golden Dyke Formation that is detectable with the TEM method exists in the area. The contact between the two formations on the traverse probably occurs at about 280S.

4. RESULTS FROM THE MOUNT ISA/CLONCURRY AREA, QUEENSLAND

BMR Cloncurry No. 5 area

This area surrounds the BMR Cloncurry No. 5 diamond-drill hole, which was drilled into a black shale unit in the upper part of the Corella Formation, and is about 15 km west of Mary Kathleen (Plate 7). The Corella Formation is in the eastern succession of the Lower Proterozoic or Carpentarian Cloncurry Complex and consists essentially of calcareous, pelitic and psammitic sediments metamorphosed to slate, schists, quartzite, and calc-silicate granofels of the greenschist facies.

The geology of the area is shown in Plate 8. The area is in a shallow north-plunging syncline which is faulted locally by a set of northeast-trending strike-slip faults. Other minor north-northeast and north-northwest faults break the area into fault blocks. Laminated calcareous siltstone of the uppermost member of the Corella Formation is exposed in the southeast and in the western third of the area where it has a north-northwesterly strike and an easterly dip of 45° to 60°. The central part of the area is underlain by black to dark grey carbonaceous shale which conformably overlies the laminated calcareous siltstone to the west and is faulted against it in the east. This shale contains conformable lenses up to 50 cm long and 5 cm thick of pyrrhotite and pyrite which weather to limonite near the surface. The shale occurs in open basin-and-dome folds, and dips rarely exceed 40° (I.H.Wilson, pers. comm.).

Several areas of Cainozoic to Recent gravels occur in the northeastern part of the area and are rarely more than 2 m thick. Recent alluvium up to 5 m thick occurs along the banks of Charleys Creek, which trends in a west-northwesterly direction across the northern part of the area.

The area was chosen for TEM work because subsurface information was available from the diamond-drill hole and because geophysical results were available from other methods. The TEM results revealed an unexpected negative response in the south of the area and a near-zero response in the centre of the area, locations where the conductive black shale was expected to produce a large TEM response. Before analysing the TEM response, the induced polarization (IP), self-potential (S-P) and magnetic results of Sampath (in prep.), and detailed IP results obtained during the course of the TEM survey will be discussed. The IP results for traverses 100N and 300N using 60-m dipoles (Plate 9) show the high conductivity and polarizability of the black shale. On traverse 100N, apparent resistivities as low as 6 ohm-m were measured in the centre of the black shale, while on 300N apparent resistivities were less than 1 ohm-m. The western boundary of the conductive zone correlates fairly well with the lithological boundary of the black shale/ calcareous siltstone at about 300E, but to the east the resistivity boundary occurs within the mapped black shale at about 63E on 100N, and 700E on 300N. A contour map of apparent resistivity for n= 2 is shown in Plate

10; the main feature is a decrease in the resistivity towards the north. The resistivity low at 480E on traverse 300N coincides with S-P and magnetic anomalies.

A contour map of TEM response at 2.3 ms is also shown in Plate 10. The anomalous area occurs over the black shale, the contours following the same trend as the apparent resistivity contours. The largest TEM response occurs at 480E in the north of the area and coincides with the position of anomalies found with other methods.

To investigate the area more fully, a north-south traverse was surveyed on 480E using TEM (60x50-m and 25x30-m loops) and IP (25-m dipole spacing), the results of which are presented in Plate 11. Negative TEM values were obtained south of 130N, with a plateau of low amplitude TEM response just to the north. A highly conductive body at about 300N would cause the large anomaly in the north of the area; alternatively the shale may be more conducting in the north.

The 25-m dipole IP data (Plate 11) show that generally there is a near-surface resistive layer underlain by more conducting rocks which to the north of the drill hole have apparent resistivities as low as 0.1 ohm-m. Frequency effects along the traverse are fairly consistent, being about 20 percent.

Assuming that the black shale has a resistivity of about 5 ohm-m in the centre of the area it would be expected that the TEM response for a 50-m loop would be 400 microvolts at 1 ms, and 70 microvolts at 2 ms; clearly from Plate 11 this is not so. To explain the TEM response it is necessary to examine the transient decay curves. Typical transient decay curves are given in Plate 12. Curves A, B, C, and D are for various black shale units surveyed in 1972 and 1973 in the Northern Territory and Queensland. Decay curves at 480E/150N, 200N and 375N in the BMR Cloncurry No. 5 area are also shown; the curves at

480E/150N and 200N have large amplitudes at early times, but have decayed to zero by 3ms. Decay curves are also shown in Plate 13, where a linear display has been used to enable negative values to be plotted. Around 100N the transient is initially positive, then goes negative and recovers with low amplitude to zero. Around 50N the transient is entirely negative for all sample times measured. The negative readings were present for different loop sizes and also when the loop was lifted off the ground to counter any possible capacitive coupling effects.

The validity of the negative values was demonstrated by a set of readings taken independently by CSIRO with equipment with digital signal storage facilities which average the signal over many hundreds of cycles; these results are also shown in Plate 13.

There are two possible causes of the anomalous transient response:

(a) an IP effect being measured inductively, and

(b) interference effects caused by layering.

(a) Inductive IP measurements. The first hypothesis is that IP effects are being recorded inductively by the TEM equipment. Time-domain IP transient decays have the opposite polarity to TEM transient decays and, if an IP effect was being introduced into the TEM response, negative values or anomalously fast decays could theoretically be recorded. Morrison, Phillips, & O'Brien (1969) describe the effect of polarization on TEM response, and state that polarization effects are detectable for certain types of polarization; measurements were made on several mineralized rock samples of the complex conductivity function which reduces to expressions involving the apparent rock conductivity and apparent rock dielectric permittivity. The transient response for one of the samples (IP-1, p.98) had a fast decay which crossed zero and recovered with a very low amplitude. The curve is similar to anomalous decay curves shown in Plates 12 and 13 from the BMR Cloncurry No. 5 area. The rapid decay is explained by the use of Ampere's law involving a time-derivative term (related to dielectric permittivity) which is normally neglected. Morrison et al. (Op.cit.) state that if the time-derivative term is dominant, the secondary magnetic field must be negative with positive slope, resulting in a decay curve such as IP-1.

From the results in Plate 11, it can be seen that the frequency effect is fairly constant along the traverse, and that north of the drill hole values of apparent resistivity decrease markedly. This decrease could explain the change in shape of decay curves (Plate 13) on different parts of the traverse, the response being more inductive north of the drill hole owing to increased conductivity. However, Hohmann et al. (1970) describe field tests conducted in two areas containing strong conventional IP anomalies to determine experimentally whether inductive IP measurements are feasible. The field tests consisted of measurements of the amplitudes of the electric and magnetic fields about an horizontal loop of wire carrying current at frequencies ranging from 15 Hz to 1500 Hz. The presence of polarizable material was not evident in the inductive data; in fact, the observations could be fitted to theoretical curves for non-polarizable models.

Thus it is not clear whether an IP effect can be measured inductively.

(b) Reflection phenomena. Another possible explanation for the negative TEM readings is that they are electromagnetic reflection phenomena involving interference between different parts of the frequency spectrum. The reflection phenomenon is discussed by Yost et al. (1952), who described a model study of transients using a flat horizontal loop over stacks of horizontally layered sheets of metallic materials. When a ½-inch sheet of Dow metal was introduced at a depth of ½-inch in a stack of aluminium sheets, the signal received was modified such that the reflected signal first increased, then rapidly decreased to negative values, before recovering to zero. However, only the reflected signal was measured in this experiment; the signal produced from the homogeneous, or boundary wave, signal was cancelled out. Thus it is not known if reflection phenomena can be of such a magnitude to make the total transient negative. This would be a case to test with scale-model studies.

Quantitative analysis of the apparent resistivity data from the 25-m dipole IP survey was attempted in order to determine the main geological differences across the area. Referring to Plate 11 for 25-m dipoles it can be seen that the pseudo-section can be separated into three portions:

(a) around 100 N

(b) around 200 N

(c) around 300 N

For each, the ground may be considered to be ronghly horizontally layered with a resistive layer overlying a more conductive layer. By using apparent resistivity values for n = 2,3,and 4 in the above three portions a depth section was computed using a resistivity inversion program of Vozoff & Jupp (1974).

Portion (a) fits well to a model consisting of a top layer of thickness 15 m having a resistivity of 33 ohm-m and a lower layer with resistivity of 4 ohm-m. For portions (b) and (c) the top layer thins to 11.6 m and 7.7 m respectively while the lower layer has much lower resistivity of 0.2 ohm-m. South of 25N the response is indicative of a lateral resistivity contact, possibly due to the calcareous siltstone.

Referring to Plate 9 for 60-m dipoles the top thin resistive layer is no longer visible; this agrees with scale-model studies when the layer is much thinner than the dipole spacing. The anomaly at 300N is interpreted as being caused by a wide conductive body extending to at least 150 m depth. The anomaly at 100N is more complex: it has a similar pattern to a 200-m-wide body, infinite in depth extent, except for the gradual increase of apparent resistivity values with depth. A finite body extending to a depth of 80 m would give a gradual increase but would have very high apparent resistivity values in the centre for n = 4 and 5, which do not appear in the field data. It is possible that a combination of the cases occurs, that is, a top conductive body about 50 to 150 m thick grading into a less conductive body at depth.

It can be seen that except for a top, thin, resistive layer there are no other near-surface layers evident from the data which could cause reflection phenomena.

Appendix 2 gives measurements made on samples from the BMR Cloncurry No. 5 drill hole. Frequency-domain and time-domain IP measurements were made on samples from one foot, 27ft, 58 ft, 61 ft and 61 ft 3 in depths. The high IP readings are consistent with the field data. The resistivity measurements on the drill-core samples support the field results and indicate the existence of a near surface zone of high resistivity underlain by zone of much lower resistivity.

There is an obvious need for more work to explain the anomalously low and negative TEM values, to examine the type of environment in which a highly conductive sequence can be missed when using the TEM method, and to determine if IP is in fact being measured inductively, and if so, whether the TEM system can be modified to develop an inductive IP tool and in which environments such a tool would be successful.

To gain better geo-electric control in the BMR Cloncurry No. 5 area resistivity and induced polarization depth-soundings should be made at 100N, 200N, and 300N. If the depth-soundings are not successful because the ground is not sufficiently horizontally layered, geo-electric control could be obtained from a vertical drill hole south of BMR Cloncurry No. 5 at about 70N, drilled to at least 150 m or until it passes through the black shale into the underlying resistive formation, whichever is shallower. IP and resistivity logs should be run and laboratory measurements should be made on the core. The geological section could then be modelled to determine whether the cause of the anomalous values are reflection phenomena, or an inductive IP response is being recorded.

Dobbyn area

Results of TEM model studies carried out by BMR indicated that a dual-loop configuration gives optimum detectability of a narrow steeply dipping conductor (Spies, in prep.). A dual loop consists of two adjoining single loops connected in series.

The Dobbyn area was chosen to make field tests using the dual-loop configuration. The area has been extensively surveyed with geophysical methods such as IP, Turam, gravity, magnetic, and S-P, the results of which are described by Gardener (1964, 1965) and Smith (1968).

The area lies within the Leichhardt Metamorphics which Carter, Brooks & Walker (1961, p.60) describe as consisting essentially of highly to moderately metamorphosed acid lavas, with some metamorphosed sediments, metabasalts, and rare tuff. More detailed geological studies in the Dobbyn area by W.B. Dallwitz are included in earlier geophysical reports (Gardener, 1964, 1965, 1968a) and some are included in this report.

Eight diamond-drill holes were drilled in 1966 to test geophysical anomalies found in earlier surveys, the results indicating that induced polarization anomalies are due to sulphides, predominantly pyrite, which occur in steeply dipping narrow lodes (Gardener, 1968a). Resistivity measurements on core samples gave values for the mineralized zone as low as 50 ohm-m, and for the host-rock of several thousand ohm-metres.

Several traverses were chosen for TEM work over diamond-drill holes where drilling results indicated the presence of steeply dipping narrow mineralized zones. These were DDH 1, 2, 4, 6, 10, and 11. Traverses were pegged at 25-m intervals and tied in to permanent marks put in by Gardener (1965). Initially 50-m loops were used with 50 per cent loop overlap to outline the anomalies, and then one traverse was chosen over DDH 1 for detailed work using different loop sizes. Signal Levels on all traverses were generally low because of the moderate conductivity and limited size of the mineralized body. Reading accuracy was about 5 microvolts in this area owing to a moderate amount of electrical interference.

Detailed work was done on traverse DDH 1 (traverse 7000N of the old grid). The geological log of DDH 1 given by Gardener (1968a) shows basic rock (altered dolerite) from 77 to 119 m (253 - 391') with acid volcanic rocks above and below. A sulphide zone, intersected near the bottom of the basic rock, extends a few feet into the lower acid volcanics. Plate 14 gives a comparison of geophysical results. Gossan occurs on the surface at 2400E, and if the sulphides intersected by DDH 1 are continuous with the gossan the sulphide zone has a steep easterly dip.

Sulphides are the source of the IP anomaly. A local magnetic low of 150 gammas coincides with the Turam anomaly. The magnetic profile also shows high magnetic values east and west of the Turam anomaly. The frequency effect anomaly is closest to the surface at the Turam anomaly, and this suggests the existence of near-surface sulphides not intersected by the drill hole.

The TEM results using 100-m, 50-m, and 25-m loops are shown in Plate 15 for both single-loop and dual-loop configurations. The profile shapes obtained are similar to the response of a narrow steeply diping near-surface conductor obtained from model studies (Spies, 1974a, in prep.). The profile shape for a single loop has two maxima separated by a distance equal to the loop size. The dip of the body can be computed from the ratio of the amplitude of the larger peak to the smaller peak by the relation:

$$\frac{e(t)\ max_L}{e(t)\ max_S} = e^{2.7\phi}$$ (Velikin & Bulgakov, 1967, p.14)

where ϕ is the angle between the plane of the plate and the vertical,
$e(t)\ max_L$ is the amplitude of the larger peak,
$e(t)\ max_S$ is the amplitude of the smaller peak,
substituting the values derived from the profiles, $\phi = 20^\circ$ (dip = 70°) for both 100-m and 50 m loop sizes; this agrees with the 80° dip estimated from drilling results (Plate 14).

Results with the dual-loop configuration are also shown. The main peak occurs directly over the top of the body, with a smaller peak either side. The profile shape agrees with the shape from model studies. For a dipping body the minor peak on the down-dip side is larger than the one on the up-dip side. A relation evidently exists between the amplitudes of the peaks and the dip of the conductor and modelling has been done (Spies, in prep.) to investigate the relation.

Advantages of the dual-loop configuration are a reduction of electrical interference from sources where the phase is identical in the two loops (power lines, etc.), and the production of an anomaly peak directly over the top of the conductor instead of to the side as with a single loop. Disadvantages are that electrical interference from impulse sources (such as wind moving the loop wire) may be increased, and the additional time required to lay out the dual loop.

Pymurra and Arrolla areas

A TEM survey was made east of Cloncurry in the Pymurra and Arrolla areas (Plate 7), which are extensively covered by Canozoic sandy and black soil underlain by Mesozoic sandstone, mudstone, and shale which locally form the western limit of the great Artesian Basin. Undifferentiated Precambrian rocks underly the Mesozoic sediments and crop out in the western part of the Pymurra area.

The survey was carried out with the aim of determining if TEM profiling can be used to detect lateral variations in resistivity of Precambrian rocks buried under Mesozoic sediments and of determining if the TEM method can be used for depth-sounding. Both the areas surveyed had independent geo-electric control from resistivity profiling and depth-sounding data.

TEM profiling. Traverse 25N in the Pymurra area was surveyed from 8000W to 2500E using 50-m loops. The results, and those obtained from a resistivity survey using a Schlumberger configuration carried out by Ogilvy (in prep.), are shown in Plate 16. Precambrian rocks crop out in the west of the area and are characterized by a fairly low TEM response. The Mesozoic cover starts at about 3000W and thickens to the east. The resistivity results show that these sediments are highly conductive and cause the higher TEM response in the east of the area.

There is reasonable correlation between the TEM results and the resistivity results. Slate beds around 7600W and 7100W are more conducting than adjacent beds, and cause TEM anomalies of up to 80 microvolts/amp at t = 1.1 ms. The anomaly at 6100W could be caused by saline water under the creek bed and cannot definitely be attributed to changes in Precambrian rock type. The low apparent resistivity anomaly at 4500W has no corresponding TEM anomaly.

The asymptotic expression for the TEM response of a homogeneous half-space is given in Appendix 1 as

$$\frac{e(t)}{I} \simeq 1.58 \times 10^{-16} \quad \frac{b^4}{t^{5/2}} \; \sigma^{3/2}$$

where b = radius of loop (metres)

t = sample time (seconds)

σ = conductivity of the half space (mho/m)

Thus, over a uniform ground a transient decay curve at late times will have a slope of -2.5 on a log-log plot, and the conductivity can be derived from e(t)/I. Using this relation for decay curves at 7100W (slate) and 8000W (amphibolite and volcanics), the resistivities are calculated at 10 ohm-m and 50 ohm-m respectively, and agree reasonably well with the resistivity data. Thus in the area of Precambrian outcrop surveyed the resistivity contrast is only about five.

The conducting Mesozoic cover begins at about 3000W and thickens to the east. Resistivity depth-soundings show this layer to be 10 m thick at 2000W, 60 m thick at 00, and 90 m thick at 1500E, to have a resistivity between one and ten ohm-metres, and to be overlain by Cainozoic sediments 5 to 10 thick with resistivities of 5 to 30 ohm-m (Ogilvy, in prep.). In general the TEM response increases to the east, corresponding to a decrease in resistivity. Minor variations in the profiles could be caused by variations in the thickness of the Mesozoic and Cainozoic sediments. It must be concluded that unless there are units in the Precambrian strata which have much lower resistivities than that of the Mesozoic sediments (and this was not so in the Precambrian outcrop in the western part of the traverse), the TEM method is not able to detect lateral variations in resistivity beneath the Mesozoic cover.

TEM depth-sounding. Different elements of a transient decay curve contain differing proportions of high and low frequency components, and thus the possibility arises of using the TEM method for depth-sounding. Morrison et al. (1969) point out that at early times the response is due to both low and high frequency groups, whereas at later times only the low frequency response remains; this observation, coupled with the fact that skin depth varies inversely as the square-root of the frequency, suggests that the early part of the transient response is governed by the rapid decay at shallow depths whilst the later part of the response is due to the lower frequency energy which has penetrated to greater depths. This agrees with theoretical studies of Wait (1956) and Negi & Verma (1972) and results of scale-model studies (Spies, 1974a).

Lee & Lewis (1974) have calculated the TEM response of various multilayered structures and have shown that at short times the induced voltage is asymptotic to that produced for a uniform ground of conductivity equal to the top layer. Occasionally, at larger times, the curves asymptotically approach the curve for a half-space with the conductivity of the lower layer. By analysing the shape of the transient decay curve it is possible to distinguish layers at depths of up to twice the loop size.

TEM depth-soundings were made at four locations in the Pymurra area and one in the Arrolla area. Loop sizes used were 100, 50, 25, 12, 6, 3, 1.5 and 0.8 m square. Up to four loop positions were read for each loop size at each locality and averaged, and measurements were made at all sample times possible (20 in all). When using small loop sizes, up to 48 turns of wire were used to measure the small response which, when corrected for the number of turns used, was as low as one nannovolt/amp. When using multiturn loops it was necessary to ensure that false transients due to self-inductance were not recorded. This was achieved by measuring e(t)/I at early times with an increasing number of turns of wire and verifying that the response was proportional to the square of the number of turns. With the smallest loop it was possible to lift the loop off the ground so that the response of the ground was negligible, to check that false transients were not recorded.

Geo-electric control was provided from resistivity depth-sounding using equatorial dipole and Schlumberger arrays (Ogilvy, in prep.).

The decay curves at Pymurra 00 are representative of the depth sounding results and are presented in Plate 17. For large loops at early times the curves have a fairly constant slope of about -3, whereas at late times the curves tend to flatten out. For small loops all the curves have a constant slope of about -1.5.

The theoretical expression for the asymptotic response of a half-space (Appendix 1) was used as a first approximation for the response using the 100-m loop.

Substituting values in this expression the apparent conductivity at t = 1 ms is calculated at 0.11 mho/m, and decreases to 0.095 mho/m at t = 10 ms. These values agree with resistivity measurements as a first estimate of the bulk conductivity of the top 50 m.

However, the expression does not appear to hold for small loops, because when field values are substituted in the expression the apparent conductivity values become anomalously high.

To aid in the interpretation of the field results computer modelling was done by T. Lee at Macquarie University using the theory developed for the transient response of a large loop on a layered ground (Lee & Lewis, 1974).

The ground was assumed to be horizontally layered, and estimates of the resistivity section were made by using the resistivity depth-sounding data of Ogilvy (in prep.). The assumed resistivity section and theoretical TEM results are shown in Plate 17. There is reasonable fit between the theoretical and field values for the 100-m and 50-m loops, but for smaller loops the fit is poor.

The difference in curve fit for large loops can be explained by:

(a) Uncertainty in the resistivity depth-section. If the upper layers were more conducting, the response would be increased at early times with only a minimal effect on later times. This would bring the curves closer together.

(b) Inaccuracies in the field results; these would mainly exhibit themselves at late times when the signal level is small.

Within experimental errors, the fit between field and theoretical results is reasonable for large loops (100 to 50 m). Little is known about the theoretical response of smaller loops so the results cannot be effectively interpreted. Further work is needed to study the response of small loops.

5. CONCLUSIONS

The field tests of the TEM method demonstrated advantages and disadvantages compared with other electromagnetic methods. The fieldwork is at times slower than with other methods, but more information is available. An analysis of the anomalies recorded at different sample times can indicate the conductivity of the source in a similar manner to variable frequency measurements with continuous wave methods.

In the Rum Jungle area, two traverses were surveyed to determine if the TEM method could determine the boundary between the Coomalie Dolomite and the Golden Dyke Formation. The results indicate that in the Crater Lake area southeast of the Rum Jungle Complex the boundary can be detected, and in the Gould area east of the Waterhouse Complex it cannot owing to lack of conductivity contrast between the two formations.

In the Woodcutters and Mount Minza areas the results indicate the amount of information available in the data compared with the information which was available from previous Slingram and Turam electromagnetic surveys. In both areas there was good correlation with previous geophysical methods; the use of different loop sizes and loop overlap provided better definition of anomalies necessary for quantitative interpretation.

In the Cloncurry No. 5 area anomalously low and negative TEM values were obtained over parts of a conducting carbonaceous shale which should have given high values throughout. Additional field and laboratory work are recommended to investigate the phenomenom.

Experiments with a dual-loop configuration in the Dobbyn area demonstrated advantages of a dual-loop configuration over a single loop for detecting steeply dipping narrow conductors.

To determine if the TEM method could be used for resistivity profiling and depth-sounding in areas of homogeneous rock types, an experimental survey was made in the area east of Cloncurry where Mesozoic rocks overlie Precambrian rocks. The results indicate that the TEM method can be used for these purposes in appropriate circumstances. In the area where the tests were made the Mesozoic rocks are of conductivity and thickness that prevented penetration through them.

Depth-sounding experiments made in the areas east of Cloncurry showed reasonable correlation between results from large loops and theoretical results. Further work is needed to study the response from small loops.

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APPENDIX 1

The TEM response over a homogeneous half-space

Lee & Lewis (1974) give the TEM response over a homogeneous half-space as

$$e(t)/I = -(2b \; \mu \; I \; \sqrt{\pi} \; /t) \; F(t/(\sigma \mu \; b^2))$$

where b = radius of the loop

t = sample time

σ = conductivity of the half-space

μ = magnetic permeability of the half-space

They have evaluated $F(t/\sigma\mu b^2)$ numerically and as e(t)/I, μ, b, and t are known σ can be obtained.

For large values of time t, the TEM response approaches the asymtotic expression

$$e(t)/I \simeq \frac{bI\mu\sqrt{\pi}}{20t} \; (\sigma\mu b^2/t)^{3/2}$$

$$= 1.58 \times 10^{-16} \; b^4 \; \sigma^{3/2} \; / \; t^{5/2}$$

Thus over a uniform ground the transient decay will have a slope of -2.5 on a log-log plot and the conductivity can be derived from

$$\sigma = 3.46 \times 10^{10} \left\{ \frac{t^{5/2}}{b^4} \; \frac{e(t)}{I} \right\}^{2/3}$$

A large value of time t is defined by $3.6\,t \gg \sigma\mu b^2$

APPENDIX 2

BMR Cloncurry No. 5 drill hole - resistivity and IP measurements

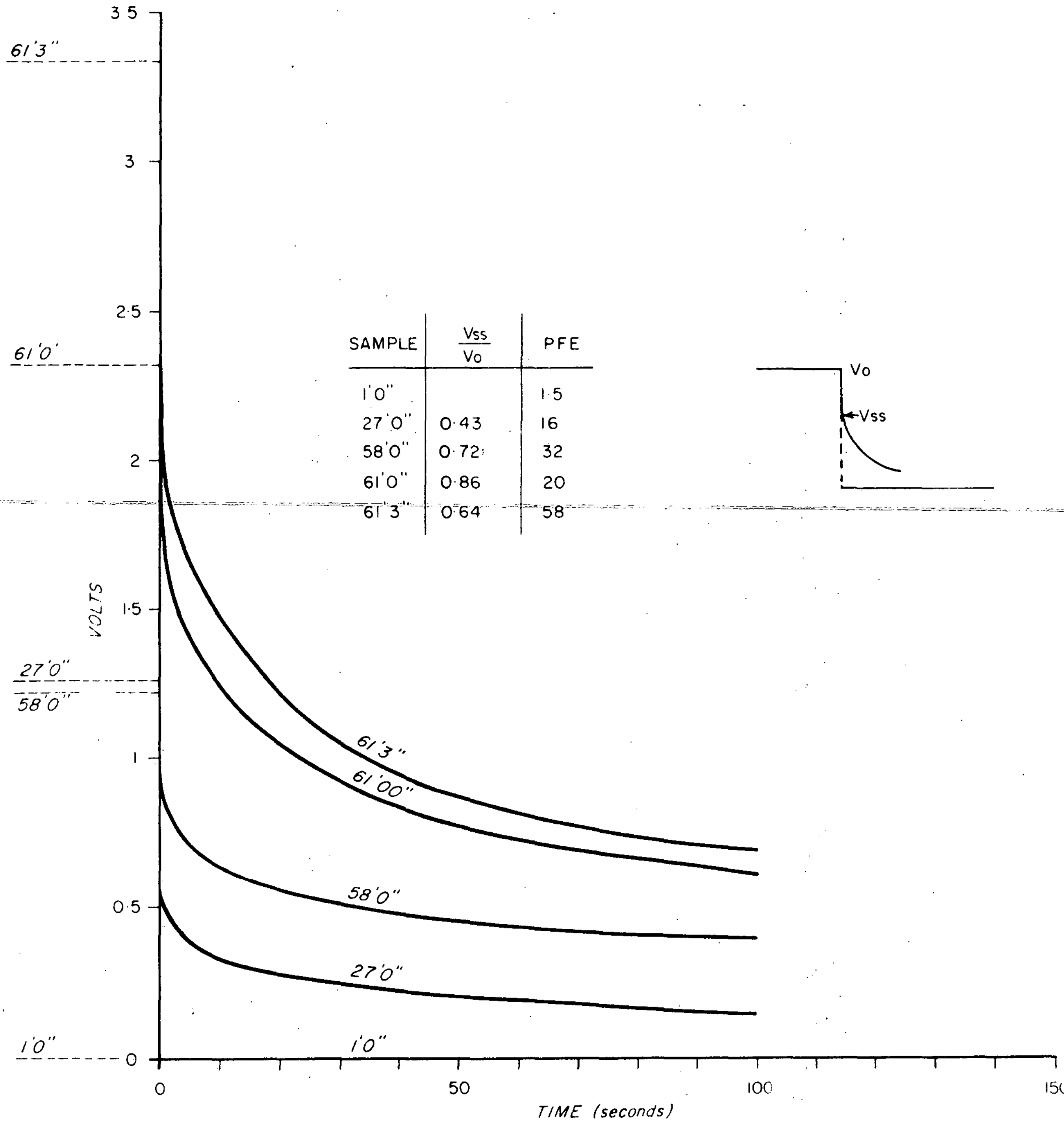
(Pore water conductivity = 0.035 mho/m, temperature 22°C)

Frequency (Hz)	Sample Depth and Resistivity (ohm-m)				
	27'	58'	61'0"	61'3"	1'
0.01	23.2	31.6	63.7	26.6	350
0.03	21.7	28.3	61.3	23.6	
0.1	20.1	24.5	56.8	21.0	345
0.3	18.5	19.6	49.4	17.5	
1	16.4	15.2	40.7	12.1	330
3	15.1	12.7	35.7	8.15	
5	14.4	11.6	34.3	6.68	
10	13.8	10.3	32.7	5.1	325
100	11.6	7.8	30.1	3.0	296
1000	9.6	6.3	28.7	2.4	227
PERCENT FREQUENCY EFFECT PER DECADE	16	32	20	58	1.5

$$PFE = \frac{\rho_1 - \rho_{10}}{\rho_1} \times 100$$

All samples are pyrrhotitic pyritic black shale.

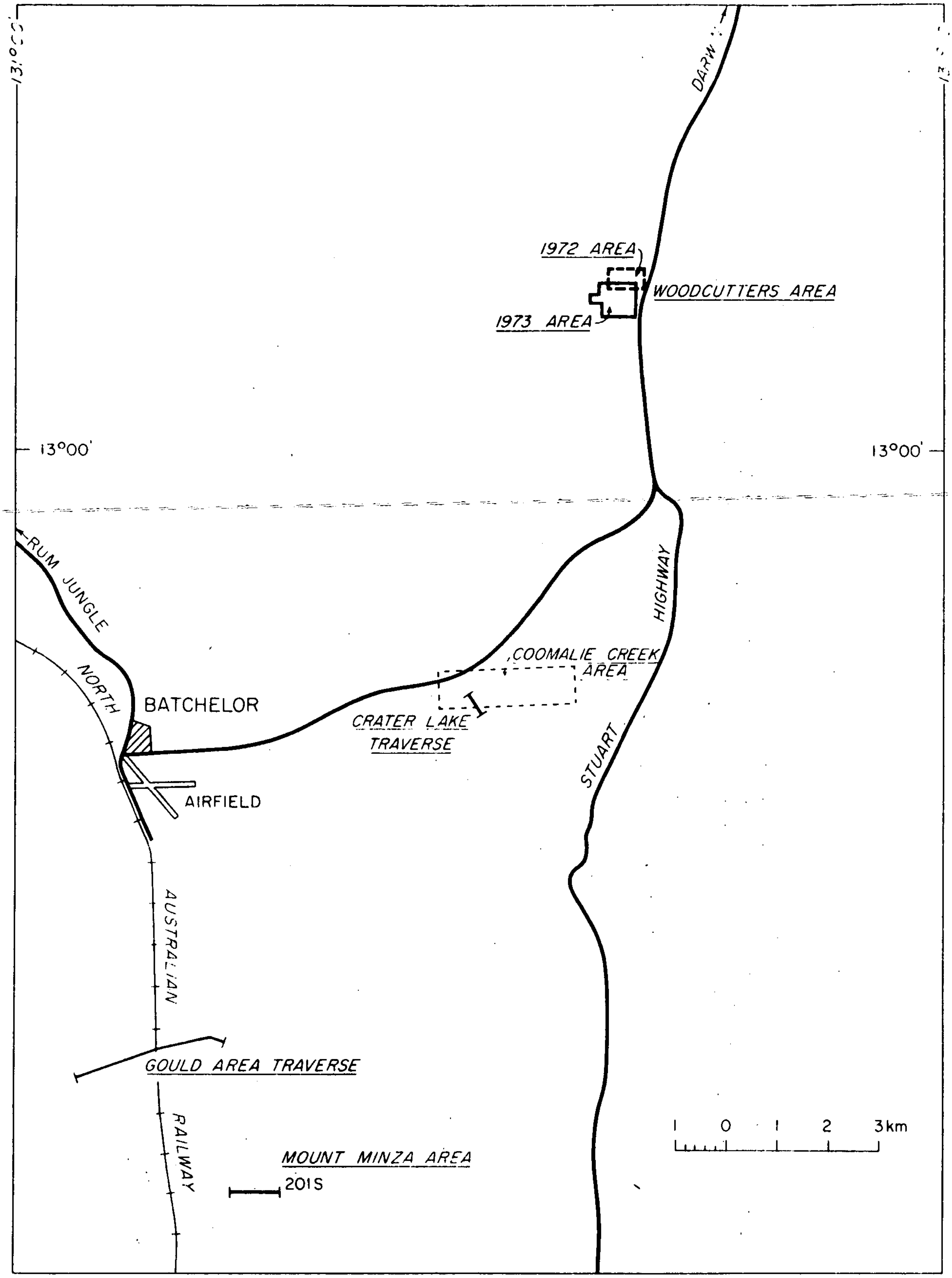
Fig. A



SAMPLE	Vss/Vo	PFE
1'0"		1·5
27'0"	0·43	16
58'0"	0·72	32
61'0"	0·86	20
61'3"	0·64	58

BMR CLONCURRY No. 5 DRILL HOLE IP MEASUREMENTS

PLATE I

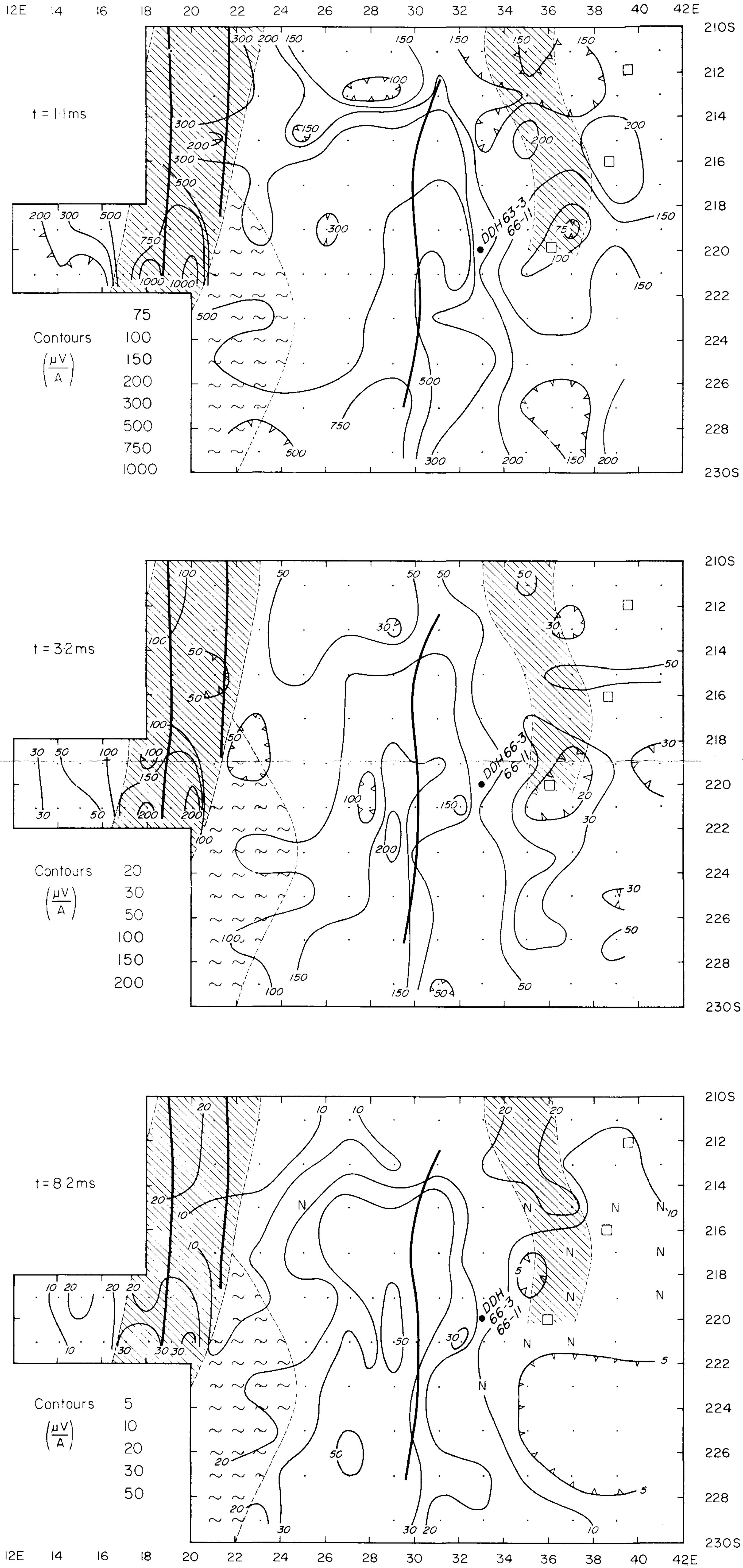


LOCALITY MAP
RUM JUNGLE AREA, NT

Record No 1974/191

D52/B7-641A

Record No. 1974/191



LEGEND

Undifferentiated shale and schist

Black shale

Chloritic schist and amphibolite

Mineralization intersection

Slingram anomaly axis

TEM station (60m loops)

N *No reading possible because of noise*

60 metre loops

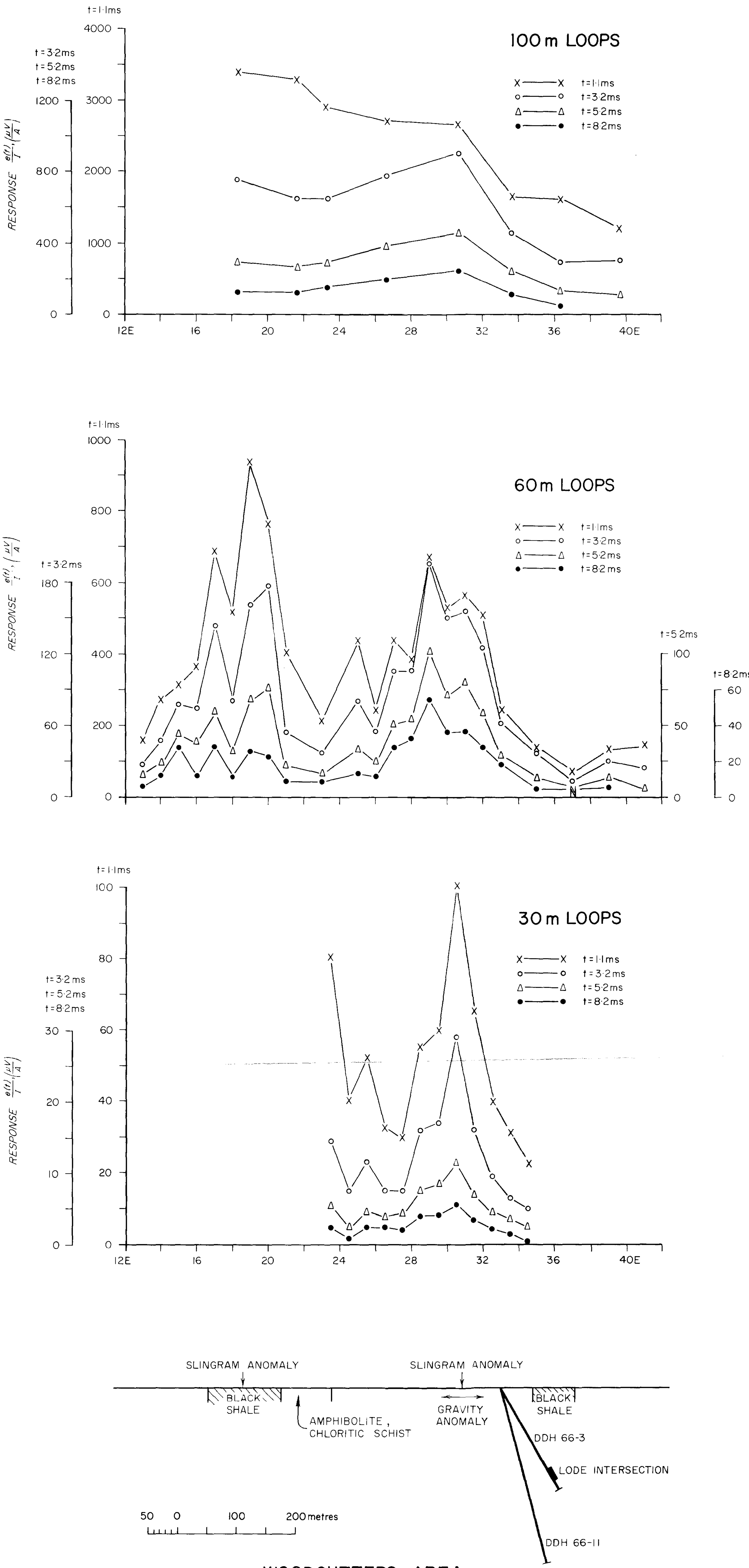
50 0 100 200 metres

WOODCUTTERS AREA
TEM CONTOURS AND
GEOLOGY

D52/B7-642

PLATE 2

Record No. 1974/191

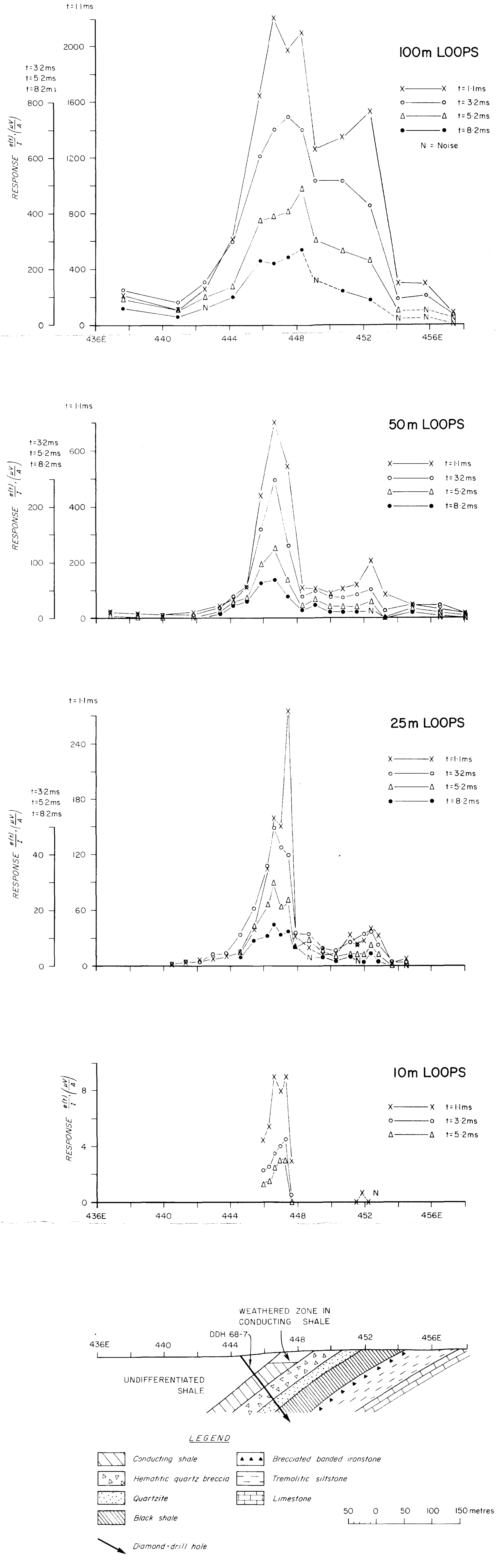


WOODCUTTERS AREA
TRAVERSE 220 S
TEM PROFILES, GEOPHYSICAL ANOMALIES, AND GEOLOGY

D52/B7-643

PLATE 3

Record No 1974/191

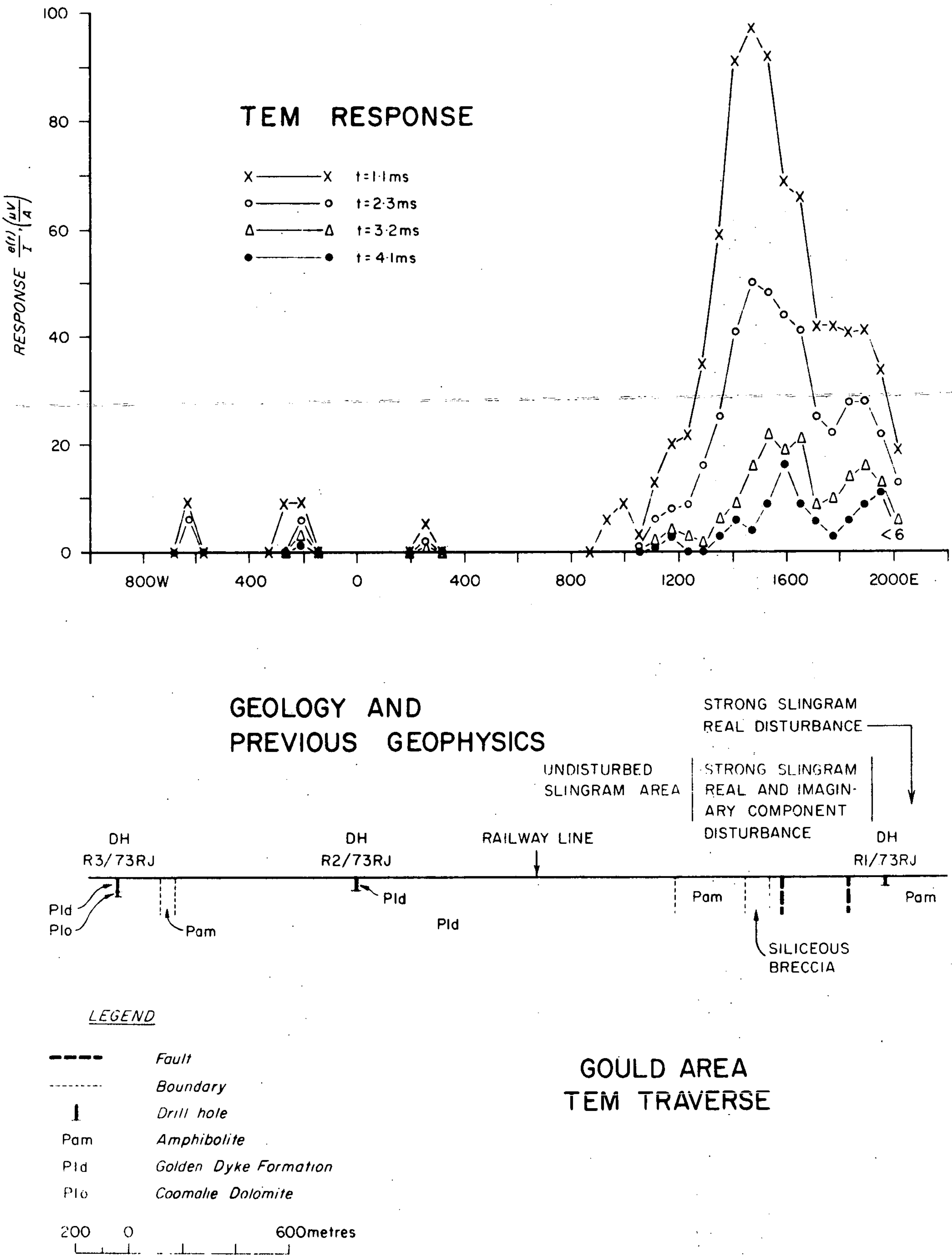


D52/B7-644

PLATE 4

MOUNT MINZA AREA TRAVERSE 201 S
TEM PROFILES AND GEOLOGY

PLATE 5

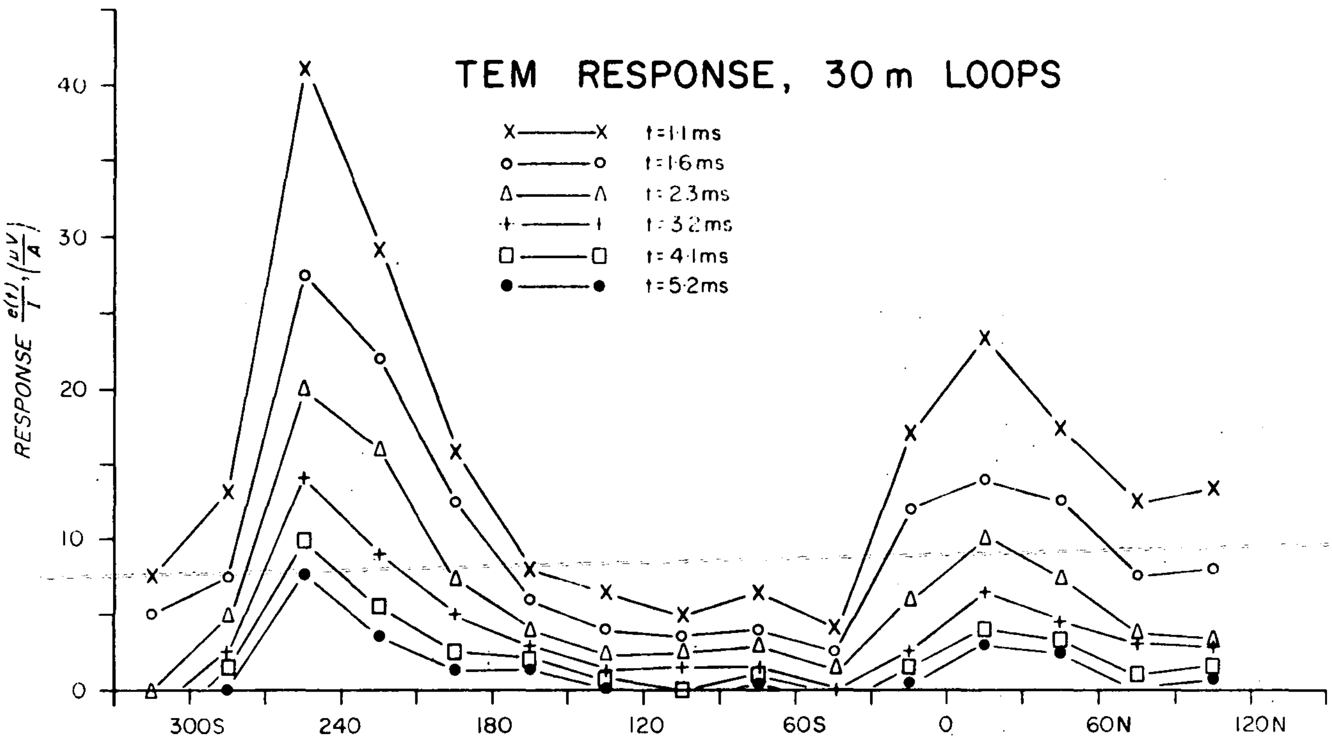


GOULD AREA
TEM TRAVERSE

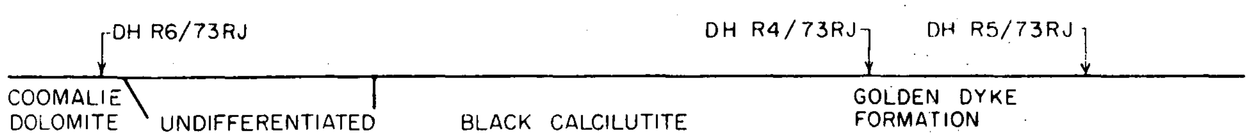
Record No 1974/191

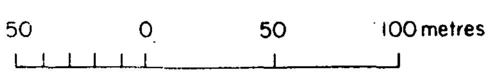
D52/B7-645A

PLATE 6



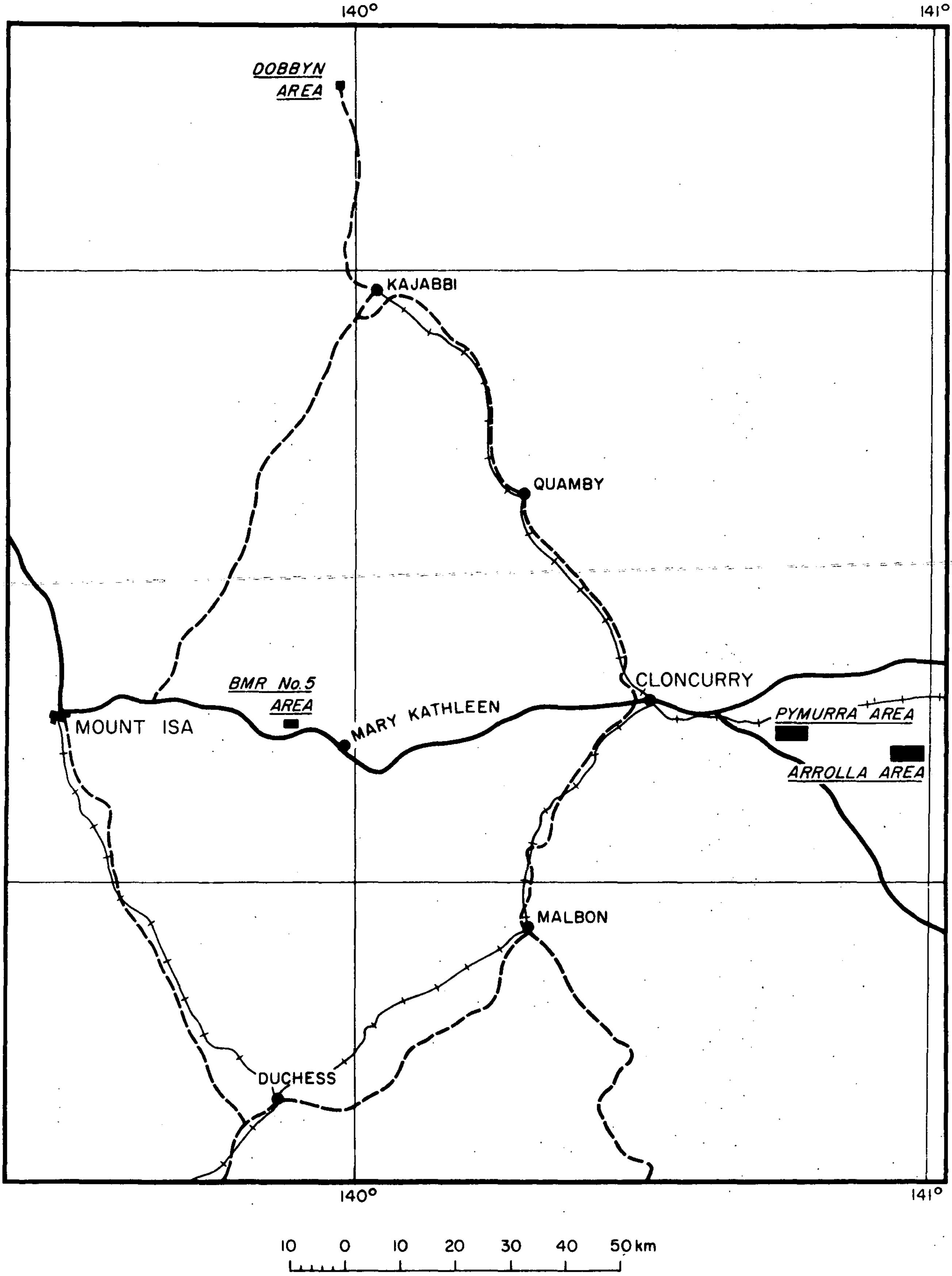
GEOLOGY





CRATER LAKE AREA
TEM TRAVERSE

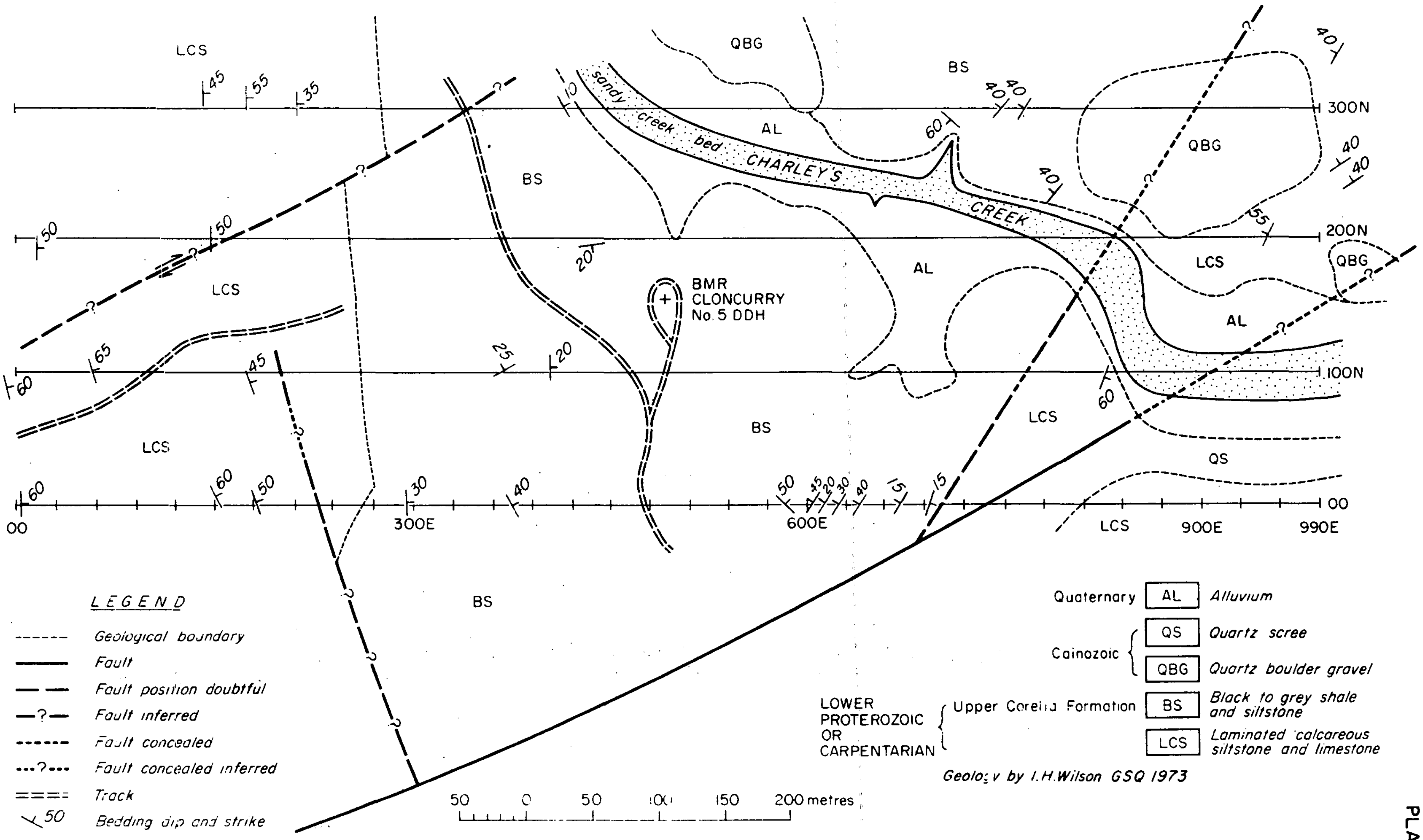
PLATE 7



LOCALITY MAP
MOUNT ISA/CLONCURRY AREA
QUEENSLAND

Record No 1974/191

F54/B7-47A

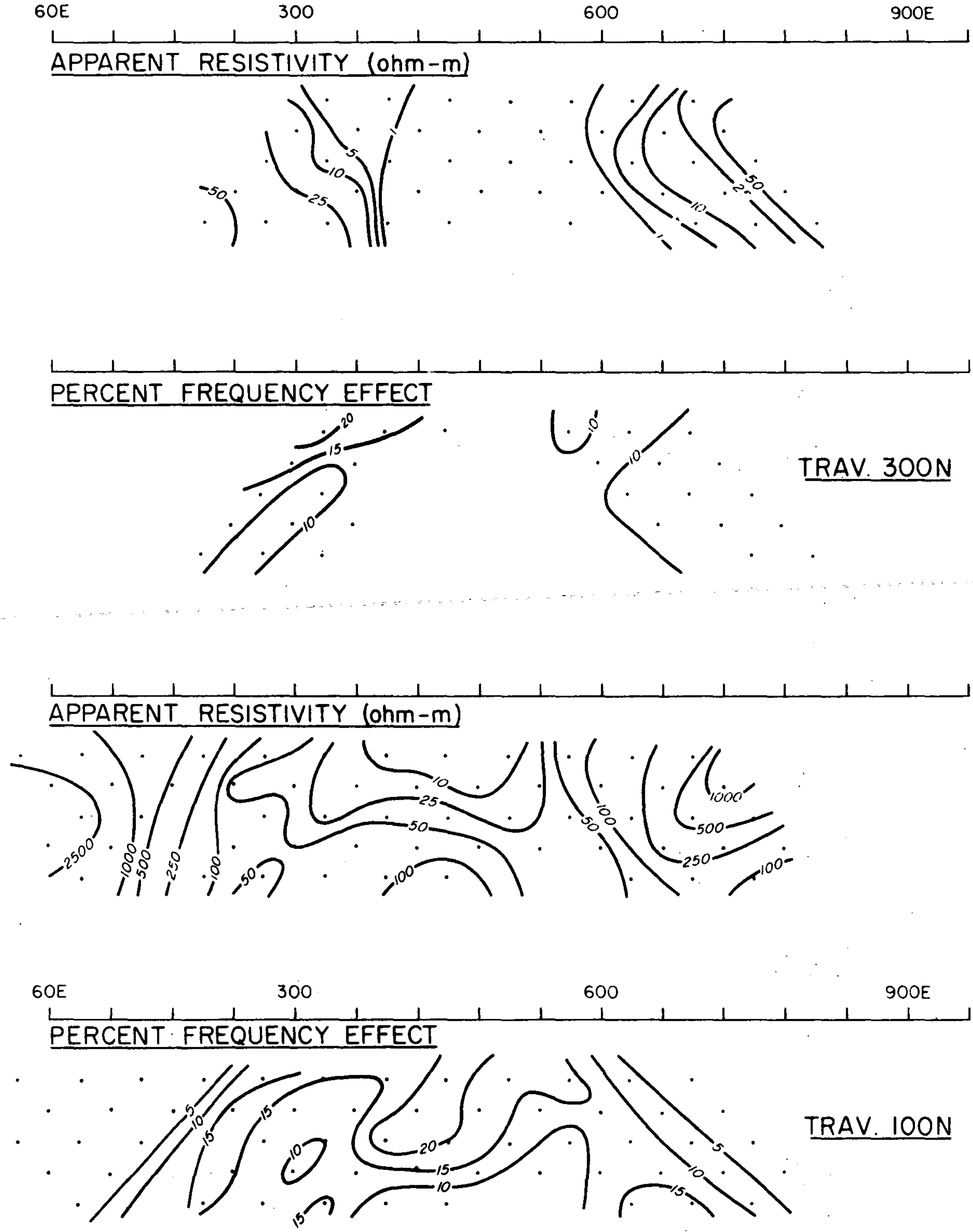


BMR CLONCURRY No. 5 AREA GEOLOGY

F54/B7-48A

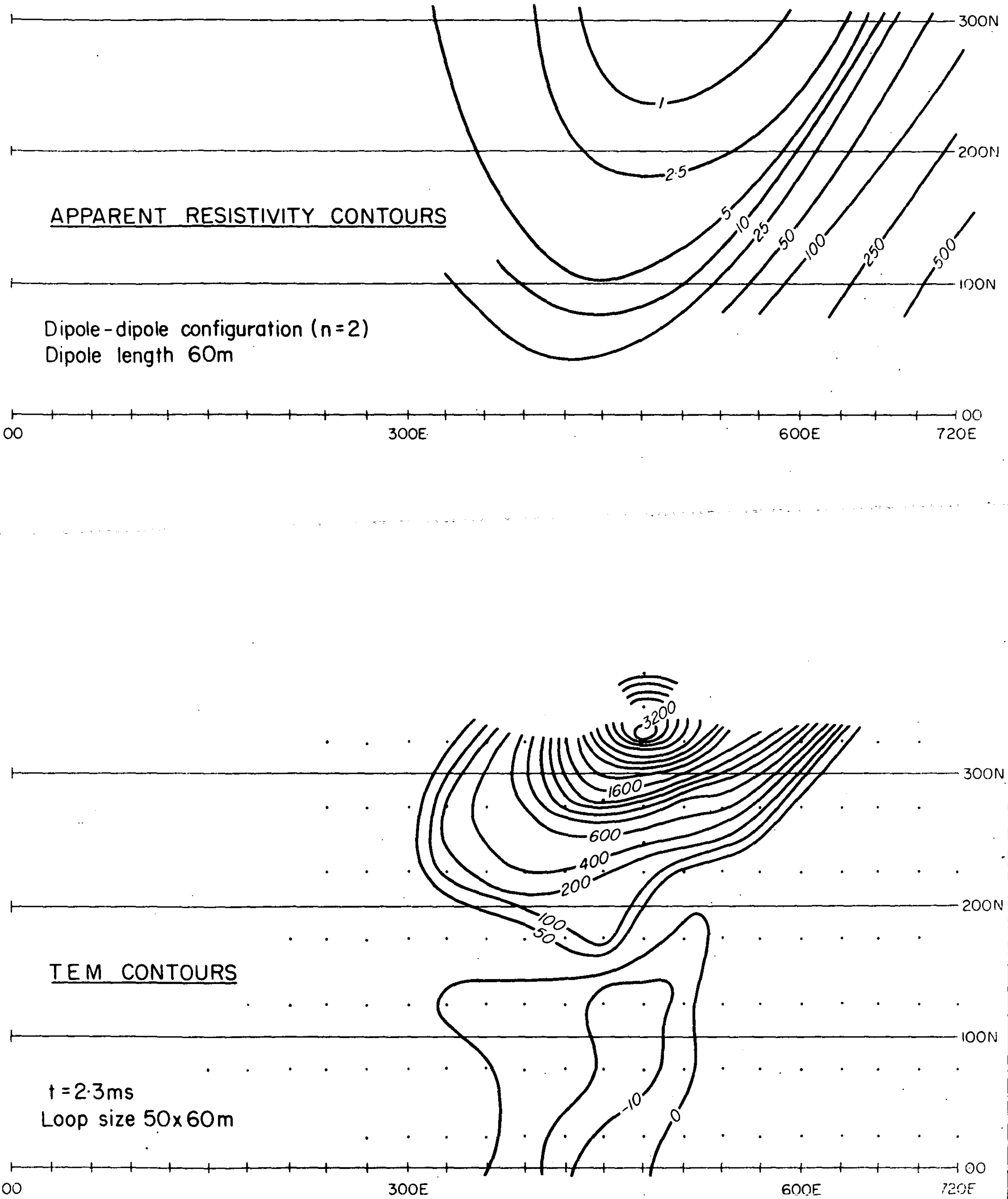
PLATE 8

PLATE 9



BMR CLONCURRY No. 5 AREA
INDUCED POLARIZATION RESULTS
TRAVERSES 300 N AND 100 N

PLATE 10

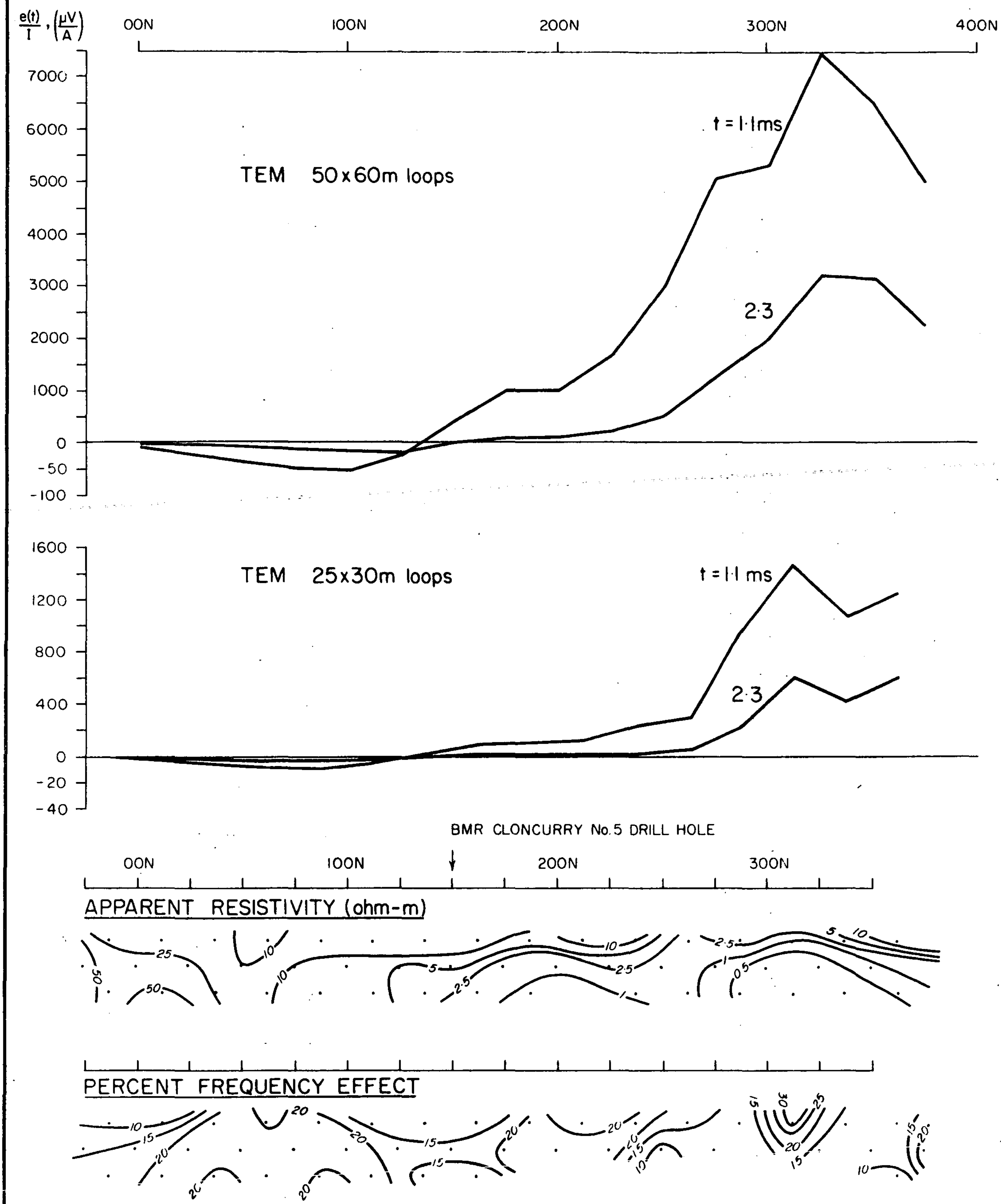


BMR CLONCURRY No. 5 AREA
APPARENT RESISTIVITY AND TEM CONTOURS

Record No. 1974/191

F54/B7-50A

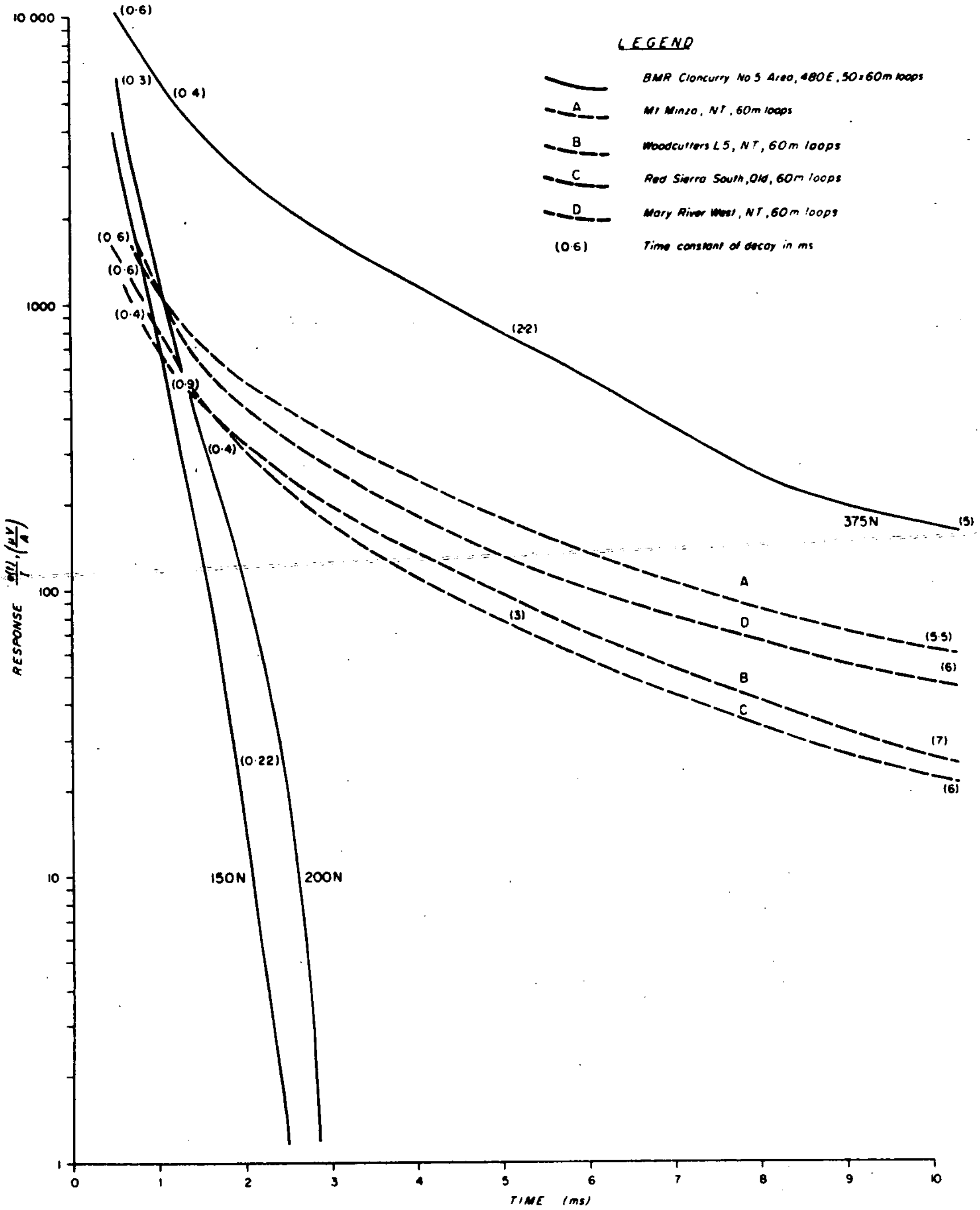
PLATE 11



BMR CLONCURRY No. 5 AREA
TEM AND INDUCED POLARIZATION RESULTS
TRAVERSE 480 E

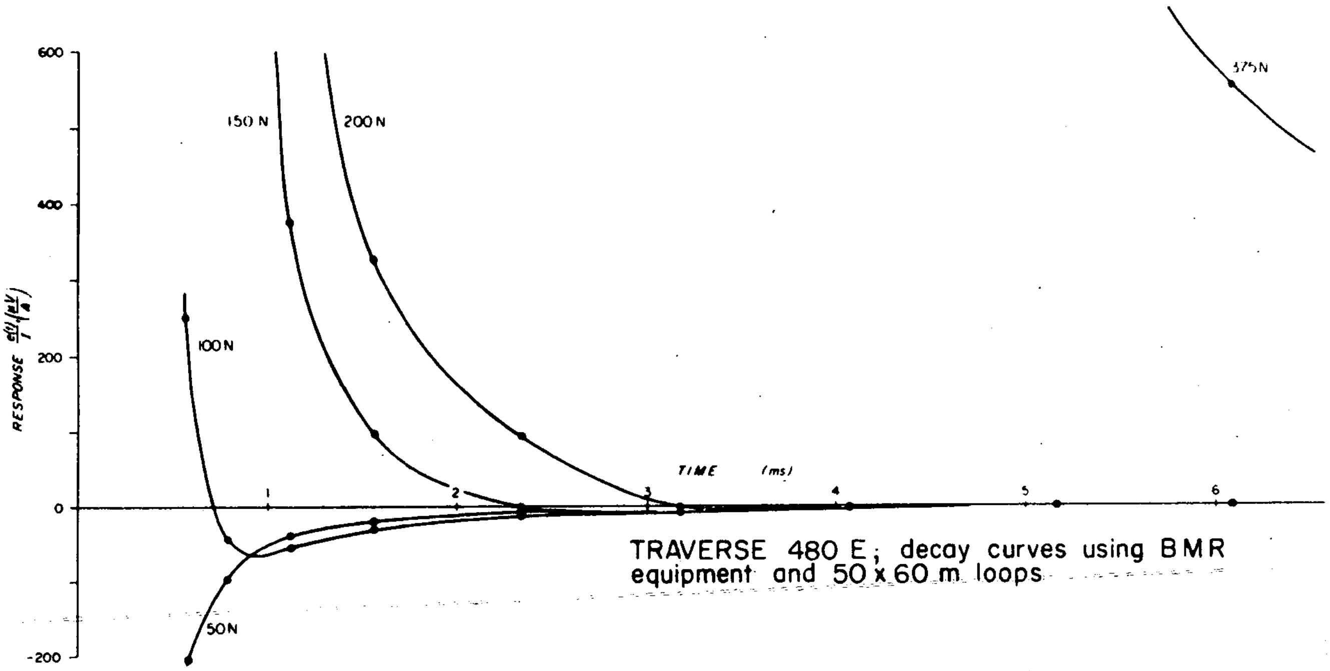
Record No. 1974/191

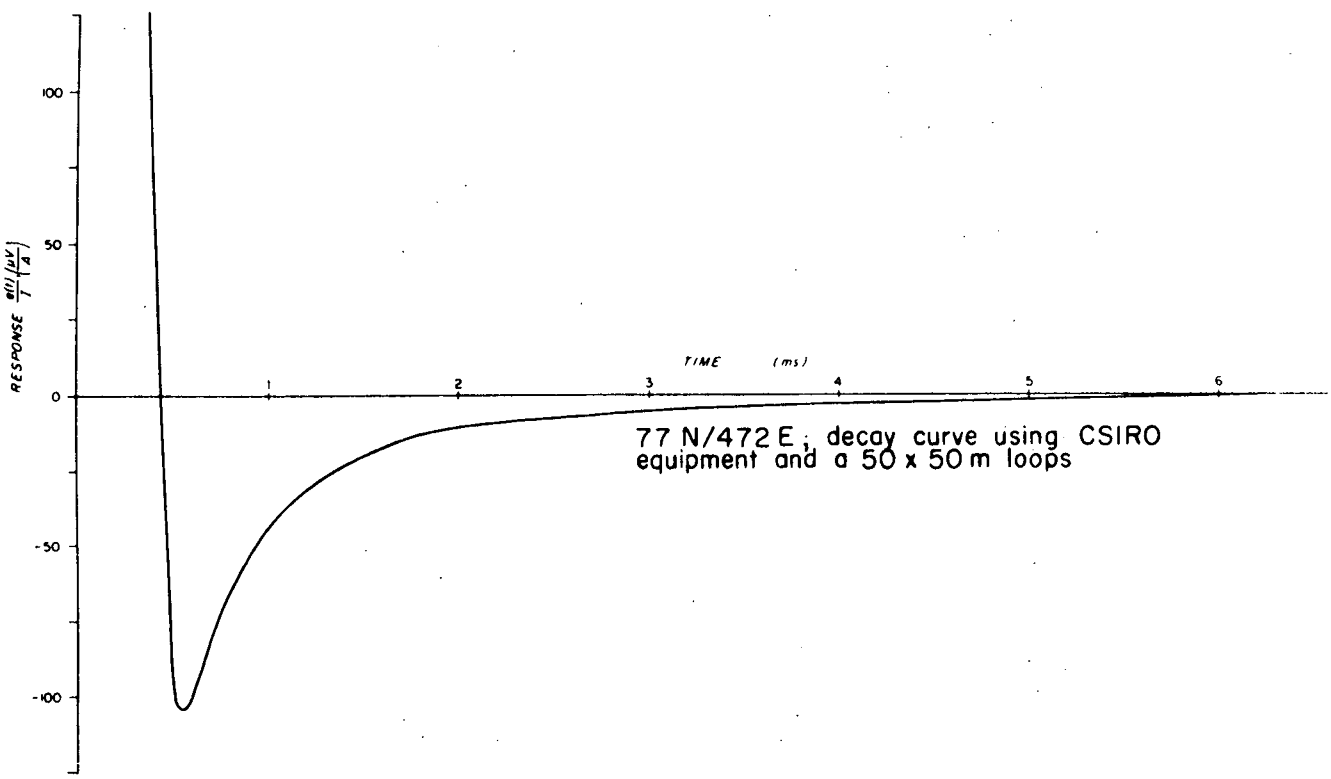
F54/B7-51A



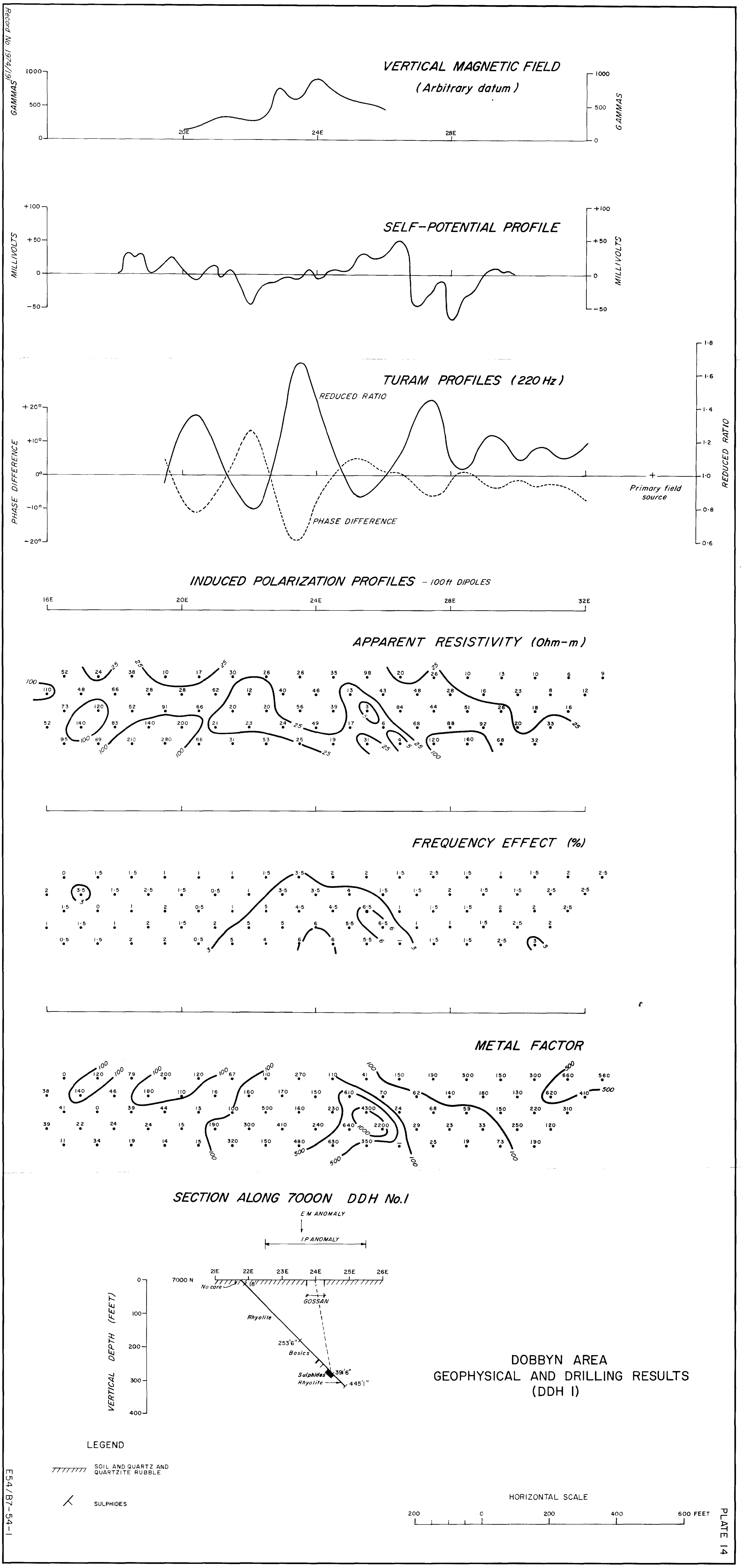
TEM DECAY CURVES

PLATE 13



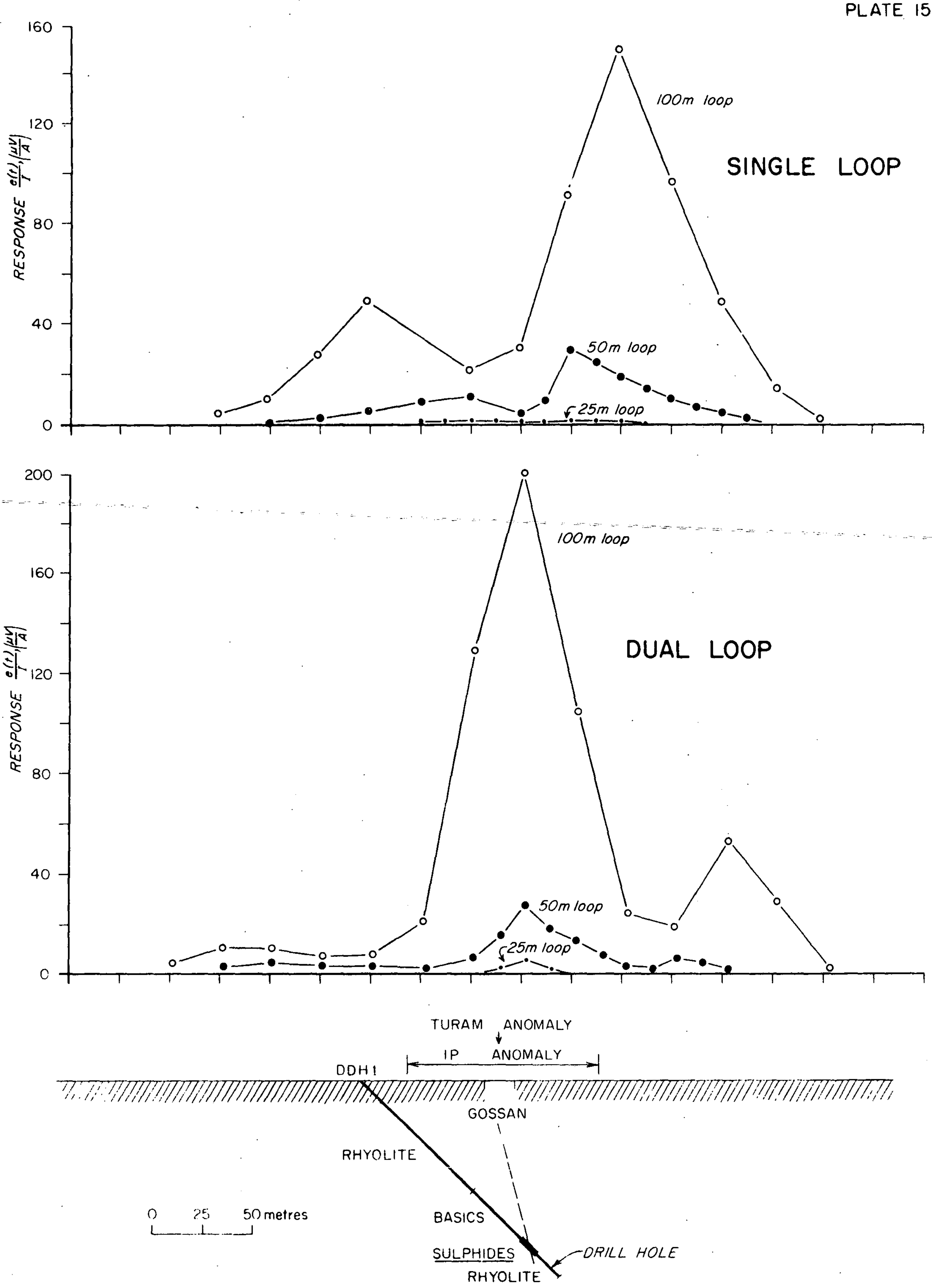


BMR CLONCURRY No. 5 AREA
TEM DECAY CURVES



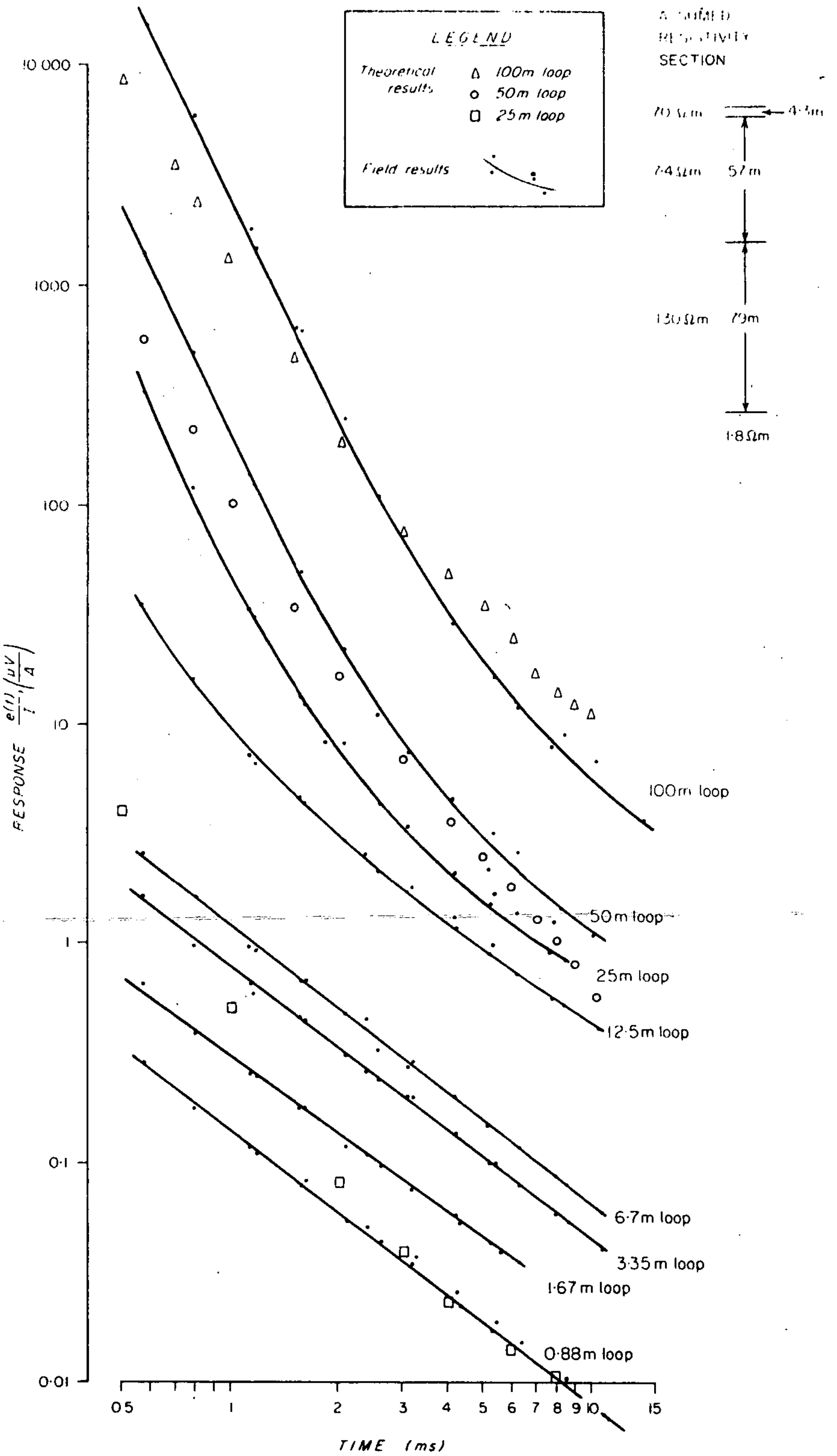
DOBBYN AREA
GEOPHYSICAL AND DRILLING RESULTS
(DDH I)

PLATE 14



DOBBYN AREA TEM PROFILES AND DRILLING RESULTS (DDH 1)

PYMURRA AREA
TEM AND APPARENT
RESISTIVITY PROFILES



PYMURRA AREA
TEM DECAY CURVES