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BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1975/90

Musa River Hydro-electric Scheme Seismic Survey, P.N.G., 1972

by

I.D. Bishop, G.R. Pettifer and E.J. Polak

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SUMMARY

In July-October 1972 the Engineering Geophysics Group of the Bureau of Mineral Resources, Geology and Geophysics (BMR) carried out a detailed seismic refraction survey over two proposed dam sites in the Musa Gorge in Eastern Papua. The work was part of a study of the technical feasibility of construction of a hydro-electric scheme on the Musa River. The study is being conducted by the Commonwealth Department of Works on behalf of the Papua New Guinea Electricity Commission, and includes detailed geological mapping by the Papua New Guinea Geological Survey and a diamond drilling program.

The results of the survey show extensive low-velocity zones at the top of the left bank at both dam sites. Sheared or jointed bedrock occurs in only a few places on the right bank. Basic differences in the weathering profiles were also found between the left and right banks. Anisotropy recorded in bedrock and overburden velocities suggests jointing or shearing which strikes generally across the dam axis. A major set of shear planes and joints dipping to the west roughly parallel to the steep slopes of the right bank and trending approximately north is postulated to explain the differences in the weathering characteristics of the bedrock and overburden between the left and right banks.

Overburden velocities were found to be highly variable; their analysis suggests that deeper excavations will be required at Dam Site 2. Depths to fresh bedrock beneath the river at the base of each dam site attain a maximum value of 30 m. Depths to bedrock are slightly less at Dam Site 2 than at Dam Site 1.

A major scree deposit up to 50 m thick occurs in a proposed spillway area above the downstream power station site. Low velocity over-burden underlies the upper right and left abutments of Dam Site 2, on the slopes above the proposed upstream power station site. Investigation of a major landslide downstream from the dam sites shows high velocity ultramafic bedrock some 100 m above river level. The present survey together with recent geological mapping and drilling suggests that this bedrock refractor represents the base of the landslide and that the slide consists mainly of mudstone, tuff and agglomerate of the Pleistocene Daomara River Beds.

The reservoir will flood the low-lying Musa Valley graben. A deep refraction probe carried out across the graben, through Safia airstrip, showed 635 m of late Pleistocene to Recent alluvium in the graben. Possibly as much

as 890 m of subsidence has taken place on the northern boundary fault of the graben in late Pleistocene and Recent times. A 150-m deep reservoir would impose an additional 11-percent loading on the bedrock in addition to the weight of the alluvium in the graben. As a result an increase in seismicity may be expected.

1. INTRODUCTION

The Papua New Guinea Electricity Commission is considering the construction of a major hydro-electric scheme on the Musa River, approximately 160 km east of Port Moresby. The Commonwealth Department of Works is preparing the technical feasibility study of the project. Geological survey (Smith & Green, 1961; Cumming & Carter 1969; Robinson, 1971; Macias, 1971) and geophysical surveys (Taylor, 1971 contributing to the study, have been carried out by the Bureau of Mineral Resources (BMR) and the Geological Survey of Papua New Guinea over five possible dam sites in the Musa Gorge. As a result of these investigations Carter (1971) recommended the two upstream dam sites for further study.

In July-October 1972 a party from the Engineering Geophysics Group of BMR consisting of G.R. Pettifer (Party Leader), I.D. Bishop (Geophysicist), and W.J.C. Pearson (Draftsman) carried out a detailed shallow seismic refraction survey. E. Polak (Supervising Geophysicist) worked with the party for 5 weeks and G.M. Pounder from the Geological Survey of Papua New Guinea assisted the party throughout the survey. The Commonwealth Department of Works provided additional local labour and arranged topographic surveys, transport, accommodation and food. The results of this survey are presented in this Record.

The purpose of the survey was to prepare detailed seismic profiles over the proposed alternative sites for the dams, power stations, spillways, and tunnels. The party also investigated a large landslide deposit which was found to encroach upon the toe of the downstream dam site. Further movement of this slide may endanger a possible power station site.

Twenty-eight seismic traverses totalling 12,685 m in length were completed (Plate 1). The steepness of the Musa Gorge made work difficult. Slopes average about 35°, some are as steep as 60°, and in places there are cliffs. The team used bush ladders often, and safety ropes on some traverses. Careful preparation of the traverses by the Commonwealth Department of Works survey team was most helpful and is gratefully acknowledged.

The water impounded by the proposed dam will flood an area of 650 km^2. The scheme is in a zone of recent tectonic instability (Robinson, 1971), and the extra loading of the crust may trigger further activity. Accordingly the survey determined the thickness of alluvium beneath Safia airstrip in order to enable the effect of the extra crustal loading to be calculated.

In this report 'bedrock' means the highest velocity refractor identified at any locality and 'overburden' means all overlying material which includes soil, unconsolidated rocks, and rocks at various stages of weathering.

Where reference is made to distances ('chainages') along traverses, the slope value is given and the corresponding horizontal distance follows in brackets.

The directions 'left' and 'right' are as observed when passing downstream - the standard nomenclature.

The criterion adopted for rippability in this report is that rocks with a velocity less than 1500 m/sec are rippable with mechanical excavators.

2. DESCRIPTION OF MUSA HYDRO-ELECTRIC SCHEME AND LAYOUT OF TRAVERSES

The proposed hydro-electric scheme is located in the Musa Gorge about 6 km northeast of Safia airstrip (Pl. 1). During the survey the access was by light plane to Safia and then by boat down-river. An access road has since been built from Pongani on the north coast. The scheme will generate up to 500 MW of power to supply Port Moresby and a possible future industrial complex at Oro Bay.

The proposed dam will be a rock-fill or gravel-fill structure up to 180 m high, having either a concrete face plate or an impervious core. Plate 3 shows the lay-out of traverses in relation to the alternative dam sites and all auxiliary structures for a proposed impervious core dam with a crest level of 275 m above sea level. Smaller dams having crest levels 215 and 155 m have been considered as alternatives.

Traverse A covers the axis of Dam Site 1 and traverse H that of Dam Site 2. A general network of traverses - B, C, D, E, F, G, I, N, O, Q, R, S, U, W - covers the area of the two dam sites. Two alternative power station sites have been proposed for Dam Site 1. The first, at the base of Dam Site 2, is covered by Traverses M and T. The second, which is also proposed as the power station site for Dam Site 2, lies well downstream and is covered by the network of

Traverses PB, PC, PD and PE. Traverses T and Z cover the diversion tunnel line and intake tunnel respestively for Dam Site 1.

Chute structures are proposed for spillways on the left bank and an alternative spillway for a 275-m crest-level dam wall at Dam Site 2 is located along the line of Traverse PA on the right bank.

No traverses were undertaken specifically to investigate possible borrow-pit areas; a network of traverses (J, K and L) investigates a major landslide deposit downstream from Dam Site 2. The presence of this landslide and its instability was a major factor in rejecting the three dam sites (nos. 3, 4 and 5) farther downstream which had been investigated in a previous survey (Carter, 1971).

3. GEOLOGY

3.1 General

The geological summary given here is based mainly on previous descriptions of the general dam-site area and its environs (Smith & Green, 1961; Davies, 1968; Cumming and Carter, 1969; Macias, 1971, 1973; Robinson, 1971). After the present survey L. Macias of the Geological Survey of Papua New Guinea mapped the geology along the seismic traverses in detail and carried out a test diamond drilling program. His results are incorporated with the seismic traverses in a separate geological report (Macias, 1973). Particular points arising from the detailed mapping are referred to in Section 7 of the present report (Results and Interpretation) and the geology of the four diamond-drill holes (Pl. 3) has been taken into account in the seismic interpretation. Plate 2 shows the main geological features mapped in the dam-site area during the 1970 geological investigation (Macias, 1971).

The gorge cuts northeast through the Didana Range in Eastern Papua (Pl. 1) and is up to 280 m deep. Upstream from the gorge, the Musa Valley is a southeast-trending graben which originated in the Pleistocene and has continued to develop in Recent times. Alluvium has filled the graben to an unknown thickness and the cutting of the gorge has kept pace with the subsidence and infilling of the graben.

In the area of the dam sites two main rock units have been mapped. The most widespread is the Upper Cretaceous Didana Ultramafic Complex

(Robinson, 1971). The ultramafic rocks of the complex are generally highly altered to serpentine and carbonate. In places they are intruded by gabbro, and high in the gorge the contact with gabbro is gradational (Macias, 1971). Extensive shearing is present in places and shear zones up to seven metres wide have been mapped. The Pleistocene Domara River Beds (interbedded conglomerate, agglomerate, tuff, mudstone) crop out high up on the left bank of the dame site area, and dip steeply to the southwest, towards the Musa Valley. The dip was probably caused by drag during movement on the northeastern boundary fault of the graben (Robinson, 1971).

A major landslide deposit consisting of ultramafic rock overlain by weathered Domara River Beds is located just downstream from Dam Site 2. Owing to the steepness of the gorge, slope stability is recognized as a major factor for consideration in design and construction. Macias (1973) gives a detailed study of slope stabilities of critical areas, based on analysis of joint orientations mapped during the 1972-1973 field season.

The depth and intensity of weathering is generally greater on the upper slopes. At river level boulders, gravel, and scree overlie fresh bedrock.

3.2 Specific geological features and problems

Particular geological features and problems of relevance to the present geophysical survey have been noted by Carter (1971) from previous geological and geophysical investigations, and are listed below.

3.2.1. Foundation conditions beneath the river

The depth to bedrock beneath the river at the base of each dam site and the nature of the bedrock and overburden are of importance in the design and construction of the dam.

3.2.2. Slope stability

The landslide deposit and several Quaternary scree slopes indicate that slope surfaces within the gorge are generally unstable. Both possible sites for a power station are at the bottom of steep slopes, and if these are unstable the power station may have to be built underground. The slopes of Trig Point

Rebol above the downstream power station site show evidence of an extensive (Quaternary) rock-fall. The alternative spillway (Trav. PA, Pl. 3) for Dam Site 2 crosses this area. Between Dam Sites 1 and 2 on the left bank, in the vicinity of Traverses B, C, D, and F, a large area of (Quaternary) colluvium has been mapped (Pl. 2).

Evidence of low bedrock velocities in the right abutment and at the top of the left abutment of Dam Site 2 (Taylor, 1971), and the presence of a photogeological lineament on the right bank of Dam Site 1, emphasize the need for care in investigating slope stability in the dam areas.

3.2.3. Shear zones, joints, and faults

Shearing and jointing of the rocks has been noted throughout most of the gorge area with no preferred orientation evident. However, regional mapping of the Musa hydro-electric project area (Robinson, 1971), suggests a regional fracture pattern consistent with a pattern expected from compressive stresses applied from the north-northeast.

Jointing caused by the relief of overburden pressure associated with the rapid erosion of the gorge can be expected parallel to the sides of the gorge and to the slope surfaces. However the extent of jointing and shearing is unknown. Previous seismic work (Pl. 4, 7; Taylor, 1971), on the top of the right abutment of Dam Site 2 (Trav.A2, Pl. 3) and near Trig Point Bev (Trav. B2, Pl. 3) above the left abutment showed that the deepest refractor detected had a relatively low seismic velocity of 2300-2600 m/s indicating weathered, sheared, or jointed bedrock. The gorge itself is considered to coincide with a major lineament (Pl. 2) which extends from the left bank of Dam Site 1 downstream to the Old Village Gully (Pl. 3). Some anisotropy of bedrock velocity has been observed (Taylor, 1971).

3.2.4. Landslide

The shape and nature of the rock mass of the landslide is important in determining the future stability of the slide. Previous seismic work detected a bedrock velocity of 2500 m/s in the upper part of the slide which could represent the velocity of either the Domara River Beds or fractured ultramafics. The depth to fresh ultramafic rock in Situ beneath the slide is unknown.

3.2.5. Rippability and construction materials

Several sources have been suggested for rock fill for the dam. The present survey gives information which may indicate stripping depths and rippability of the overburden in the area of the dam walls, and suitable areas for excavation of rock fill. The landslide has been considered as a possible source of rockfill. Gravel deposits in the Musa Valley are another possible source.

3.2.6. Thickness of alluvium in the Musa Valley

Taylor (1971) showed that the thickness of alluvium in the Musa Valley is greater than 150 m. The difference between the elevation of the Domara River Beds on the Didana Range at Trig Point Bev and their minimum depth beneath the alluvium at Safia airstrip shows that the Musa graben may have subsided at least 400 m in Late Pleistocene to Recent times.

4. PREVIOUS GEOPHYSICAL WORK

The 1970 reconnaissance seismic survey (Taylor, 1971) comprised 4300 m of seismic refraction traversing of 19 traverses, over 5 possible dam sites (Pl. 3). The survey was carried out during a wet period under difficult conditions. Of necessity the seismic traversing was confined mainly to the upper slopes of the gorge, although some work was carried out on the left side of Dam Site 1 (Trav. B1, Pl. 3), on the banks of the river at the lower accelerograph site (Pl. 3) and on traverses A7, A8, A9, A10 (Pl. 3). Geophone spacings of 10 feet (3 m), 25 feet (7.6m), and 50 feet (13.3m) were used in the survey. The spacings used were generally too large to detect narrow low-velocity zones, though the presence of some irregularities in bedrock profile was noted and was cited as representing possible low-velocity zones in the bedrock. The depth of weathering was found to be generally less than 33 m (although in places up to 40 m) and bedrock velocities ranged from 5500 m/s at river level to 2100 m/s on the upper slopes. The velocity of both transverse and longitudinal waves was recorded in several places in order to compute the in situ Poisson's ratio and modulus of elasticity (see Table 2).

A refraction probe at Safia airstrip failed to detect the base of the alluvial deposits and indicated an alluvium thickness greater than 150 m.

The seismic results from the 1970 dam-site survey are incorporated in the interpretation of the present survey results. Minor reinterpretation of some of the 1970 results has been necessary where the present detailed coverage has suggested it.

5. SURVEY METHODS, EQUIPMENT AND WORKING CONDITIONS

The standard 24-channel SIE PSU-19 seismic refraction equipment, and 20Hz TIC geophones, were used for recording in the field. Geophone spacings of 5 m were used for detailed coverage within the areas of the central impervious cores of the proposed dams and at the base of proposed power station sites. The close spacing was used in order to obtain maximum overburden velocity information and to increase the chance of detection of possible low-velocity zones in the bedrock. Elsewhere, where deep weathering was expected and detailed seismic coverage was not essential, geophone spacings of 10 m, and in a few cases 15 m, were used. In routine traversing, five shots were fired for each spread - one at each end, one in the centre, and long shots at distances up to 350 m off each end of the seismic spread, to obtain bedrock arrivals throughout the full length of the spread. Where practicable, shots were placed in the river to obtain maximum seismic energy, and broadside shooting was used in some cases to supplement bedrock information obtained from long shots, or where inaccessible terrain prevented a long shot being placed off-end at a sufficiently large offset. Shot-point information is given on each seismic profile (Pls. 4 to 31).

The river level was the lowest on record and enabled seismic traverses to be carried out across the river in three places - Traverses A, H and J (Pl. 3). The geophones (Geospace HS1, 14 H marsh phones) were cemented in concrete blocks placed on the water bottom at intervals across the river. Shots were fired off-end and broadside upstream and downstream. The low river level exposed several beaches, and enabled detailed refraction work to be carried out at the base of Dam Sites 1 and 2 (Trav. E and M, Pl. 3). Shear-wave velocities were recorded on Traverses M and J (right bank).

In some places, particularly on parts of the left bank at Dam Site 2 and right bank at Dam Sites 1 and 2, the slopes are too steep to carry out seismic work safely and some modification of the proposed seismic coverage was necessary. Access to the dam-site area from the base camp at the stream gauging station near the mouth of the gorge was by boat, the low level of the river enabling safe river transport of equipment and personnel. This greatly facilitated the operation of the seismic survey.

However, the very dry weather during the survey (unlike the seismic survey of 1970) caused great difficulty with crossfeed problems owing to electrical interference of the shot-moment pulse with the recording equipment. Electrical effects are set up in the plasma associated with the explosion. If the ground is dry, EM induction is high and crossfeed occurs. If the ground is damp the ground conductivity is increased and inductive effects such as crossfeed are dissipated.

In addition, the survey was plagued by breaks in the seismic cables from rocks thrown up by the shots.

The seismic records vary in quality from fair to satisfactory.

For the deep seismic refraction probe carried out at Safia airstrip in the Musa Valley, a spread length of 330 m with a geophone spacing of 15 m was employed. A maximum shot offset of 3050 m was used. The spread was located at the eastern end of Safia airstrip, perpendicular to the strip.

6. METHODS AND LIMITATIONS OF THE INTERPRETATION

The discussion of results, conclusions and recommendations of this report are based on the interpretations presented in the seismic profiles. (Pls 4 to 31). The methods and principles used in producing the interpreted seismic profiles, together with the inherent limitations and ambiguities are outlined below. Conceivably in some places more than one interpretation may be possible. However, where subsequent drilling has been carried out the seismic interpretation agrees well with the lithology from the drill logs (Section 7, Results and Interpretation).

Plates 4 to 31 show time-distance plots, shot-point information, topographic sections, and interpreted seismic profiles for each seismic traverse of the dam-site survey. The time-distance plots have been included at the request of the Commonwealth Department of Works as a guide to the interpretation adopted by the authors. Further guidance on the interpretation of the time-distance plots is given in the Appendix.

A brief explanation of the presentation of the time-distance data is given below, taking Records 26 to 30 from Traverse A, left bank (Pl. 4) as an example.

Points A210, A314, A367, A422 and A555 (River) are slope chainages at which shots were fired into the spread, and they therefore label the various shot points for a geophone spread laid out between slope chainages A315 and A420 at 5-m spacing. Reciprocal geophones were also situated at the positions of the long shots at A210 and A535. The short shots were fired at A314 and A422, the centre shot at A367. Shots that were fired beyond the end of a traverse are given a distinctive notation, for example A00-66 (Records 1 to 5, Pl. 4) meaning A00 chainage minus 66 m.

6.1 Methods and principles

The routine reciprocal methods of seismic refraction interpretation was used throughout (Hawkins, 1961) to obtain the 'time depth' to bedrock. The step-out time procedure (Heiland, 1946) was used where reverse long-shot information was not available (e.g. top of the landslide area), and for broadside shots (e.g. river traverses). On these locations only one time-distance plot for the long shot is shown.

The bedrock velocities were obtained by taking the half difference between the reverse long-shot times from bedrock for each geophone (Vale, 1960). This procedure removes differences in thickness of the overburden and topographical effects, leaving a time-distance plot which reflects the variations in bedrock velocity. Bedrock velocities are shown in Plates 4 to 31 as figures in brackets below the bedrock surface.

The overburden velocities were obtained from the short and centre-shot arrival times and are noted on the time-distance plots. However, these are only apparent velocities (up-dip and down-dip velocities), and the actual velocities used in computation of depth of overburden layers are obtained from the harmonic mean of the two velocities. From the intercept times and velocities of the overburden layers a depth to bedrock was computed. A depth conversion factor at each shot-point was calculated from the ratio obtained by dividing bedrock depth by the half-intercept time to the bedrock. The factors varies from shot-point, and a factor for each geophone position was obtained by interpolating between each pair of shot points and ensuring that conversion factors agreed at traverse intersections. The depth to bedrock for each geophone station was then derived by multiplying the computed time depth (obtained by the reciprocal method) by the interpolated depth conversion factor. Points representing bedrock depths normal to the topographic surface were then plotted, or in cases of severe topographic variations, distances to bedrock were derived by plotting arcs centred on the geophone positions. The bedrock profile line connects the points and the envelope of arcs. Overburden velocities and depths are shown on Plates 4 to 31.

6.2 Limitations and ambiguities

Ambiguity in the interpretation arises mainly from limitations imposed by the seismic coverage, data quality, and topography.

Perhaps the greatest ambiguity is in the interpretation of the shallow-layer velocities. The scatter and spacing of the time-distance data near the shot may be such as to make is possible to interpret a number of different velocities from the same data. The velocities chosen affect the respective intercept times, interpreted shallow-layer depths, and conversion factors, and hence the bedrock profile. Ambiguity of overburden velocity information can be caused as follows:

(1) The reciprocal method assumes the presence of layered overburden as a basis for interpretation. In practice, in the Musa gorge area, the overburden is highly variable in places giving differential weathering, jointing and shearing, and large floating boulders of comparatively fresh rock are common. Any lateral change in the subsoil from, say, weathered sheared rock to a slightly weathered floating boulder, will give the same effect on the time-distance curve as, say, weathered rock overlying slightly weathered rock. The shot points may not be in a suitable position to distinguish between the two possibilities.

(2) Elevation differences are large, especially on traverses parallel to the river that cross numerous spurs and gullies, and may distort the near-shot time-distance data.

(3) Where the overburden is very thin, often too few geophones detected arrivals from the refractor to allow its velocity to be defined with any certainty. In an extreme case this is known as the blind zone problem (Hawkins and Maggs, 1961), in which a layer is too thin to be detected by seismic

refraction methods because refractions from that layer appear only as second arrivals.

(4) On traverses which were down slope, occasional difficulties were experienced in distinguishing between bedrock arrivals and lower-velocity overburden arrivals from shots fired at the lower end of a spread. This is a result of the up-slope increase in the depth of weathering, causing the apparent velocity of bedrock to decrease and even approach the overburden velocity.

(5) Where the step-out-time method was used, an assumed bedrock velocity was used to derive the time depths. This means that if any major zones are present where velocity is appreciably less than that of bedrock they will not be detected and the depth to bedrock will appear greater than it really is.

7. RESULTS AND INTERPRETATION

Plate 34 gives an overall picture of bedrock velocities and depths of rippable material in relation to the geology as mapped by Macias (1970). In the following discussion of results, no attempt is made to document systematically the results for each traverse; instead a broad interpretation is given, and where particular anomalous zones have been detected, their significance is noted.

7.1.1. Seismic velocities

By combining information from geological drill logs (Pls 4, 5, 7, 13), geological mapping (Pl. 2), laboratory measurements on the drill cores (Pl. 33), and interpreted seismic velocities, certain categories of rock and soil have been identified with certain ranges in seismic velocity (Table 1).

Several zones of lower velocity (2100-3000 m/s) were found within the bedrock, particularly on the left bank of the dam-site area. These zones are caused by either shearing, jointing, or weathering of the bedrock, or a combination of any or all of these processes. The low-velocity zones vary in width from 25 m to over 200 m along slope.

Bedrock velocities at river level were found to be high (4000-5500 m/s), and no evidence of major low-velocity zones was found. The bedrock velocities generally decrease with height above river level on the left bank but high-velocity bedrock appears to underlie most of the upper part of the

TABLE 1. SEISMIC VELOCITIES

Colluvial deposits (Quaternary)

Material	Seismic velocity (m/s)
Unconsolidated silt and gravel	600-900 m/s
Scree, talus, and boulders	1100-1500 m/s
Water-saturated boulder gravel	1800-2000 m/s

Domara River Beds (Pleistocene)

Material	Seismic velocity (m/s)
Soil	300-600 m/s
Highly weathered bedrock	700-1200 m/s
Moderately weathered to slightly weathered bedrock	2000-2300 m/s
Fresh rock (not found in dam site area)	> 2300 m/s

Didana Ultramafic Complex (Upper Cretaceous)

Material	Seismic velocity (m/s)
Soil	300-700 m/s
Highly weathered bedrock	700-1500 m/s
Moderately weathered bedrock	1500-2100 m/s
Water-saturated jointed rock (river bed)	1800-2000 m/s
Slightly weathered, sheared, or jointed bedrock	2100-3000 m/s
Slightly weathered to fresh bedrock more or less jointed	3000-6000 m/s

right bank.

Where anisotropy of bedrock velocities has been noted at traverse intersections, this may be evidence of a local preferred joint direction. Lower seismic velocities can be expected across joint-plane surfaces, and higher seismic velocities parallel to the joint direction.

7.1.2. Depths to bedrock

The extensive weathering in the dam site area is reflected in the depths to bedrock, which range from 5 m at river level to as much as 35 m at the top of the left bank and 60 m at the top of the right bank. A maximum depth of 65 m to bedrock was recorded upstream from Dam Site 1 on Traverse D (Chainage 373 (0)). Beneath the Musa River at the base of Dam Sites 1 and 2, depths of between 25 and 30 m were recorded.

7.2. Measurements of bedrock properties

Table 2 lists the field measurements of the ratio of longitudinal and transverse velocities, the computed value of Poisson's ratio (σ) and the modulus of elasticity (E) of bedrock. Table 2 also lists laboratory determinations of modulus of elasticity, density, and porosity which were carried out by Dr M. Idnurm of the BMR Rock Measurements Laboratory.

Polak (1967) gives the formulas for calculation of σ and E from the ratio of longitudinal (V_L) and traverse (V_T) velocities:

(1)
$$\sigma = \frac{\frac{1}{2}\left(\frac{V_L}{V_T}\right)^2 - 1}{\left(\frac{V_L}{V_T}\right)^2 - 1}$$

(2)
$$E = \rho \frac{(1-2\sigma)(1+\sigma)\,V_L^2}{(1-\sigma)}$$

From the second formula above it is obvious that an estimate of the variation of density (ρ) with longitudinal velocity (V_L) is necessary to

TABLE 2. FIELD AND LABORATORY DETERMINATIONS OF ELASTIC CONSTANTS

Field Results (1970 and 1972)

Location	V_L/V_T	Poisson's ratio	Longitudinal velocity (V_L)	Modulus of elasticity (E) ($X10^5$ kg/cm^2)
A1	1.77	0.27	3350	2.52
A3	1.80	0.28	2740	1.61
A3	1.77	0.27	3050	2.07
A3	1.71	0.24	4570	5.15
A4	1.66	0.22	1830	0.78
A6	1.72	0.24	3810	3.49
A6	1.80	0.28	3810	3.22
A8	1.80	0.28	3960	3.50
B2	1.55	0.14	2590	1.75
B3	1.90	0.31	2740	1.49
M	2.0	0.33	4400	3.74
J(-200 to -430)	1.78	0.27	4000	3.66

Laboratory Results (1972)

Drill hole and depth (m)	Longitudinal velocity (V_L)	Density (g/cm^3)	Porosity (%)	Poisson's ratio	Modulus of elasticity (x10^{5}kg/cm^2)	Logarithmic decrement
DDO(23m)	6700	3.11	0.2	0.28	11.2	-
(27m)	4700	2.90	1.5	*	*	-
(36.5m)	5860	2.82	0.5	0.38	5.5	-
(42.8m)	6180	3.02	0.3	0.33	8.1	0.04
DDP(22.2m)	6000	2.91	0.7	0.32	7.4	0.02
(37.2m)	3710	2.79	4.6	0.35	2.6	-
(41.7m)	6250	3.02	0.2	0.28	9.4	-
DDQ(5.4m)	5140	2.56	2.0	0.31	5.1	0.04
(14.4m)	5400	2.63	2.0	*	*	-
(23.4m)	5050	2.65	2.0	*	*	-
(43.1m)	5180	2.71	2.0	0.36	4.5	-
(50.5m)	5540	2.60	1.0	0.33	5.6	0.04
DDR(76.0m)	5640	2.66	1.0	0.33	5.8	0.07
(81.8m)	5550	2.69	1.0	0.27	6.8	0.02

* Core too short to be determined.

calculate the modulus of elasticity from field data. Taylor (1971) assumed an in-situ density of 2.65 g/cm^3 as a first approximation. Laboratory measurements were carried out on cores from all four diamond drill holes (Table 2) to determine the density-velocity relationship. Plate 32 shows a plot of density versus longitudinal velocity. The plot shows that densities measured on cores from Drill holes DDO and DDP at Dam Site 1 exhibit great differences for a wide range of seismic velocities and may be indicative of the wide range of rock composition and weathering in this area. By contrast, in the landslide area (Drill holes DDQ and DDR), rock density is relatively constant (2.63 ± 0.08 g/cm^3) for a narrow range of seismic velocities, and this is consistent with the fact that rock in the landslide area is fresh and has a high serpentine content (density of serpentine is 2.6 g/cm^3) (Macias, 1971).

The density data from Dam Site 1 (Drill holes DDO and DDP) has been subjected to linear regression analysis as a first-order approximation to an empirical density-velocity relationship, which is given by

$$E = 2.2(\mp 0.3) \times 10^{-2} (V_L)^{2k} g/cm^2$$

The plot shows that in general, the laboratory measurements were carried out on fresher, less-jointed, higher-velocity rock than the in-situ measurements, and thus effectively supplement the in-situ measurements. The values of dynamic modulus of elasticity from laboratory data are less than would be expected from extrapolating the field data; this could be due either to an overestimation of the density in calculation of modulus of elasticity for the field data or a deterioration of rock strength between the time of coring and laboratory testing.

It is important to stress that values of E derived from seismic velocities represent only an apparent value for the rock mass over which the measurements are taken, and where a rock mass is free to move along joint surfaces the movement or compression of the rock mass under load may be determined more by the properties of the joints and joint surfaces, than by the values of E quoted in this report.

Porosity measurements were also carried out on the drill cores. Porosities measured were less than 1.5 percent in the landslide area and between 1 and 2 percent at Dam Site 1.

7.3 Dam Site 1 (Pls 3 & 4)

The impervious core at Dam Site 1 meets the bedrock surface approximately between chainages 603 and 780 metres for a dam of 275 m crest level. Several zones of lower velocity (2200-3000 m/s) are evident in the bedrock on the left bank of Dam Site 1 (Pl. 34), and are listed in Table 3. Just over half of the left bank part of traverse A is underlain by these lower-velocity zones. The seismic coverage is insufficient to determine whether these zones are connected and continuous with similar zones on adjacent traverses, or isolated.

TABLE 3. LOWER-VELOCITY ZONES IN BEDROCK, DAM SITE 1 (LEFT BANK)

Traverse	Slope chainage(m)	Horizontal chainage(m)	Velocity(m/s)
A	35 - 80	35 - 78	2600
	115 - 170	110 - 164	2800
	215 - 315	208 - 299	2200 - 2600
	430 - 455	389 - 404	3000
B	40 - 60	39 - 59	2600
D	160 - 215	479 - 527	2300
	415 - 580	704 - 858	2500
G	75 - 150	69 - 137	3000

By contrast, on the right bank of Dam Site 1, major lower-velocity zones are absent. Within the area of the impervious core on the right bank of Traverse A, two small anomalies in the form of late arrivals in the time/distance data, between chainages 620(537) and 640(564) and 665(577), may indicate narrow low-velocity zones. Evidence of a low bedrock velocity (3300 m/s) was also found on Traverse B (Pl. 5) between chainages 570(477) and 625(509); this zone corresponds to a major geological lineament on the right bank (Pl. 2; Macias, 1971).

The seismic results and the topographic profile of Traverse A (Pl. 4) illustrate differences in the rock weathering of the left and the right bank of Dam Site 1. Moderately to completely weathered material predominates on the left bank, where a 2000-2800 m/s slightly weathered layer is mainly absent. On the left bank, the only evidence of this layer is found on Traverse A, near chainage 200(192) and on Traverse D, upstream from the axis of Dam Site 1, mainly on top of the ridges. If such slightly weathered material is present elsewhere on the left bank, then it is too thin to be detected by the seismic refraction method.

On the right bank of Dam Site 1, weathering is generally deeper than on the left bank, and the weathering profile is more conventional. On the higher slopes, generally 10-17 m of moderately to highly weathered rock overlies slightly weathered (2100 to 2400 m/s) rock, which in turn overlies fresh bedrock. The slightly weathered layer is strongly developed over most of the right bank, except near the river level, where highly weathered rock directly overlies fresh bedrock. On Traverse A the slightly weathered (2300 m/s) layer is up to 35 m thick. The 2300 m/s layer may contain zones of higher permeability than the bedrock.

The three basic differences, then, between the left and right banks in Dam Site 1 are the steeper right bank, the greater intensity of weathering in the overburden of the left bank, and the greater abundance of lower velocity zones in bedrock on the left bank. To account for these differences one can postulate sets of steeply dipping joints closely parallelling the slope of the right bank, and intersecting the slope of the left bank at a high angle. The thinner cover of lower-velocity material on the right bank could thus be caused by the weathered material continuously 'flaking' off along these joints. This hypothesis could also account for the deeper weathering of the overburden and bedrock on the left bank, because water would percolate more effectively along the joints here where they are at a high angle to the slope. The strike of these joints would be normal to the dam axis. Macias (1973) analysed joint directions and slope stability for the left and right abutments, showing two joint sets striking across the direction of the dam axis and dipping steeply. The right bank shows marginally greater slope stability than the left bank.

At the base of Dam Site 1, bedrock velocities of 4400 m/s were recorded on Traverse E along the river bed and 3500 m/s on Traverse A across the river bed. This marked velocity anisotropy may be the result of such a joint trend, which could either be stress-induced or an inherent property of the ultramafic rock. Velocity anisotropy having a similar orientation was also measured in the overburden: 2700 m/s was recorded along Traverse E and 2000 m/s on Traverse A. This suggests that the direction of maximum permeability is across the dam axis at the base of Dam Site 1. The overburden is up to 27 m thick and is interpreted as highly jointed, slightly weathered rock. Because of the anisotropy there is little possibility that appreciable quantities of boulder gravel are present.

Farther downstream on Traverse E, a velocity of 1800 m/s is interpreted as representing water-saturated gravel. The 1800 m/s refractor extends beneath the Quaternary colluvial deposits on the left bank (Pl. 2) which are bounded by Traverses B, C, D and F (Pls 5, 6, 7, 9). This area shows up to 15 m of colluvium (900 m/s) overlying boulder gravel or weathered rock. More drilling should be done here. Depths to bedrock of up to 40 m are recorded. Up-slope from this area on traverse B (Pl. 5) up to 25 m of scree (1500 m/s) overlies fresh bedrock.

The rippability depths shown on Plate 30 are a guide only, and are subject to the limitations defining overburden velocities which have already been discussed. They are based on the criterion that rock with a velocity of less than 1500 m/s is rippable with mechanical excavators. However, because of the highly-jointed nature of the rock in the Musa dam site area rock having a velocity greater than 1500 m/s may be rippable.

Traverses U and Z (Pls 28, 31) cover the intake portal of the Dam Site 1 diversion tunnel. At river level, boulder gravel (1900 m/s) and weathered rock up to 33 m thick occur near the intake portal area. Bedrock depths of up to 35 m are encountered along traverse Z. Weathering is uniform along traverse Z and generally 10 m of moderately to highly weathered rock, overlies up to 25 m of slightly weathered rock (2400 m/s). Evidence of shearing or jointing within the bedrock (velocity 2,800 m/s) occurs on Traverse U (Pl. 28), between chainages 70(70) and 150(147), some 50 m north of the intake portal. Traverses S (Pl. 26) and T (Pl. 27) were sited along the approximate alignment of the diversion tunnel line leading to the Upstream Power Station Site. These tunnels are sited well within the bedrock at an approximate reduced level of 100 m. Bedrock velocities along traverses S and T vary between 3400 and 5000 m/s. Minor shearing, jointing or weathering in the bedrock may be expected in places where the velocity is close to 3400 m/s. Whether these lower-velocity zones extend to the full depth of the tunnel is impossible to determine from the seismic results. No indication of a preferred direction of jointing along the tunnel line is evident from the seismic results.

The alternative tunnel line to the Downstream Power Station Site passes well beneath Trig Point Rebel, where the 1970 geophysical survey (Taylor, 1971) showed the sheared bedrock surface on Traverse A6 (Pl. 34) at a reduced level of about 330 m. Anistropy of bedrock velocities at Trig Point Rebel suggests jointing directions across the alternative tunnel alignment some 200 m above tunnel level.

7.3.1. Upstream Power Station Site

Traverse T (Pl. 27), Traverse H (Pl. 11), Traverse M (Pl. 16), and Traverses A7 and A8 (Pl. 34 and Taylor, 1971) cover the general area of the Upstream Power Station Site. Traverses H, Q (Pl. 24), and R (Pl. 25) cover the slopes above the site. The results of Traverse H show that between chainages 395(299) and 455(355) bedrock is overlain by up to 15 m of unconsolidated scree and colluvial material (800-1200 m/s). This is at the base of the steep slope of the right abutment of Dam Site 2. Beneath the Musa River, between chainages 345(254) to 395(299) on Traverse H, up to 20 m of 1900-2100 m/s heavily jointed rock or boulder gravel overlies fresh bedrock.

The seismic results show that the upper slopes above the power station site are weathered to a great depth. Velocities of 1500 m/s corresponding to a modulus of elasticity of 0.5×10^5 kg/cm^2 (Pl. 33), are recorded in the overburden along Traverse H at the top of the slope. Up to 60 m of this material overlies fresh bedrock. Velocity anisotropy within the overburden at the intersections of Traverse Q with R and Traverse R with H, and the general decrease in velocity toward the river, suggest jointing within the bedrock at a high angle to the direction of Traverse H and to the potential direction of sliding. These results suggest potential instability of the slopes of the right abutment above this power station site.

On the left bank at Traverse H, relatively high-velocity overburden (2000-2900 m/s) overlies high-velocity bedrock on the lower slopes (chainages H230(173) to H345(245)) but higher up (chainages H-10 (1) to H230(173)), sheared, jointed, or weathered bedrock (2300 m/s) underlies highly weathered material (1100 m/s) up to 30 m thick.

The other power station site is discussed in Section 7.4.2.

7.3.2. Spillway, Dam Site 1

Plate 3 shows a possible spillway on the left bank of Dam Site 1. Several low-velocity zones occur close to and within the alignment of the spillway. These occur in Traverse B (Pl. 5, chainages 40(39) to 60(59)), Traverse D (Pl. 7, chainages 415(704) to 580(858)), Traverse C (Pl. 6, chainages 640(612) to 690(660)) and on upper slopes near Trig Point Bev on Traverse H (Pl. 11, chainages 10 (1) to 230(173)). The slopes above the spillway, and the potential instability of the upper slopes may influence the design and siting of the spillway in this area.

7.4. Dam Site 2

The schematic diagram of a possible construction plan for Dam Site 2 is shown in Plate 3.

Traverse H (Pl. 11) shows the cross section of the axis of Dam Site 2. The top of the impervious core of a dam wall of crest level 275 m would meet the bedrock surface at a horizontal chainage of 43 metres on the left bank. The elevation of the base of moderately weathered (1500-1800 m/s) rock on the top of the right abutment (intersection point, Traverses R (Pl. 25) and H, H700(530), R17 is 215 m. Thus, on the right bank, a dam of crest level 275 m would extend across the ridge covered by Traverse R, beyond the area of the present seismic coverage.

The most significant feature of the seismic profile on Traverse H is the layer of extensively sheared (or jointed) and deeply weathered rock which mantles the upper slope on the left bank (chainages 10(1) to 220(167)). This indicates an area of possible high permeability. The overburden is extensively weathered (1100 to 1200 m/s) and easily rippable, and the 2300 m/s refractor would be suitable bedrock for an impermeable core. Long-shot offsets of up to 300 m were employed on Traverse H and failed to detect a velocity higher than the 2300 m/s refractor above H220(167). This indicates that unless the low-velocity surface layer thickens up-slope towards Trig Point Bev (so that the bedrock apparent velocity from a long shot in the river is 2300 m/s), then the sharp change in bedrock velocity above H220(167) may extend to a depth of 95 m.

The sharp discontinuity in bedrock and overburden velocity which occurs at H220(167) may be the northeastern limit of the major zone of shearing or jointing suggested in Section 7.3. Downslope from this discontinuity, between chainages 220(167) and 345(254), slightly weathered rock (2000 to 2900 m/s) at a maximum depth of 10 m overlies fresh bedrock. Depths to bedrock range from 30 m at H220(167) to 10 m at river level. The slightly weathered bedrock is not rippable and will probably form an effective bedrock for the impervious core.

Elsewhere on the left bank probable shearing is evident on Traverse C (Pl. 6), between chainages 640(612) to 690(660) in the area of the permeable core and along Traverse D (Pl. 7), from chainages 415(704) to 518(801). In general, the coverage of the left bank is sparse because of the dangerous nature of the terrain; however the results suggest a major zone of lower bedrock velocities over most of the upper left bank.

The top of the right abutment of Dam Site 2 has up to 10 m of moderately to highly weathered rippable rock overlying a 1500-1800-m/s, slightly to moderately weathered layer. The 1500-1800-m/s layer is rippable on the top edge of the abutment at H590(426), where a velocity of 1500 m/s was recorded, although the excavation may need to be up to 40 m deep. Joints in the 1500-1800-m/s layer trend across the dam wall axis (section 7.3.2), and higher permeability can be expected in this direction. A bedrock velocity of 500 m/s was recorded at the top of the right abutment, but the true velocity is probably less than this because of the large topographic effect sustained by shooting long shots in the river and 100 m offset from H700 over the far side of the ridge covered by Traverse R. However, Traverses H and R indicated higher-velocity bedrock than the 1970 survey (Taylor 1971, Traverse A2) in this area.

Beneath the Musa River up to 30 m of heavily jointed rock and/or possibly boulder gravel (1900-2100 m/s) overlies fresh bedrock (Trav. M, Pl. 16). Evidence of minor velocity anisotropy in the overburden and bedrock was found (overburden velocities of 1900 m/s across the river and 2100 parallel to the river; bedrock velocities of 4000 across the river and 4400 parallel to the river). This suggests joint directions and possibly maximum permeability across the dam site axis; however, the anisotropy appears to be less prominent at the base of Dam Site 2 than at Dam Site 1.

7.4.1. Diversion tunnel intake portal, Dam Site 2

Traverse B (Pl. 5) covers the area close to the diversion tunnel intake portal for Dam Site 2. Up to 6 m of rippable (1400 m/s) overburden overlies fresh bedrock. No evidence of major low-velocity zones in bedrock is found. The tunnel line passes beneath Trig Point Rebel and the outlet portal is near the downstream power station site on Traverse PE (Pl. 23). Section 7.3. (Dam Site 1) includes a discussion of the tunnel line.

The outlet portal is in an area where highly weathered overburden (1300 m/s) up to 39 m thick directly overlies slightly jointed or sheared bedrock (3000 m/s). Scree from a major Quaternary rock fall in the area (Pl. 2, Section 7.4.3.) may be a factor contributing to the 1300 m/s velocity of surface layer. The bedrock velocities do not show any strong anisotropy at the downstream power station site, and this would suggest that a preferred joint direction is absent.

7.4.2. Downstream power station site

Traverse PC (Pl. 21), PE (Pl. 23) and A10 (Pl. 34; Taylor, 1971) cover the foundations of the downstream power station site. Moderately jointed or sheared bedrock underlies the site at a maximum depth of 20 m. Overburden velocities vary from 1300 m/s on Traverse PE to 2000 m/s on Traverse PC (chainages 200(178) to 280(251)). The 2000 m/s velocity probably represents slightly weathered rock. Shallow bedrock (less then 7 m) occurs in the river bed on the end of Traverse PC. Farther upstream, on Traverse A10, bedrock shallows to 5 m and shows less evidence of jointing or shearing (3800 m/s).

Above the power station site is a major (Quaternary) rockfall (colluvium). This is covered by Traverses PA (Pl. 19), PB (Pl. 20), PC (Pl. 21) and PE (Pl. 23). The seismic results suggest that the colluvium (850-1500 m/s) is concentrated in an area bounded by chainages 300(266) and 650(575) on Traverse PA, chainages 0(0) and 350(294) on Traverse PB, and above chainage 150(133) on Traverse PC. The colluvium is up to 50 m deep and everywhere overlies fresh bedrock, except at the southwestern end of Traverse PB. Here the top of the bedrock is 65 m deep and it is overlain by a 1900 m/s slightly weathered layer of ultramafic rock. In this section, the rockfall material thins to 17 m.

The topographic profiles of Traverses PA, PC, and PE show the shelf-like topography of the Quaternary slide mass. The bedrock beneath the slide appears to shelve also, and the bedrock velocity PA (4200 m/s), indicates no major jointing or shears. However on the upstream toe of the slide mass a sheared zone is indicated by Traverse PE.

7.4.3. Spillway works, Dam Site 2

The spillway proposed for Dam Site 2 (Pl. 3) crosses the rockfall above the downstream power station site (Trav. PA, Pl. 19, Pl. 2) and over 350 m of its length would be sited on potentially unstable scree. For construction of the spillway area at the top of the saddle covered by Traverse A6 (Taylor, 1971) over 50 m of excavation may be required. The results from Traverses A6 and PA suggest that the joint direction parallels Traverse A6 in this area, but the interpretation of the results is complicated by the topographic distortion of travel-time data over the top of the ridge on Traverse PA, and the fact that the bedrock has not been reached on Traverse A6.

The results suggest that the area considered may be unsuitable for spillway construction.

7.5. Landslide area

The landslide is shown in Plate 2 and is covered by Traverses T (Pl. 13), K (Pl. 14) and L (Pl. 15). Traverse J along the landslide axis, coincides with Diamond Drill-holes DDQ and DDR (Macias, 1973) whose schematic logs are shown on Plate 13. Drill-hole DDR passed through 64 m of completely to moderately weathered interbedded tuff, agglomerate, conglomerate, and mudstone of the Pleistocene Domara River Beds, and entered fresh to slightly weathered ultramafic rock. A major shear zone was intersected between depths of 66.4 and 73 m, indicating that there has been movement at or very close to the contact between the weathered Domara River Beds and the immediately underlying ultramafic rocks. The steep westward dip of the Domara River Beds in the landslide as compared to their dip in situ just above the landslide suggests this movement has been rotational about a horizontal axis. Orientation of core in the ultramafics at the bottom of Drill-hole DDR was not possible owing to caving of the hole in the Pleistocene section, so it was not possible to determine the direction of jointing; however in Drill-hole DDQ (Pl. 2) the joint pattern measured in oriented core of fresh ultramafic rock has a similar orientation to the joint pattern in the rest of the dam site area. Macias (1973) concludes that the rock at river level on Traverse J has not been rotated.

The seismic profile across the landslide agrees very well with the results of Drill-hole DDR and enables the profile of the boundary between the weathered Domara River Beds and fresh ultramafic rock to be defined. The bedrock surface along Traverse J has a serrated profile. It is suggested that this effect is due to differential weathering along the individual strata of the dipping Domara River Beds. The log of Drill-hole DDR shows variable degrees of weathering for each lithological unit within the Beds. The serrated effect also reflects the direction of dip of the Domara River Beds. The true bedrock profile is probably a smoothed version of the bedrock profile as shown. The presence of these deep pockets of differential weathering probably accounts for the severe attenuation of seismic energy experienced in this and the previous survey (Taylor, 1971).

The slide base dips steeply near the western end of Traverse J (intersection point, traverses J and K) and here the discrepancy in depths to bedrock between Traverse J and Traverse K can be accounted for by the hypothesis that the refractions on Traverse K are obtained from the steeply dipping side of the landslide base, whereas on Traverse J, they emanate from bedrock in situ beneath the slide mass.

The high bedrock velocities beneath the landslide suggest that no shattering of the ultramafic rocks immediately beneath the Domara River Beds has occurred as a result of the sliding process; however, strong velocity anisotropy is evident at the intersection of Traverses J and L. Bedrock velocities of 3000 m/s along Traverse L (Pl. 15) and 4500 m/s on Traverse J indicate predominant jointing parallel to Traverse J. This velocity anisotropy is not recorded at river level, at the intersection of Traverse J with Traverse C (Pl. 6). At either end of Traverse L high bedrock velocities are recorded and are interpreted as delineating the lateral extent of the slide mass (see also Appendix, Location G).

If a major zone of sheared or jointed rocks of low velocity occurs below the higher-velocity bedrock surface, the seismic refraction method can give no indication of its presence. The drilling has defined one major shear zone at the boundary between the Domara River Beds and the ultramafic rock in Drill-hole DDR. The seismic results suggest the outcrop of the Domara River Beds/ultramafic rock boundary is between J200(238) and J220(221). A second shear zone some 0.6 m wide was intersected by Drill-hole DDQ at a depth of 35 m.

Macias (1973) concludes that the bedrock profile beneath the landslide and the shear zone intersected in Drill-hole DDR represents the base of the major slide in the area, based principally on the conclusion that no rotation of the ultramafic rock has occurred at Drill-hole DDQ. The narrow shear intersected at a depth of 35 m in hole DDQ lies approximately on the theoretical slide surface (Macias, 1971) but is probably of minor significance. The comparatively shallow bedrock and high bedrock velocities below the intersection of Traverses L and J suggest that the rock in the vicinity has not undergone any significant shearing.

A possible alternative explanation for the profile of the landslide is that a block of ultramafic rock has been downfaulted, and secondary sliding and rotation of the Domara River Beds has occurred. The shape of the base of the Domara River Beds suggests that they have stabilized, and further movement can be expected only in the unconsolidated material on the edge of the plateau.

7.6. Depth of Alluvium, Musa Valley

Plate 35 shows the interpreted results for the deep seismic refraction probe which was carried out at Safia airstrip. The probe was oriented across the strike of the valley. Table 4 summarizes the results.

TABLE 4. SEISMIC RESULTS, MUSA VALLEY GRABEN

Depth (m)	Velocity (m/s)	Interpreted lithology
0-4	300	Soil
4-65	1700	Unconsolidated alluvium
65-341	1900	Alluvium (increasing consolidation)
341-635	2200	Alluvium (increasing consolidation and containing boulders)
635-1550	2900	Domara River Beds (highest velocity measured)
>1550	5000	(velocity assumed for calculation; represents ultramafics or metamorphics)

In Plate 35, a schematic sketch (after Robinson, 1971) is shown of the inferred subsurface geology across the Musa Valley, which is a Pleistocene to Recent graben. The seismic results shows that late Pleistocene to Recent movement may have amounted to at least 635 m. This indicates recent tectonic instability within the hydro-electric project area.

Rothé (1970) has studied several dams in areas that have been subject to increased earthquake activity as a result of filling of the reservoir, particularly the Kariba Dam (Zambezi River), Hoover Dam (USA) and Vogorno Dam (Switzerland), which have all been subject to active fault movement within the vicinity of the dam. Rothé concluded that the danger of seismic activity was particularly great in reservoirs deeper than 100 m where fault zones are active.

Considering that these conditions obtain in the proposed Musa project and in view of the large thickness of alluvium beneath the reservoir area, the amplification of earthquake motion within the reservoir area would be considerable. Calculations of the natural period of the fundamental mode of vibration of the alluvium in the Musa Valley, assuming a shear-wave velocity of 0.4 to 0.5 times the longitudinal velocity for the sediments, give values of between 0.3 and 3 s (Borcherdt, 1970). The lower periods correspond to vibration of the near-surface unconsolidated layer (1700 m/s), whilst the 3 s period takes into account the oscillation of the entire 635 m thickness of alluvium. Strong amplification of seismic ground motion can be expected for near-harmonic ground waves with periods in this range. Further studies of vibration of water in large reservoirs (Newmark & Rosenblueth, 1971, Sherard et al., 1963) show that for a dam of the geometry of the Musa reservoir, the period (T) of natural vibration of the water is given by

$$T = \frac{0.278H}{100}$$

where H is the water depth in metres and 0.278 is an empirically determined factor.

For a dam 150 m deep the period is 0.42. Compounded with the similar oscillation period of the upper layers of the alluvium, water-wave oscillation in the reservoir can be expected to be severe.

Assuming a density of 2.2 g/cm^3 for the alluvium, 150 m of water in the reservoir would impose an extra loading equal to 11 percent of the weight of the alluvium. Considering the active movement evident up to Recent times, it is not unreasonable to predict that an 11-percent loading of the Musa graben would initiate increased seismicity. Nikolayev (1972) reviewed previous studies of the problem of earthquake activity associated with filling of reservoirs and recommends a systematic approach to study of the problem, mainly involving installation of three-component seismometers of both long and short period within the proposed reservoir area, and establishment of a precise levelling network, to obtain data on pre-filling seismicity.

8. CONCLUSIONS

The conclusions given below are derived from the seismic results and from previously existing geological information (Macias, 1971). The most recent geological results are the subject of a separate report (Macias, 1973), and have not been considered in depth in the present report.

8.1 Zones of low-velocity bedrock

Extensive zones of low-velocity bedrock (2300-3000 m/s) are evident on the top left banks of Dam Sites 1 and 2. The low-velocity zones may be due to shearing, jointing, or weathering, or combinations of any of these processes and may represent zones of higher permeability.

A low-velocity zone 45 m wide was detected on Traverse C near the axis of Dam Site 2 within the area of the impervious core. A low-velocity zone on Traverse B (right bank) corresponds to a major photogeological lineament.

8.2 Dam-site overburden and foundation conditions

At the base of each damsite, 25-30 m of closely jointed, slightly weathered rock and boulder gravel overlies fresh bedrock. Bedrock appears to be slightly shallower beneath the Musa River at Dam Site 2 than at Dam Site 1. Velocity anisotropy in the overburden and bedrock, at the base of each dam site, indicates jointing and probably higher permeability in a direction perpendicular to the dam axes. The anisotropy appears to be stronger at the base of Dam Site 1.

At Dam Site 1, basic differences in the weathering profiles between the left and right banks are evident. On the left bank, depths to bedrock range from 5 m at river level to 35 m at the top. Overburden consists mainly of highly to completely weathered, rippable material, and there is evidence that slightly weathered rock is found mainly on isolated ridges.

Depths to bedrock on the right bank range from 5 m at river level to about 50 m at the top of the abutment. A slightly weathered layer overlain by up to 14 m of rippable highly weathered rock is widespread. Rippability appears to be highly variable in the area of Dam Site 1. The general required depth of excavation of the overburden at Dam Site 1 is less than at Dam Site 2 (particularly on the left bank).

At the top half of the left bank at Dam Site 2, 25-33 m of low-velocity, highly weathered, rippable material overlies the low-velocity bedrock. Below the intercept point of Traverses D and H, slightly weathered material dominates. Jointing at the top of the right abutment within the slightly weathered layer is perpendicular to the dam axis.

8.3 Joints or shears at the dam sites

On the basis of 8.1 and 8.2, a major set of joints or shears is postulated as a possible explanation for the major differences between the weathering profiles and topography of the left and right banks of the dam sites. The planes of weakness would trend roughly perpendicular to the dam axis and this direction may represent the direction in which maximum permeability can be expected. The surface of the joints or shear planes would closely parallel the slopes of the right bank and intersect the left bank at a high angle.

8.4 Intake portals of diversion tunnels

The site for the intake portal of the diversion tunnel for Dam Site 1 is in an area where up to 33 m of boulder gravel and weathered rock overlies fresh bedrock. The portal is 50 m upstream from a major low-velocity zone which is 80 m wide. No preferred joint direction is evident in the area of the tunnel line.

The intake portal of the diversion tunnel for Dam Site 2 is located in a shallow bedrock area where less than 6 m of rippable material overlies fresh bedrock. Joint directions on top of Trig Point Rebel trend across the tunnel alignment; however, as this is some 200 m above tunnel level, joint directions at tunnel level are uncertain. The outlet portal is located in 30 m of low-velocity, highly weathered rock and scree, which overlies moderately jointed or sheared rock.

8.5 Power station sites

The upstream power station site may be endangered by the potentially unstable slopes of the right abutment of Dam Site 2. The upper slopes of Trig Point Bev are potentially unstable also, with up to 30 m of 1100 m/s material evident. The transfer of the power station farther downstream near Traverse J, would appear to minimize effects of slope stability because of the wider profile of the gorge in this area.

The downstream power station site is at the base of a major Quaternary rockfall, which attains a maximum depth of 50 m. Seismic data show shallow (less than 20 m), moderately jointed bedrock beneath the site, and evidence that the bedrock is shallower beneath the river.

8.6 Spillway sites

The spillway chute structure for Dam Site 1 crosses below the low-velocity material on the upper slopes of Trig Point Bev (Trav. H). The spillway for Dam Site 2 crosses the area of Quaternary scree behind the downstream power station site.

8.7 Landslide west of Dam Site 2

Investigation of the landslide indicates that the base of the Domara River Beds in the landslide is some 100 m above river level and crops out near chainage J220(221). Up to 65 m of highly to moderately weathered Domara River Beds overlies fresh ultramafic bedrock and forms the major part of the slide mass. Velocity anisotropy beneath the landslide indicates that the main joint direction in the bedrock is parallel to the axis of the slide (Trav. J). Shallow high-velocity bedrock occurs near the river, below the base of the landslide. Drilling and surface geological mapping of the landslide area suggest that the ultramafic rock/Domara Beds boundary defined by seismic refraction coincides with the base of the landslide (Macias, 1973). Any deeper plane or planes of failure, within the fresh ultramafic bedrock would not be detectable by the refraction method, except if it was of considerable thickness.

8.8 Elasticity (E) and longitudinal velocity (V_L)

Laboratory measurements on cores and field determination of the ratio of longitudinal velocity to shear wave velocity show that the relationship between the modulus of elasticity (E) and longitudinal velocity (V_L) is as follows:

$$E = (2.2 \mp 0.3)\ V_L^2\ kg/cm^2$$

It is emphasized however, that the calculated value of E is always an apparent value for a rock mass sampled. The compressibility of rock masses which are free to move on joint planes may be determined more by the properties of the joint surface than by the apparent value of E derived from seismic velocity.

8.9 Induced seismicity

The thickness of late Pleistocene to Recent alluvium in the Musa Valley graben is interpreted as 635 m, suggesting at least this amount of movement on the northern boundary fault of the graben in late Pleistocene to Recent times. The natural period of vibration of the alluvial material coincides closely with that of water in a reservoir 150 m deep, and therefore amplification of earthquake wave motion at these periods (0.3-3.0 sec.) can be expected. A reservoir 150 m deep would increase the load on the basement under the alluvial deposits within the Musa Graben by 11 percent, and increased seismic activity may be expected when the reservoir fills.

9. RECOMMENDATION

It is recommended that further work be based on a detailed analysis of the results of the geophysical work and the most recent geological mapping.

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APPENDIX

Interpretation of time-distance curves

Examples of the interpretation of the time-distance curves are described below. The same method applies to all plates. The locations of the examples are indicated on the plates by a capital letter in a circle.

LOCATION A - Plate 4, between A00 and A50

(i) The time-distance curves between A00 and A50 indicate an abrupt shallowing in the depth to bedrock between A00 and A00-66, and therefore the intercept time cannot be determined by extending a straight line to the ordinate at the shot-point. An alternative method was employed. The time difference between the parallel lines representing bedrock velocity from the long-shot (A00-66) and bedrock velocity from the short-shot (A00-1) was measured. This was then subtracted from the long-shot arrival time at A00 to give the intercept time. Abrupt changes in the slope of the bedrock surface are very common. On Plate 4 they are apparent also at A260, A315, A365, A535 and A700.

(ii) Several arrival times are displaced from the straight lines shown (e.g. at A105, A205 and A700). This is caused by irregularities in the ground and bedrock surfaces, and by the inhomogeneity of the overburden. Apparent bedrock velocities, as indicated by the slope of the lines, are not used in the computation.

(iii) The marked step between A100 and A110 on the long-shot plot indicates that there is a difference of arrival times from the two shots fired at A00-1. This may be the result of misplacement of one of the shots, or a change in the physical conditions at the shot-point after the first shot was fired. Some of these 'steps' are not shown for other traverses.

LOCATION B - Plate 4, between A320 and A550

Both long shots indicate a very uneven bedrock surface. An uplift in the bedrock is indicated by a broken line. The interpretation is shown as uncertain. All seismic waves will travel in a straight path through the uplift, giving too short a reciprocal time and therefore too deep an interface.

LOCATION C - Plate 4, between A660 and A690.

The double step in the time-distance curve (slope chainage A675) is an expression of a steep buried cliff.

LOCATION D - Plate 4, between A820 and A960.

It is not certain whether the long shot at A955 + 70 was fired far enough away for the wave refracted from the bottom refractor to be picked up by the nearer geophones. No attempt was made therefore to calculate the intercept time at short point A872.

LOCATION E - Plate 6, shots at C362 and C367.

No arrival times are available from two refractors corresponding to 300 m/s and 550 m/s observed at C365. Thicknesses of these layers were assumed to find the intercept times to calculate the average velocity. The small errors in the intercept times will not lower the accuracy by more than 2 percent.

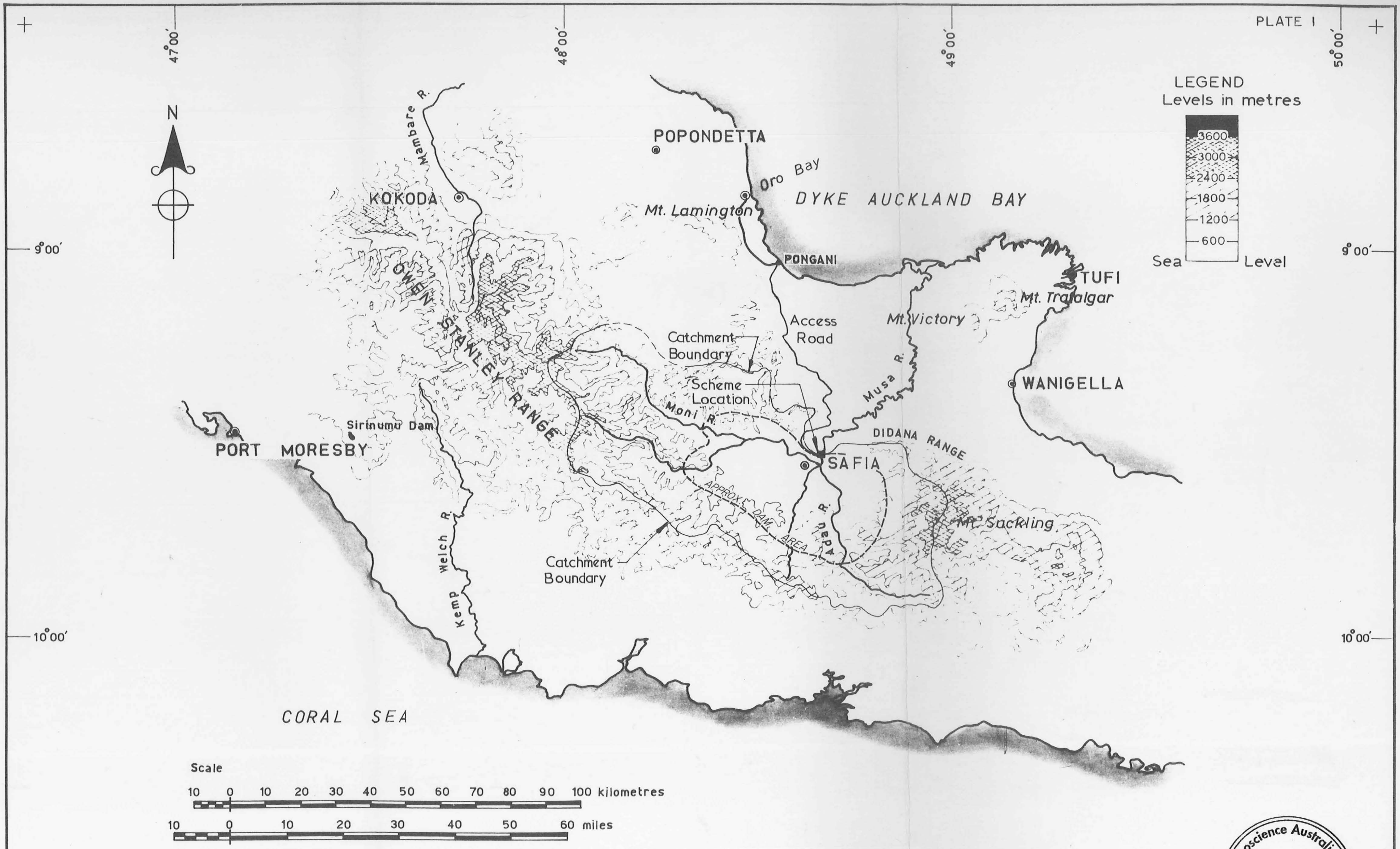
LOCATION F - Plate 8, point E40.

Velocity anisotropy is indicated at the intersection of two traverses. The difference in depth shown on Traverses A and E is partly due to the fact that the refracted waves do not come from the same position on bedrock. A similar situation exists at the intersection of Traverses C (Pl. 6) and H (Pl. 16).

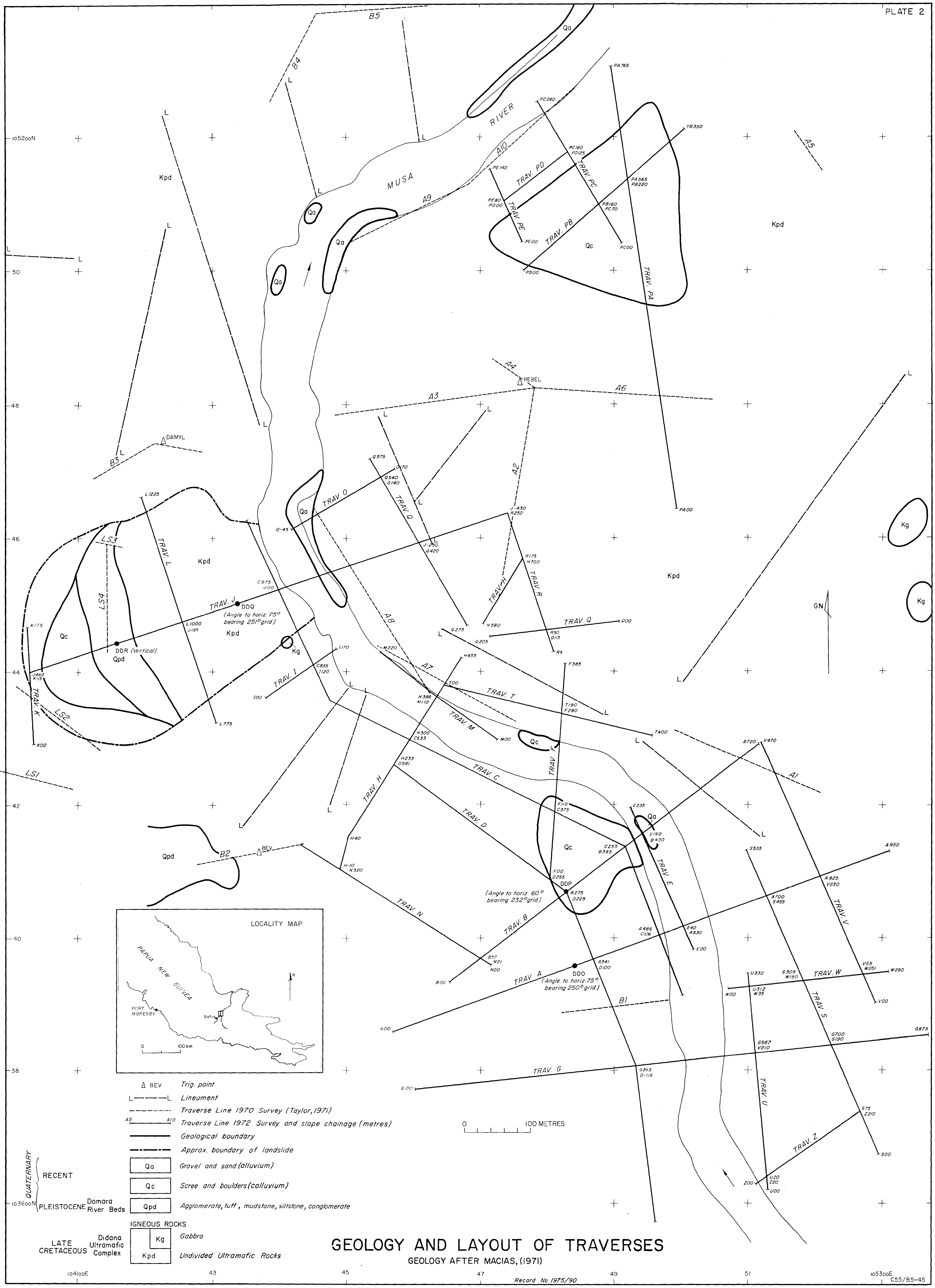
LOCATION G - Plate 15, between L1150 and L1225.

The reversed slope of the travel-time curve from L935 indicates that there is a gradual slope in the bedrock interface in relation to the topographical high at L1150 located in the low-velocity material. The broadside shots confirmed it. A similar situation exists from L820 to L880.

PLATE I



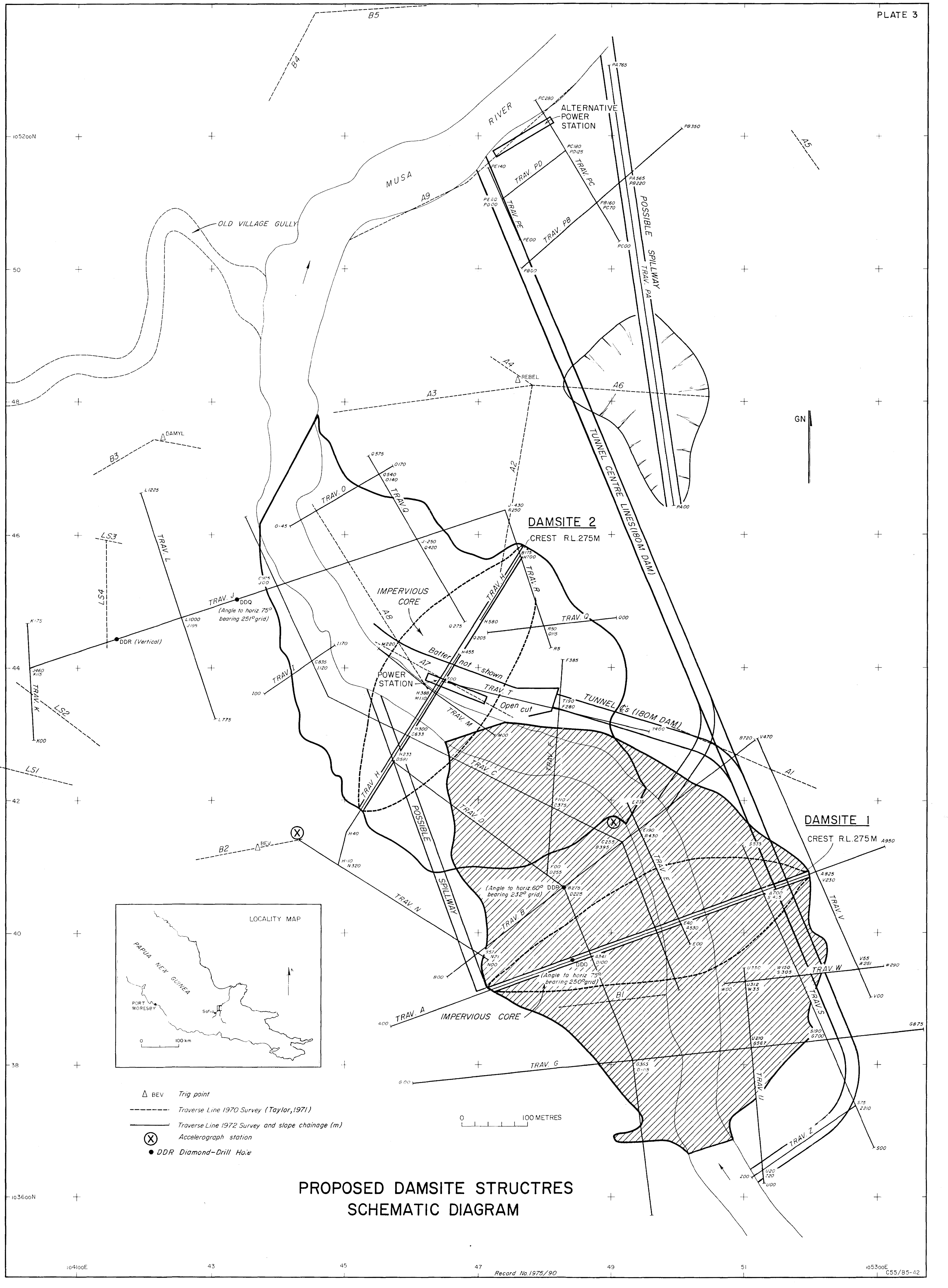
LOCALITY MAP
MUSA RIVER HYDROELECTRIC SCHEME



GEOLOGY AND LAYOUT OF TRAVERSES

GEOLOGY AFTER MACIAS, (1971)

PLATE 3



PROPOSED DAMSITE STRUCTRES
SCHEMATIC DIAGRAM

TRAVERSE 'A'

(AXIS DAMSITE 1)

Record No 1975/90

C55/B5-20

TRAVERSE 'B'

(DAMSITE 1,2)

Record No 1975/90

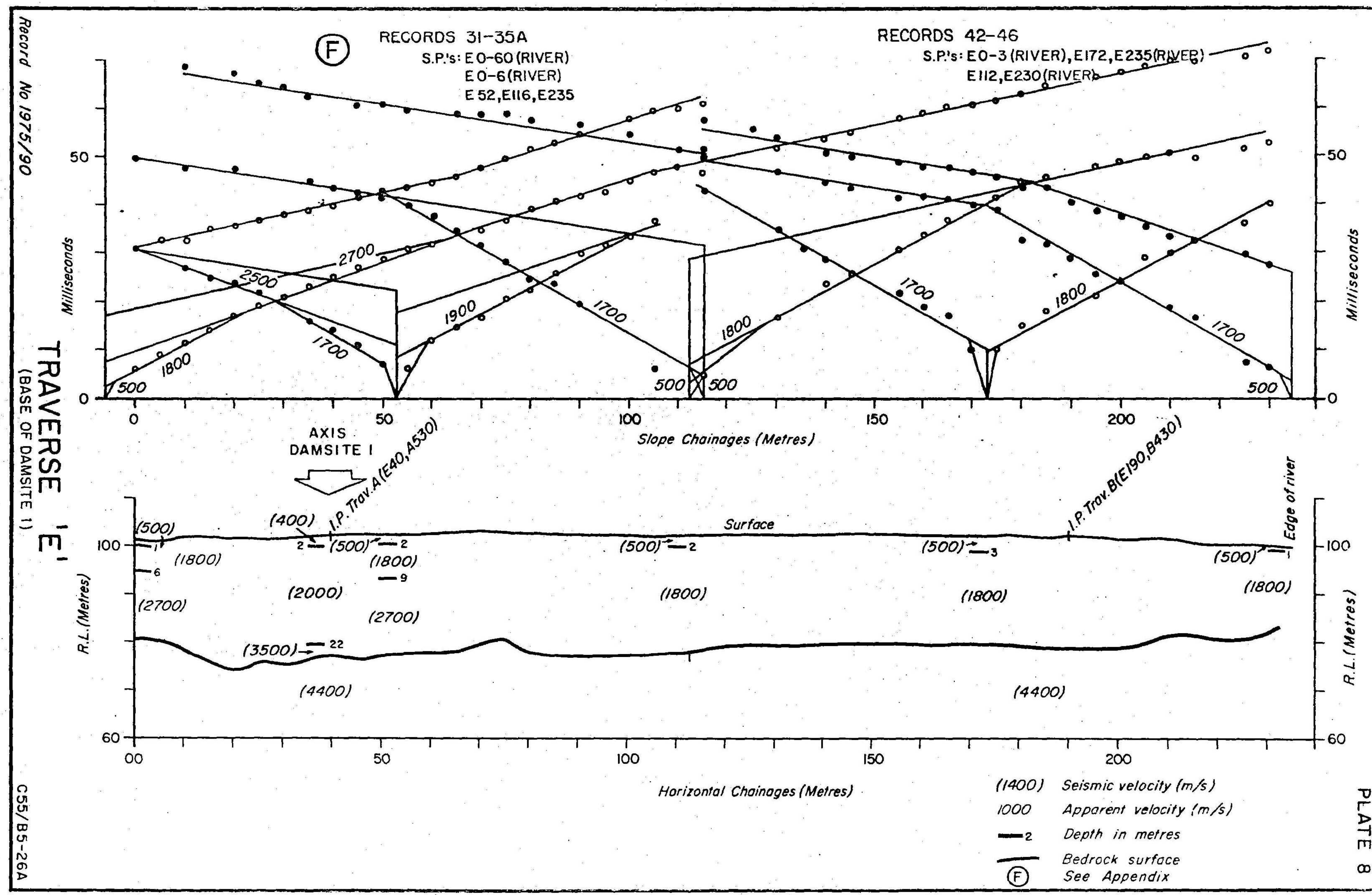
C55/B5-19

PLATE 6
RECORDS 47–51
S.P.'s : C00 (RIVER)
C70
C160
C225
C260 + 100
RECORDS 52–56
S.P.'s: C 255–100
C 254
C 312
C 367
C 462
E
RECORDS 76–80B
S.P.'s: C255
C 362
C 422
C 482
C 595
RECORDS 84–88
S.P.'s: C365
C478
C593
C533
C597
C710
RECORDS 89A–93
S.P.'s: C480
C593
C655
C 707, C825
F
SHOTS NOT IN LINE WITH FULL SPREAD
RECORDS 98–102
S.P.'s: C 595
C 703
C 770
C 862
C973
RECORDS 103–107
S.P.'s: C 770
C 859
C 955
C 1070 (RIVER 10m OFFSET)
C 1110 (" " ")
MILLISECONDS
SLOPE CHAINAGES (METRES)
AXIS DAMSITE 1
AXIS DAMSITE 2
Change in direction
LANDSLIDE AREA
R.L. (METRES)
HORIZONTAL CHAINAGES (METRES)
LEGEND
(4000) Seismic velocity (m/s)
2600 Apparent seismic velocity (m/s)
5·0 Depth in metres
Bedrock surface
Topographic surface and slope chainage
E See Appendix
TRAVERSE 'C'
(DAMSITES 1,2)
Record No 1975/90
C55/B5-10

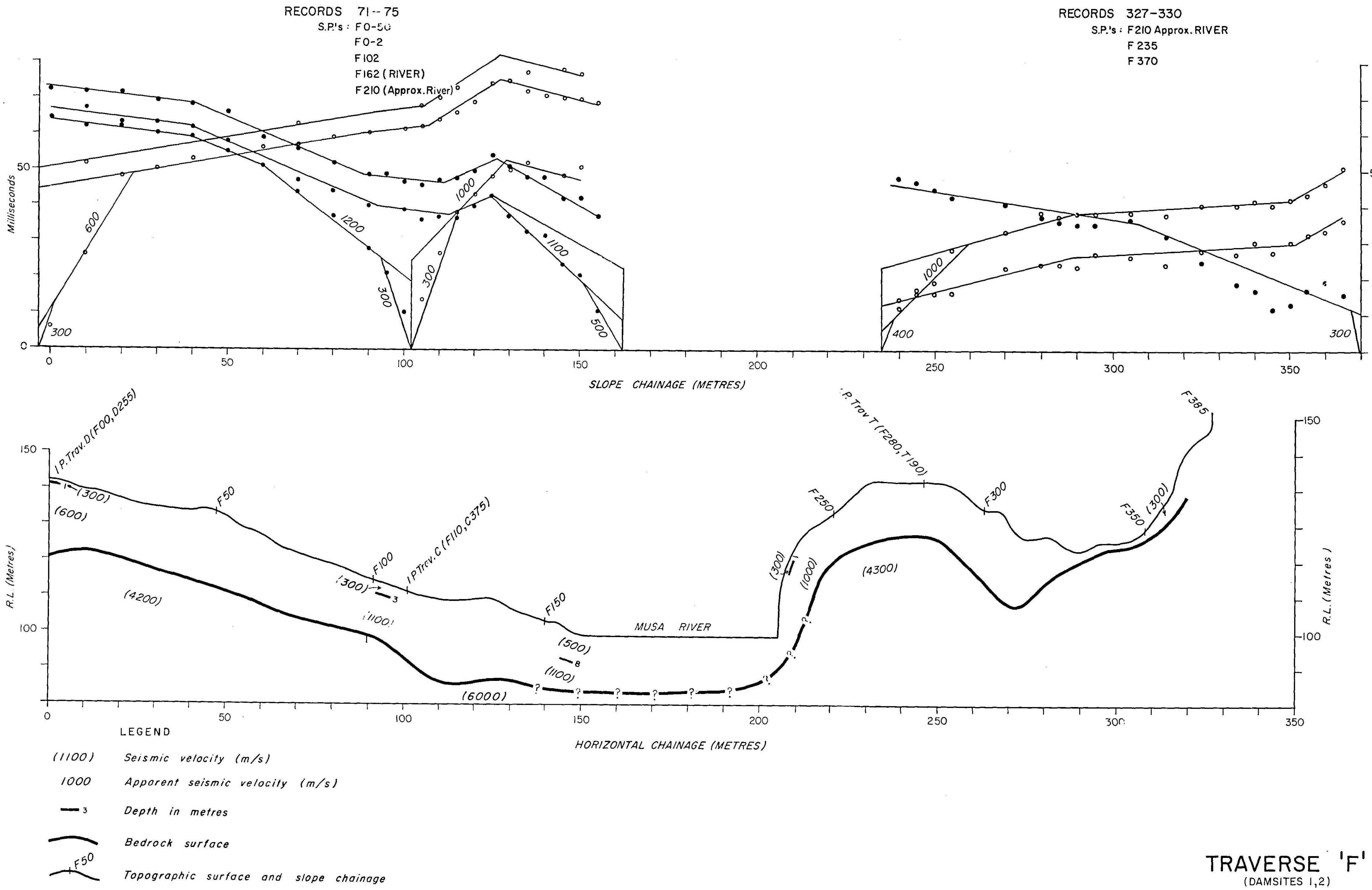
TRAVERSE 'D'
(DAMSITES 1,2)

Record No. 1975/90

C55/B5-21



Record No 1975/90
TRAVERSE 'E'
(BASE OF DAMSITE 1)
RECORDS 31-35A
S.P.'s: E0-60 (RIVER)
E0-6 (RIVER)
E52, E116, E235
RECORDS 42-46
S.P.'s: E0-3 (RIVER), E172, E235 (RIVER)
E112, E230 (RIVER)
Milliseconds
Slope Chainages (Metres)
AXIS DAMSITE I
I.P. Trav. A (E40, A530)
I.P. Trav. B (E190, B430)
Edge of river
Surface
R.L. (Metres)
Horizontal Chainages (Metres)
(1400) Seismic velocity (m/s)
1000 Apparent velocity (m/s)
2 Depth in metres
Bedrock surface
F See Appendix
PLATE 8
C55/B5-26A



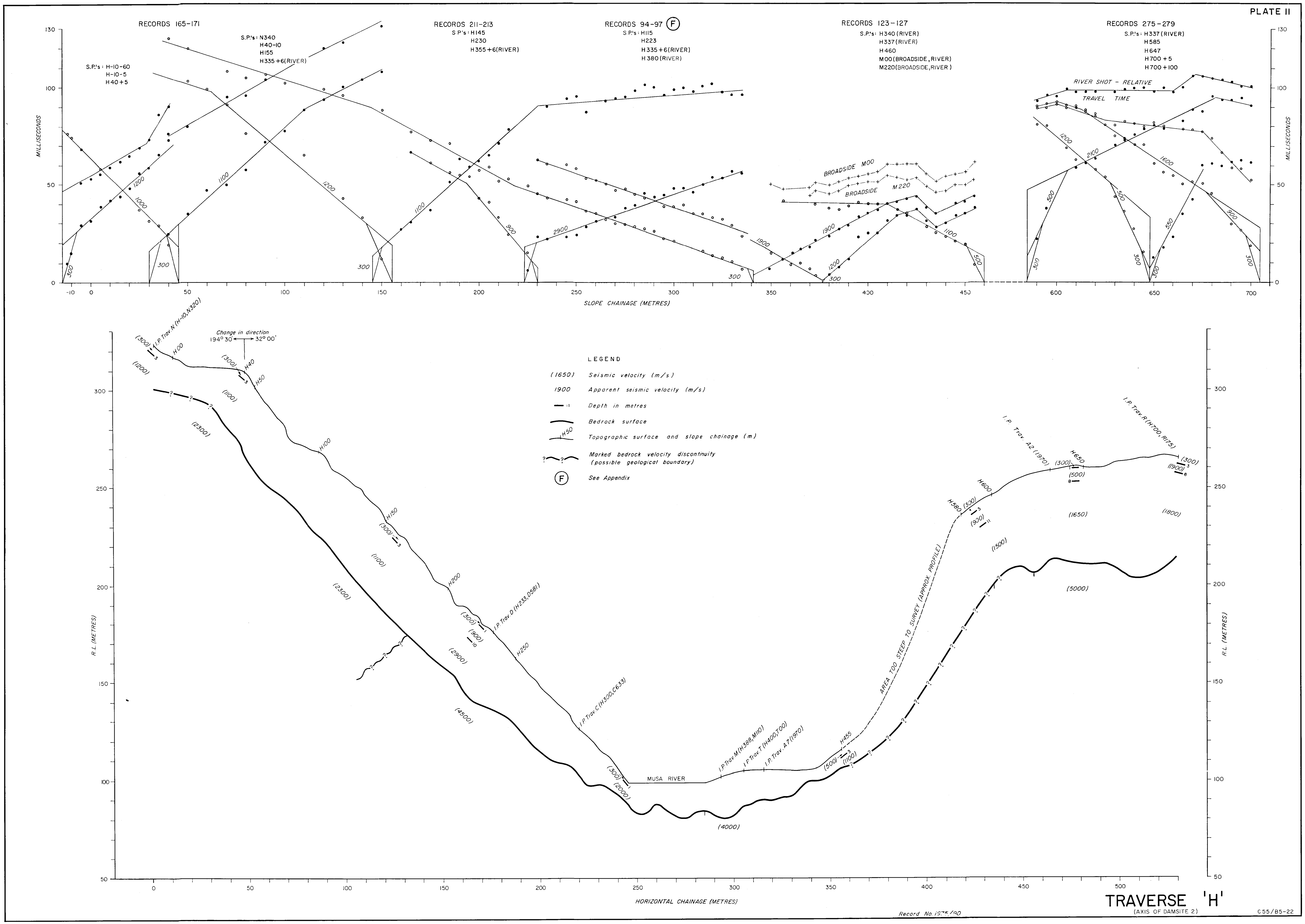
TRAVERSE 'F'
(DAMSITES 1,2)

C55/B5-12

TRAVERSE 'G'
(DAMSITE 1 ABUTMENT)

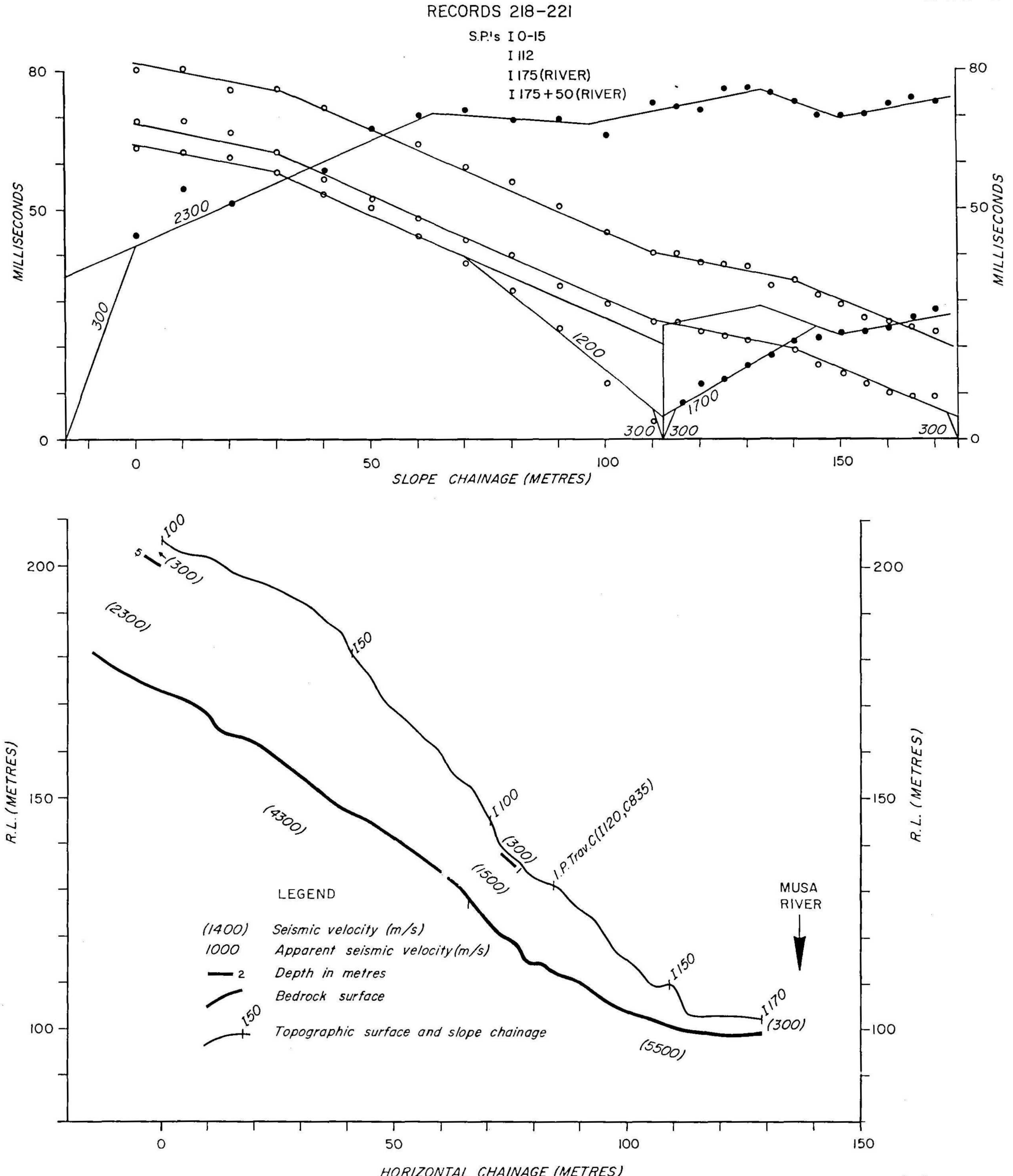
Record No.1975/90

C55/B5-38



TRAVERSE 'H'
(AXIS OF DAMSITE 2)

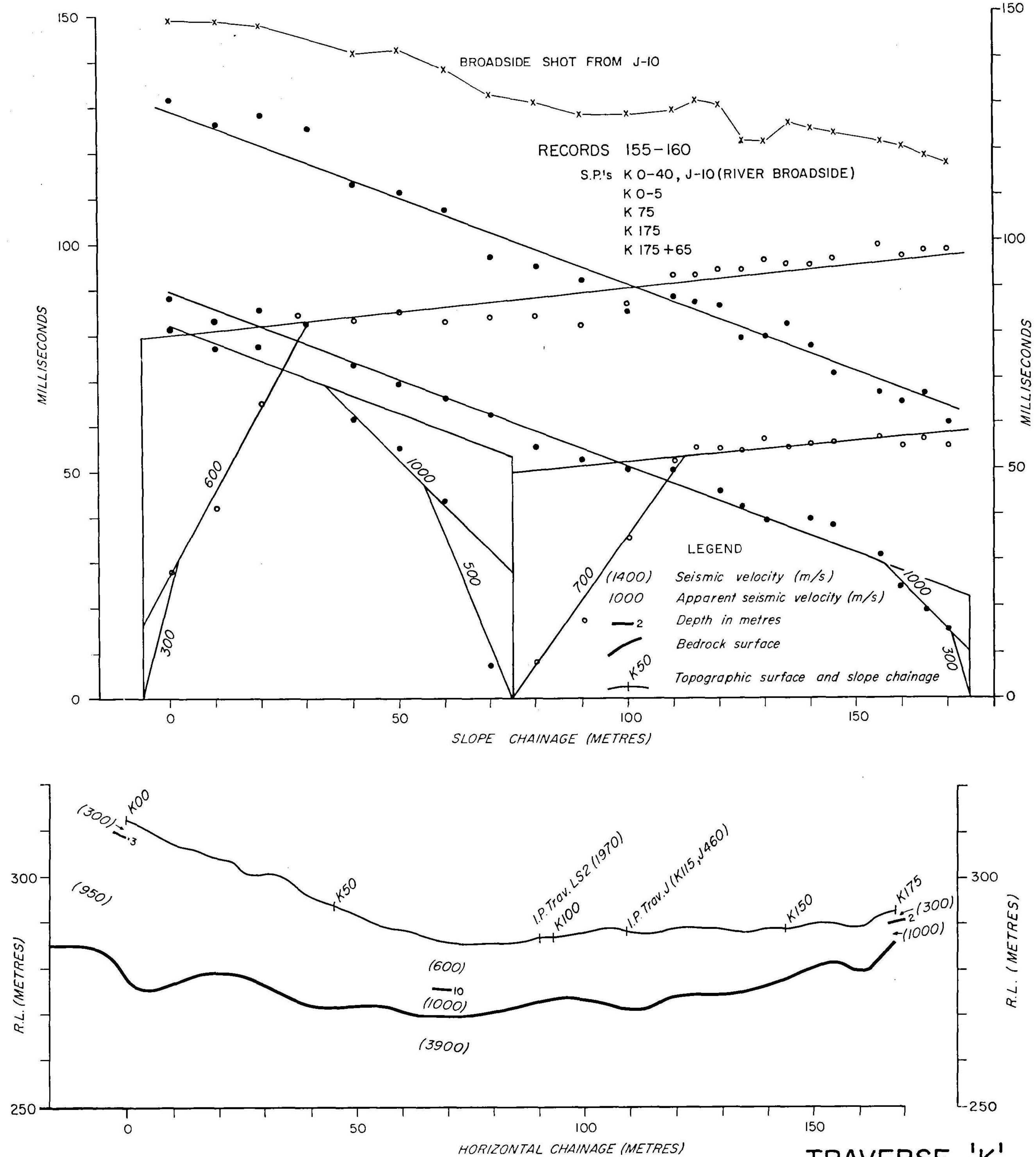
PLATE 12



TRAVERSE 'I'

(DAMSITE 2)

PLATE 13
RECORDS 150-154
S.P.'s: J-10 (RIVER) J163, 403 J344, 461
RECORDS 140-144
S.P.'s J-10 (RIVER) J167 J227 J347 J462
RECORDS 108A-112
S.P.'s J-55 (RIVER) J-10 (RIVER) J57 J175 J290
RECORDS 290-296
S.P.'s J-205 J-130 J-55 (RIVER) Q435 (BROADSIDE)
RECORDS 270-274
S.P.'s J-430-100 J-435 J-315 J-195 J-55 (RIVER)
RECORDS 129-133
S.P.'s: J-135 J-55 (RIVER) J-5 (RIVER)
SEE INSET BELOW
BROADSIDE FROM Q435
BROADSIDE UPSTREAM
BROADSIDE DOWNSTREAM
CLIFF
MILLISECONDS
SLOPE CHAINAGE (METRES)
DDR J330 (Vertical)
PLEISTOCENE DOMARA RIVER BEDS
SHEAR ZONE
ULTRAMAFICS
DDQ J80 (Angle to horizontal 75°)
(True length of drill hole)
MUSA RIVER
INSET
BROADSIDE LAYOUT
MUSA
J TRAVERSE
RIVER
LEGEND
Clastics, tuff and agglomerate
Conglomerate
Mudstone
PLEISTOCENE DOMARA RIVER BEDS
Didana ultramafic complex
LATE CRETACEOUS
Shear zone
(4500) Seismic velocity (m/s)
1500 Apparent seismic velocity (m/s)
Depth (m)
Bedrock surface
Topographic surface and slope chainage (m)
(Drill hole geological logs after Macias, 1973)
F Fresh
SW Slightly weathered
MW Moderately weathered
HW Highly weathered
CW Completly weathered
U/M Ultramafics
Depth in metres
R.L. (METRES)
HORIZONTAL CHAINAGE (METRES)
TRAVERSE 'J'
(LANDSLIDE AREA)
Record No.1975/90
C55/B5-36



TRAVERSE 'K'

(LANDSLIDE AREA)

C55/B5-16

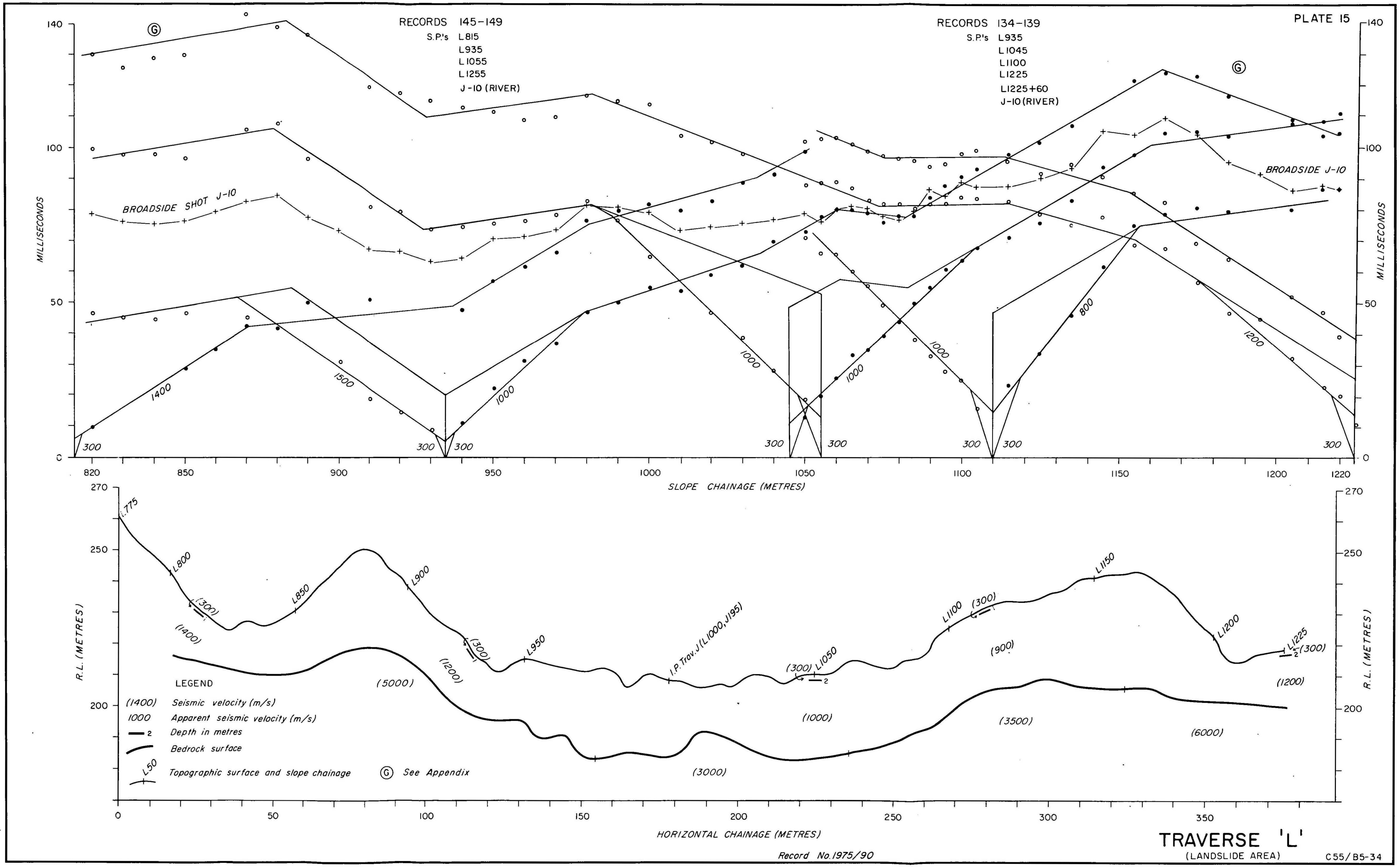
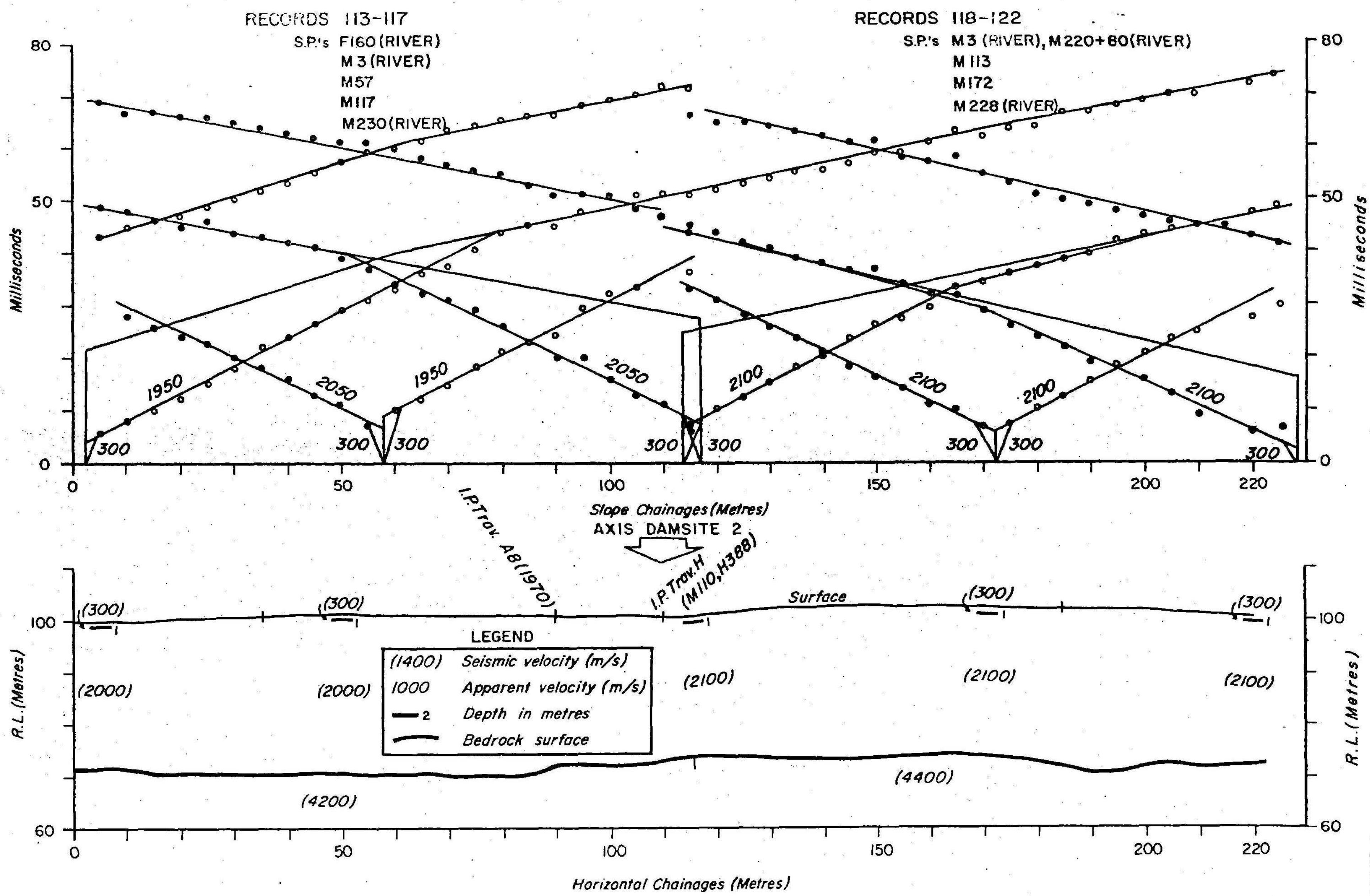


PLATE 15
RECORDS 145-149
S.P.'s L815
L935
L1055
L1255
J-10 (RIVER)
RECORDS 134-139
S.P.'s L935
L1045
L1100
L1225
L1225+60
J-10 (RIVER)
BROADSIDE SHOT J-10
BROADSIDE J-10
MILLISECONDS
SLOPE CHAINAGE (METRES)
R.L. (METRES)
HORIZONTAL CHAINAGE (METRES)
LEGEND
(1400) Seismic velocity (m/s)
1000 Apparent seismic velocity (m/s)
2 Depth in metres
Bedrock surface
L50 Topographic surface and slope chainage
G See Appendix
I.P. Trav. J (L1000, J195)
TRAVERSE 'L'
(LANDSLIDE AREA)
Record No.1975/90
C55/B5-34

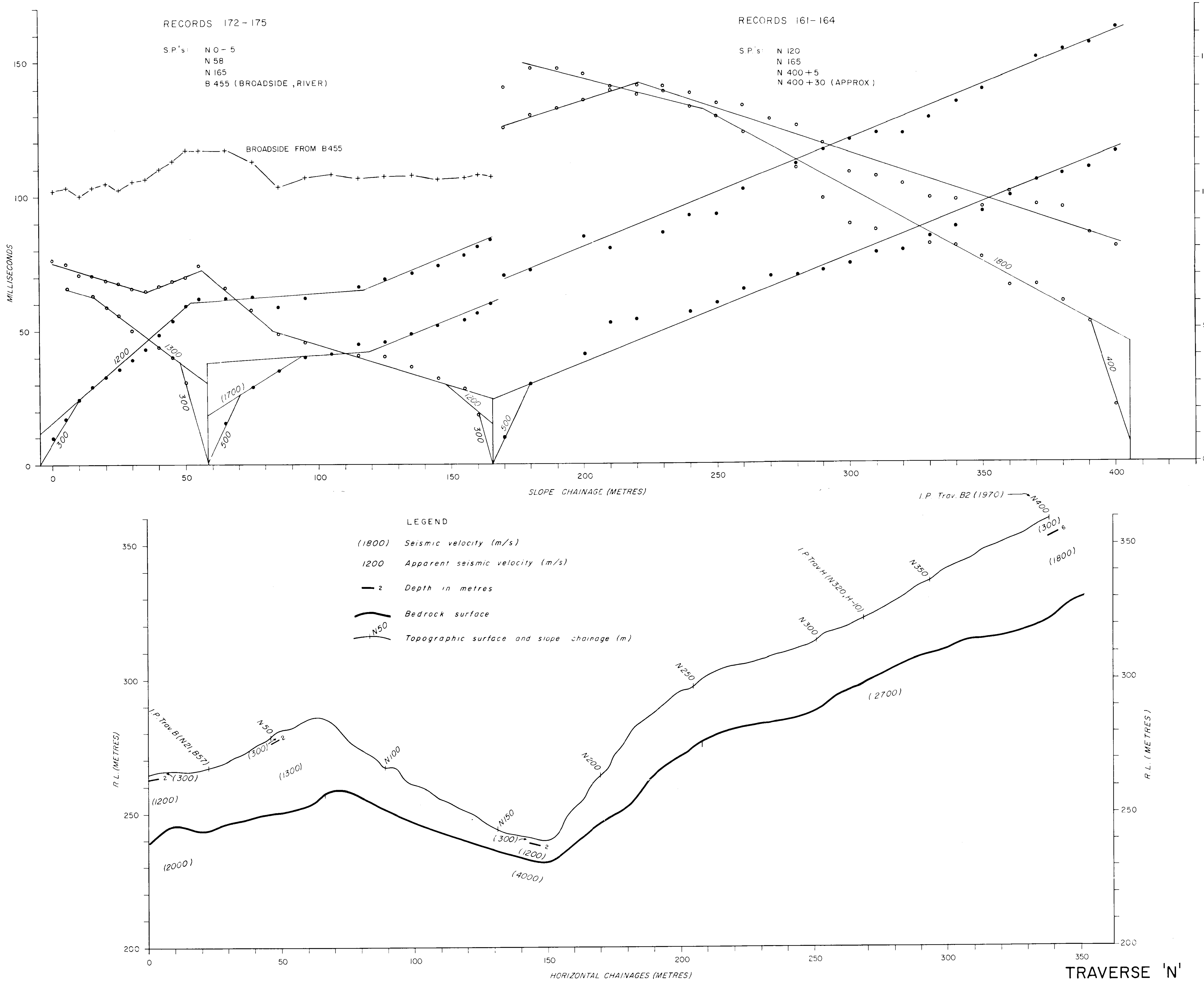
Record No 1975/90

TRAVERSE 'M'
(BASE OF DAMSITE 2)



C55/B5-27A

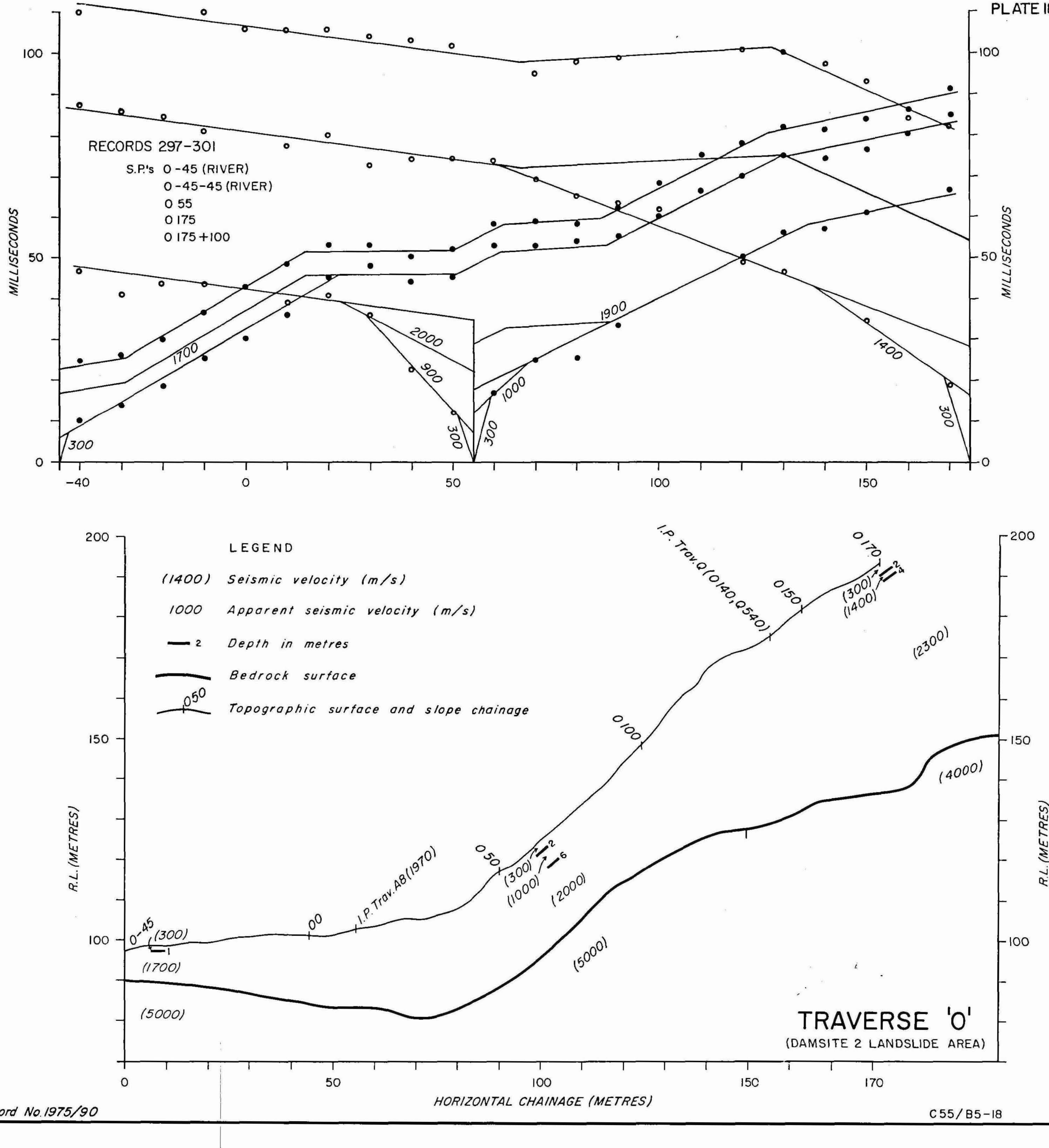
PLATE 16



TRAVERSE 'N'
(DAMSITE 2 LEFT CREST)

Record No.1975/90

C55/B5-23



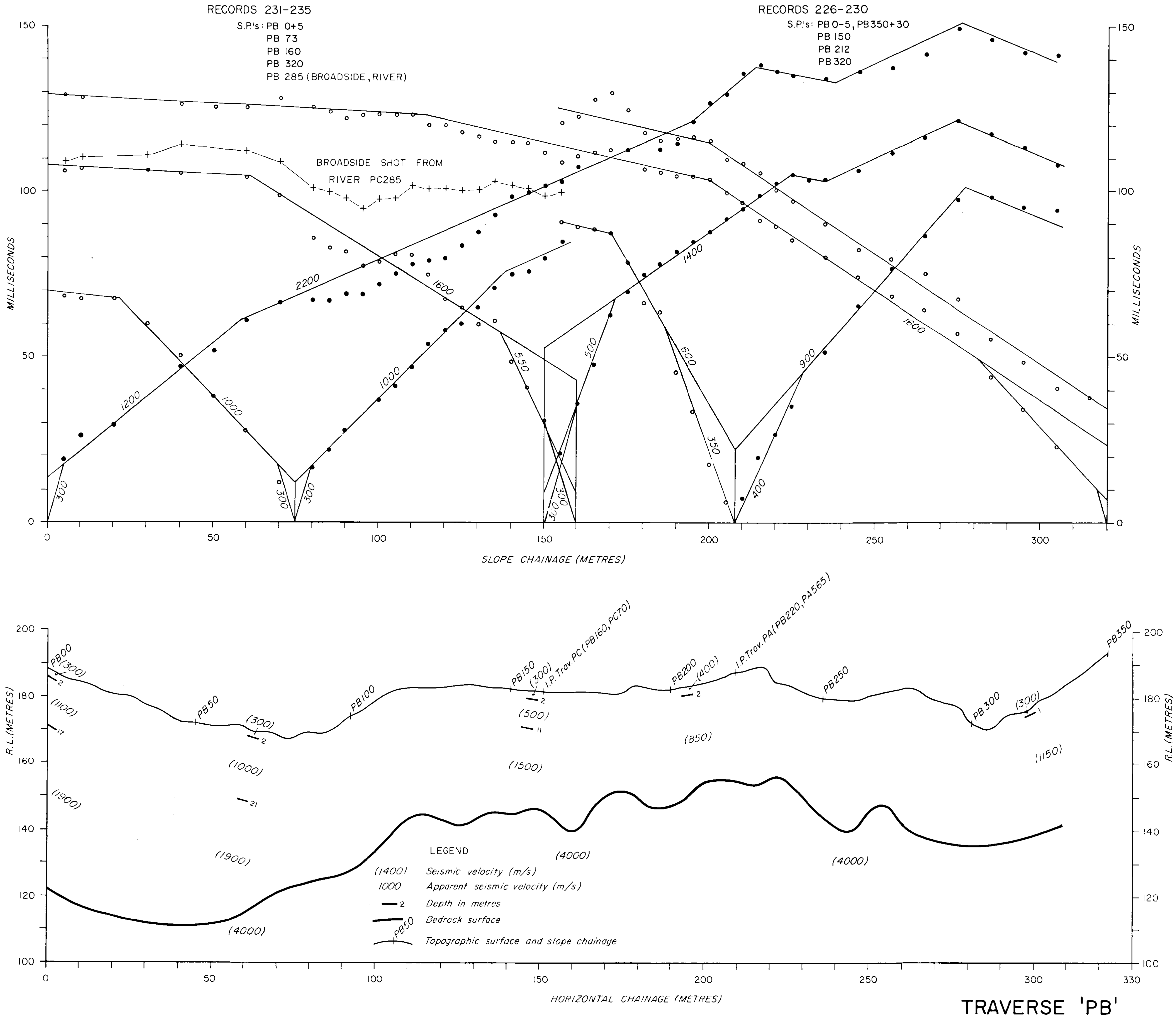
TRAVERSE 'O'

(DAMSITE 2 LANDSLIDE AREA)

TRAVERSE 'PA'
(DAMSITE 2 ALTERNATIVE SPILLWAY)

Record No.1975/90

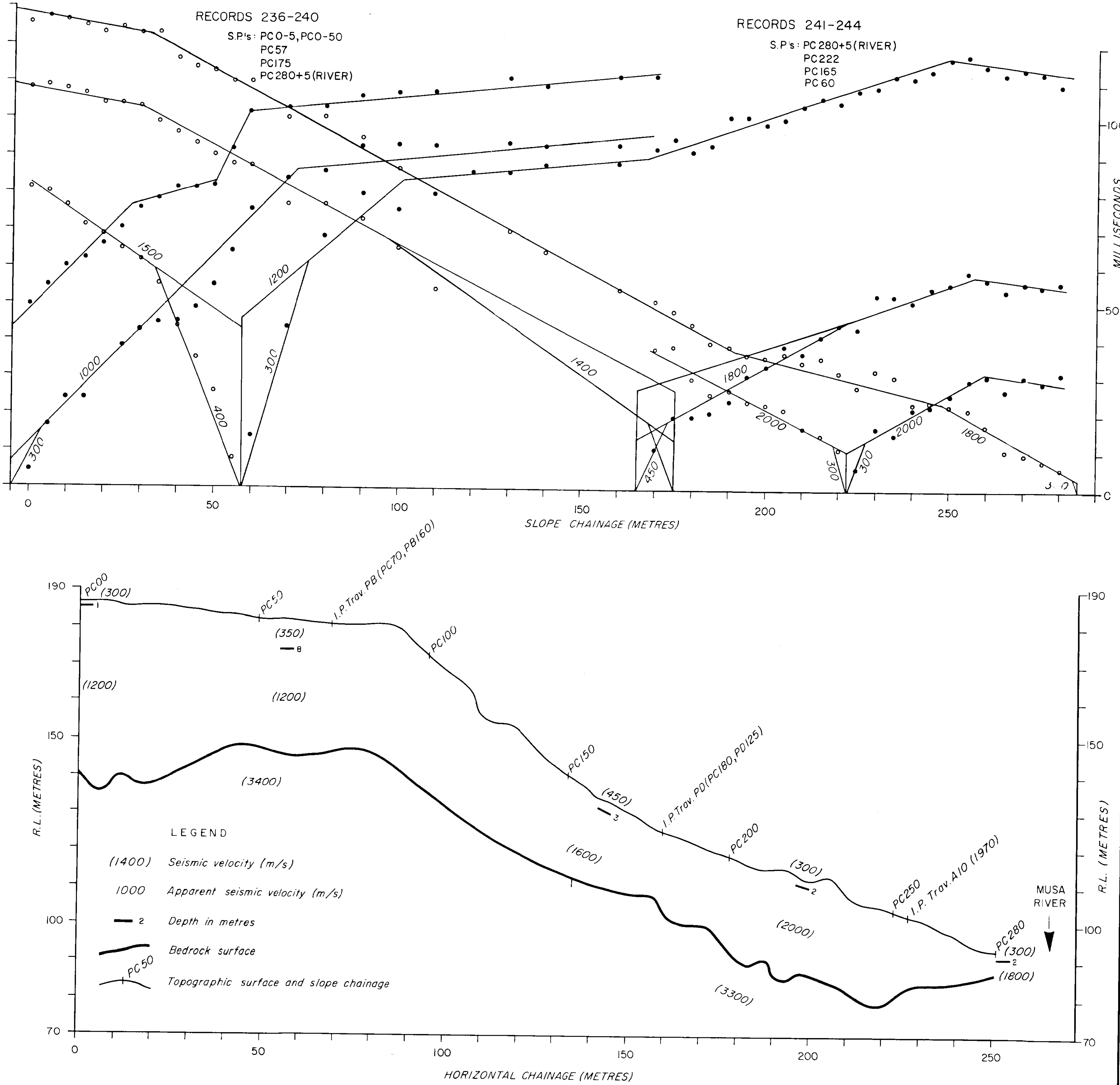
C55/B5-24



TRAVERSE 'PB'

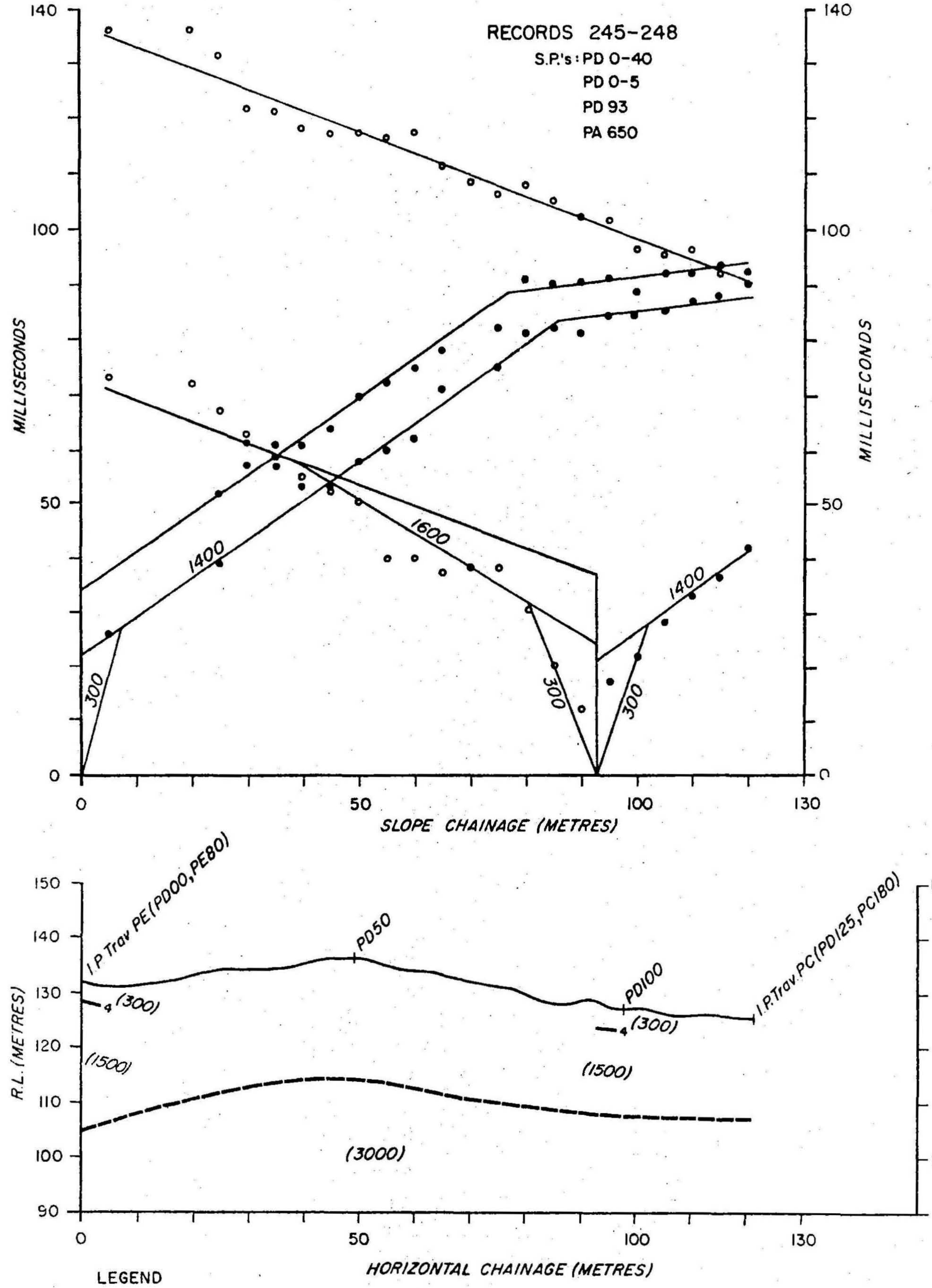
(DAMSITE 2 DOWNSTREAM POWERSTATION AREA)

C55/B5-31



TRAVERSE 'PC'

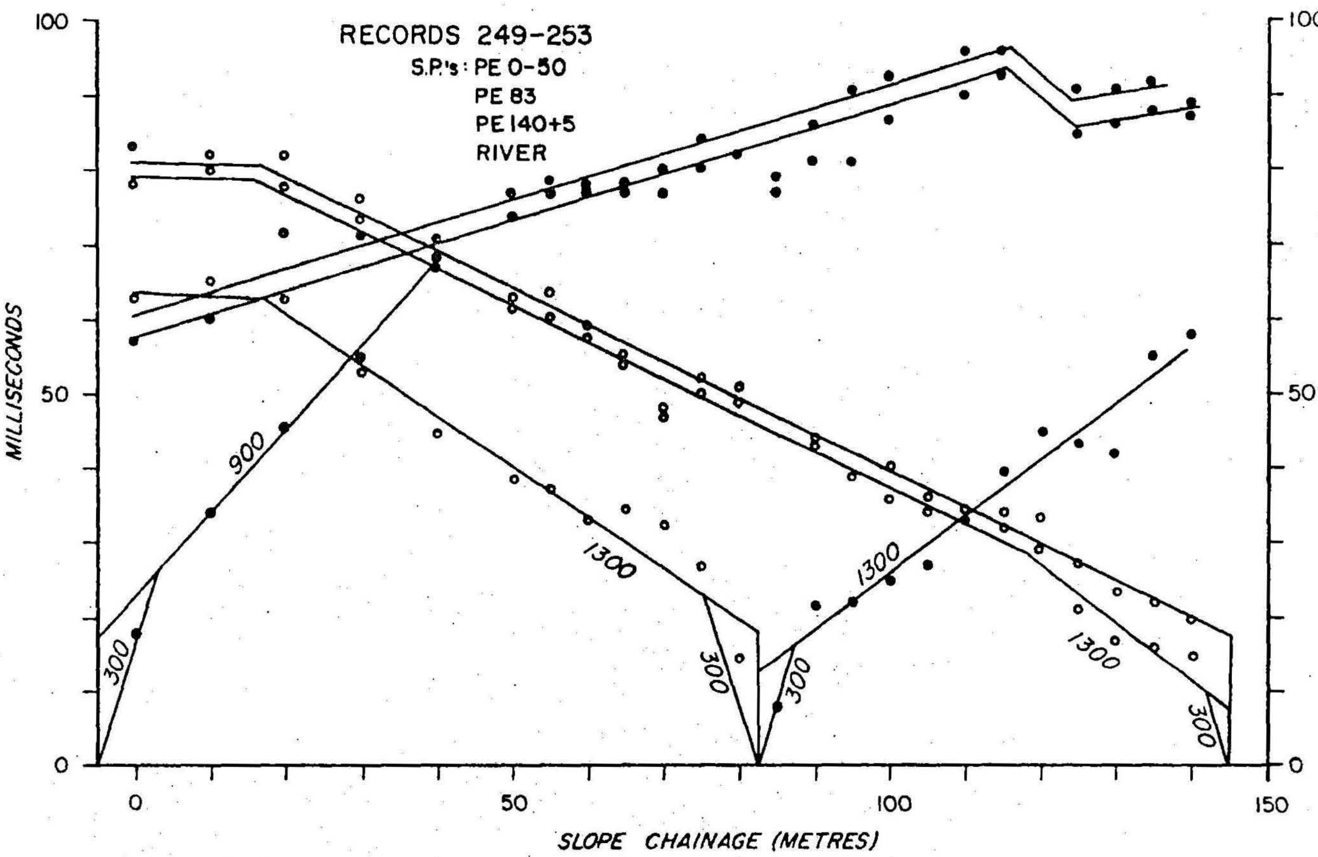
(DAMSITE 2 DOWNSTREAM POWERSTATION AREA)

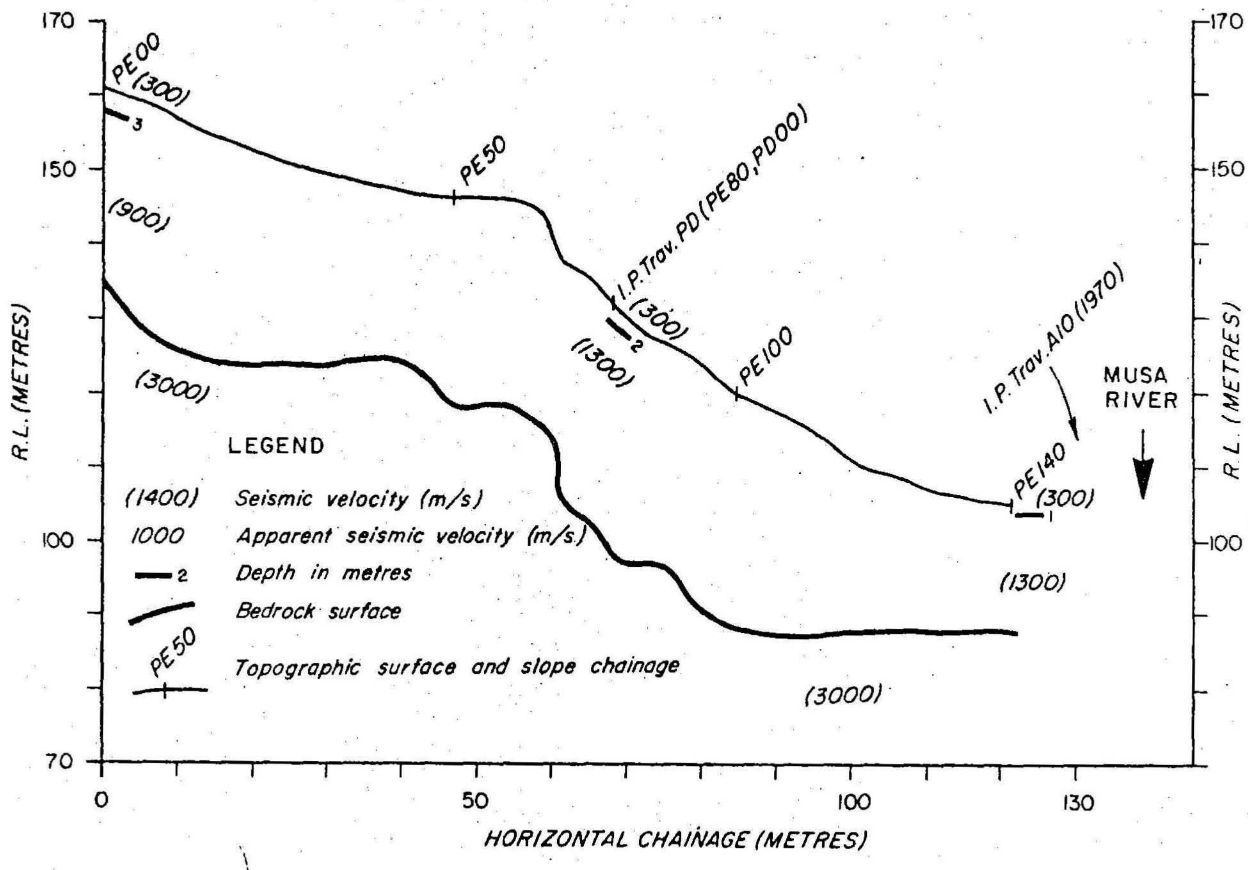


LEGEND

(1400) Seismic velocity (m/s)
1000 Apparent seismic velocity (m/s)
2 Depth in metres
Bedrock surface (approx.)
PD50 Topographic surface and slope chainage

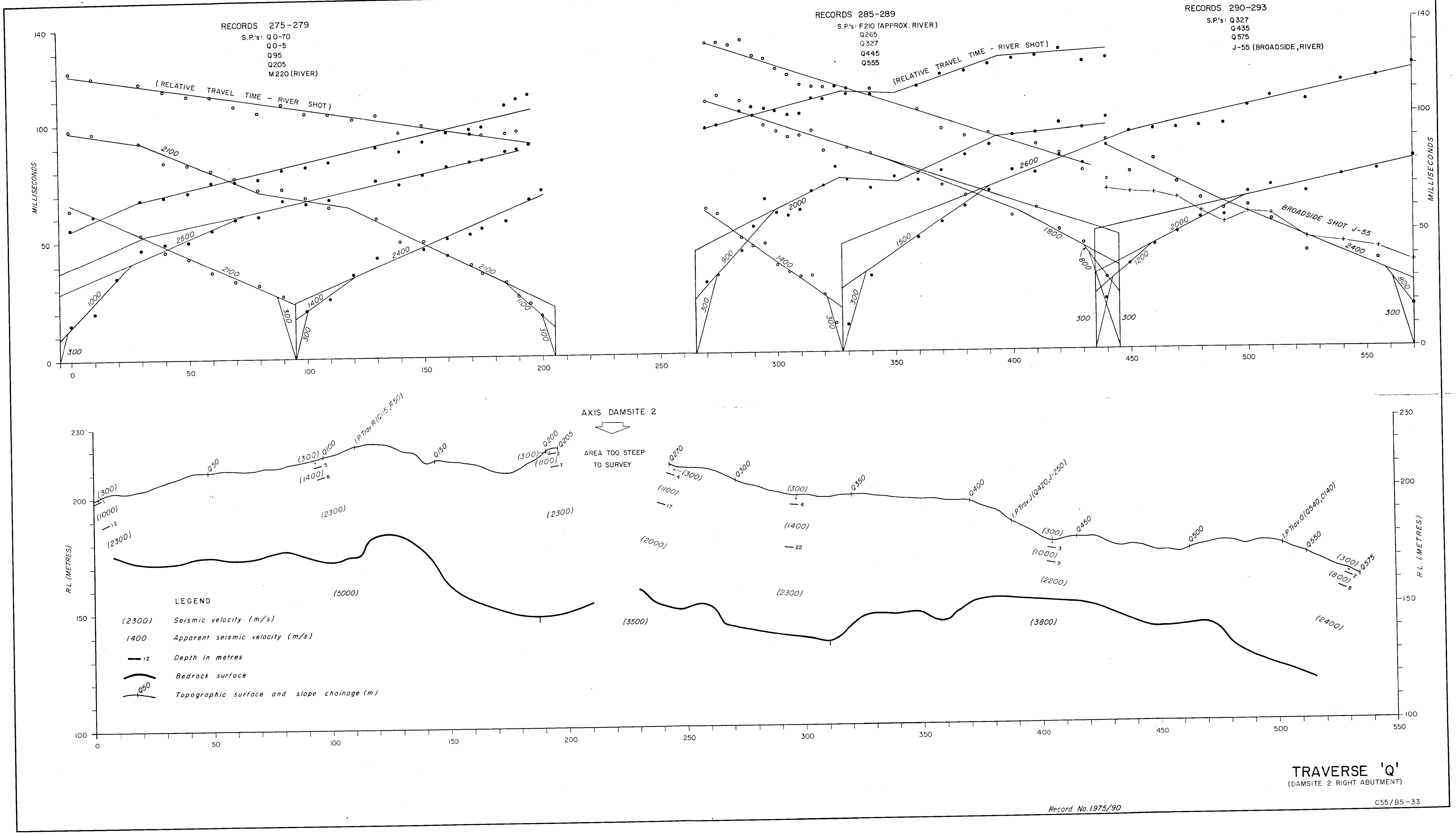
TRAVERSE 'PD'
(DAMSITE 2 DOWNSTREAM POWERSTATION AREA)



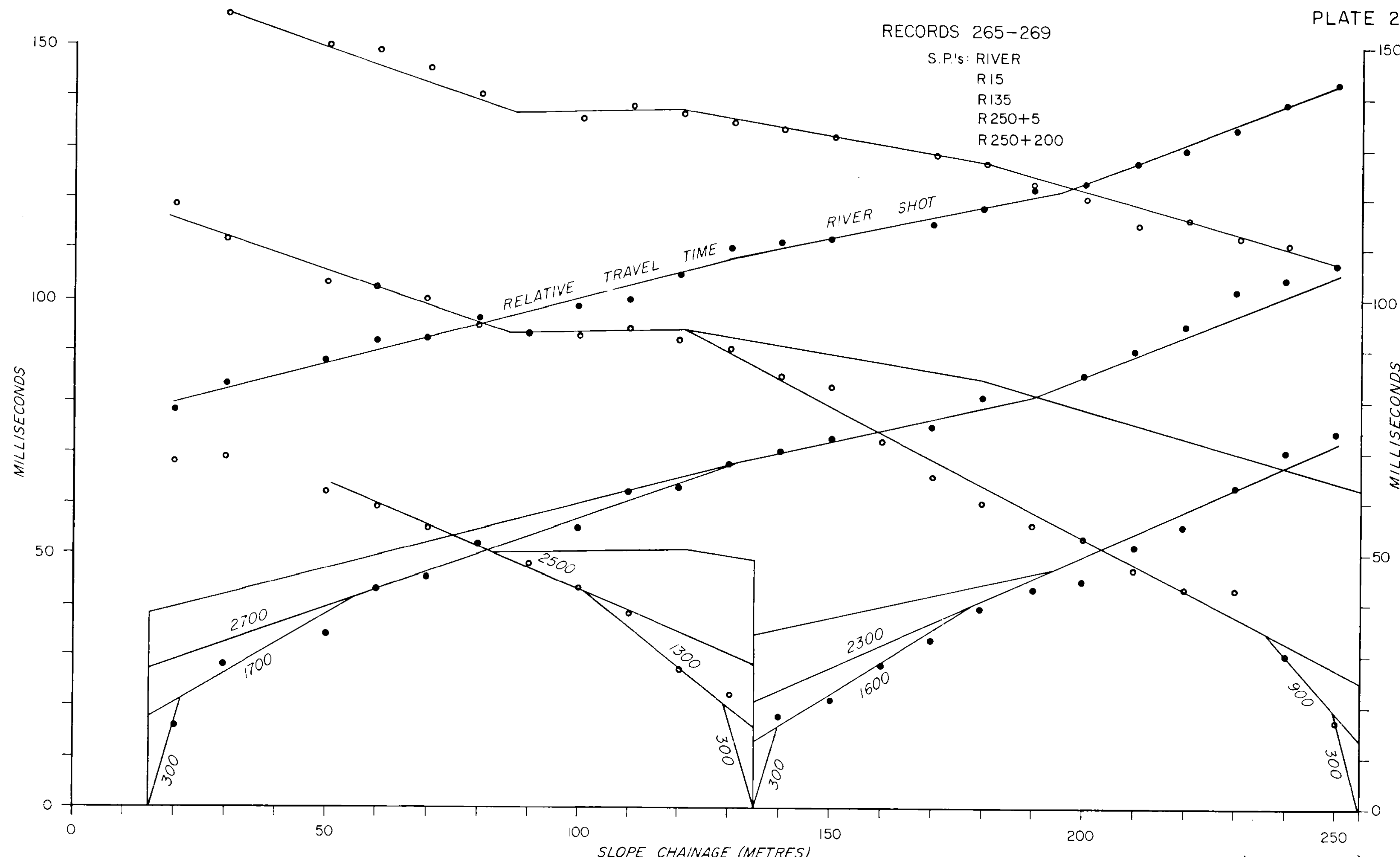


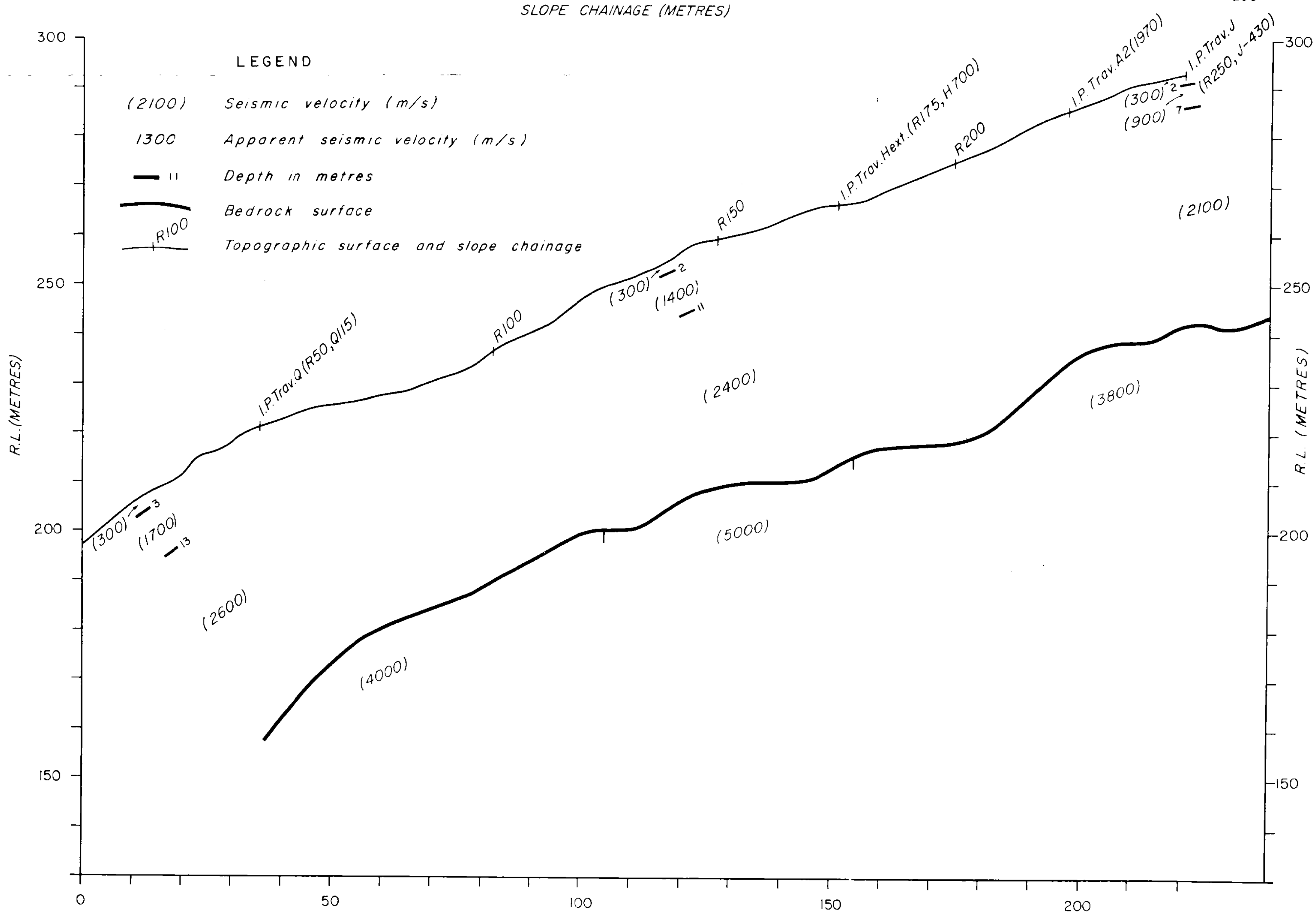
TRAVERSE 'PE'

(DAMSITE 2 DOWNSTREAM POWERSTATION AREA)



TRAVERSE 'Q'
(DAMSITE 2 RIGHT ABUTMENT)

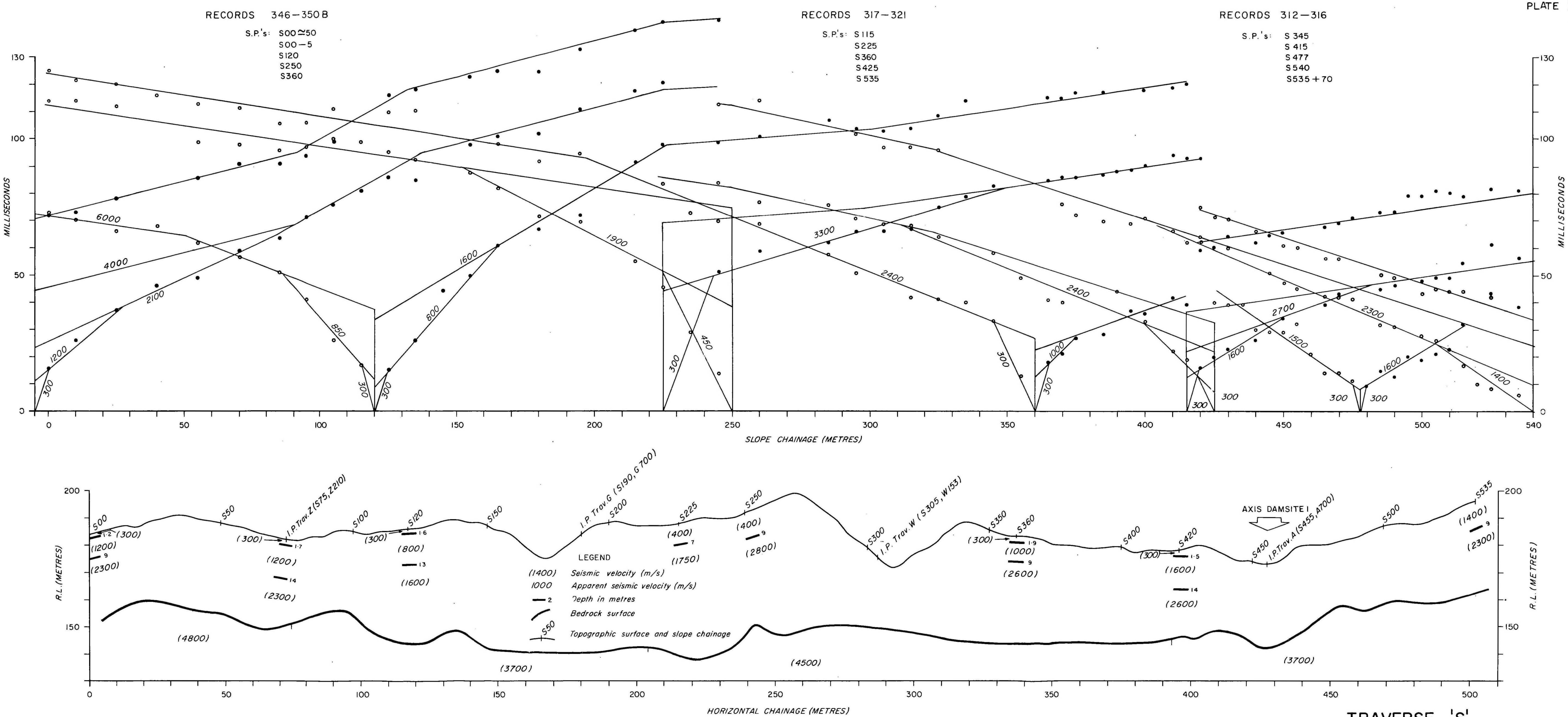




TRAVERSE 'R'

(DAMSITE 2 RIGHT ABUTMENT)

C55/B5-13



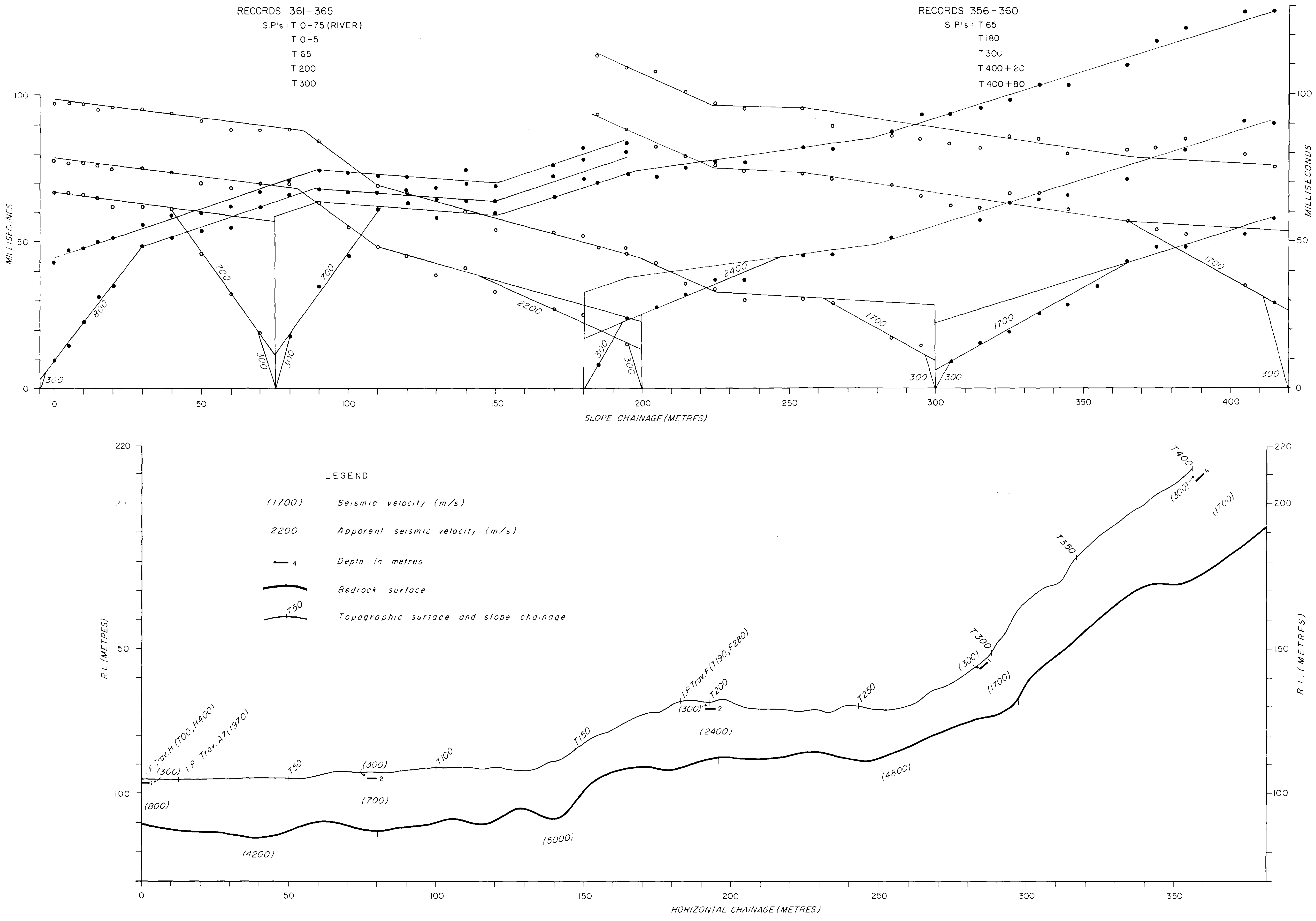
TRAVERSE 'S'

(DAMSITE I TUNNEL LINE)

Record No.1975/90

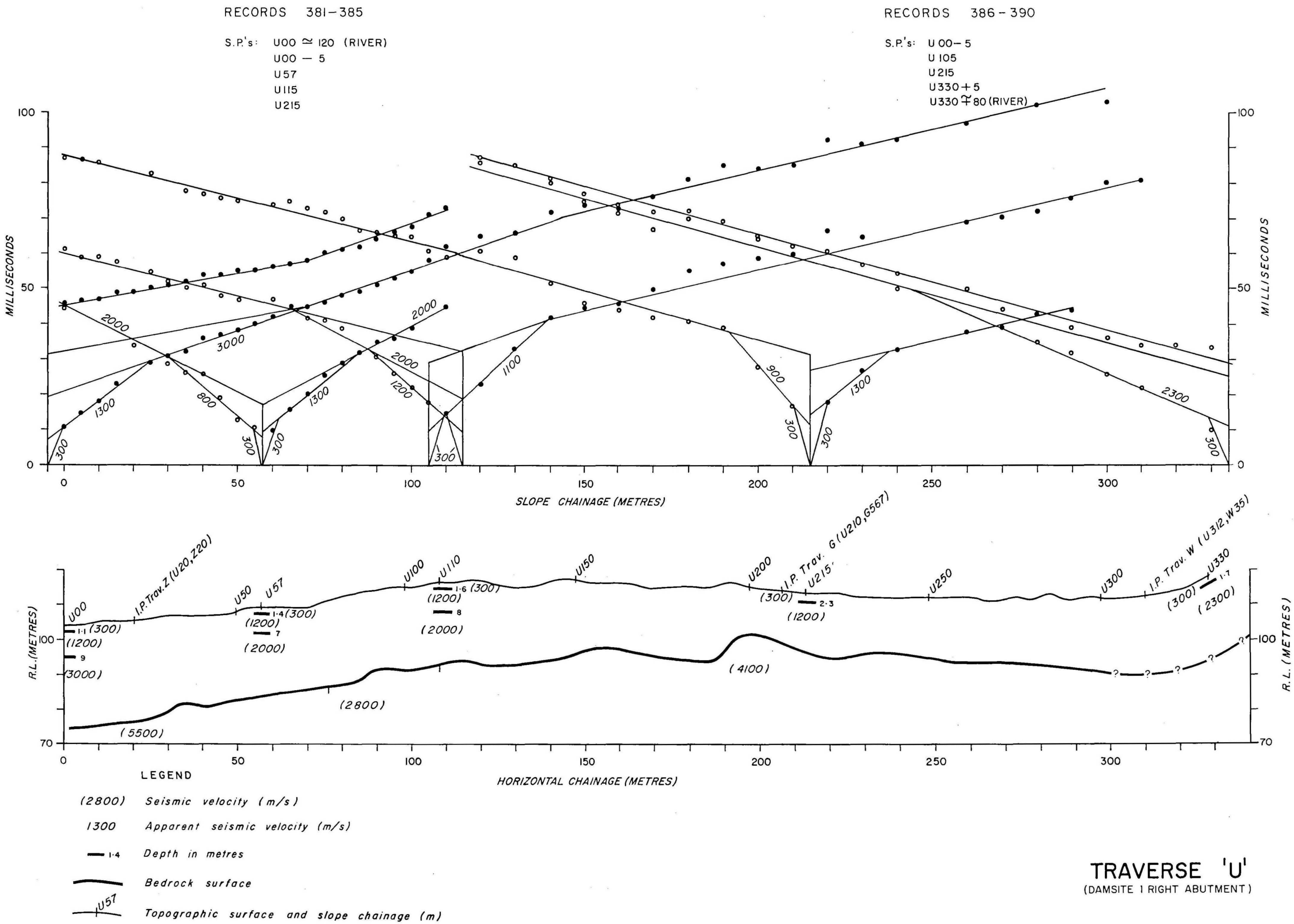
C55/B5-32

PLATE 27



TRAVERSE 'T'

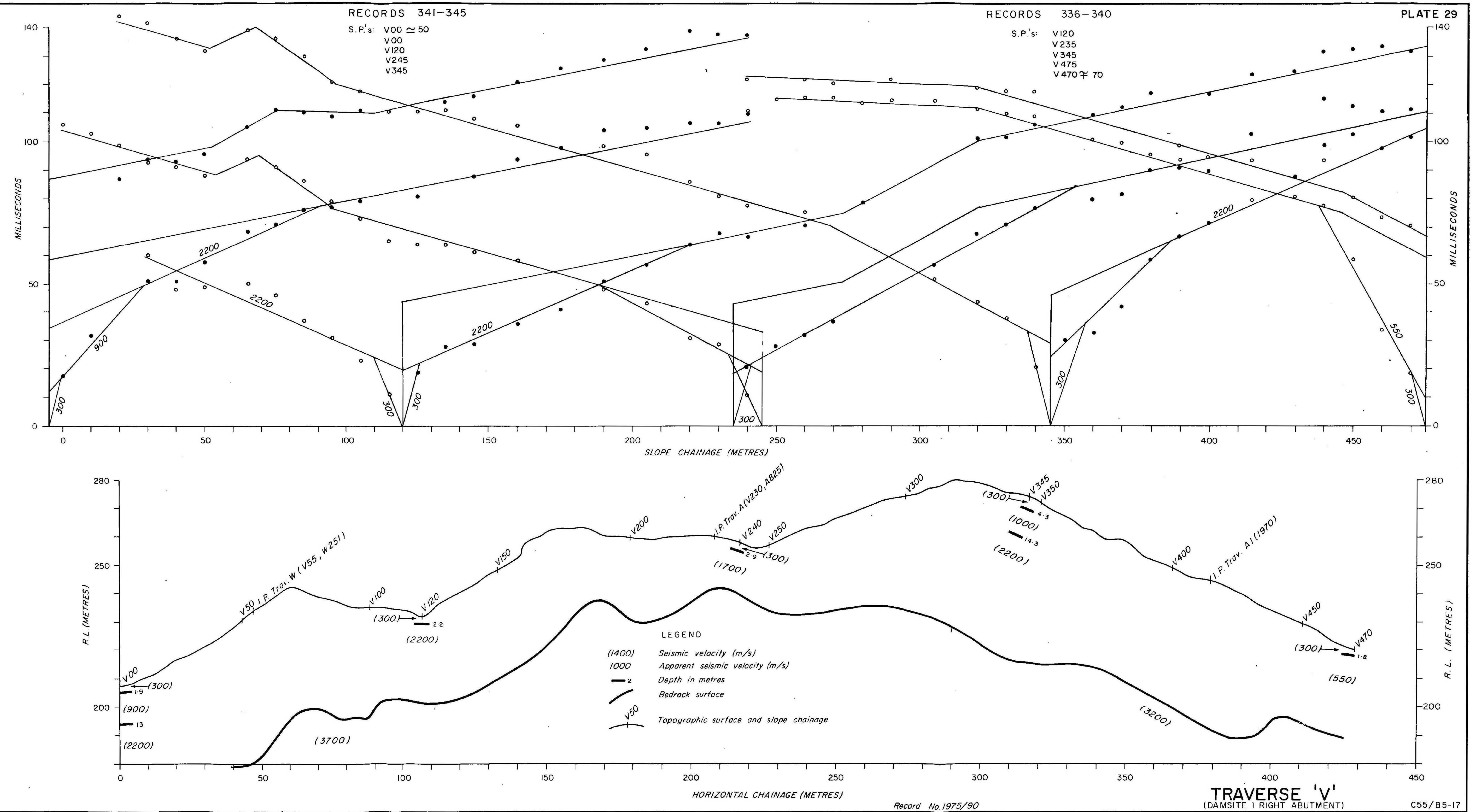
(DAMSITE 1 TUNNEL LINE)



TRAVERSE 'U'

(DAMSITE 1 RIGHT ABUTMENT)

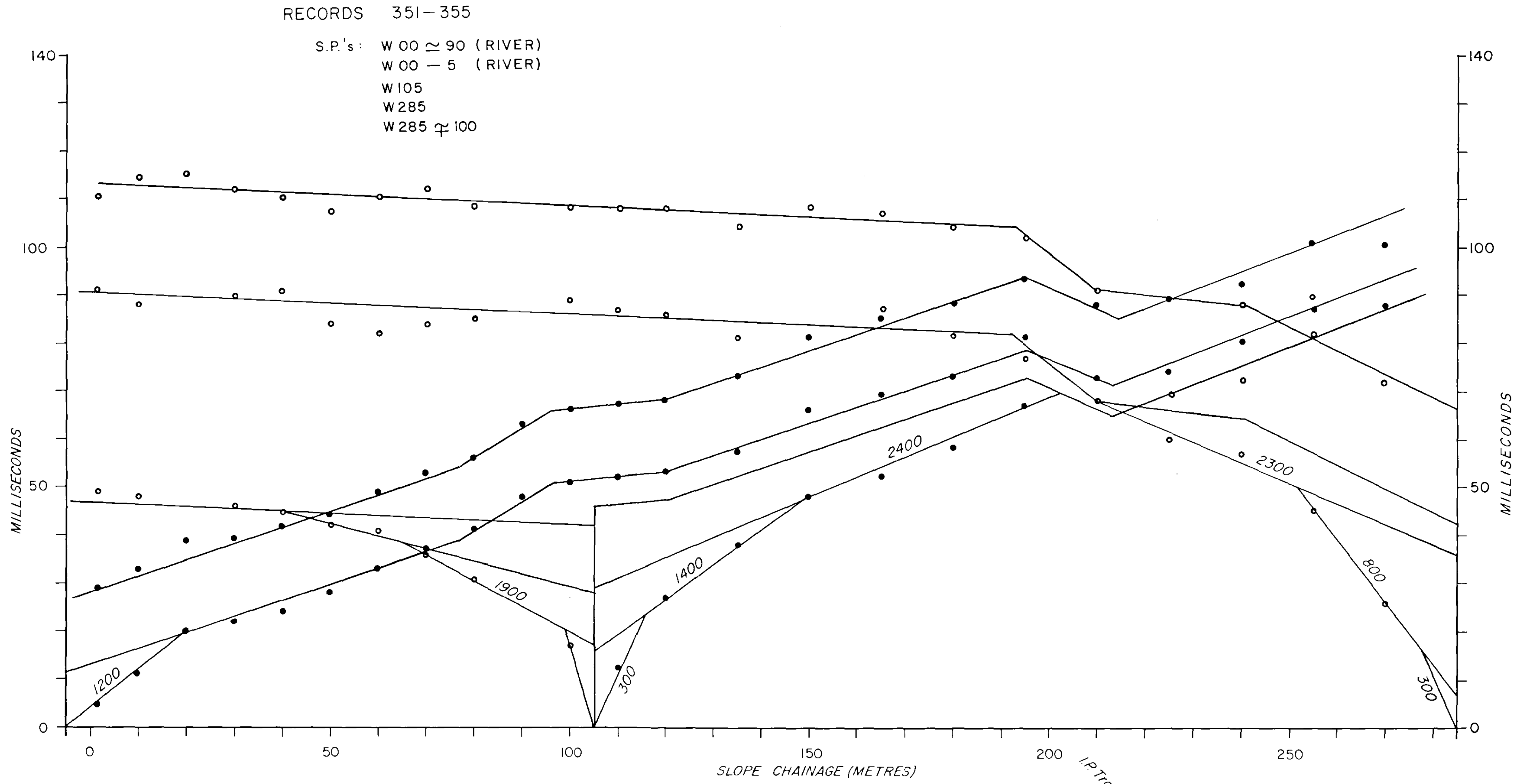
PLATE 29

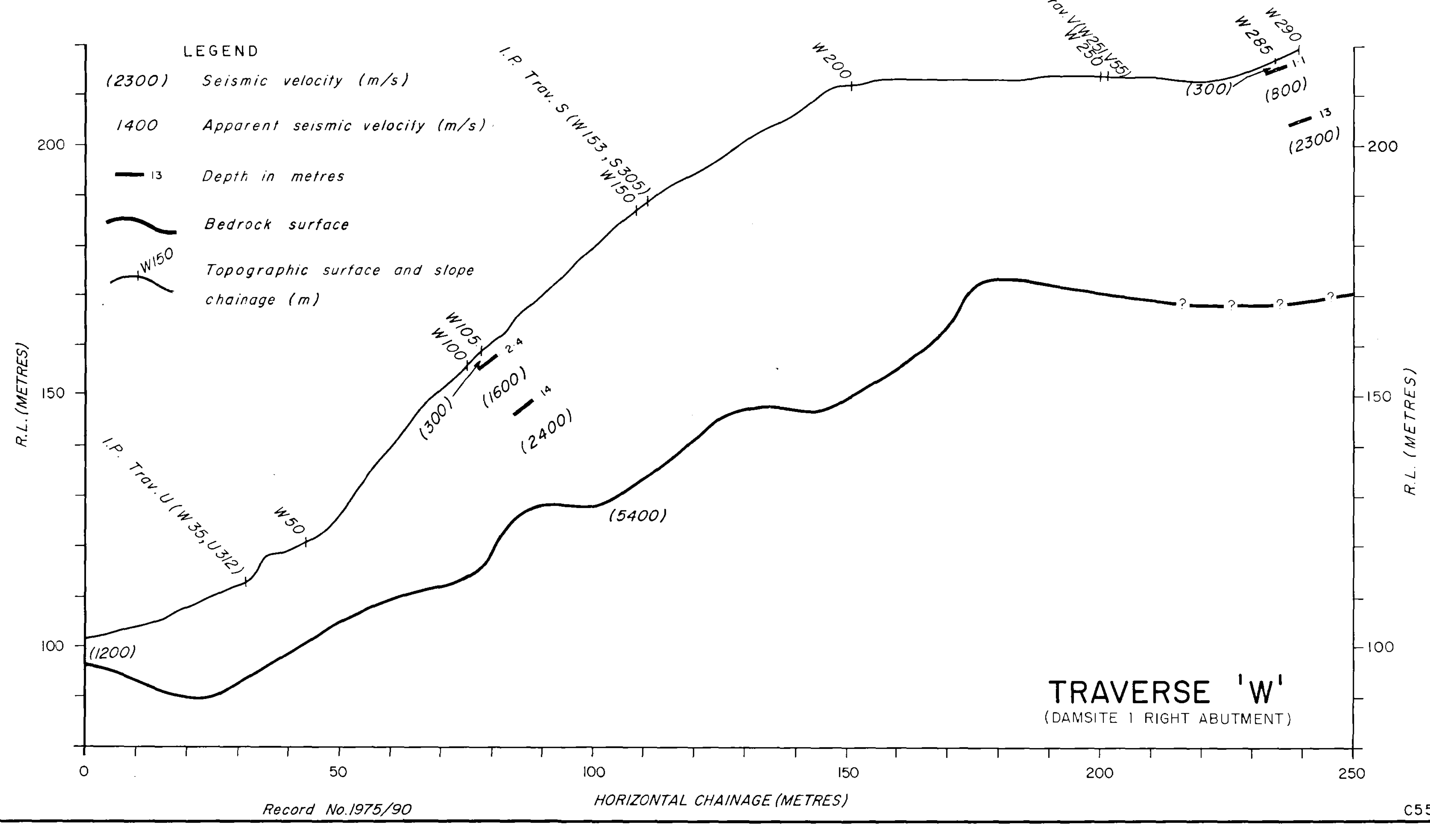


TRAVERSE 'V'
(DAMSITE I RIGHT ABUTMENT)

Record No. 1975/90

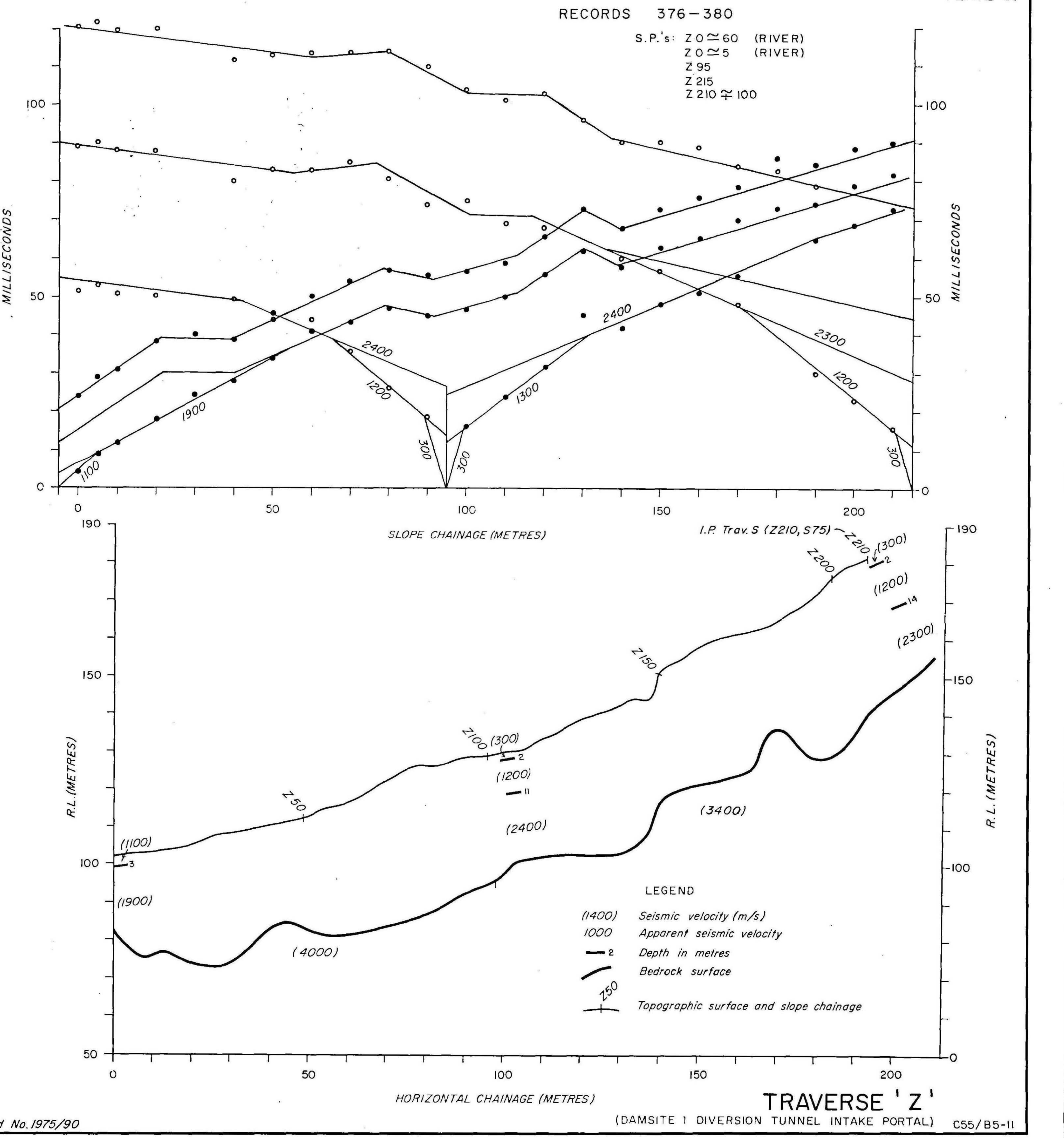
C55/B5-17





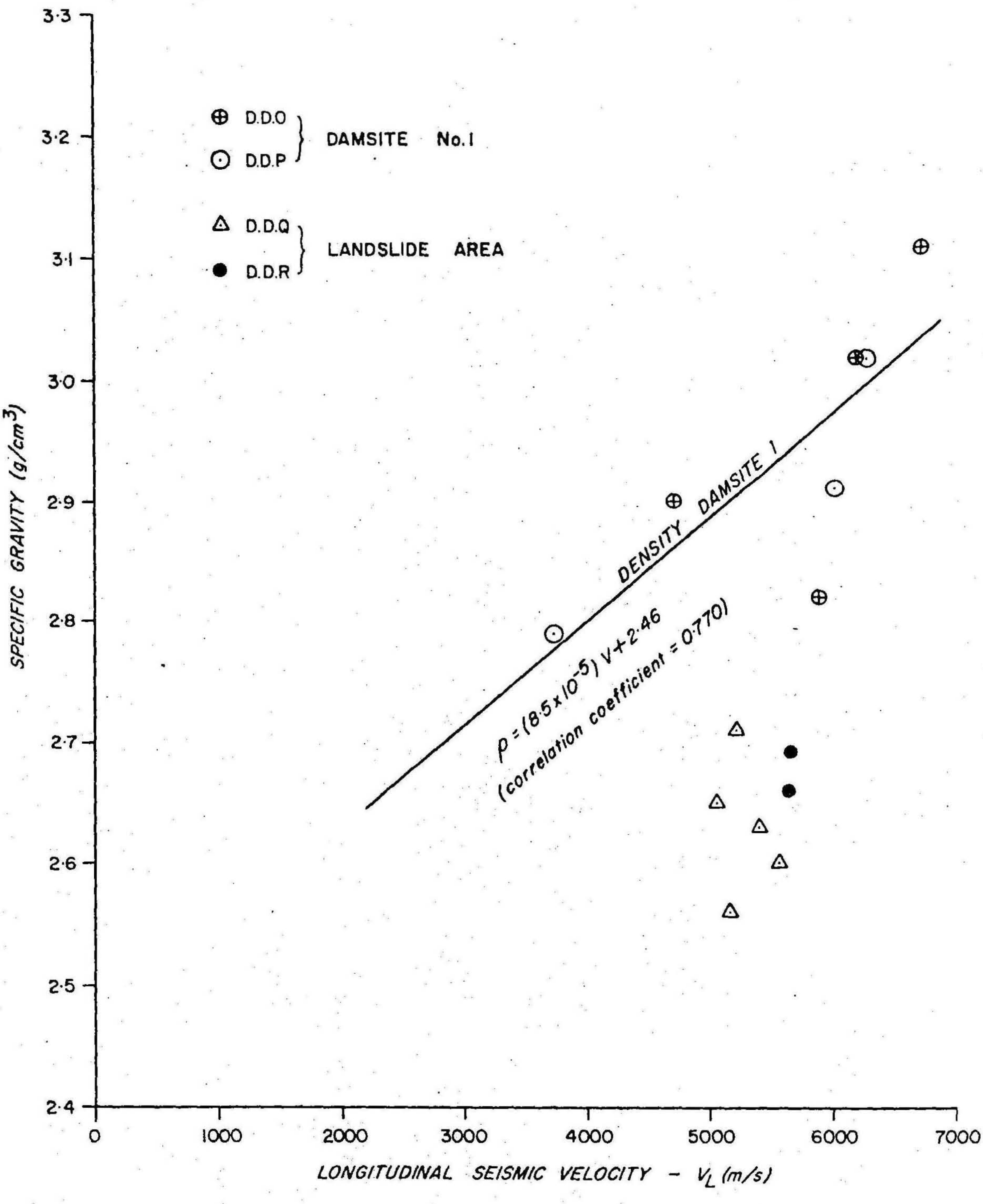
TRAVERSE 'W'

(DAMSITE 1 RIGHT ABUTMENT)

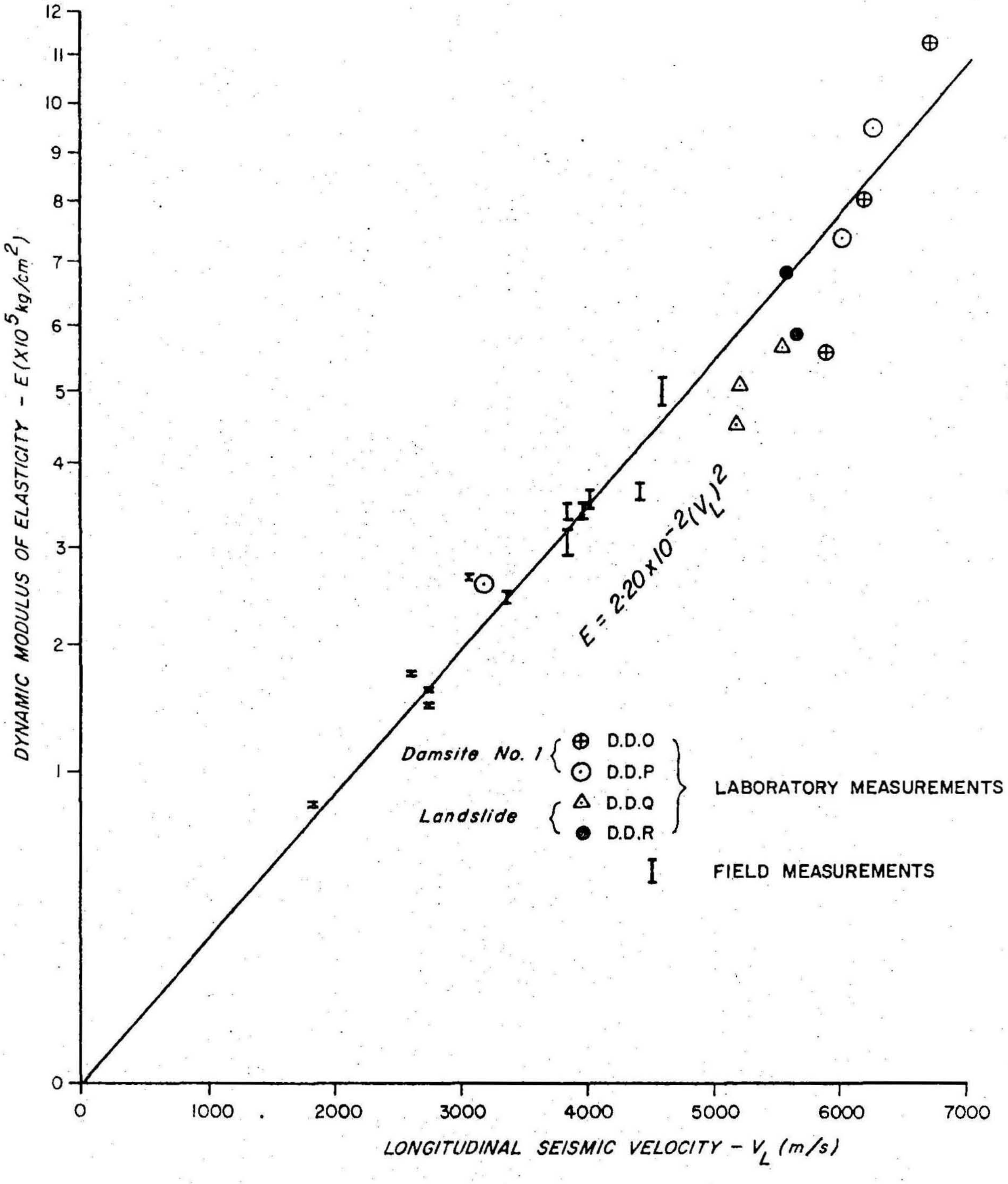


TRAVERSE 'Z'

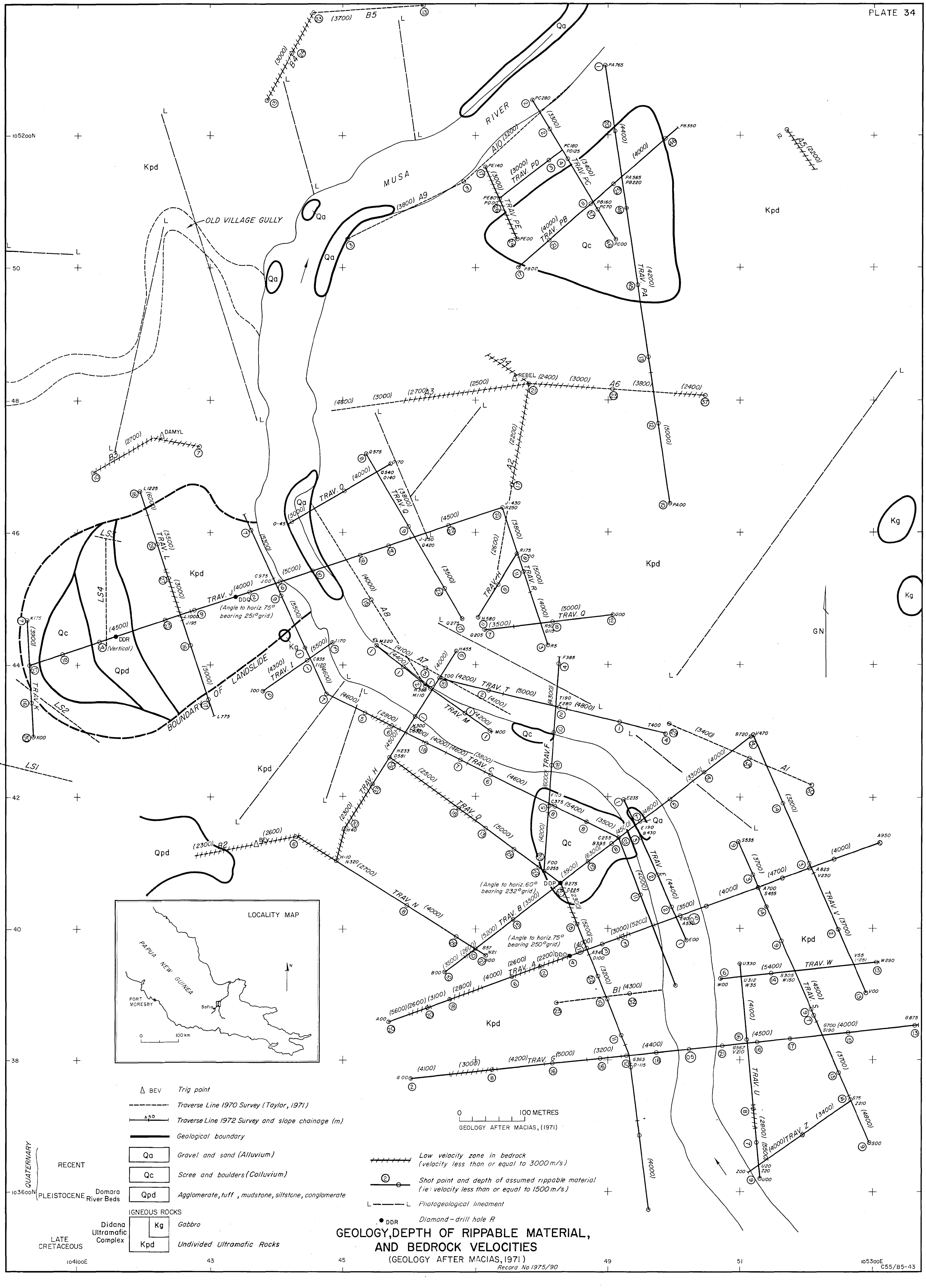
(DAMSITE 1 DIVERSION TUNNEL INTAKE PORTAL)



PLOT OF DENSITY Vs LONGITUDINAL VELOCITY

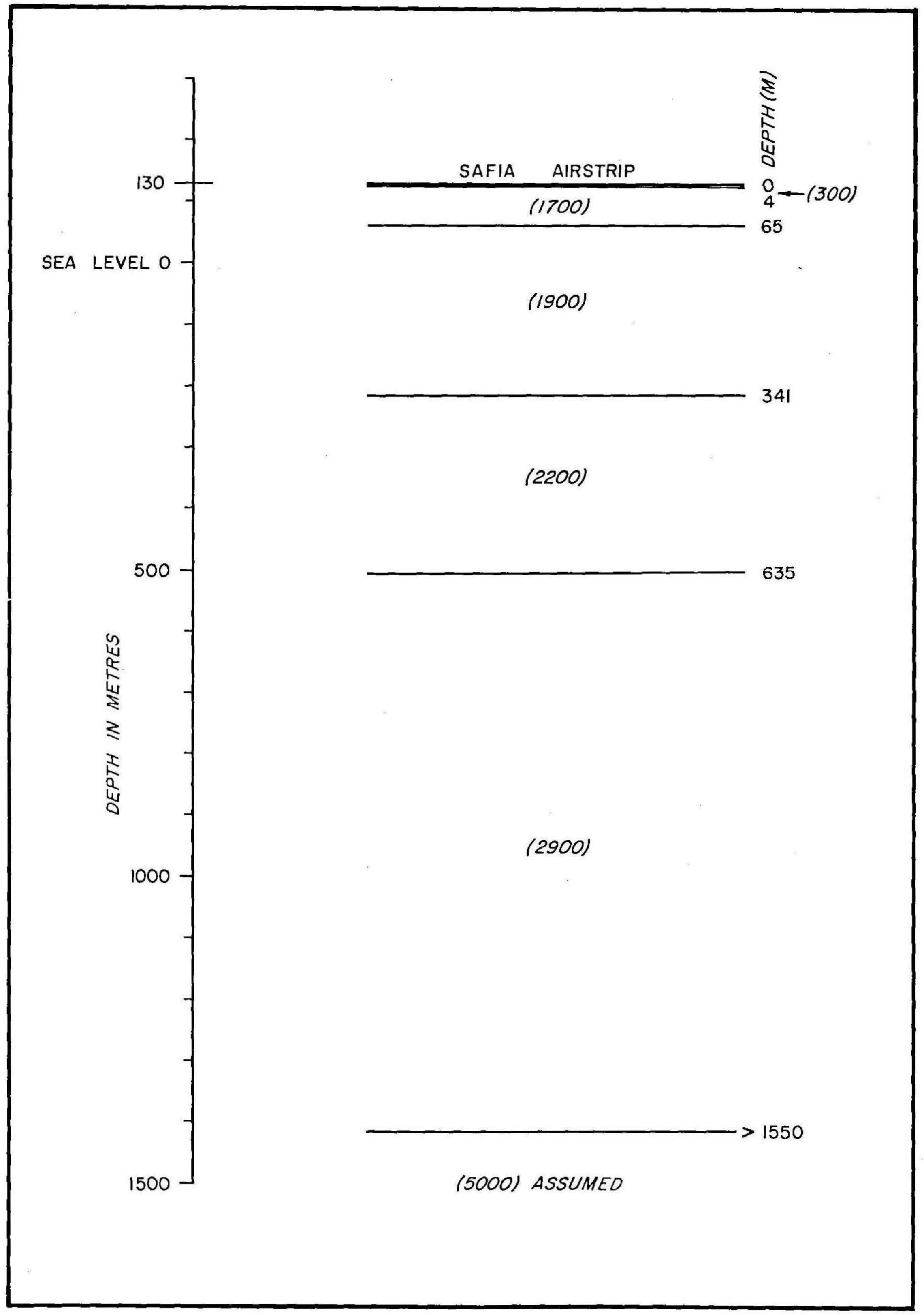


PLOT OF MODULUS OF ELASTICITY Vs LONGITUDINAL VELOCITY



GEOLOGY, DEPTH OF RIPPABLE MATERIAL, AND BEDROCK VELOCITIES

(GEOLOGY AFTER MACIAS, 1971)



SAFIA AIRSTRIP SEISMIC INTERPRETATION