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# APPLICATION OF THE SEISMIC REFRACTION METHOD TO THE STUDY OF BASEMENT ROCK AQUIFERS IN S E ZIMBABWE

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# APPLICATION OF THE SEISMIC REFRACTION METHOD TO THE STUDY OF BASEMENT ROCK AQUIFERS IN S E ZIMBABWE

J DAVIES

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## PREFACE

The work reported here was carried out as part of project 92/4 (R5551) and is funded by ODA as part of their Technology Development and Research (TDR) Programme to improve living standards and conditions in the World's developing countries. The project is designed to study sustainable water resource development, through analysis of the long-term behaviour of dug wells and boreholes in hard rock aquifer areas. The main aim of the project is to produce an understanding of the above through field study and digital modelling of such aquifer systems, the results of which will produce design criteria that can be applied by developers.

This particular report describes the applicability of refraction seismic equipment and techniques to the location of sites suitable for the construction of collector well systems in hard rock terrains in Zimbabwe. Recommendations for improved routine well siting methods enhanced through the use of seismic survey equipment have resulted.

## EXECUTIVE SUMMARY

1. The usefulness of the ABEM MINILOC seismic refraction equipment was successfully demonstrated within the Tamwa area of S.E. Zimbabwe.

2. The equipment was used to accurately determine the thickness of the upper highly weathered clayey layer of bedrock saprolite.

3. However the unit could not be used to identify depth to hard rock, this is thought to be due to the power limitations of the equipment. Frequently a sharp hard rock/weathered rock boundary does not exist, rather the interface is diffuse with the effects of weathering gradually decreasing with depth. Profiling results commonly indicate the latter style of weathering, this weathered bedrock or saprock layer being the main groundwater bearing zone forms the main target horizon for development.

4. A comprehensive procedure for the siting of dug wells or collector wells is presented which recognises the capabilities and limitations of the ABEM equipment. This is a significant advance in routine well site location methods.

**ACKNOWLEDGEMENTS**

The very helpful assistance of BGS and IH colleagues associated with the Collector Wells and Aquifer Sustainability projects in Zimbabwe, at Chiredzi and Tamwa, and in Wallingford is gratefully acknowledged.

Mr Duncan Thompson is especially thanked for initiating the author into the use of the ABEM equipment and interpretation of data produced as well as introducing the author to the Tamwa area.

BGS geophysicists Richard Carruthers and Roger Peart are thanked for their more than helpful criticisms of field technique and data analysis.

Dr Robin Herbert is thanked for his helpful advice and guidance.

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[Appendices 1-5 are the subject of a separate reference report, copies of which are available on request from BGS Keyworth]

# 1. INTRODUCTION

## 1.1 Background

The British Geological Survey (BGS) and the Institute of Hydrology (IH) are jointly studying the use of limited groundwater resources derived from crystalline basement formations via collector well systems for the small-scale irrigation of garden plots. This study is based at the Low-veld Research Station (LVS), Chiredzi, in south-eastern Zimbabwe. The initial development of collector well systems at LVS Chiredzi was described by Chilton and Talbot (1990). They latterly described the construction and testing of a collector well system at the Tamwa/Sihambe/Dhobani Kraals (Chilton and Talbot, 1992) within a discrete catchment system that is currently the subject of intensive hydrological and hydrogeological study (Fig 1). Included in the study is the sustainability of basement aquifer systems especially under prolonged drought conditions.

BGS have studied the applicability of various geophysical surveying methods to the location of sites suitable for drilling and development of groundwater production boreholes and collector well systems within crystalline basement strata, specifically within south-eastern Zimbabwe (Carruthers, 1986 and Carruthers and others, 1993). Within south-eastern Zimbabwe seismic refraction surveys, employing a hammer/strike plate energy source, were undertaken with varying degrees of success by Smith and Raines (1988) and Carruthers et al (1993). The latter report concluded that:-

*"Seismic refraction undoubtedly offers the best prospects for mapping the bedrock surface in detail although not without its own difficulties. Experience from this and previous studies indicates the importance of a sufficiently powerful energy source, even when a sensitive signal averaging record system is available. The hammer/plate system is generally inadequate for the offset shots needed for efficient bedrock coverage but a heavier weight drop system constructed locally for earlier BGS investigations (Smith and Raines, 1988) proved too cumbersome and gave insufficient improvement to justify its routine use. Small explosive charges would be ideal if both the logistical problems of storage, security etc. could be solved and augering shallow shot-holes (0.5-1 m deep) was practical. Other commercial energy sources which are produced would not usually be available in developing countries."*

The seismic survey equipment used by Carruthers et al (1993) was a 24 channel ABEM Terraloc system using a 24 geophone array, with a geophone separation of 2 m and a total of 8 multiple shot points per survey profile. This equipment has a signal enhancement facility that permits the stacking and averaging the results of a number of shots at each shot point. The raw data was stored on a 3.5" computer disc for later off-site analysis.

In response to these studies and their recommendations an ABEM MINILOC seismic refraction system was procured for use in both the collector well and aquifer sustainability projects. When tested on "hard rock " formations within the Dartmoor area depths of weathering down to 18 m were determined. The assessment of the system's capabilities under field conditions in crystalline basement formations within SE Zimbabwe was therefore proposed.

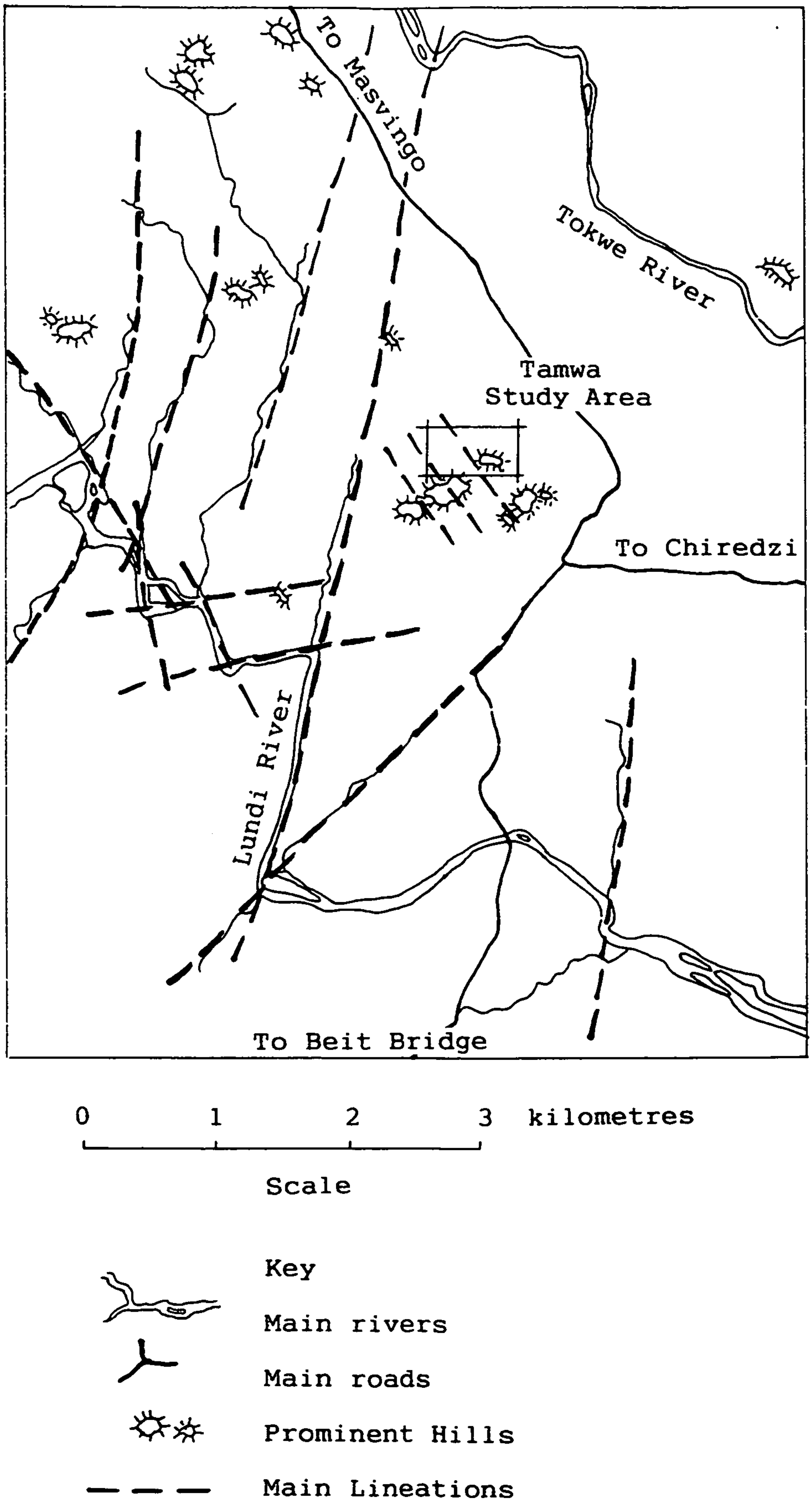



Fig 1 Study area location map.

## 1.2 Aims and Scope of this Report

The main aim of this short term project is to assess the applicability of the ABEM MINILOC seismic refraction surveying system for determination of approximate depths of weathering in crystalline basement rock formations, for location of prospective sites for dug wells and/or installation of collector well systems with the object of reducing exploration drilling requirements, and hence costs. This report describes seismic profiling and related works undertaken within the Tamwa and Chiredzi areas during the period 14th February - 11th March 1994. A description of field works undertaken during this period is given in diary form in Appendix 1. Included in the main report are an outline of the method and equipment used, details of profile surveys undertaken, and an analysis of the results obtained. A suitable survey programme is outlined. Various types of hammer/plate combinations were used and the results compared. The inter-relationship of such geophysical surveys to preliminary interpretation of aerial photographs, providing indications of the distributions of lithologies and structural lineations, and field mapping of geology is stressed.

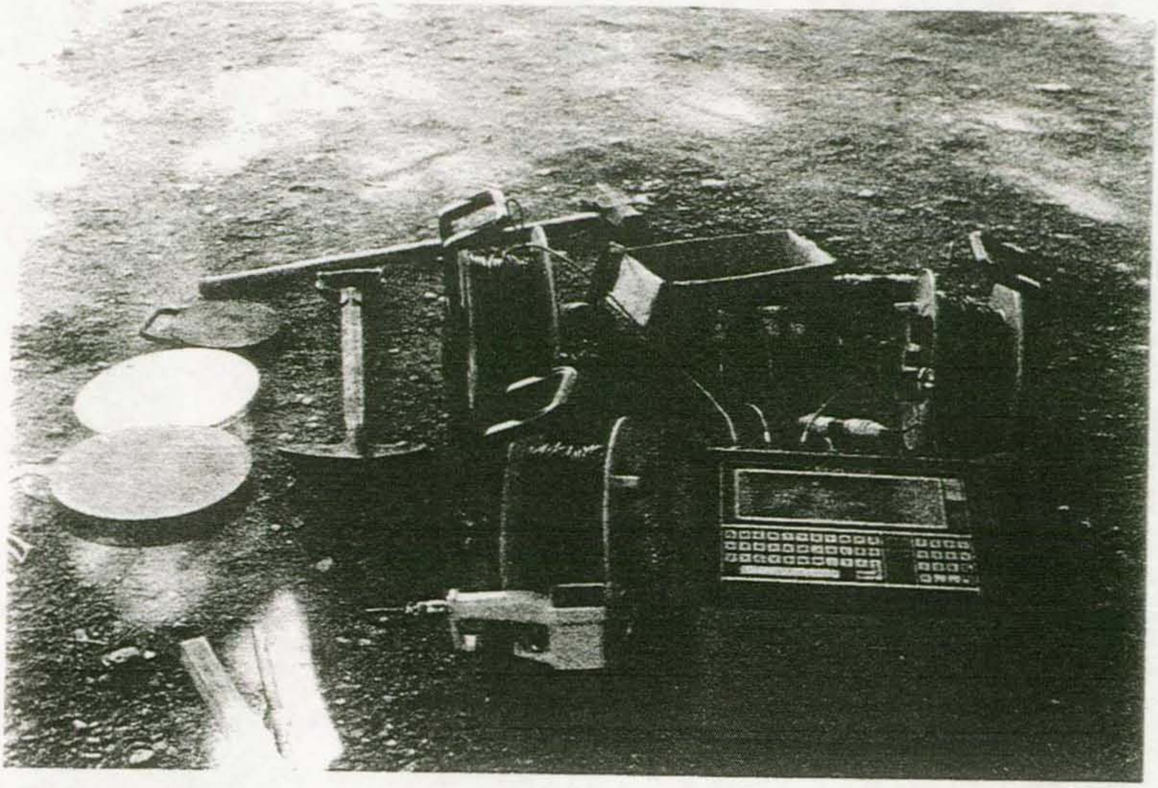
# 2. THE ABEM SYSTEM

The light-weight ABEM MINILOC system is described in detail in the manual (ABEM, 1991) reproduced in Appendix 2. This is a 3 geophone/channel seismograph system used to conduct shallow refraction surveys. Data are produced and analysed using the "principle of reciprocity". Survey results are presented on a liquid crystal display that can be down loaded to a printer to produce hard copy. The principles of the seismic refraction method are described in Parasnis (1962) and other basic text books notably those describing the application of low powered geophysical prospecting methods to engineering geology (Clayton, Simons and Matthews, 1982).

## 2.1 Equipment and Crew Requirements

The MINILOC system includes a control box, three geophones with connecting cables, a trigger unit with connecting cable, various strike plates and a large hammer (Fig 2). The system is easily man portable. A two or three man crew is required, one to strike the plate (Fig 3), one to place the triggering device and a third to operate the data collection system. When the latter system is set to run automatically the third man can be dispensed with, the set being left to operate on its own except when a premature firing is registered caused by external effects. The set then has to be reset before firing can continue.

The largest possible hammer that can be handled repeatedly with ease is required together with a strike plate of approximately the same weight as the hammer (a 14 lb or 7.5 kg hammer and equivalent plate are recommended) (Fig 3). As an alternative a heavy 43 kg weight was used instead of a hammer, dropped on the steel plate at each of the shot points (Fig 4). Three different strike plates were used, composed of aluminum, resin and steel (Fig 2), during the project, the attributes and properties of each being evaluated and compared. The three geophones used were buried below ground surface to avoid interference from the stiff breeze that blew for much of the



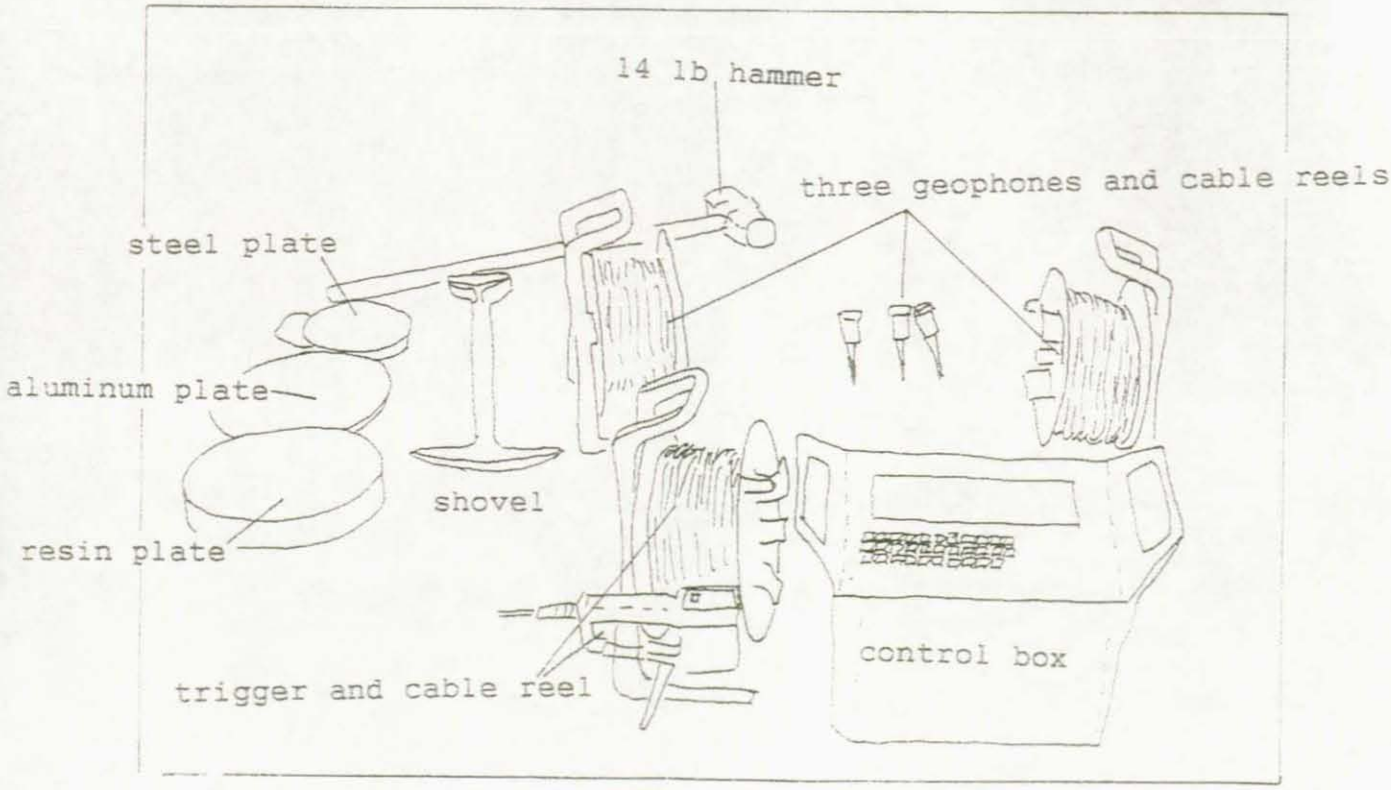



Fig 2 ABEM MINILOC seismic refraction profiling system components. Note the steel, aluminum and resin strike plates.

Fig 3 Seismic refraction profiling at Tamwa using the hammer and steel plate energy source.

Fig 4 Seismic refraction profiling at Chiredzi using the 43 kg weight and steel plate as energy source.

time. Six repeat shots/hammer blows are required at each shot point for the production of a single shot trace.

## 2.2 System Operation

The main elements of the operation of this system are described within the accompanying manual. Ideally this should be a mobile system that can be used to rapidly execute a large number of surveys in a relatively short period of time. However only 10 sets of worked results can be stored within the control box at any one time plus the last input of raw data. No system for down-loading the raw data for remote location analysis by storage on 3.5" computer disc was available. Therefore time consuming data analysis had to be undertaken on site between profile surveys. In this situation the quality of the data acquired and analysis will depend to a great degree upon the experience of the equipment operator. While the basic automatic system of survey and data analysis can be undertaken by a two man crew of very limited prior experience, to undertake the manipulations suggested within the manual an experienced operator, with at least several months of continuous equipment usage, is required.

Although the basic set of equipment is compact and technologically sophisticated there are elements that lack sufficient robustness for repeated periods of heavy field usage. For instance the trigger cable should be armoured and reinforced for it has to be dragged the entire length of the spread during the execution of a profile. Should the cable be caught on a root or stone and the operator give a tug in an effort to free it there is a very real chance that the internal, very thin conducting copper wires will break when the cable is stretched. This happened at Tamwa but fortunately the break occurred towards one end of the cable and only about 0.5 m of cable was lost. Should this happen repeatedly the cable would soon be too short for effective operation of the system. In dusty conditions the marine type cable connectors also need to be handled with care. They should be periodically dismantled and cleaned out if seizure of the couplings is to be avoided. The liquid crystal display of the main operating unit can be difficult to read in bright or poor light conditions. It also tends to fade if exposed to direct sunlight. The control box is therefore best operated within the confines of a shaded area eg within a Land Rover cab. The trigger unit needs to be reinforced as if it has to be repeatedly pushed into hard compacted soil, the handle moulding has a tendency to break. Otherwise the system is relatively easy to operate and produces satisfactory results.

# 3. AREA OF INVESTIGATION

The Tamwa area is located within the district covered by the following topographic maps:-

| | |
|---|---|
| 1:250,000 | sheet SF-36-1 Fort Victoria Edition 2 1975 |
| 1:50 000 | sheet 2030D1 |
| | sheet 2030D2 |
| | sheet 2030D3 |
| | sheet 2030D4 |

1:25,000 ortho-photo sheet 2030J8

1:25,000 aerial photograph Masvingo 1566 of 11/6/85

The Tamwa area is a small self-contained catchment system located some 7 km NW of Ngundu (Fig 1) in an area where the major drainage pattern is controlled by tectonic lineations. Rainfall is variable, occurring mainly from isolated storm events during the wet season between November and April. The elongate ENE-WSW trending valley is about 1.5 km wide and 3 km long being bounded to the north and south by elongate ridges of granulitic gneiss that give rise to several bornhardt type koppies, typical of the region (Figs 5 and 6). Rainfall run-off from such topographical features can be very rapid and intense, commonly causing flash flood conditions. Black cotton type soils are usually developed along the valley bottoms, along which driving becomes difficult to impossible after moderate rainfall. Between the valley bottoms and the lower koppie slopes thicknesses of weathering can be very variable, being dependent upon rock type, the presence of faulting and topographic setting. The present population settlement pattern was formed in 1952 by an influx of Matabele and Shona peoples ousted from white controlled farms within the then Gwelo District.

Geological data from the study area have been derived from analysis of aerial photography (lineations (Fig 7) and general geological boundaries), exploration borehole drilling and geological field mapping. Hydrogeological data have been obtained from boreholes, hand dug wells and a collector well system located within the area the locations of which are shown on Figs 8 and 9. A limited attempt was made to identify geological lineations traversing the area from aerial photographs, ortho-maps and 1:50 000 scale topographic maps (Fig 7). The main lineations are seen to trend NW-SE, normal to the main valley trend. Water samples were obtained from most of the hand dug wells and boreholes within the study area for hydrogeochemical analysis, the samples being submitted to BGS Wallingford for analysis. Water levels are currently being monitored on a weekly basis at a system of 35 hand dug wells and 65 piezometers. Basic data derived from these monitoring sites are tabulated in Appendix 3. Geological and borehole drilling data from exploration boreholes drilled at Tamwa are listed in Appendix 4, including detailed geological logs from boreholes IHA (A in Appendix 4) and OW4 (4 in Appendix 4).

## 4. FIELD STUDIES UNDERTAKEN

Following a two day introduction to the Tamwa site and initiation into the operation of the MINILOC equipment package, 22 seismic profiles were undertaken at Tamwa (Fig 10) and 2 at Chiredzi. Each profile was 108 m long with shot points at 3 m intervals (Fig 11). The weather at site was either overcast or sunny with stiff breezes. The only likely interference during profiling was from pedestrians or the odd scotch cart, although pumping at the Chiredzi collector well produced significant interference effects during the last profile run. The profiling was undertaken at the height of the maize growing season, when most plots were cultivated containing well developed maize, sorghum, sunflowers or some other crop. Therefore profiling had to be restricted to the main tracks, pathways and infrequent bare patches of ground. The use of consolidated earth tracks meant that the striker plate could be positioned on

Fig 5 View across Tamwa catchment study area.

Fig 6 Typical Bornhardt type kopje.

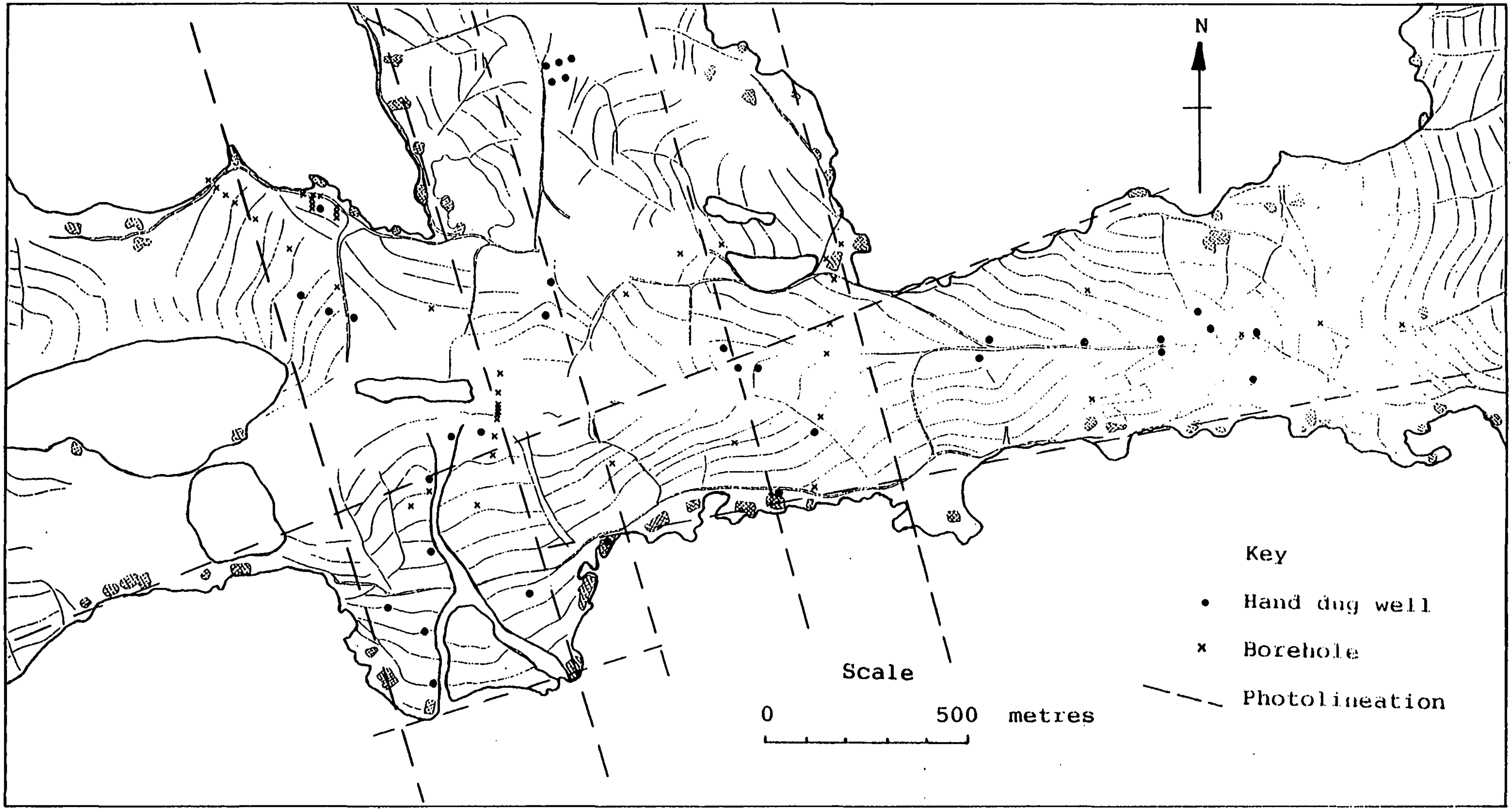



Fig 7 Tamwa study area - photolineation map

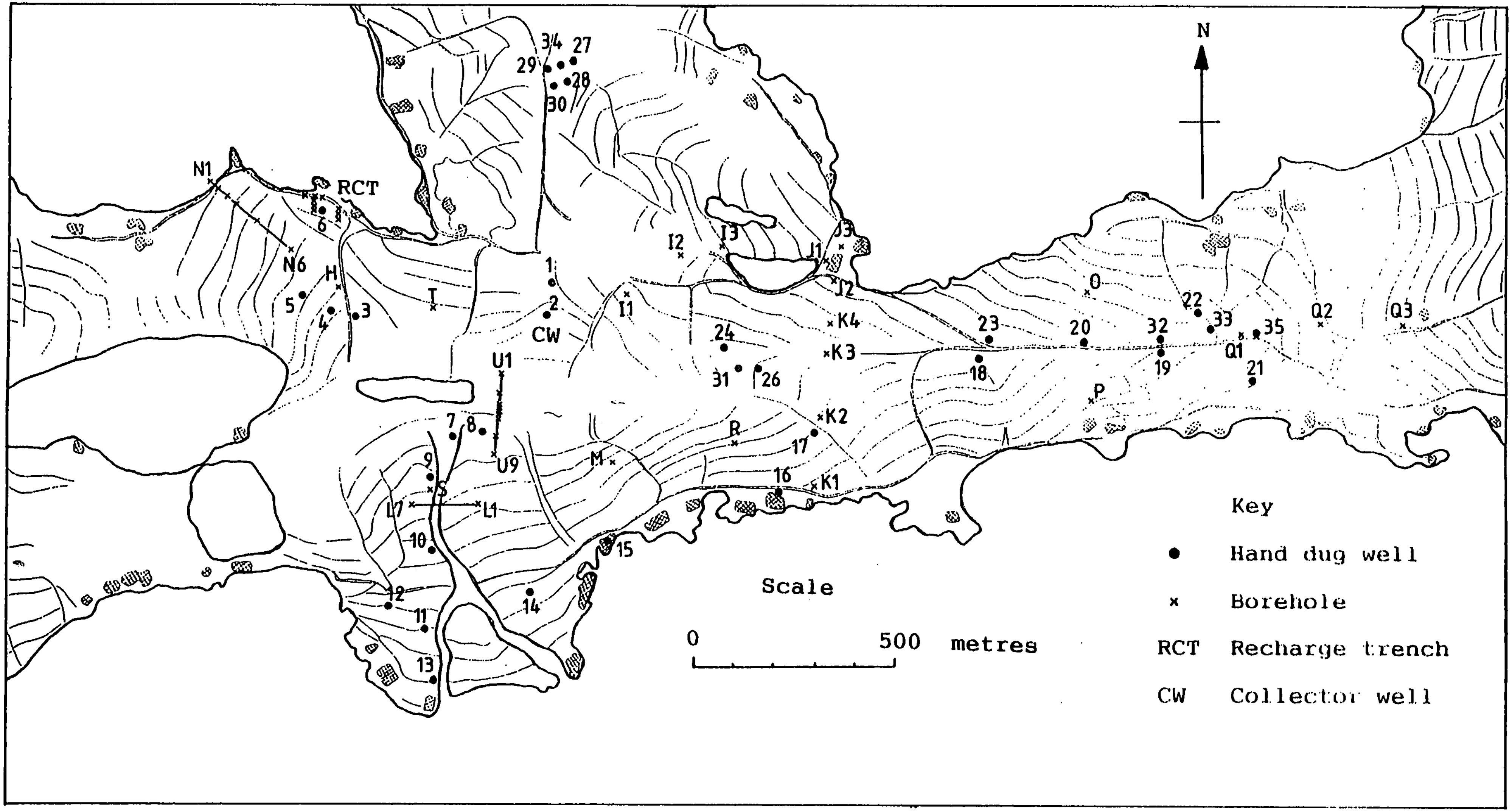



Fig 8 Tamwa study area -
hand dug well and borehole location map

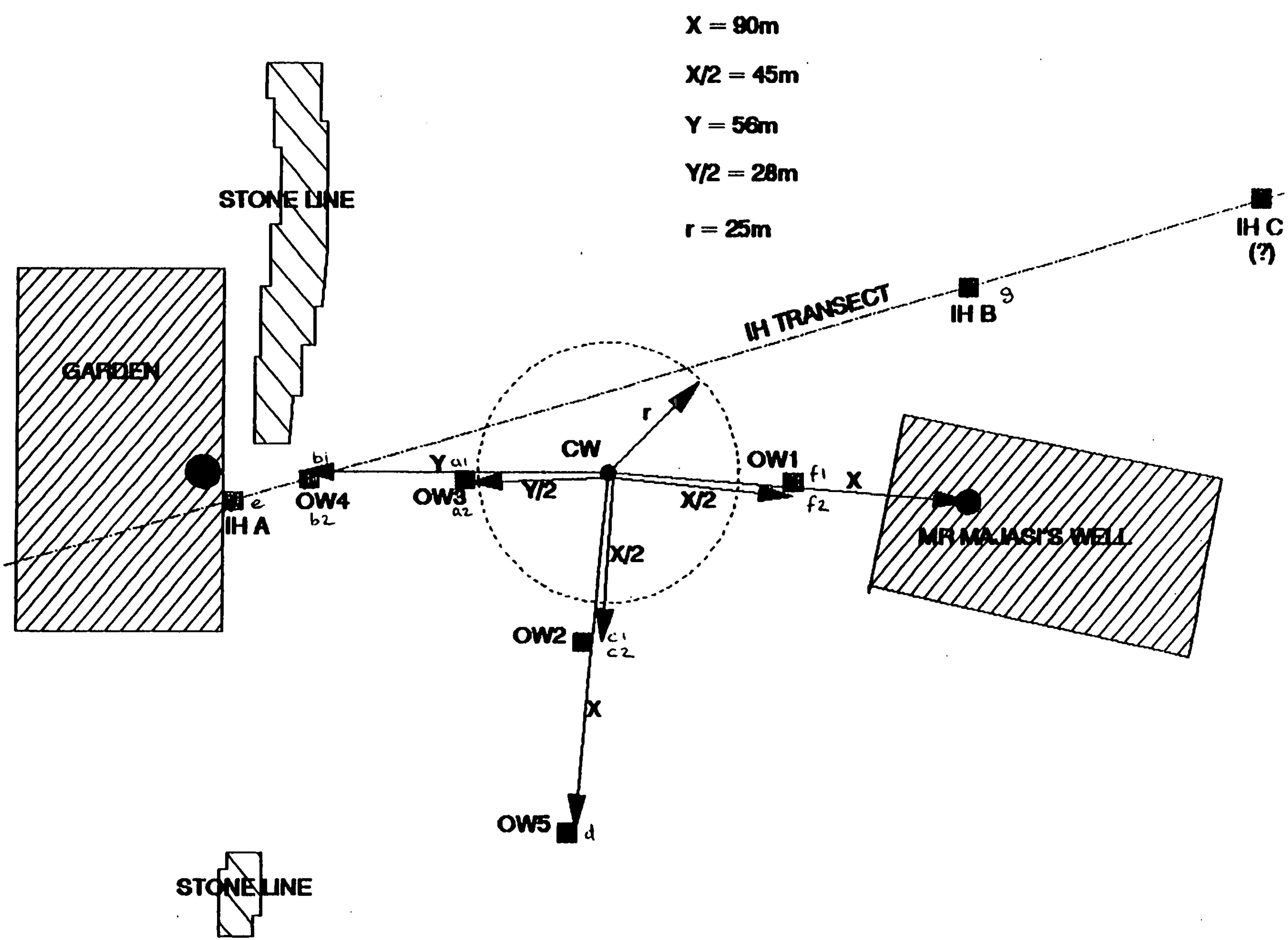



Fig 9 Observation boreholes drilled adjacent to the Tamwa Collector Well (after Price, 1992).

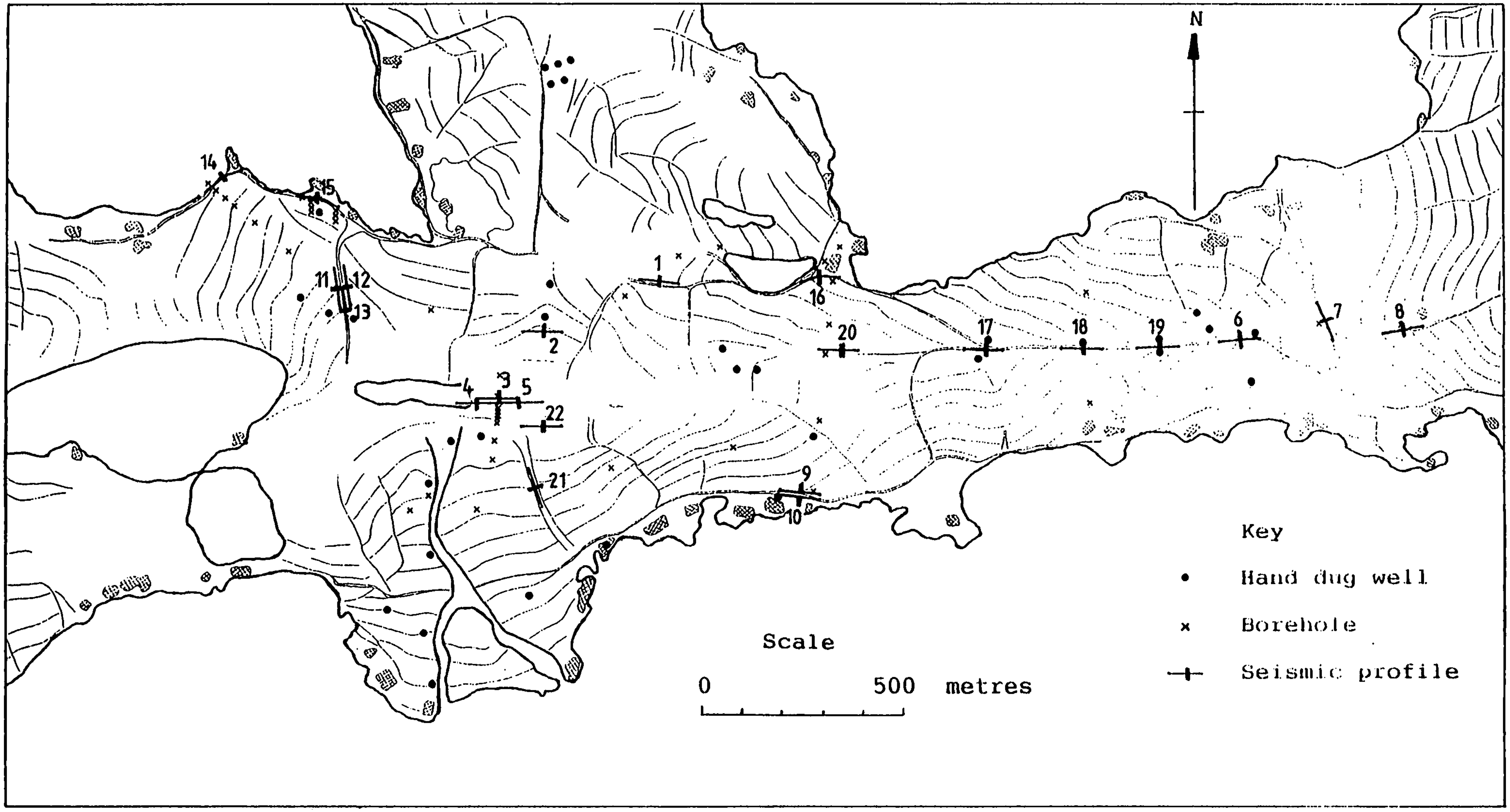



Fig 10 Tamwa study area - seismic refraction
profile location map.

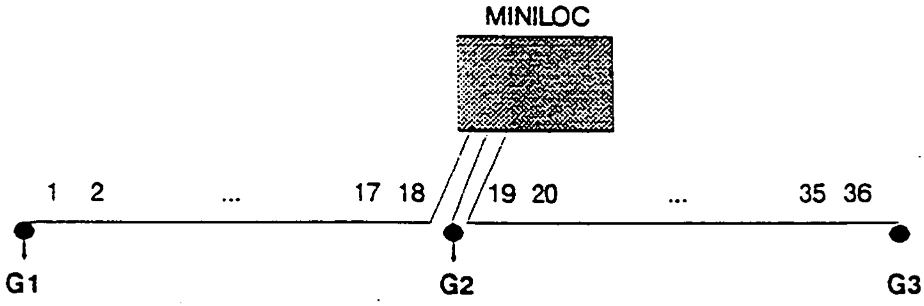



Fig 11 MINILOC layout with geophones G1, G2 and G3 and shotpoints 1 to 36.

compacted material most of the time facilitating good propagation of shock wave energy into the ground. Where surveys took place on grass or loose soil, energy was lost due to the cushioning effect of those materials. Where possible profiles were run adjacent to boreholes where the approximate thickness of weathered material and depth to bedrock were known. Comparison of the properties of three types of strike plate ie. aluminium, resin and steel, was attempted. Overlaps of profiles were also undertaken at two sites. Three profiles could comfortably be undertaken per working per day. Setting out of the cables and geophones and the execution of the survey usually took an hour. One to two hours were then required for the on-site analysis of data. Analysis of the third body of data was undertaken back at the hotel, where charging of the equipment was undertaken over-night. Some problems were experienced with the equipment, particularly the breaking of the internal copper wires within the trigger cable as previously discussed. Following repair the equipment worked satisfactorily. A two day delay was unfortunately caused by local staff being required to attend a funeral, but some of this time was profitably spent procuring a steel striker plate.

Data obtained from the profiling exercises undertaken are presented in Appendix 5.

## 5. BASIC CONCEPTS AND MODELS

The principles of seismic refraction are described in several standard geophysical text books such as Griffiths and King, (1965) and Parasnis, (1972). The application of the seismic refraction technique to shallow (<30 m depth) site investigation/ geological problems is well described in Clayton, Simons and Matthews, (1982). The refraction method uses the critical refraction of P waves at the boundaries of lithologies with different characteristic velocities (Fig 12). Critical refraction can only occur when the seismic velocity of the lower layer ($V_1$) is greater than that of the upper layer ($V_0$) and the energy rays meet the interface at the critical angle $i_c$. The critically refracted ray travels along the interface within the lower, faster layer. The shock waves produced are known as head waves that emerge from the interface at the critical angle $i_c$. The seismic record produced by a geophone located at a given distance from the shot point is a combination of direct events, refracted events (head waves), reflected events and 'ground roll' (surface waves). The distance from the shot point at which the direct wave and the head wave arrive at the ground surface simultaneously is termed the critical distance, $X_o$.

In order to determine the P wave velocities of different lithologies and depths to velocity interfaces, a time-distance graph must be plotted using the travel time data obtained from the seismic record. The time-distance graph of direct, refracted and reflected events for a simple two layer case are shown on Fig 12. Only first arrival events (i.e. direct and refracted events) are used in the interpretation of seismic refraction data. The accuracy of velocity and depth determinations are dependent upon the velocity contrast between adjacent lithologies, of the order of $V_1:V_0 > 3:1$). The time-distance curves and their interpreted profiles for a simple two horizontal layer case (Fig 12) and multi-horizontal layer case (Fig 13) are straight forward. However in practice interpretation of profiles obtained from basement lithology is often much more complex due to the presence of features such as:-

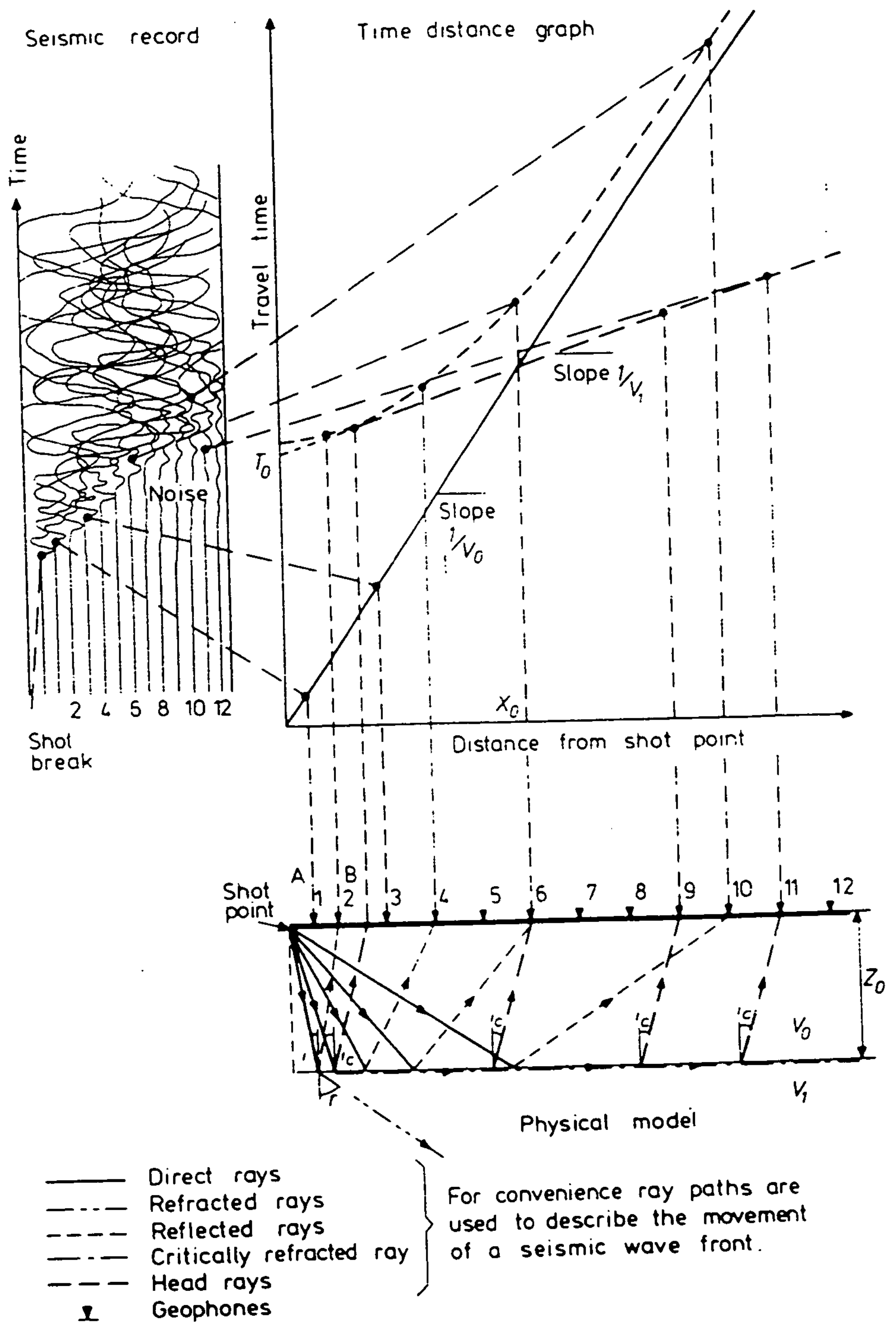



Fig 12 Principles of seismic refraction (from Clayton, Simons and Matthews, 1982).

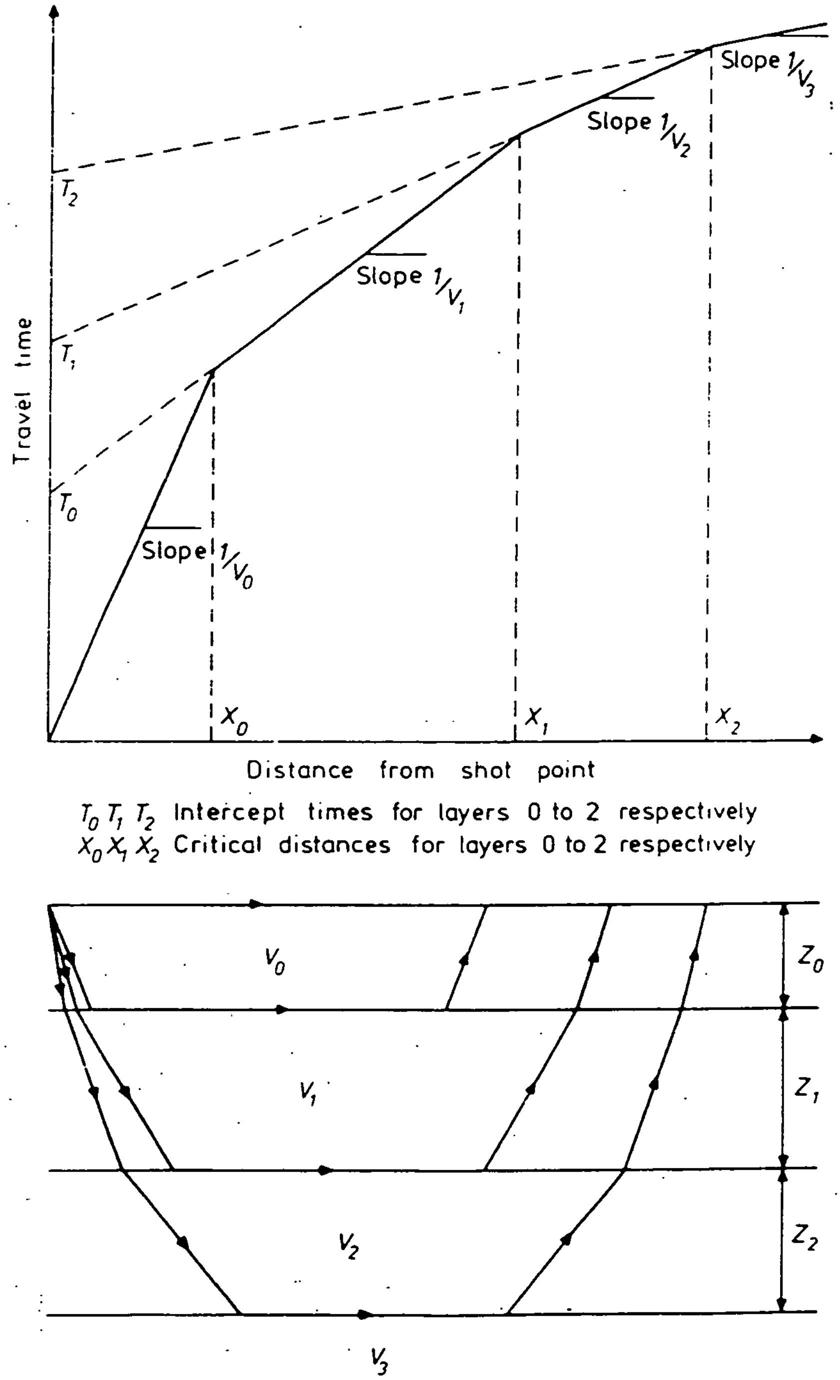



Fig 13 Time-distance graph produced by horizontal layers (from Clayton, Simons and Matthews, 1982).

- a dipping interface (Fig 14)

This is a common feature associated with the pinching and swelling of weathered zones in near surface basement strata.

- a buried channel (Fig 15)

This feature can be associated with the infill of small incised stream channels as well as localised linear weathering occurring along open fault and fracture zones.

- a simple step fault (Fig 16)
- a buried vertical fault (Fig 17)

These features are commonly associated with fault and fracture zones, but similar responses may be obtained from high dip lithological boundaries and intrusive dolerite dykes.

- a continuous velocity increase with depth (Fig 18)

This is the most common feature recognised on profiles obtained from weathered basement strata. As weathering diminishes with depth so the seismic velocity increases. Consequently seismic velocity contrasts are minimal there being no sharp interfaces to recognise.

The above models have been applied to the profiles undertaken within the Tamwa and Chiredzi areas to better understand the time-distance curves and interpreted profiles produced automatically by the MINILOC equipment as discussed below.

## 6. RESULTS

The seismic records received at three geophones during each of the 24 profiles undertaken and the initial interpretation of these results are presented in Appendix 5 of the accompanying Reference Report. The first arrival datum (the first 'pick') is shown on each shot trace. Figs 19-41 show three diagrams in the following order: (i) A geological interpretation of the seismic profiles produced. This interpretation presents the 2 or 3 layers of significantly different seismic velocities produced automatically by the ABEM equipment; (ii) A time distance plot of first arrivals at each geophone, and (iii) A comparison of field data with the arrivals and assumed seismic velocities of the best-fit model of (i).

The expected seismic velocities of sediment and rock formations typically found in south-eastern Zimbabwe are shown (Table 1). The thicknesses and seismic velocities determined for each profile are tabulated and compared with depths to hard basement recorded on the geological logs of boreholes located adjacent to the profile sites (Table 2).

In Section 7 these results are used to investigate correlations between the seismic profiles and the lithology from the drilled holes. The only significant correlation obtained was the change-over from drag bit to hammer, to the interface between the modelled seismic second and third layers, the third layer having velocities <6000 m/s and the second layer having a velocity typical of clay, c. 500 m/s.

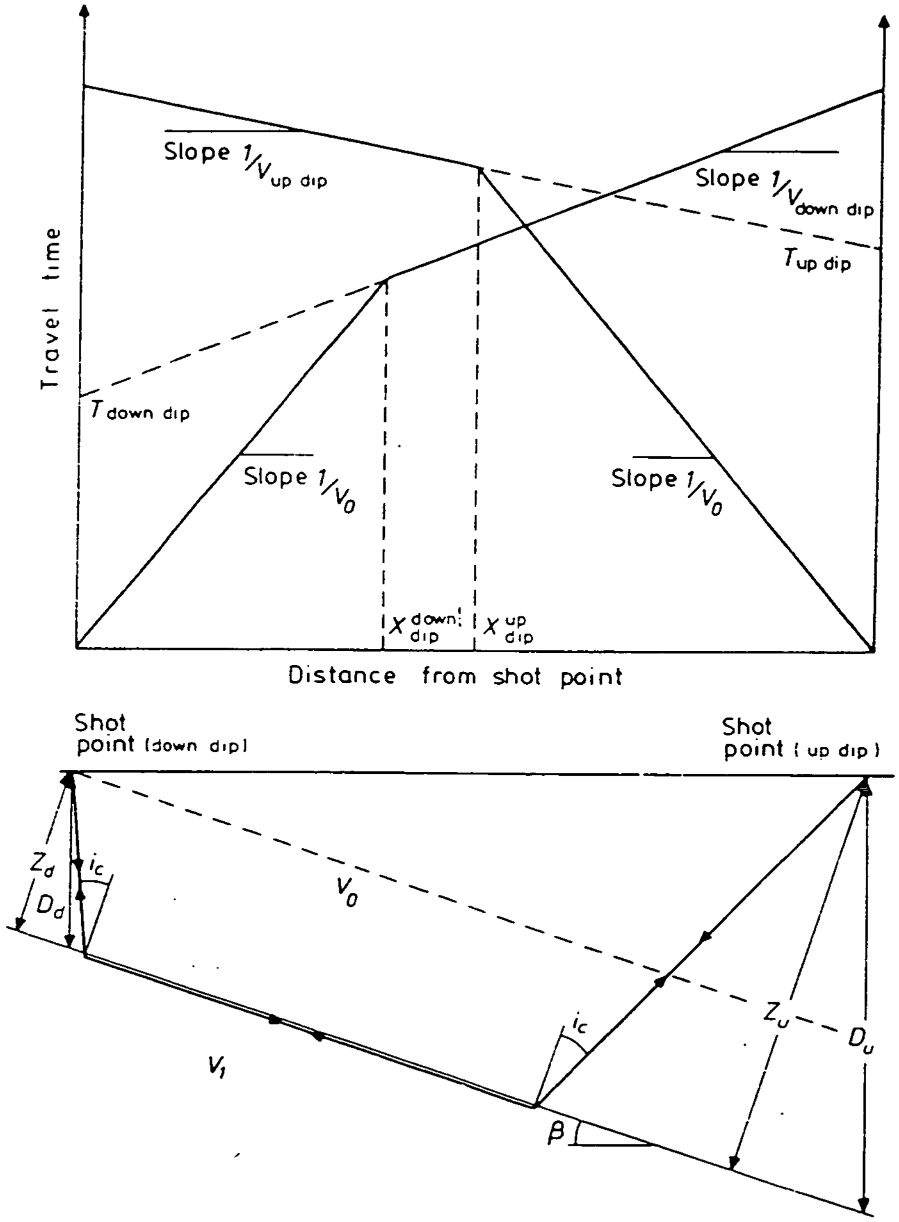



Fig 14 Time-distance graph produced by a dipping interface (from Clayton, Simons and Matthews, 1982).

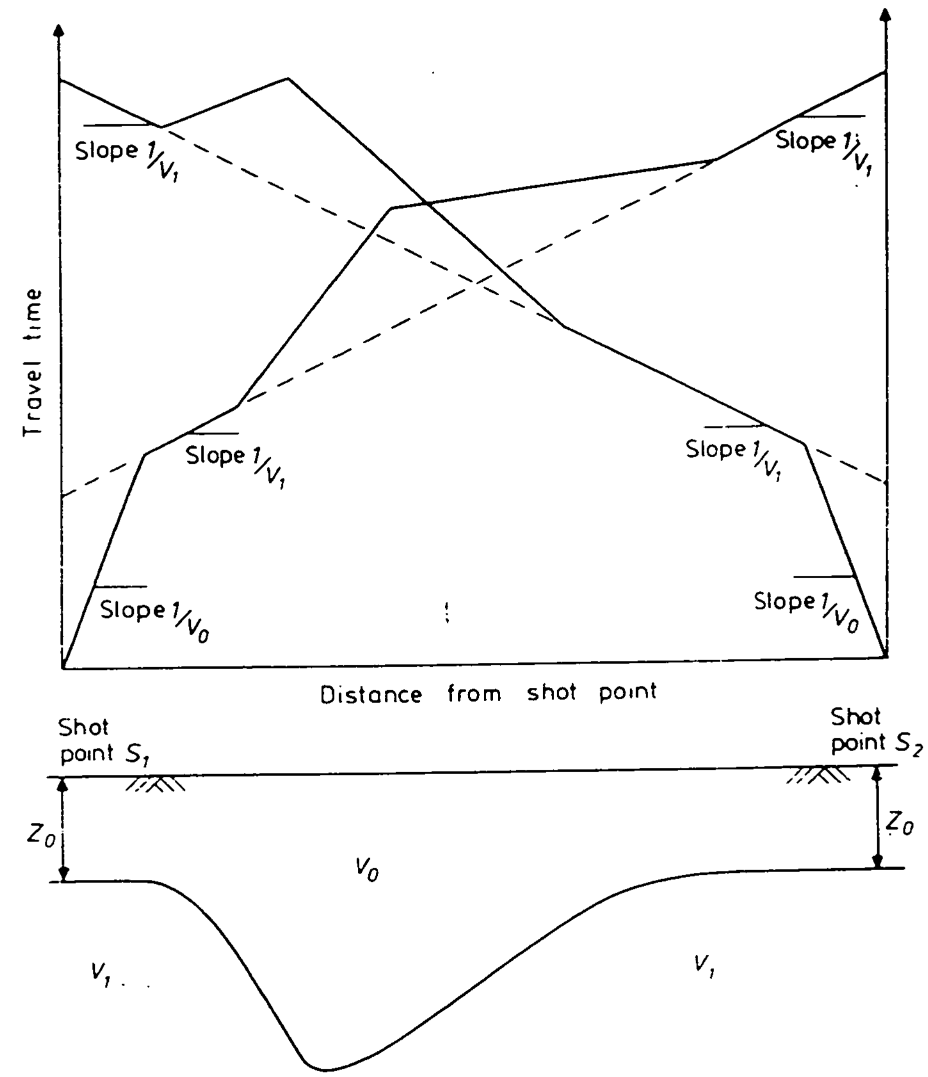



Fig 15 Time-distance graph produced by a buried channel (from Clayton, Simons and Matthews, 1982).

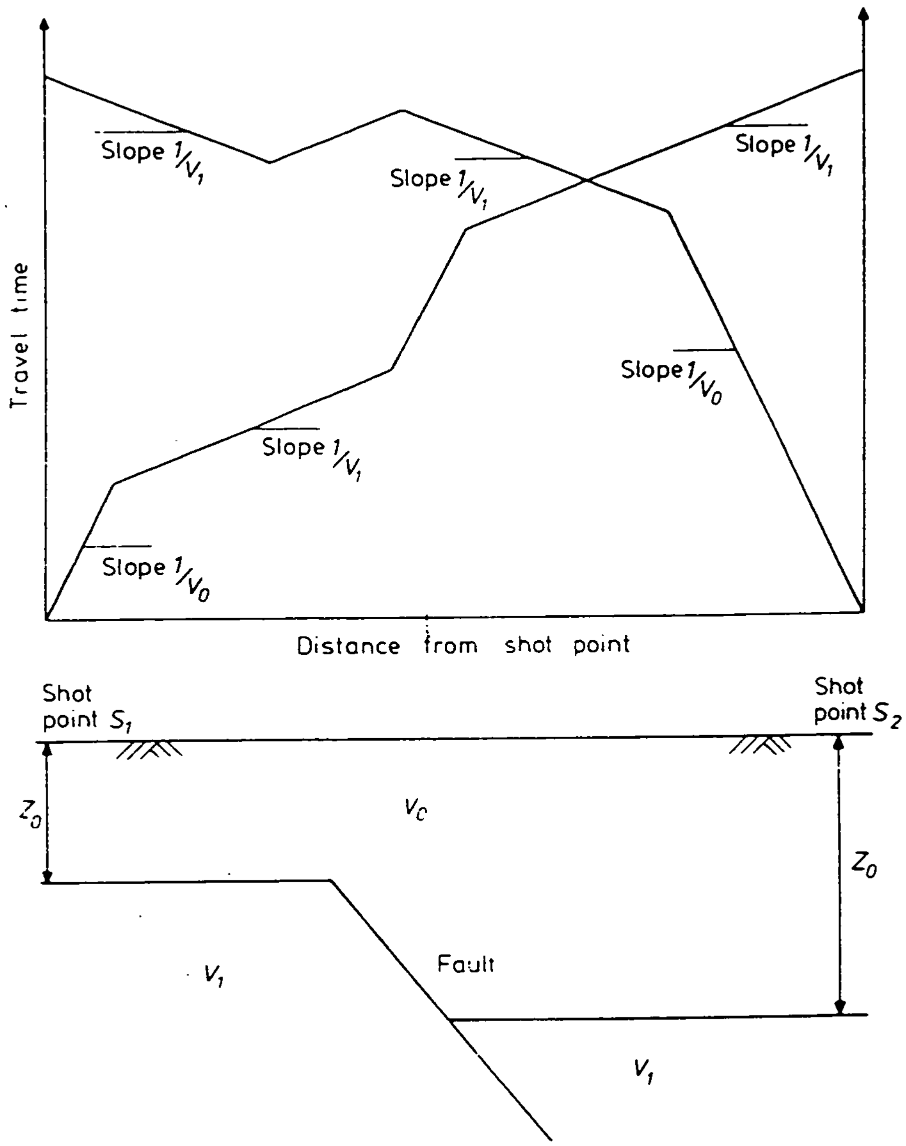



Fig 16 Time-distance graph produced by a simple step fault (from Clayton, Simons and Matthews, 1982).

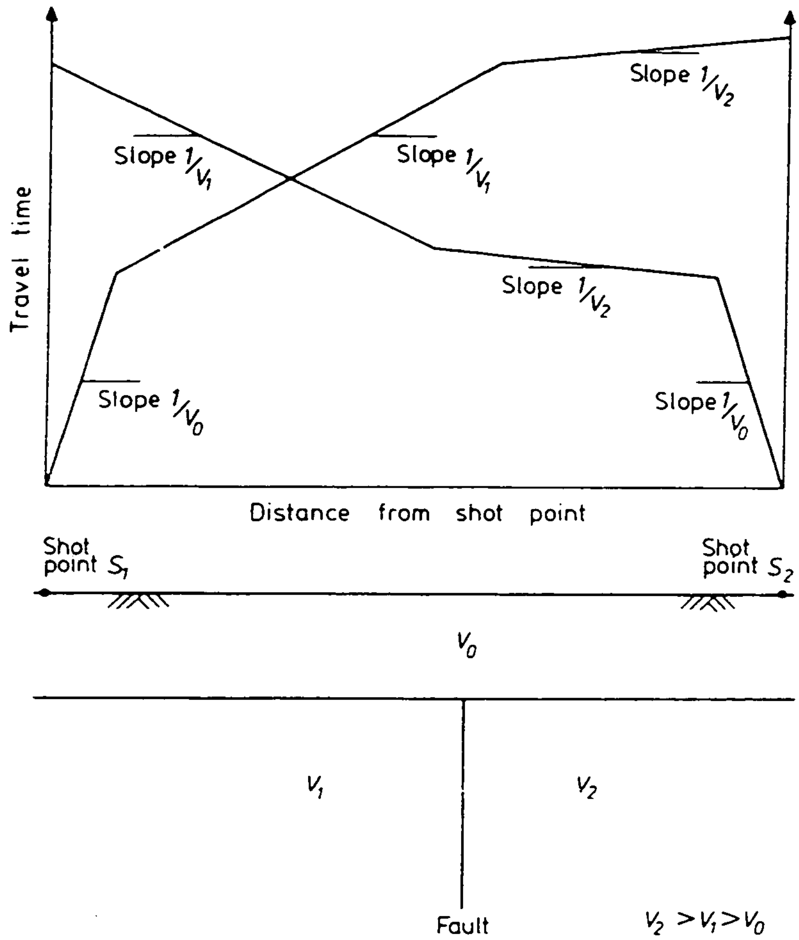



Fig 17 Time-distance graph for a buried vertical fault (from Clayton, Simons and Matthews, 1982).

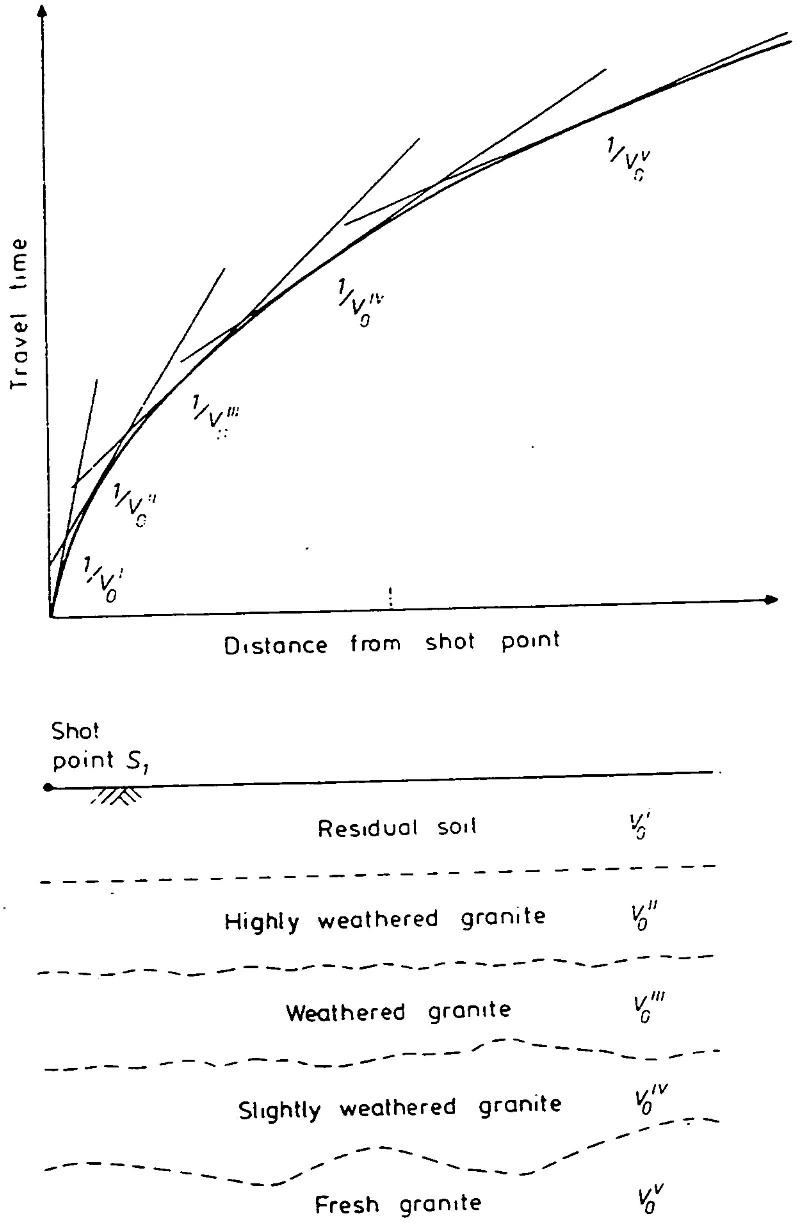



Fig 18 Time-distance graph produced by a continuous velocity increase with depth (from Clayton, Simons and Matthews, 1982).

**Table 1. Expected Seismic Velocities in Zimbabwe**

| | |
|---|---|
| Loose Soil | 300-1000 m/sec |
| Clays | 1600 m/sec |
| Saprolite | 1800-2500 m/sec |
| Saprock | 2200-3000 m/sec |
| Weathered Granite/Gneiss | 3000-4000 m/sec |
| Fractured Granite/Gneiss | 3500-4500 m/sec |
| Massive Granite/Gmeiss | 4500-6000 m/sec |
| Air | 330 m/sec |
| Water | 1450 m/sec |

NB: Interpreted velocities >6500 m/sec are not realistic

Table 2. **Correlation of Depths to Bedrock from Profiles and from Drilling Area**

| Profile | Bh No. | Hard Rock | Layer 1 | Layer 2 | Layer 3 | Layer 4 |
|---|---|---|---|---|---|---|
| 1 | I | 3.75 m | 7000 | | | |
| 2 | CW | | 0-1.5/305 | 1.5+/5000 | | |
| 3 | U3 | 5.25 m | 0-3/284 | 3+/6033 | | |
| 4 | U3 | 5.25 m | 0-3/338 | 3+/5454 | | |
| 5 | U3 | 5.25 m | 0-1/328 | 1-7/624 | 7+/9281 | |
| 6 | Q1 | 14.25 m | 0-2/252 | 2-8/977 | 8+/4656 | |
| 7 | Q2 | 10.50 m | 0-1/222 | 1-7/779 | 7+/2922 | |
| 8 | Q3 | 18.00 m | 0-2/265 | 2-10/1014 | 10+/3530 | |
| 9 | K1 | 9.00 m | 0-3/350 | 3-9.5/682 | 9.5+/2405 | |
| 10 | K1 | 9.00 m | 0-7/554 | 7-16/1298 | 16+/2538 | |
| 11 | H | 9.75 m | 0-0.5/281 | 0.5-5/404 | 5-21/404 | 21+/3085 |
| 12 | H | 9.75 m | 0-0.5/223 | 0.5-7/462 | 7-22/1999 | 22+/3258 |
| 13 | H | 9.75 m | 0-2/269 | 2-10/1593 | 10+/4160 | |
| 14 | N2 | 8.25 m | 0-2/297 | 2-14/1062 | 14+/3813 | |
| 15 | RCT | 7.00 m | 0-0.5/246 | 0.5-7/456 | 7+/6004 | |
| 16 | J2 | 2.00 m | 0-2/283 | 2+/3817 | | |
| 17 | HDW23 | >9.12 m | 0-1/221 | 1-8/728 | 8-25/3529 | 25+/6315 |
| 18 | HDW20 | >6.75 m | 0-3.5/313 | 3.5+/3191 | | |
| 19 | HDW19 | >6.30 m | 0-1/216 | 1-9/984 | 9+/4395 | |
| 20 | K3 | 9.75 m | 0-1/224 | 1-9/1109 | 9+/3454 | |
| 21 | L1 | 18.75 m | 0-2/293 | 2-7/2222 | 7+/4039 | |
| 22 | U7 | 12.00 m | 0-0.5/248 | 0.5-5/431 | 5+/4065 | |

**Profile TAMWA 2 ( Fig 19)**

This site was located between collector well and garden on the north side of the valley (Fig 10). A hammer and aluminum strike plate were used as the energy source. Shallow penetration to 4 m depth was attained with two layers be detected. The layers have a very high seismic velocity contrast, the upper layer being dry soil above hard gneiss. Deflections that are duplicated on all three time-distance graphs may be indicative of possible fracturing. Relatively early arrivals suggest bedrock highs. A prominent N-S trending photo-lineament seems to correlate with a thicker zone of weathered material crossed by the eastern end of the profile.

**Profile TAMWA 3 (Fig 20)**

This site was located on the north side of the main E-W drainage stream of the valley (Fig 10). A hammer and aluminum strike plate were used as the energy source. Shallow penetration to 6 m depth was attained with two layers detected. The layers have a very high seismic velocity contrast, the upper layer being dry soil above hard gneiss, correlating fairly well with the geological log of borehole U3. A prominent N-S lineation crossed by the central part of the profile appears to be tight fracture zone forming a subsurface high.

**Profile TAMWA 4 (Fig 21)**

This site was located on the north side of the main E-W trending drainage stream over lapping with the western 50% of TAMWA 3 (Fig 10). A hammer and aluminum strike plate were used as the energy source. Shallow penetration to 3 m depth was attained with two layers being detected. The layers have a very high seismic velocity contrast, the upper layer being dry soil above hard gneiss, correlating well with the geological log from borehole U3. A prominent N-S lineation crossed by the eastern end of the profile appears to be tight fracture zone forming subsurface high. The marked discrepancy between the interpreted and observed results as well as the high mean error of 7.6 indicative that this result is probably not reliable.

**Profile TAMWA 5 (Fig 22)**

This site was located on the north side of the main E-W trending drainage stream overlapping with the eastern 50% of TAMWA 3 (Fig 10). A hammer and aluminium strike plate energy source were used. Moderate penetration to 10 m depth was achieved with three layers being detected. The layers have high seismic velocity contrasts, the upper most layer being dry sand above dry to damp saprolite, above hard unweathered gneiss. This geological interpretation correlates with the geological log from borehole U3. A weathered zone occurs to the east of prominent N-S photo-lineation crossed by the western end of the profile. The very high seismic velocity obtained for the basement is unrealistic indicating that the interpretation is not reliable in spite of the relatively low mean error.

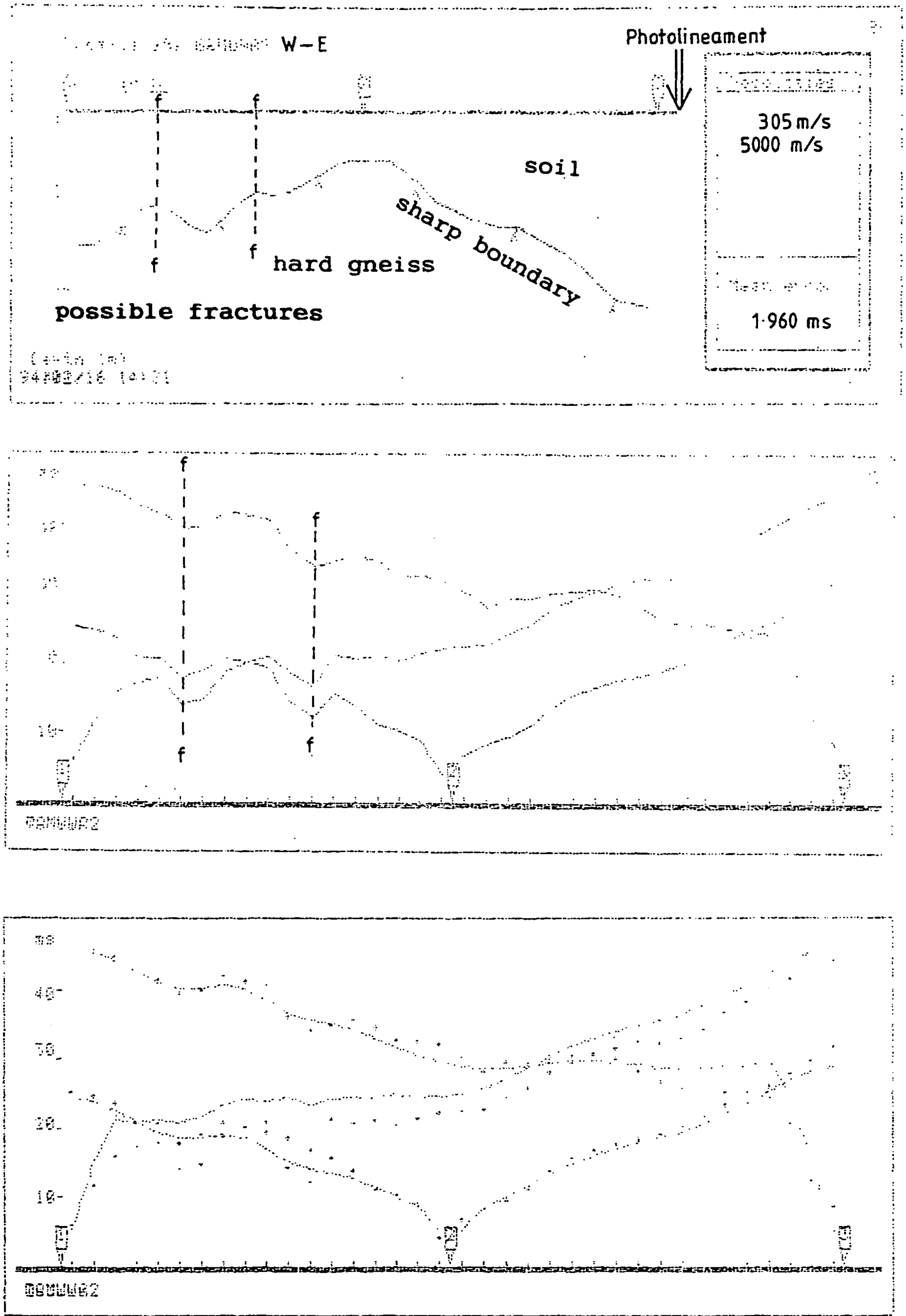



Fig 19 TAMWA 2 W-E

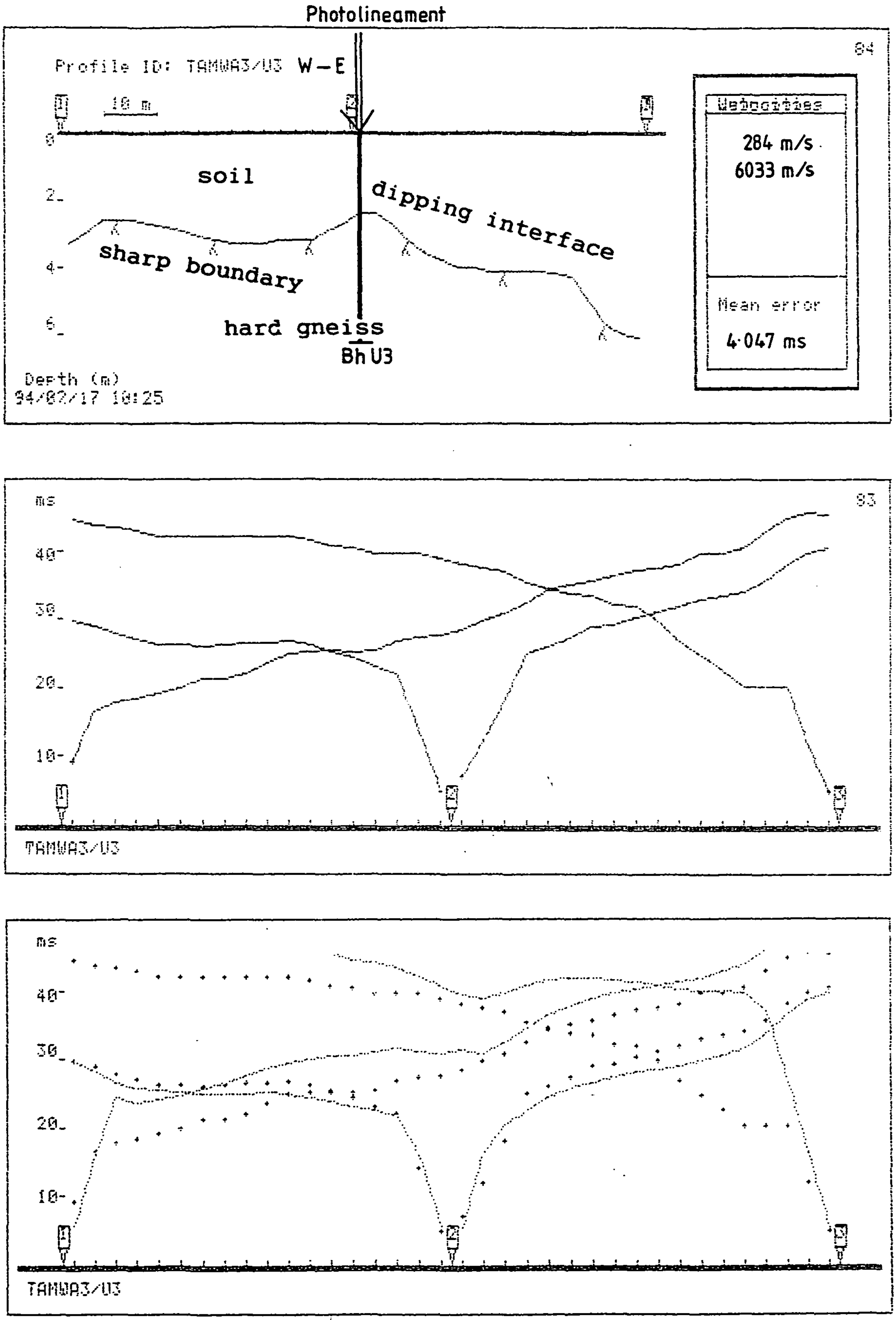



Fig 20 TAMWA 3 W-E

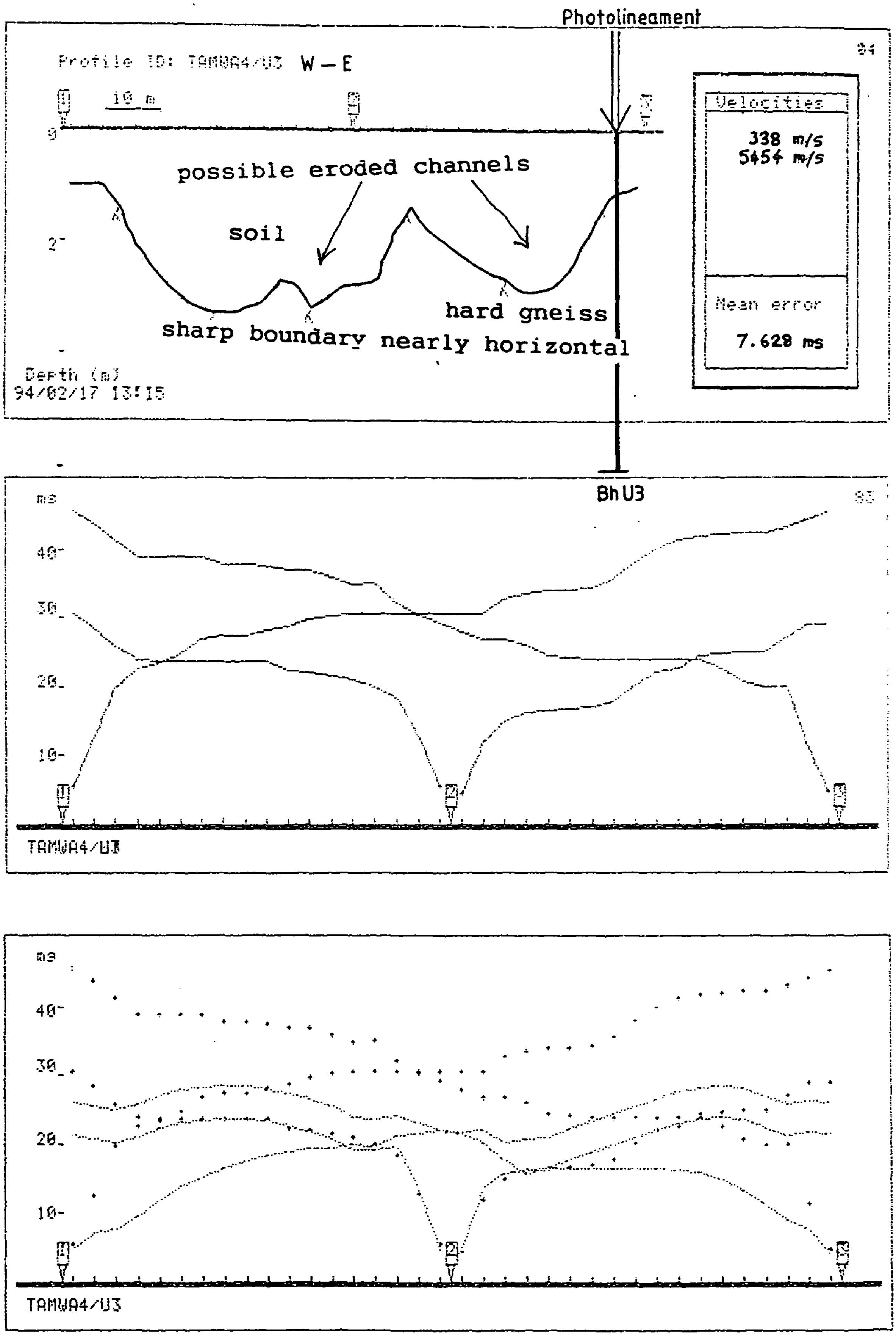



Fig 21 TAMWA 4 W-E

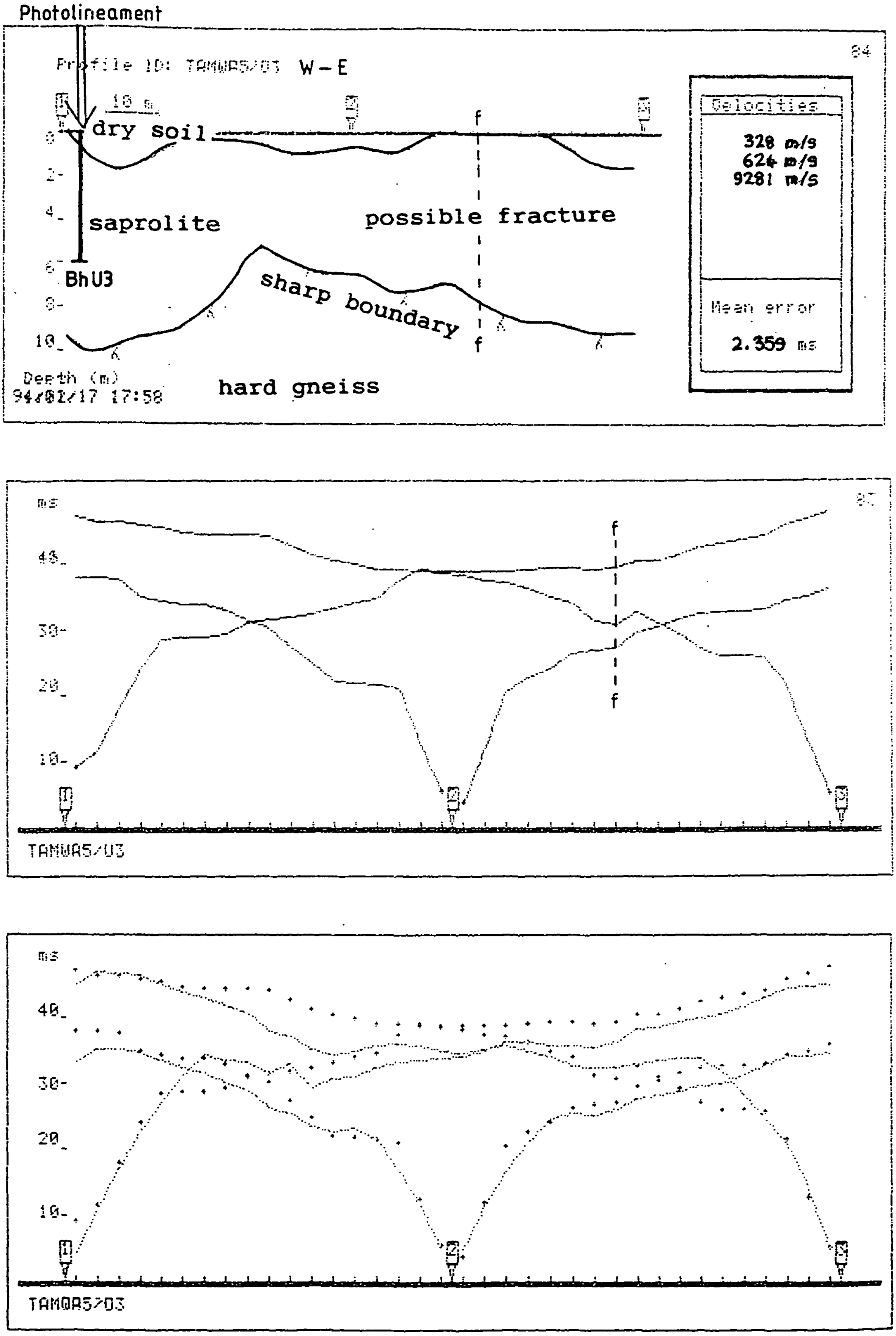



Fig 22 TAMWA 5 W-E

**Profile TAMWA 6 (Fig 23)**

This site was located parallel to the E-W axis of the valley, west of the watershed (Fig 10). A hammer and aluminum strike plate energy source were used. Moderate penetration to 10 m depth was recorded with three layers being detected. The layers have moderate seismic velocity contrasts, with dry overburden occurring above saprolite that thins from west to east, these overlying fairly hard gneiss. Hard basement was recorded at a depth of 14.25 m in the adjacent borehole Q1.

**Profile TAMWA 7 (Fig 24)**

This profile was located normal to the valley axis, just west of the watershed (Fig 10). A hammer and aluminium strike plate energy source were used. Moderate penetration to 12 m depth was achieved with three layers being detected. The layers have low seismic velocity contrasts, with dry sand overburden occurring above saprolite, the latter thinning from north to south, above weathered gneiss. Hard basement was recorded at a depth of 10.5 m in the adjacent borehole Q2.

**Profile TAMWA 8 (Fig 25)**

This profile was located parallel to the E-W valley axis on the eastern watershed (Fig 10). A hammer and aluminium strike plate energy source was used. Moderate penetration to 10 m depth was recorded with three layers being detected. The layers have low seismic velocity contrasts, with thin dry overburden occurring above wet saprolite, that in turn overlies weathered gneiss. Hard basement was recorded at a depth of 18 m in the adjacent borehole Q3.

**Profile TAMWA 9 (Fig 26)**

This profile site was located parallel to and along the southern side of the valley (Fig 10). A hammer and aluminium strike plate energy source was used. Moderate penetration to 10 m depth was recorded with three layers being detected. The layers have low seismic velocity contrasts, with dry overburden occurring above saprolite, that overly very weathered gneiss. Hard basement was recorded at a depth of 9 m in the nearby borehole K1.

**Profile TAMWA 10 (Fig 27)**

This profile was located parallel to and along the southern side of the valley at the same point as TAMWA 9 (Fig 10). A hammer and resin strike plate energy source was used. Deep penetration to 15 m depth was achieved with three layers being detected. The layers have low seismic velocity contrasts, with damp overburden occurring above saprolite, that overlies very weathered gneiss. Hard basement was recorded at a depth of 9 m in nearby borehole K1.

**Profile TAMWA 11 (Fig 28)**

This profile was located towards the western end of the valley, normal to the axis of the latter, midway between the valley side and the valley bottom (Fig 10). A hammer

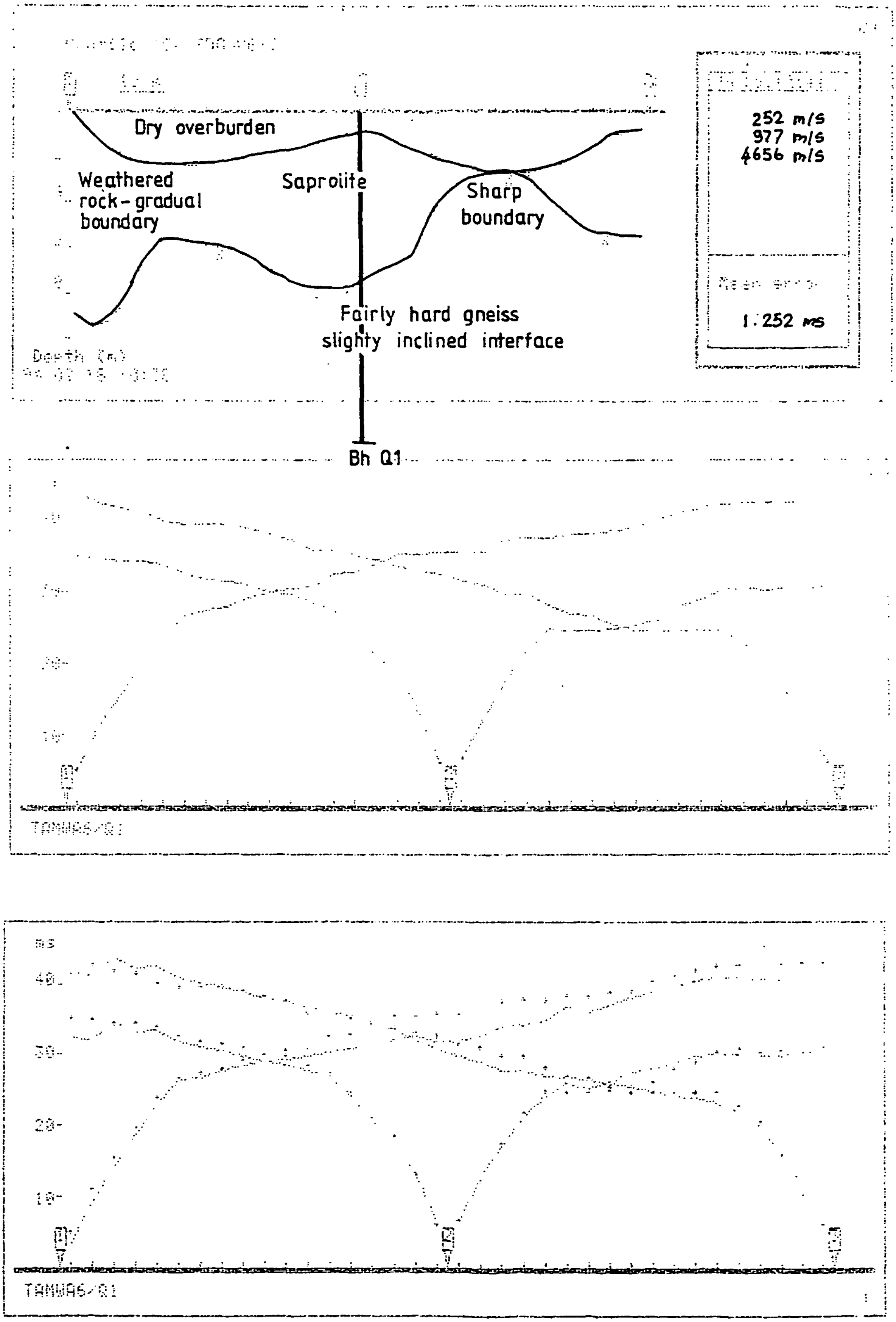



Fig 23 TAMWA 6 W-E

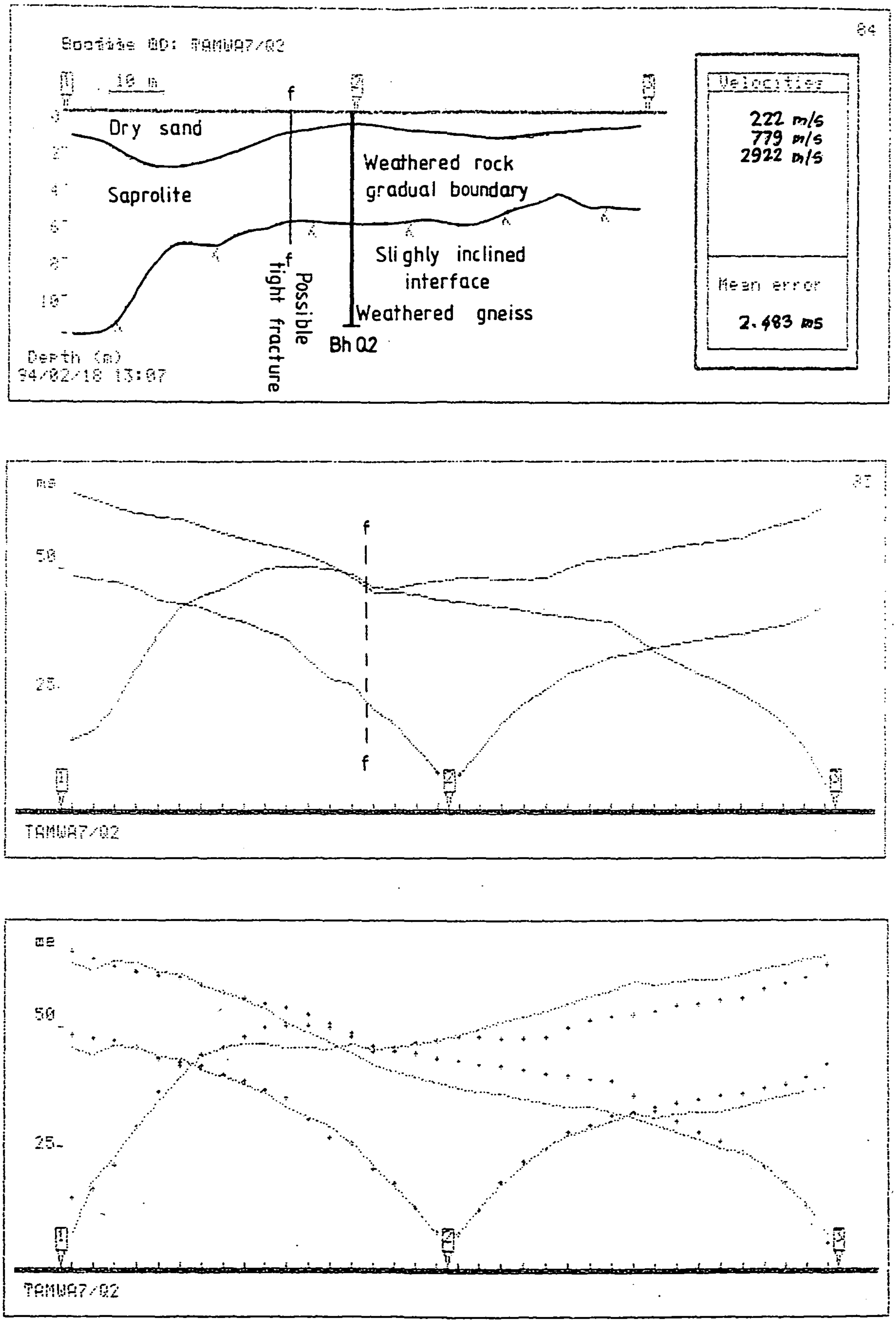



Fig 24 TAMWA 7 N-S

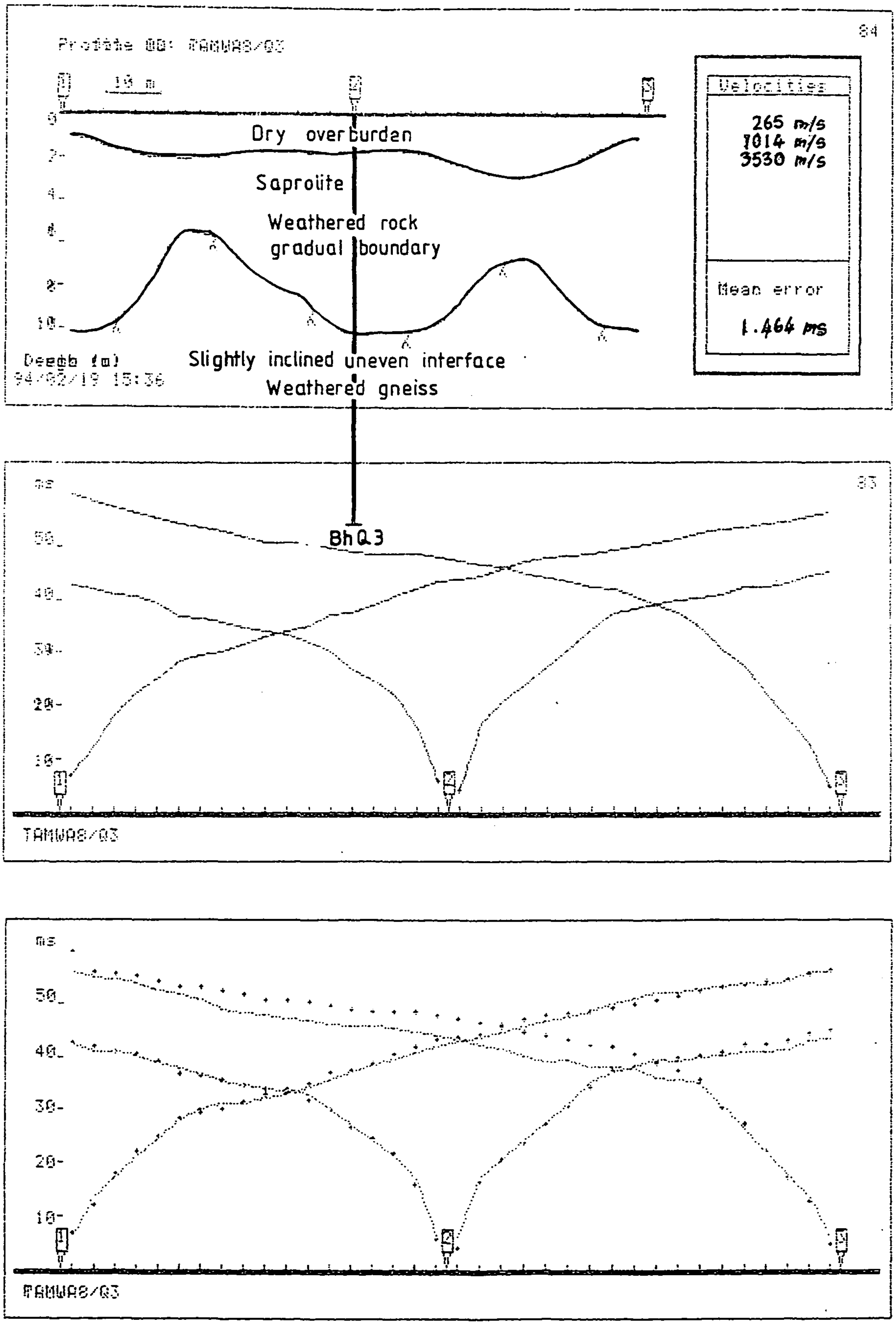
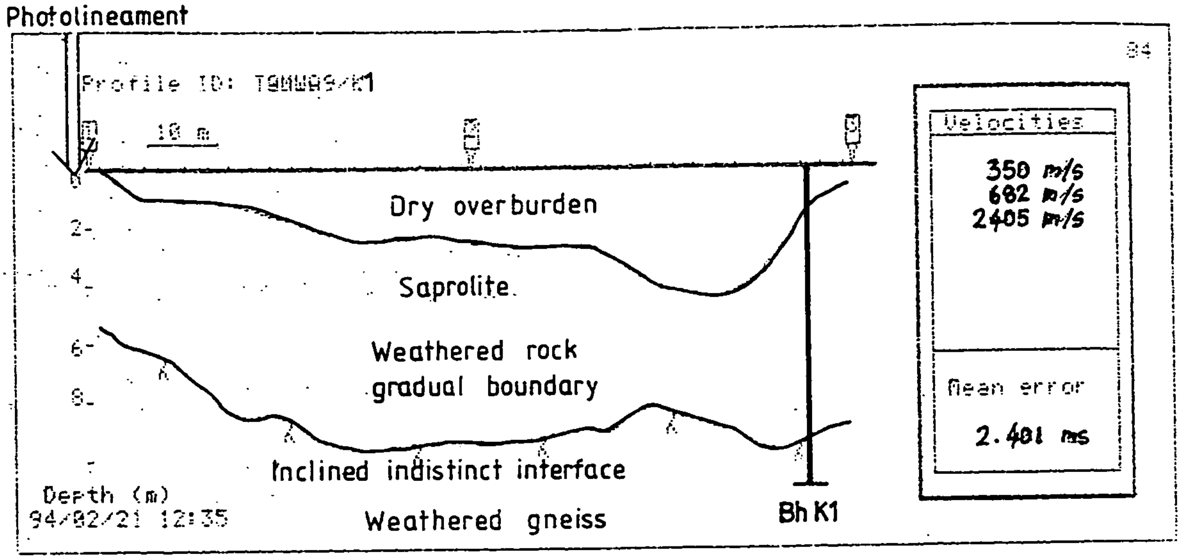
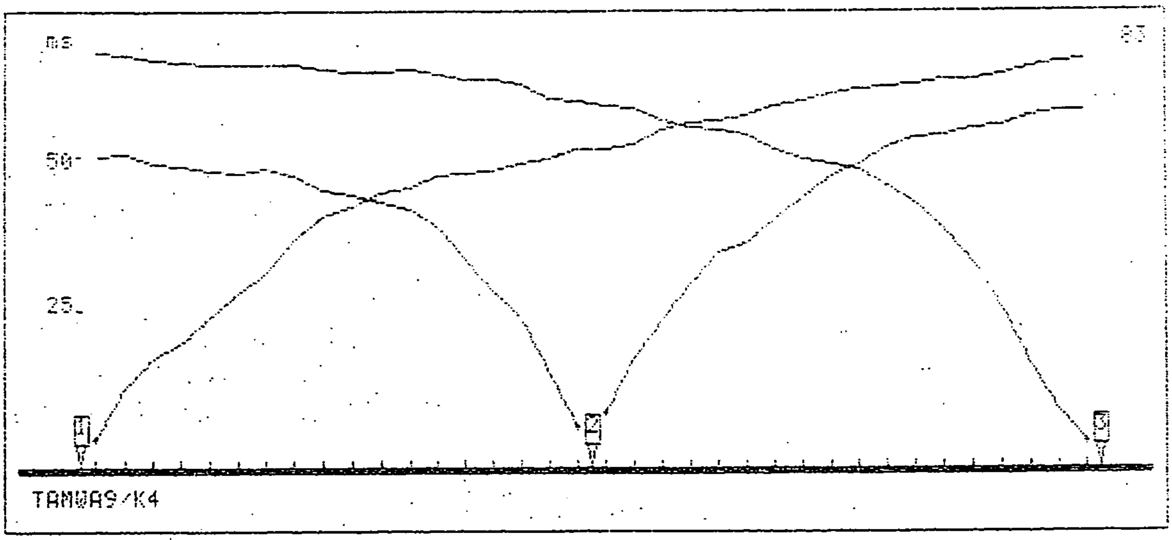



Fig 25 TAMWA 8 E-W



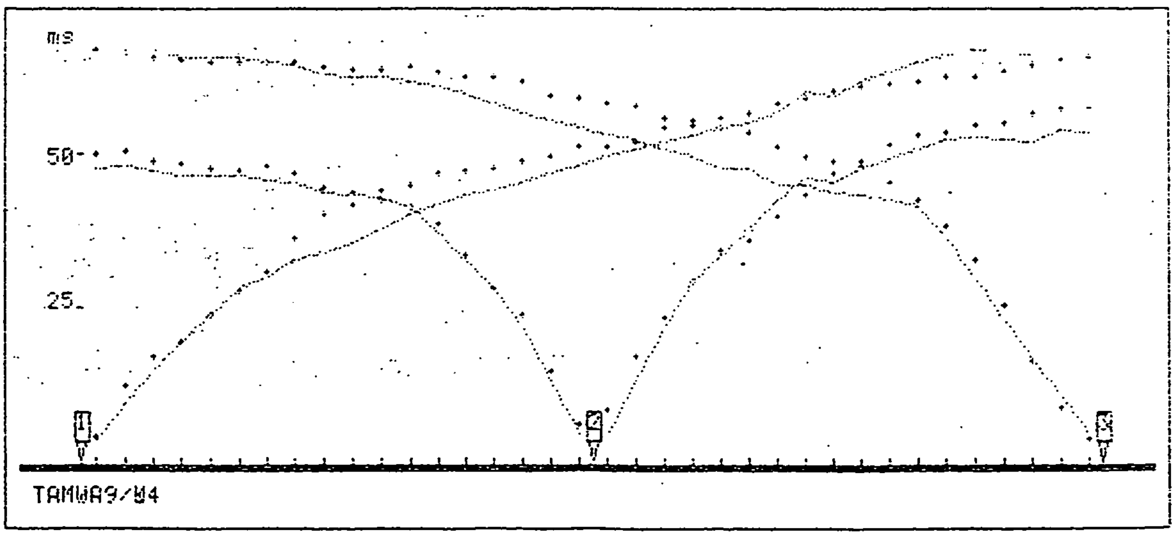




Fig 26 TAMWA 9 W-E

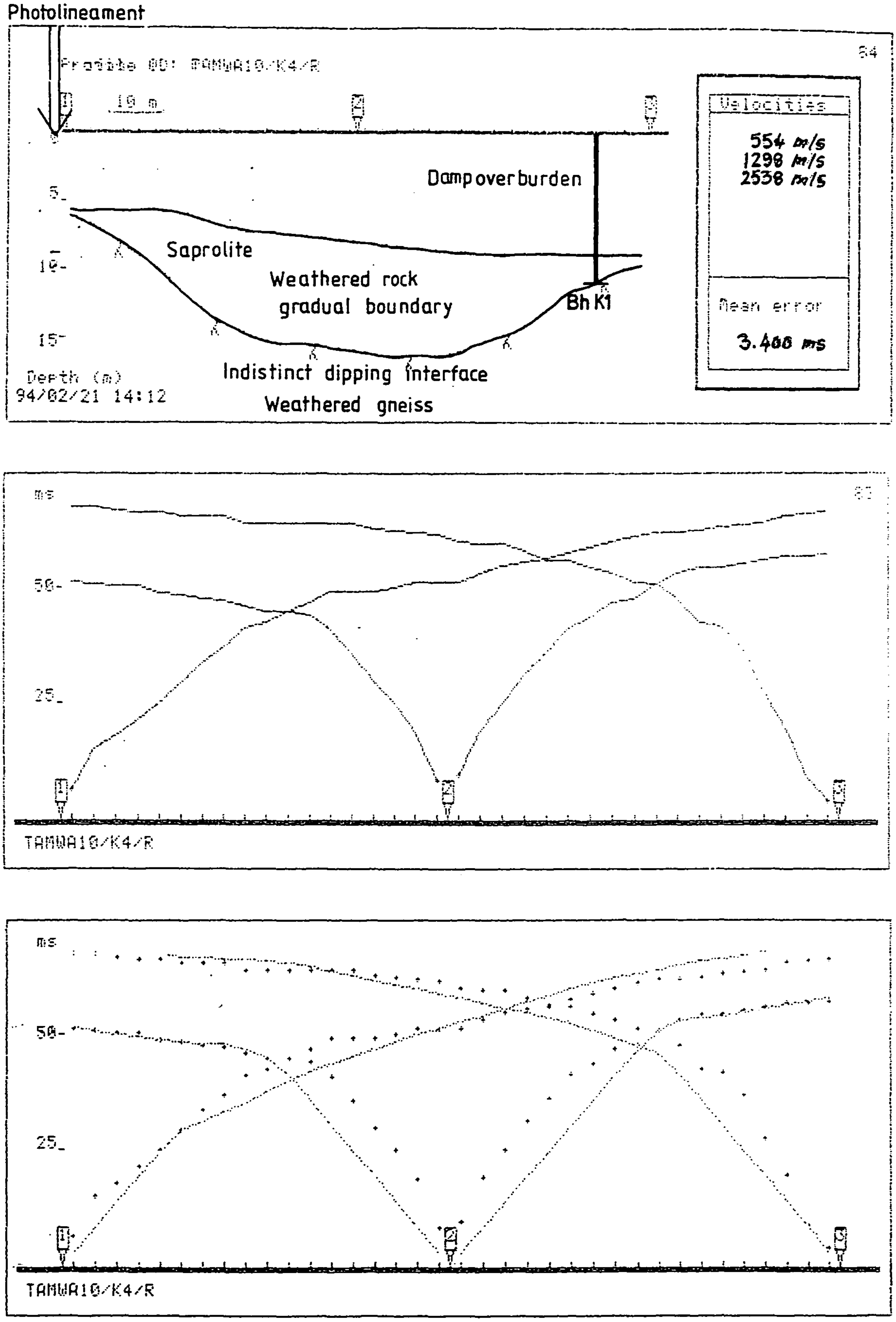



Fig 27 TAMWA 10 W-E

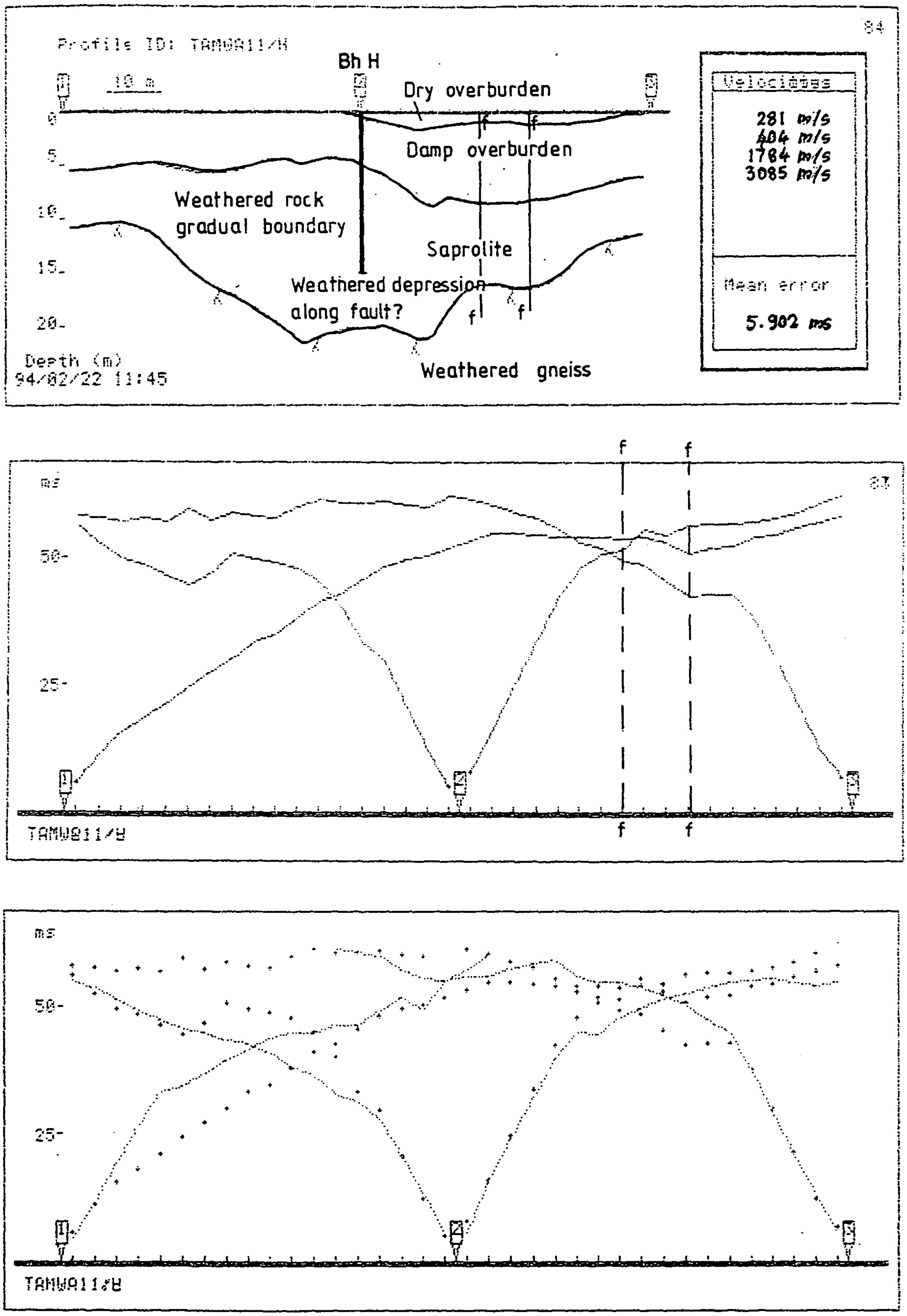



Fig 28 TAMWA 11 N-S

and aluminium strike plate energy source was used. Deep penetration to 20 m depth was recorded with four layers being detected. The layers have low seismic velocity contrasts, with thin dry overburden occurring above damp overburden. Beneath the latter saprolite overlies weathered gneiss. Hard basement was recorded at a depth of 9.75 m in the adjacent borehole H. There is some evidence of fracturing beneath the southern half of the profile.

**Profile TAMWA 12 (Fig 29)**

This profile was located normal to the valley axis midway between the valley side and the valley bottom at the same point as TAMWA 11 (Fig 10). A hammer and resin strike plate energy source was used. Deep penetration to 20 m depth was attained with four layers being recognised. These layers have low seismic velocity contrasts, with thin dry overburden overlying damp overburden. Beneath the latter saprolite overlies weathered gneiss. Hard basement was recorded at a depth of 9.75 m in the adjacent borehole H. Evidence of fracturing beneath the southern half of the profile was detected.

**Profile TAMWA 13 (Fig 30)**

This profile was located normal to the valley axis midway between the valley side and the valley bottom overlapping the southern 50% of TAMWA 11 and TAMWA 12 (Fig 10). A hammer and aluminium strike plate energy source was used. Deep penetration to 20 m depth was achieved with three layers being recognised. These layers have moderate seismic velocity contrasts, with thin dry overburden occurring above wet saprolite that in turn overlies fairly hard gneiss. The saprolite layer is thickest within possible fracture areas at the northern end of the profile. Hard basement was recorded at a depth of 9.75 m in the nearby borehole H.

**Profile TAMWA 14 (Fig 31)**

This profile was located along the north-western side of the valley (Fig 10). A hammer and aluminium strike plate energy source was used. Moderate penetration to 15 m depth was achieved with three layers being recognised. These layers have low seismic velocity contrasts, with thin dry overburden occurring above wet saprolite that in turn overlies fairly hard gneiss. Hard basement was recorded at a depth of 8.25 m in the adjacent borehole N2.

**Profile TAMWA 15 (Fig 32)**

This profile was located along the north-western side of the valley (Fig 10). A hammer and aluminium strike plate energy source was used. Moderate penetration to 8 m depth was achieved with three layers being recognised. These layers have high seismic velocity contrasts, with thin dry overburden occurring above wet saprolite that in turn overlies hard gneiss. Hard basement was recorded at a depth of 7 m in the adjacent recharge trench boreholes.

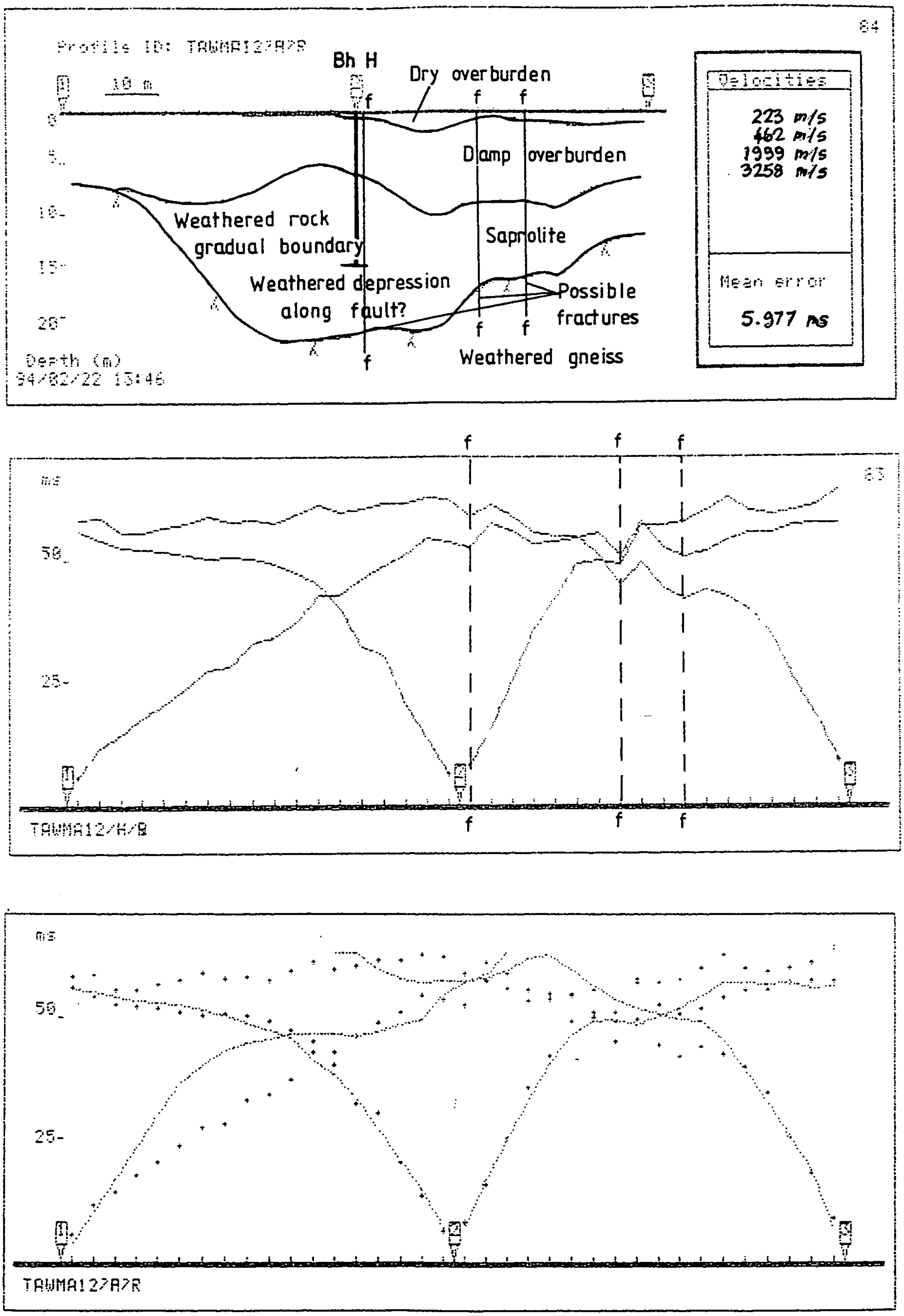
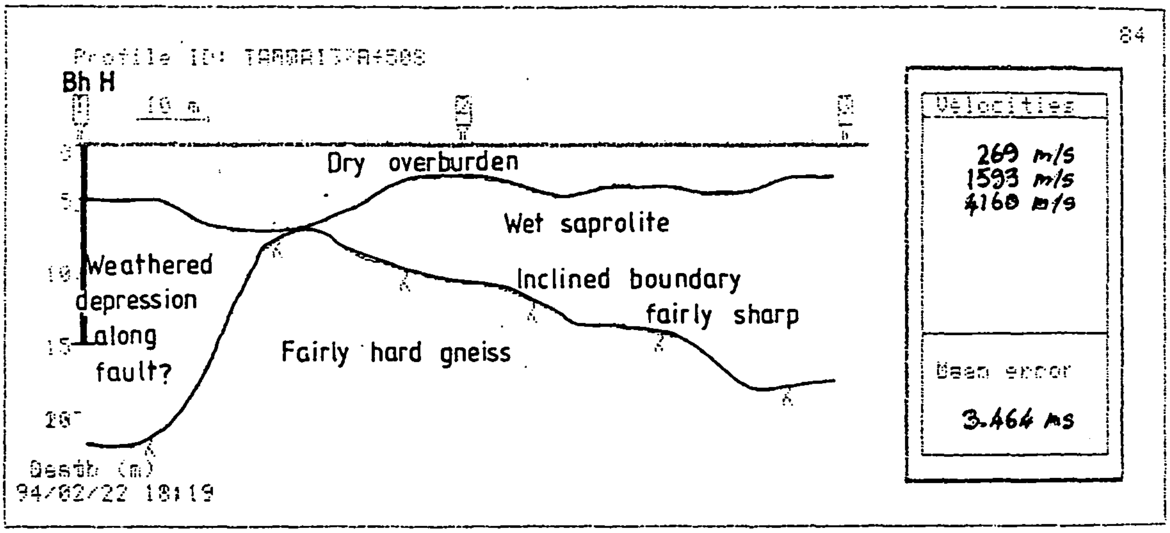
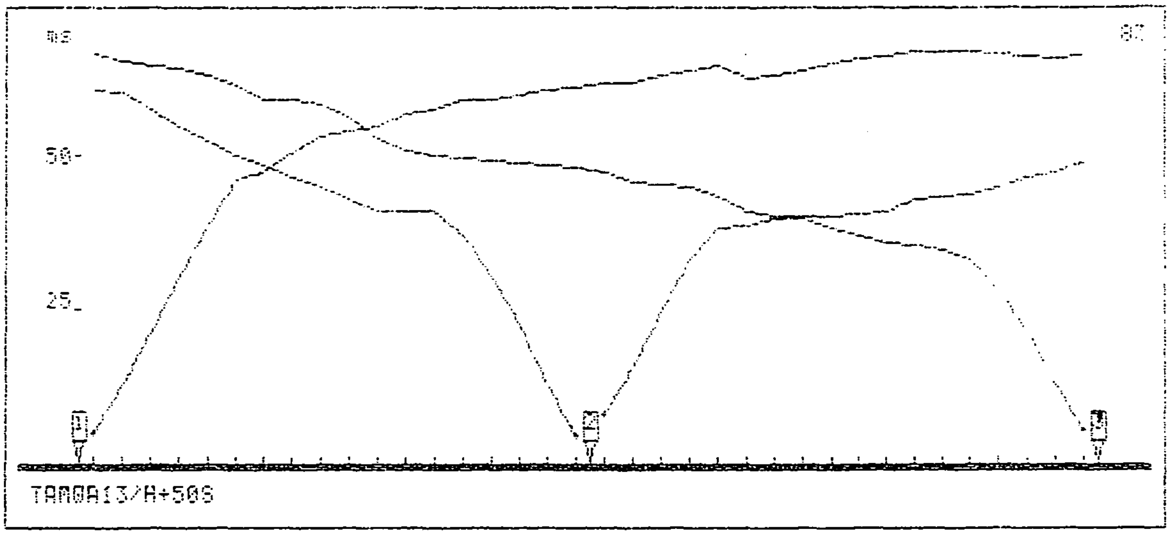



Fig 29 TAMWA 12 N-S



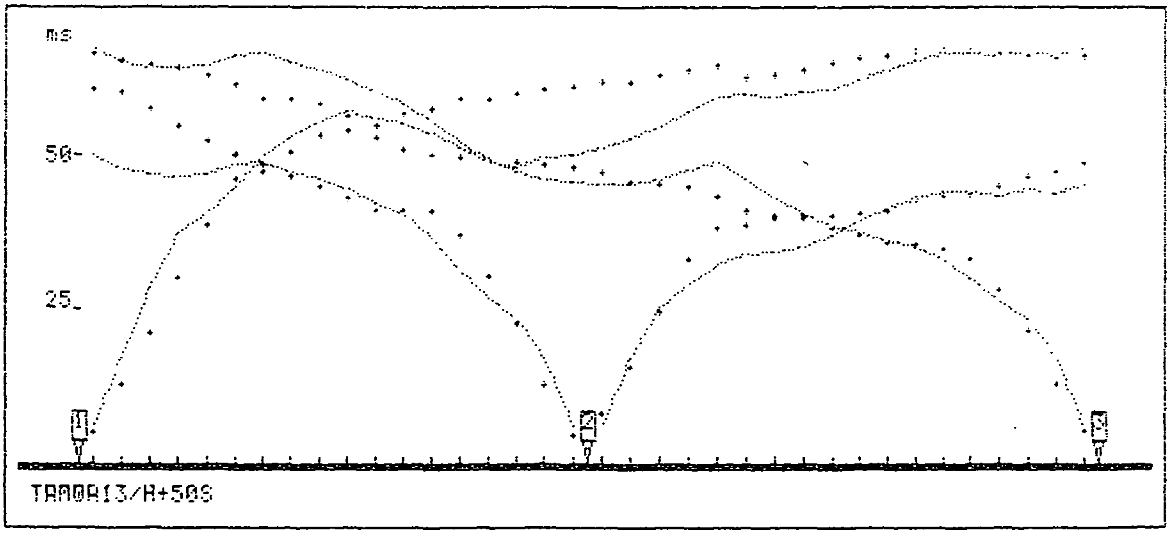




Fig 30 TAMWA 13 N-S

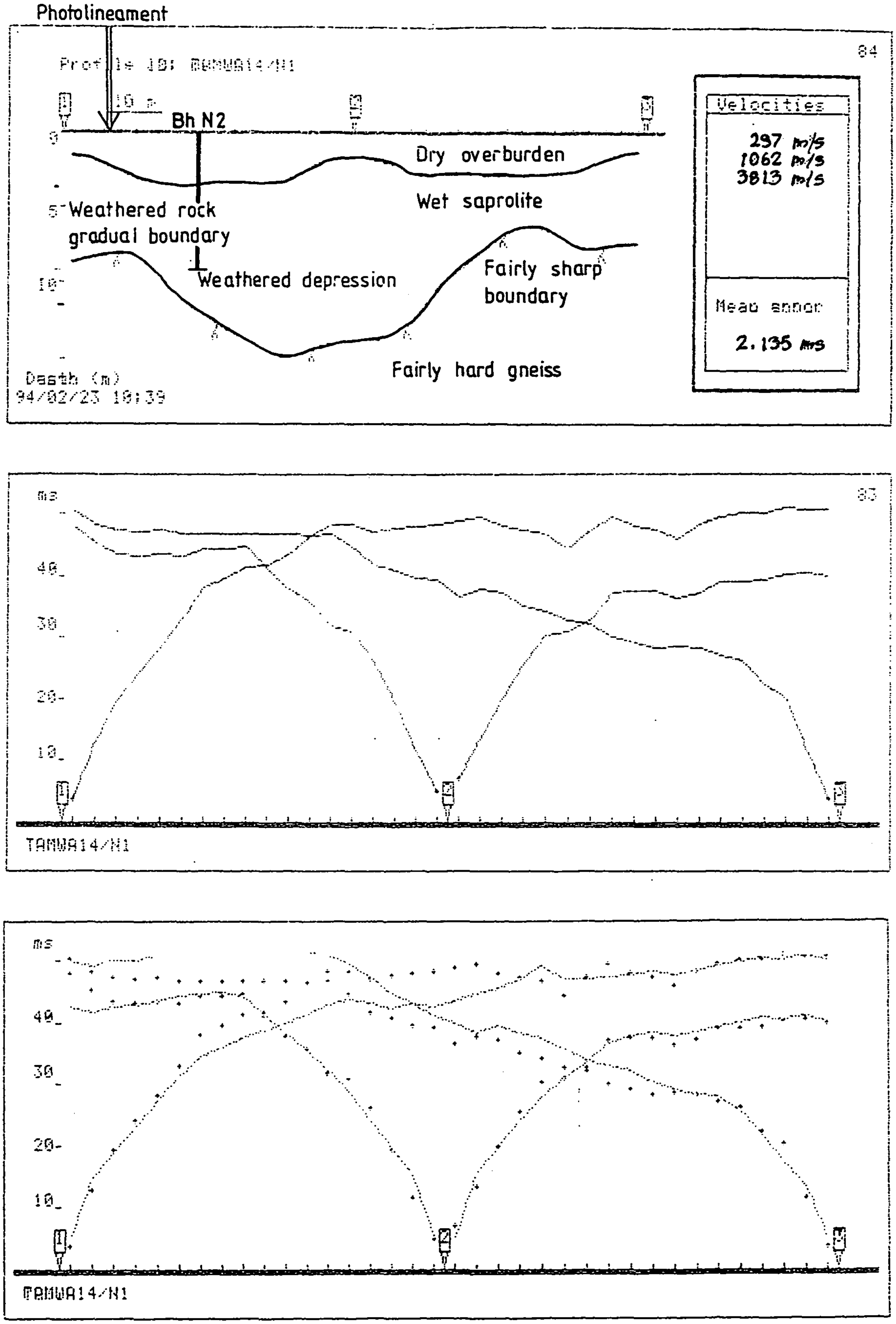



Fig 31 TAMWA 14 E-W

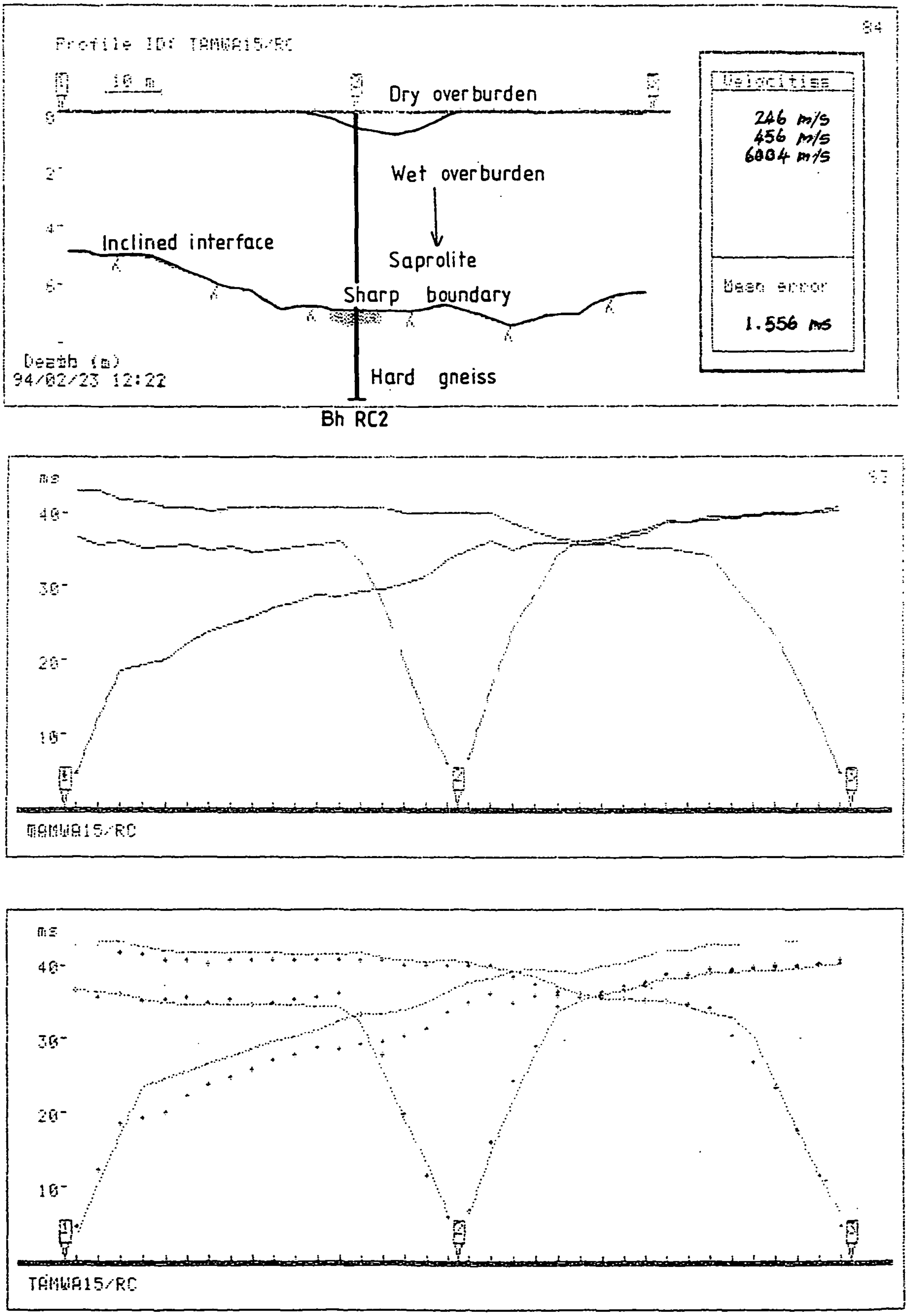



Fig 32 TAMWA 15 E-W

**Profile TAMWA 16 (Fig 33)**

This profile was located midway along the northern side of the valley (Fig 10). A hammer and aluminium strike plate energy source was used. Shallow penetration to 3 m depth was achieved with two layers being recognised. These layers have high seismic velocity contrast, with dry sand/saprolite overlying fairly hard gneiss. Hard basement was recorded at a depth of 2 m in the adjacent borehole J1.

**Profile TAMWA 17 (Fig 34)**

This profile was located along the central axis of the valley (Fig 10). A hammer and steel strike plate energy source was used. Deep penetration to 25 m depth was recorded with four layers being detected. These layers have high seismic velocity contrasts, with thin dry overburden occurring above damp saprolite. The latter is underlain by thick soft, weathered gneiss that overlies above hard gneiss. Hard basement was not met in the adjacent hand dug well number 23.

**Profile TAMWA 18 (Fig 35)**

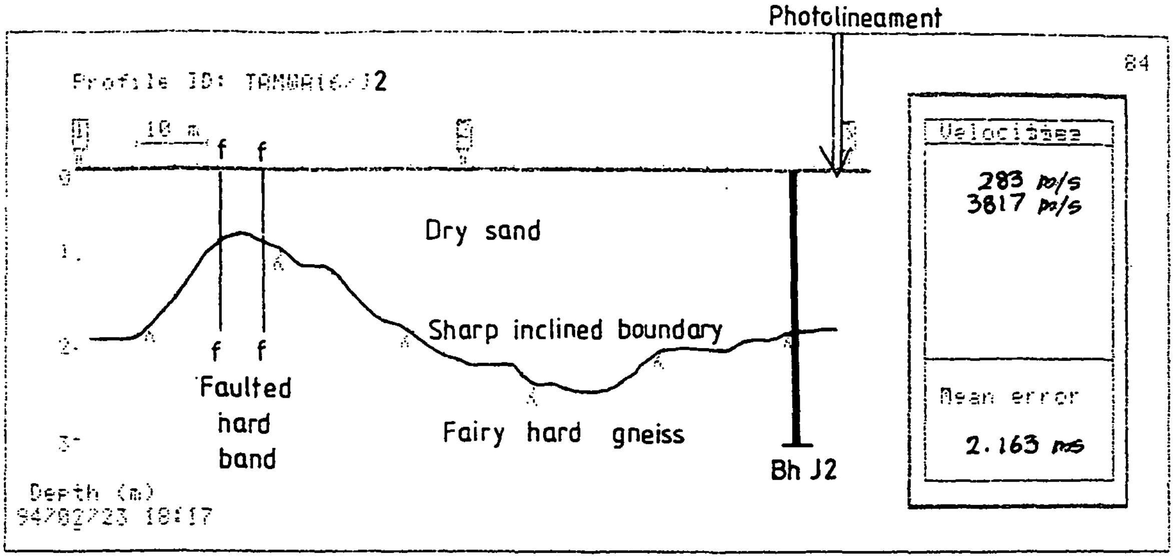
This profile was located along the central axis of the valley (Fig 10). A hammer and steel strike plate energy source was used. Shallow penetration to 4 m depth was recorded with two layers being detected. These layers have good seismic velocity contrasts, with dry overburden/saprolite overlying soft weathered gneiss. Hard basement appears to lie at a depth greater than 6.75 m, that being the depth of the adjacent hand dug well number 20.

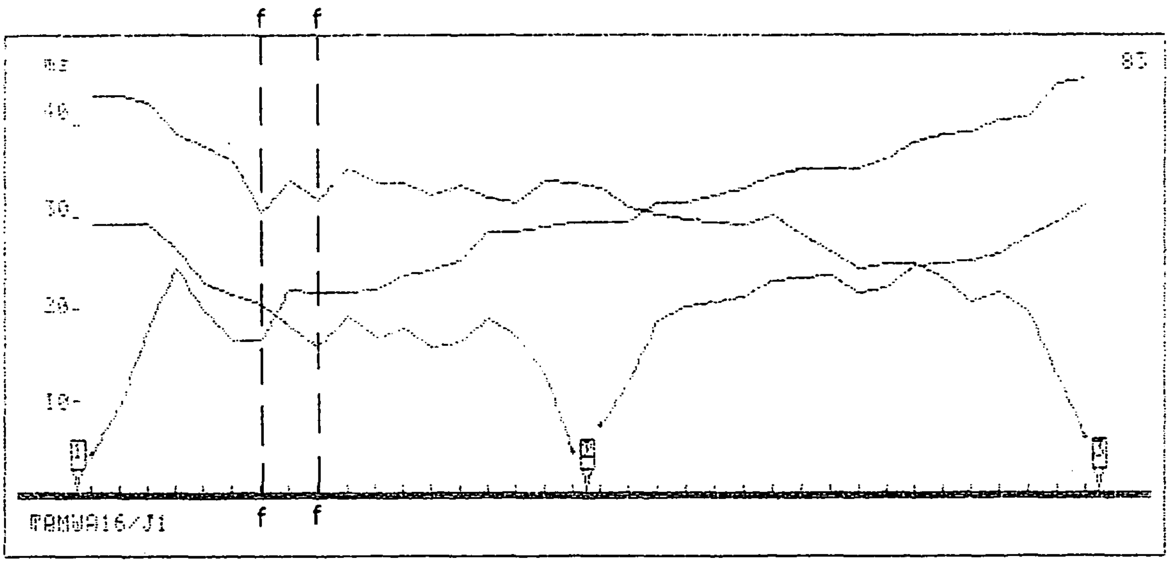
**Profile TAMWA 19 (Fig 36)**

This profile was located along the central axis of the eastern valley (Fig 10). A hammer and steel strike plate energy source was used. Moderate penetration to 8 m depth was attained with three layers being recognised. These layers have good seismic velocity contrasts, with dry overburden occurring above damp saprolite of variable thickness, the latter overlying fairly hard gneiss. Hard basement appears to lie at a depth greater than 6.3 m, that being the depth of the adjacent hand dug well number 21.

**Profile TAMWA 20 (Fig 37)**

This profile was located along the central axis of the valley (Fig 10). A hammer and steel strike plate energy source was used. Moderate penetration to 10 m was recorded with three layers being determined. These layers have good seismic velocity contrasts, with dry overburden occurring above wet saprolite that pinches out to the east, the latter overlying fairly hard gneiss. Hard basement was recorded at a depth of 9.75 m in the nearby borehole K3. The western half of the profile is underlain by fairly thick weathered saprolite that occurs to the west of a major photo-lineation feature.



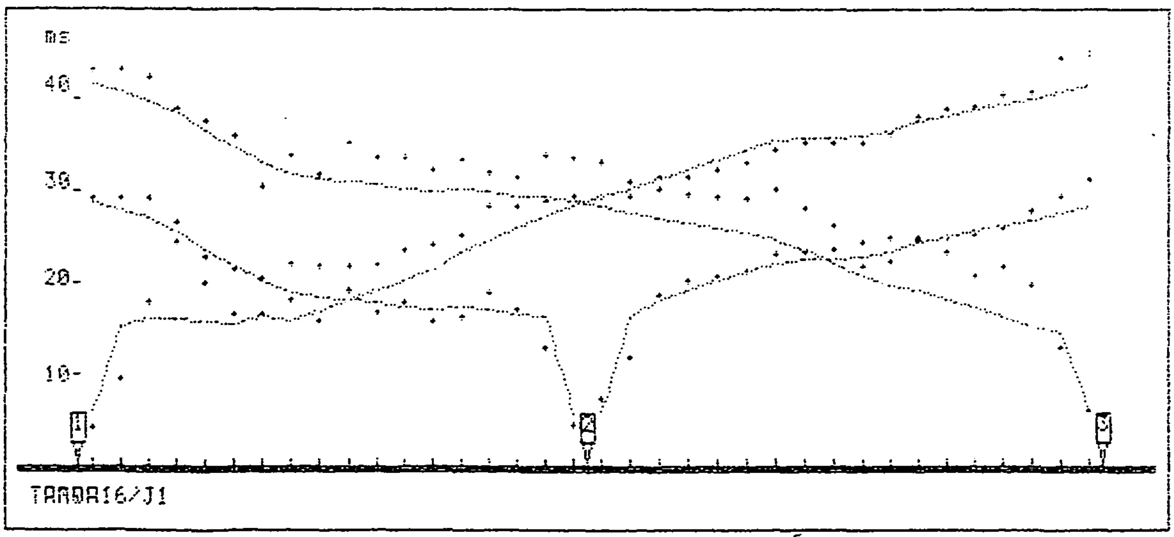




Fig 33 TAMWA 16 W-E

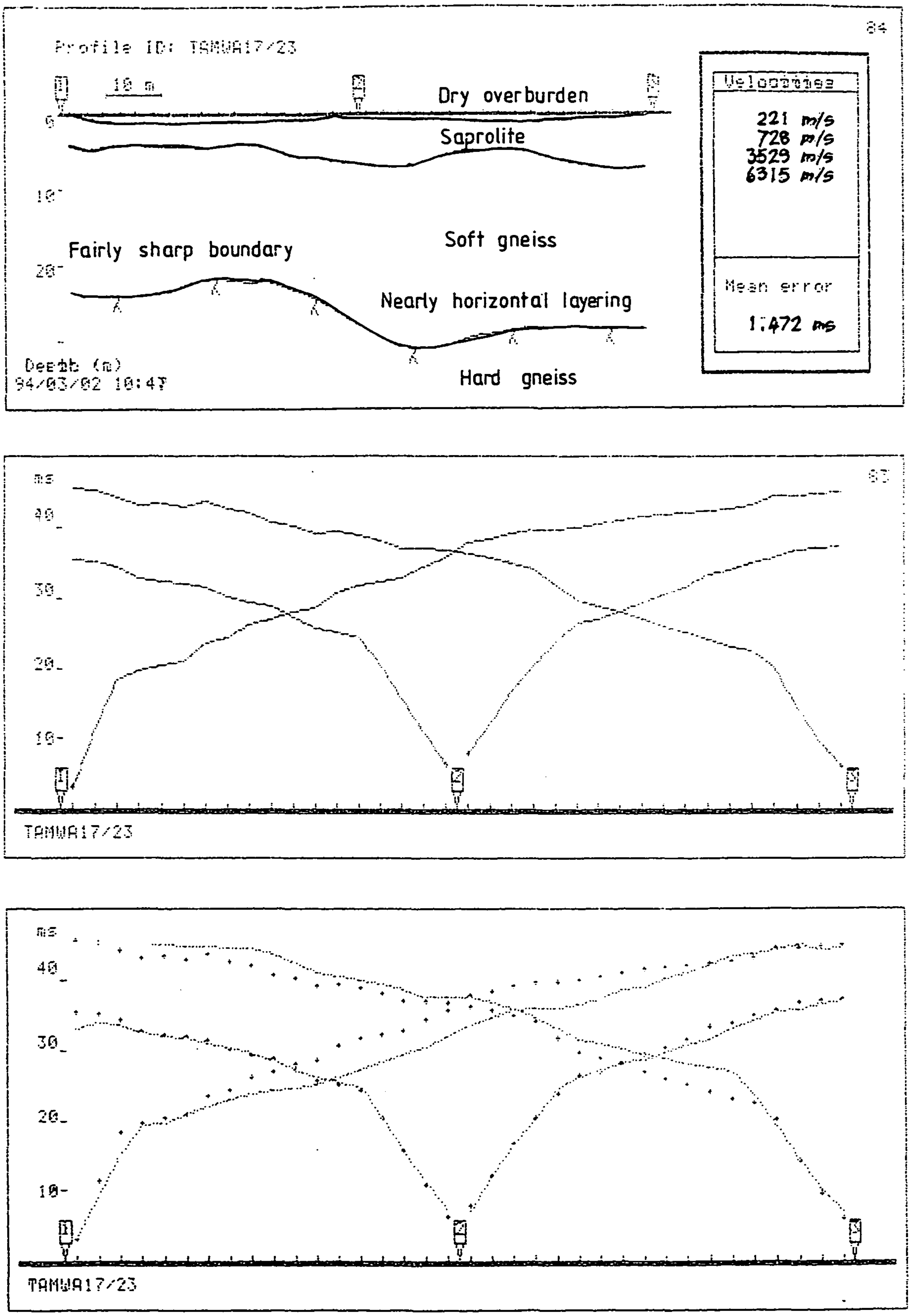



Fig 34 TAMWA 17 E-W

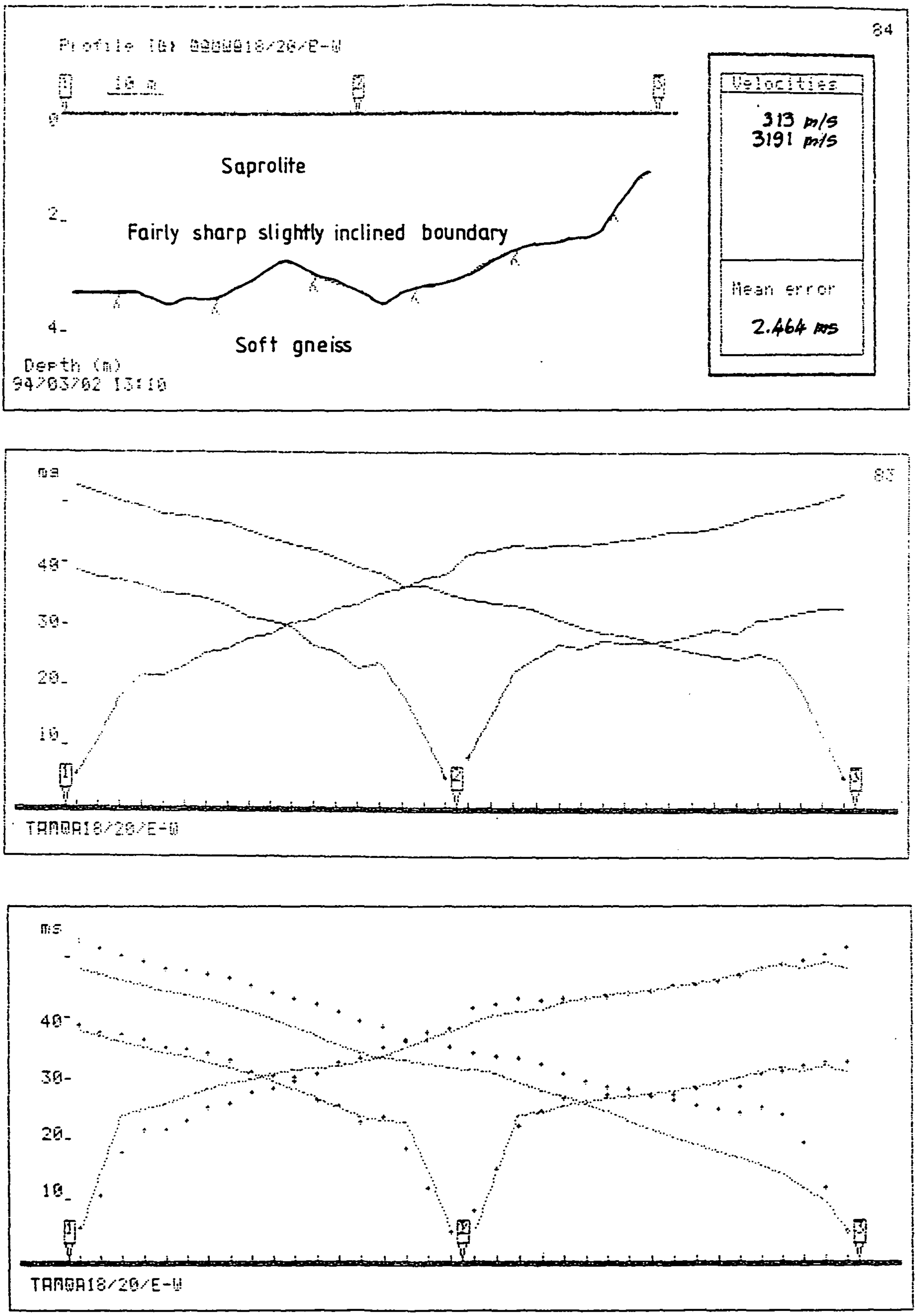



Fig 35 TAMWA 18 E-W

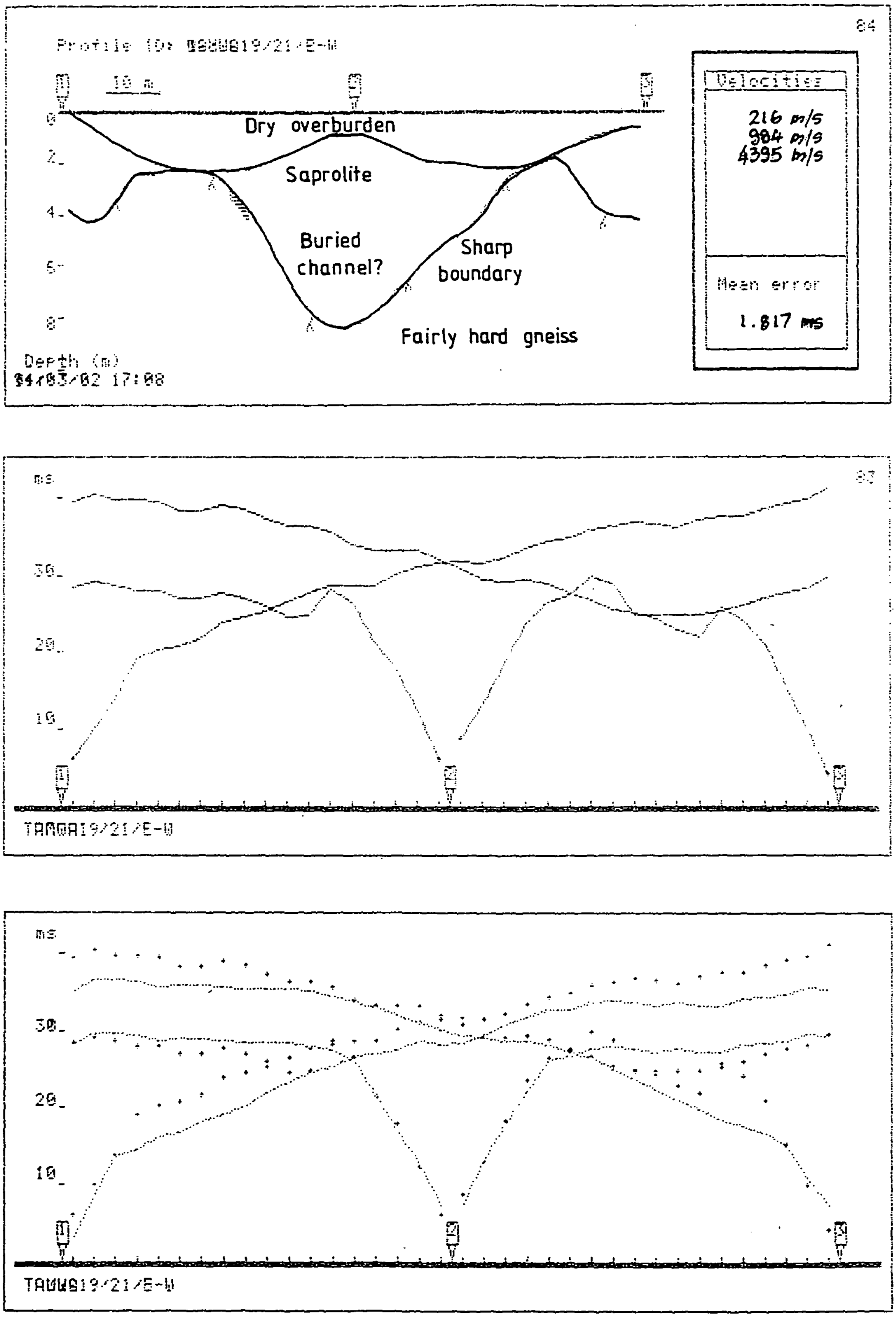
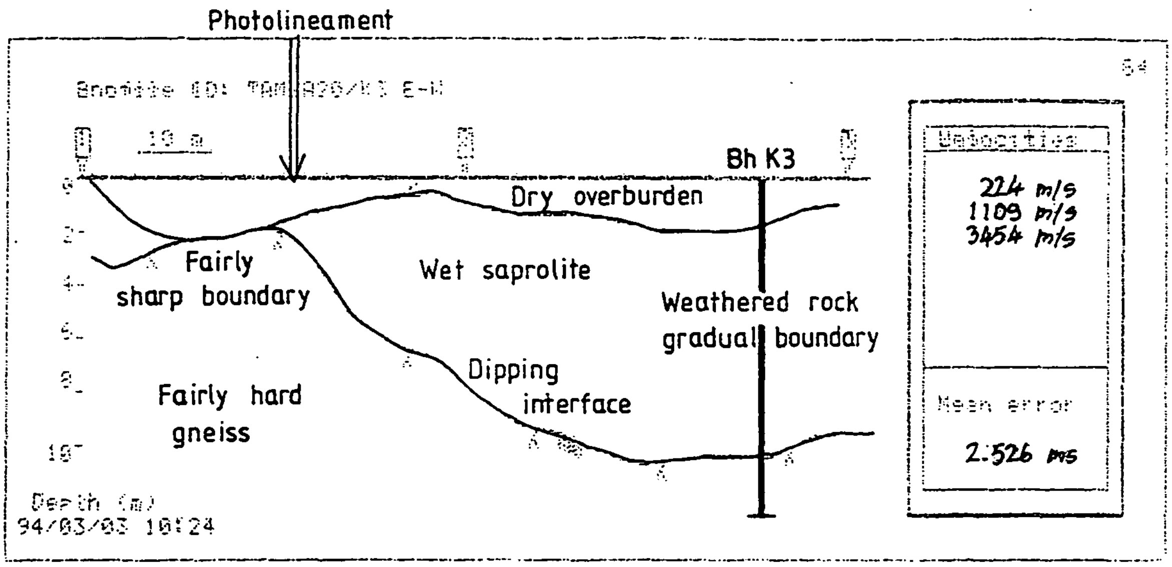
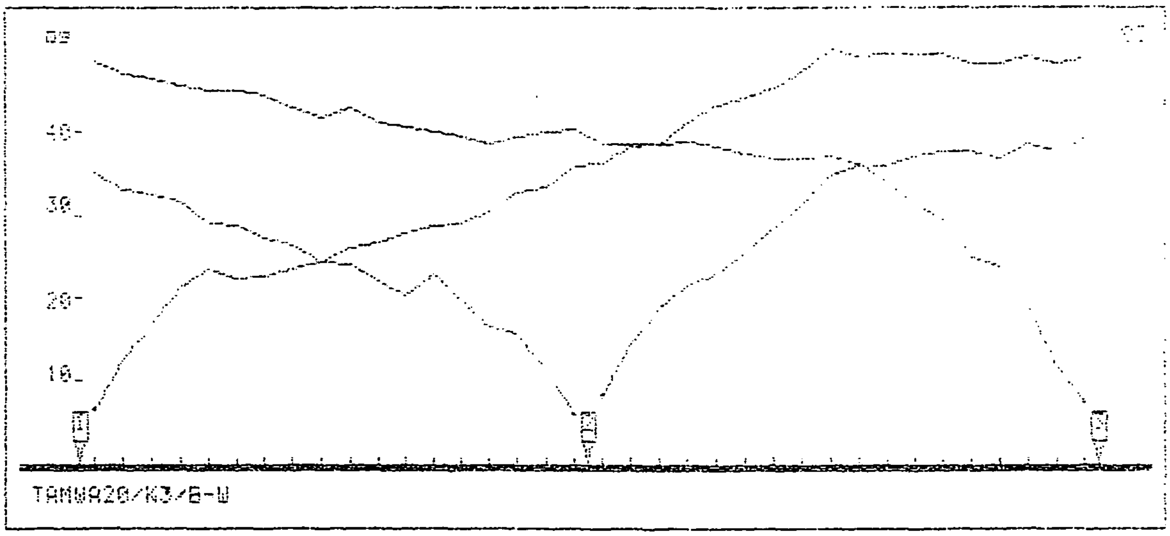



Fig 36 TAMWA 19 E-W



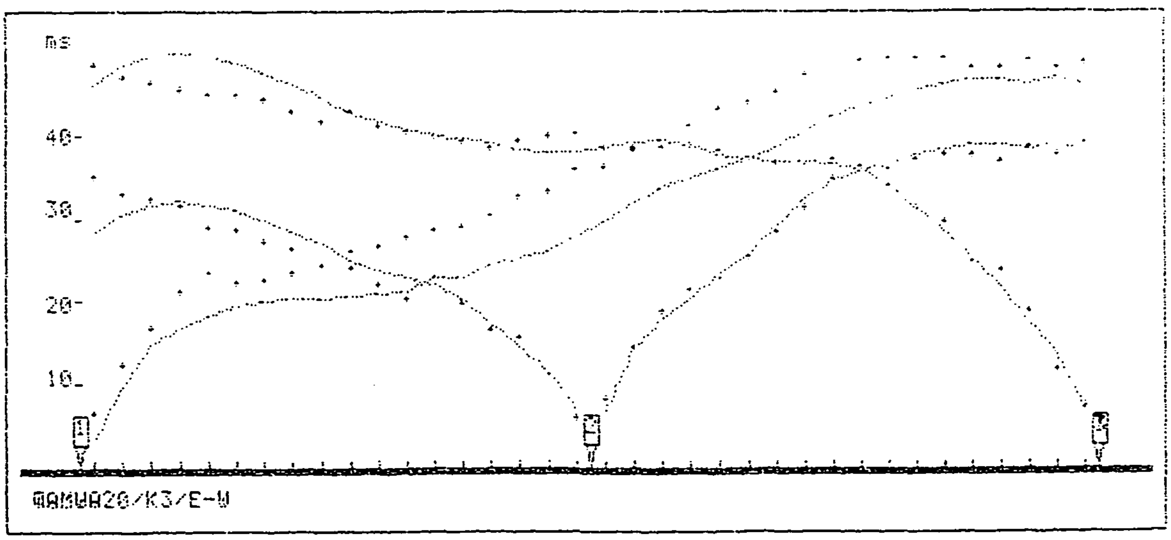




Fig 37 TAMWA 20 E-W

**Profile TAMWA 21 (Fig 38)**

This profile was located midway between the central valley axis and the southern side of the valley (Fig 10). A hammer and steel strike plate energy source was used. Deep penetration to 20 m depth was recorded with three layers being determined. These layers have good seismic velocity contrasts, with dry overburden occurring above wet saprolite that pinches out to the south, the latter overlying fairly hard gneiss. Hard basement was encountered at a depth of 18.75 m in the adjacent borehole L1. The northern half of the profile is underlain by a fairly thick weathered saprolite to the north of an apparent fracture zone.

**Profile TAMWA 22 (Fig 39)**

This profile was located along the central axis of the valley adjacent to the main stream (Fig 10). A hammer and steel strike plate energy source was used. Moderate depth of penetration to 12 m was recorded with three layers being determined. These layers have good seismic velocity contrasts, with very thin dry overburden occurring above saprolite that thickens markedly to the west, the latter overlying fairly hard gneiss. Hard basement was encountered at a depth of 12 m in the adjacent borehole U7. The western half of the profile is underlain by thicker saprolite developed within a faulted zone located to the west of a major photo-lineation feature.

**Profile CHIREDZI 23 (Fig 40)**

This site was located north of the collector well system at the Chiredzi Agricultural Research Station. A large 43.5 kg weight and steel strike plate energy source was used. Fairly moderate penetration to 8 m depth was recorded with three layers being detected. These layers have moderate seismic velocity contrasts, with dry overburden occurring above damp saprolite of variable thickness, the latter overlying weathered gneiss.

**Profile CHIREDZI 24 (Fig 41)**

This site was located north of the collector well system at the Chiredzi Agricultural Research Station at the CHIREDZI 1 site. A hammer and steel strike plate energy source was used. Moderate penetration to 15 m depth was attained with three layers being recognised. These layers have moderate seismic velocity contrasts, with dry overburden occurring above damp saprolite that thickens to the west, the latter overlying weathered gneiss.

## 7. INTERPRETATION OF RESULTS

### 7.1 Accuracy of Seismic Data

Comparisons of results obtained using hammer and steel and resin plates, at sites TAMWA 9 and 10 as well as TAMWA 11 and 12, and the use of hammer and large weight with a steel plate as energy sources, were made. The results are shown as a series of seismic traces recorded at each of three geophones per profile in

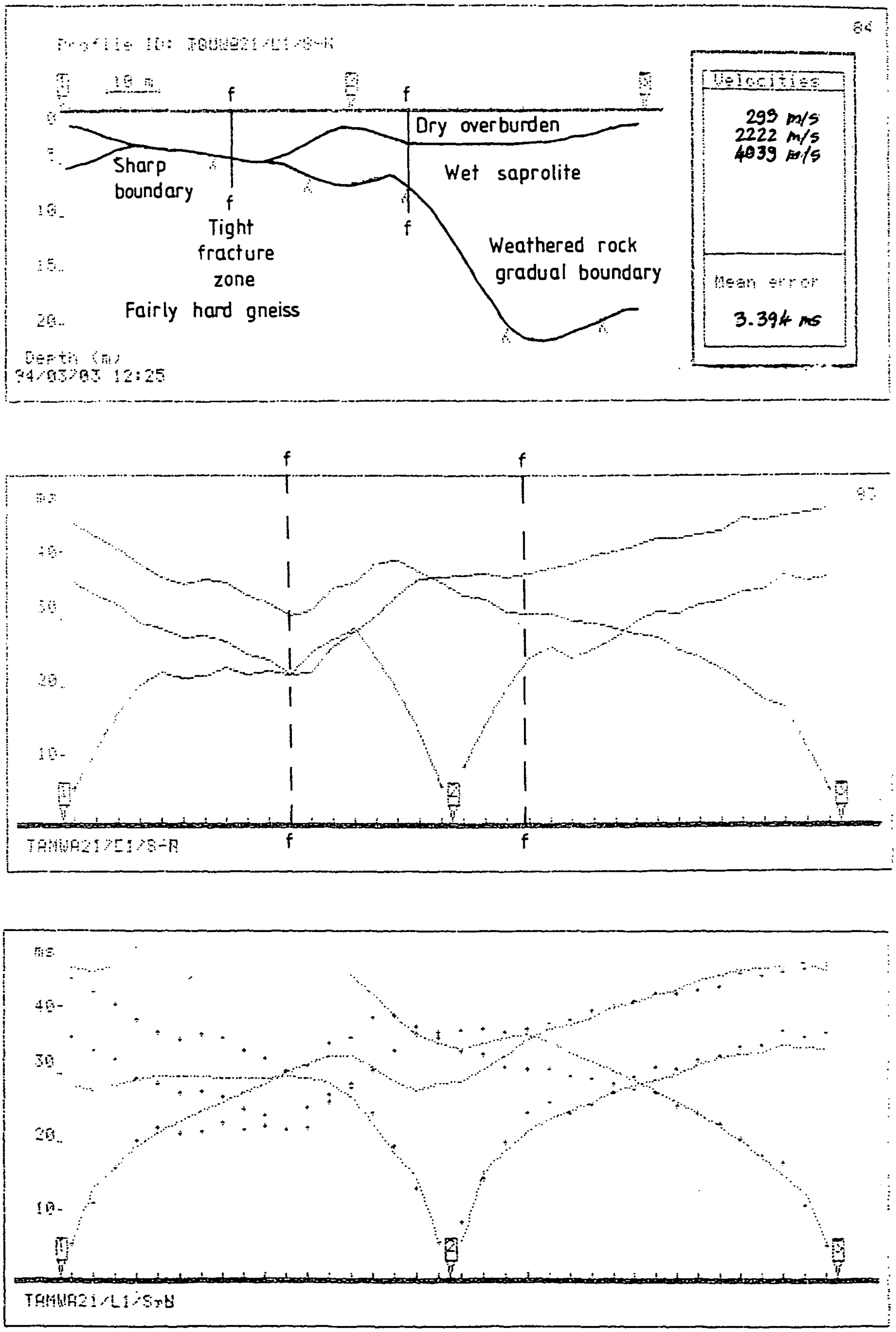



Fig 38 TAMWA 21 S-N

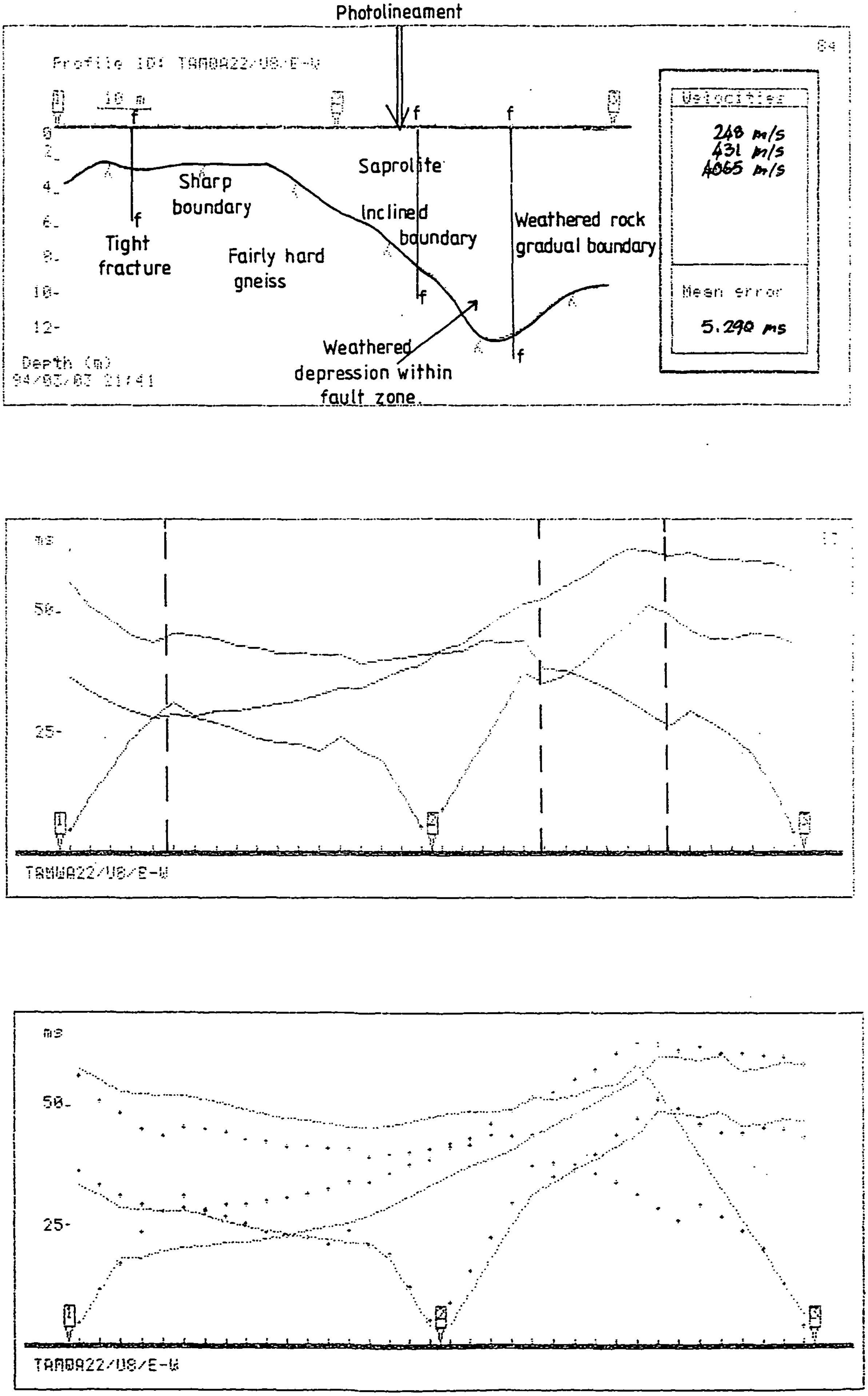



Fig 39 TAMWA 22 E-W

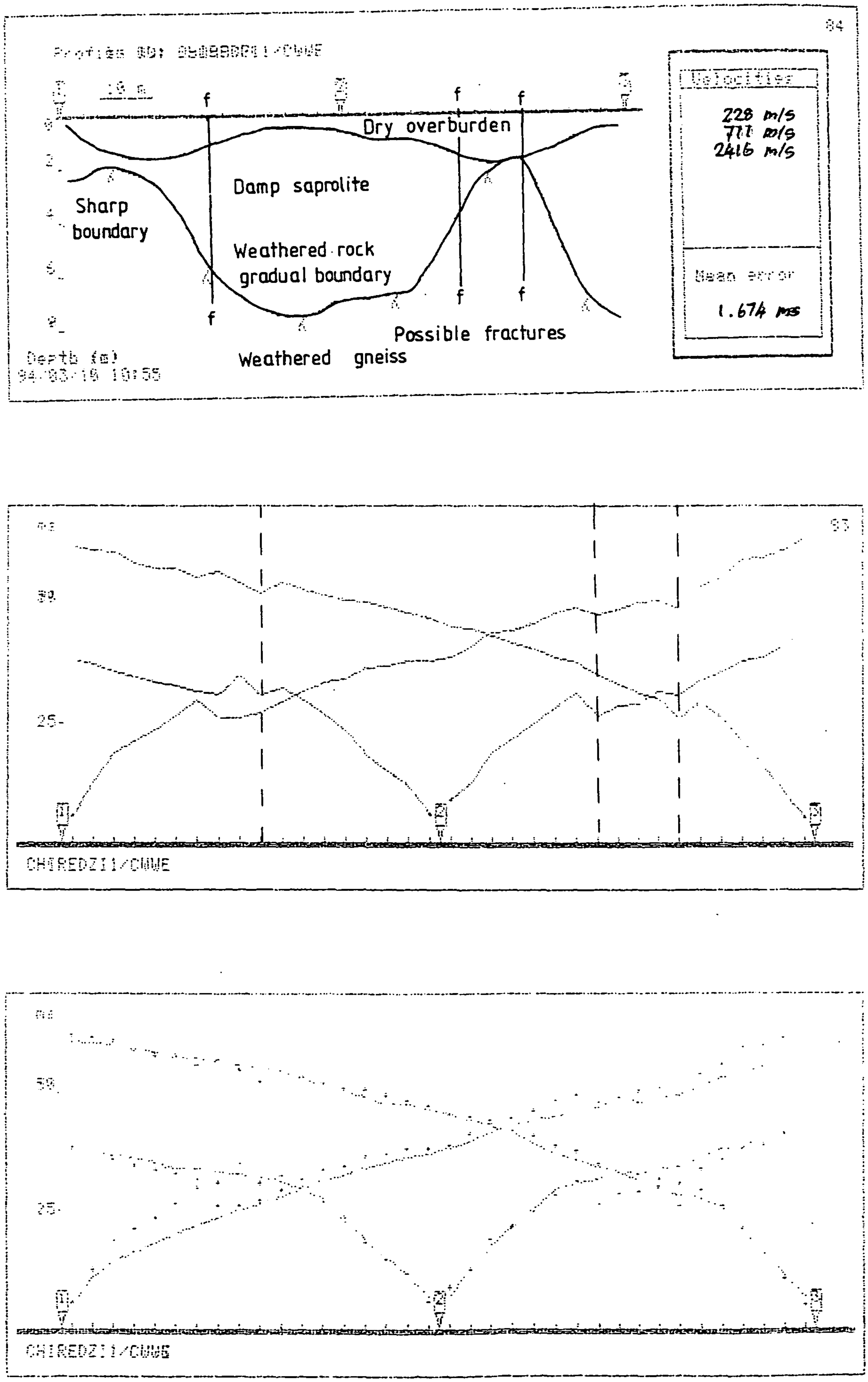
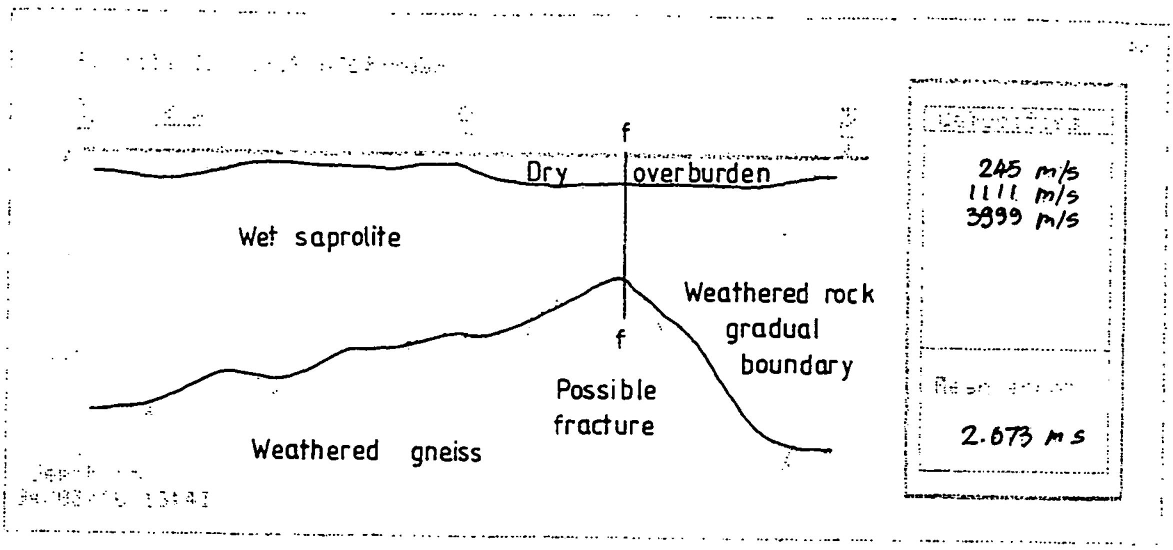
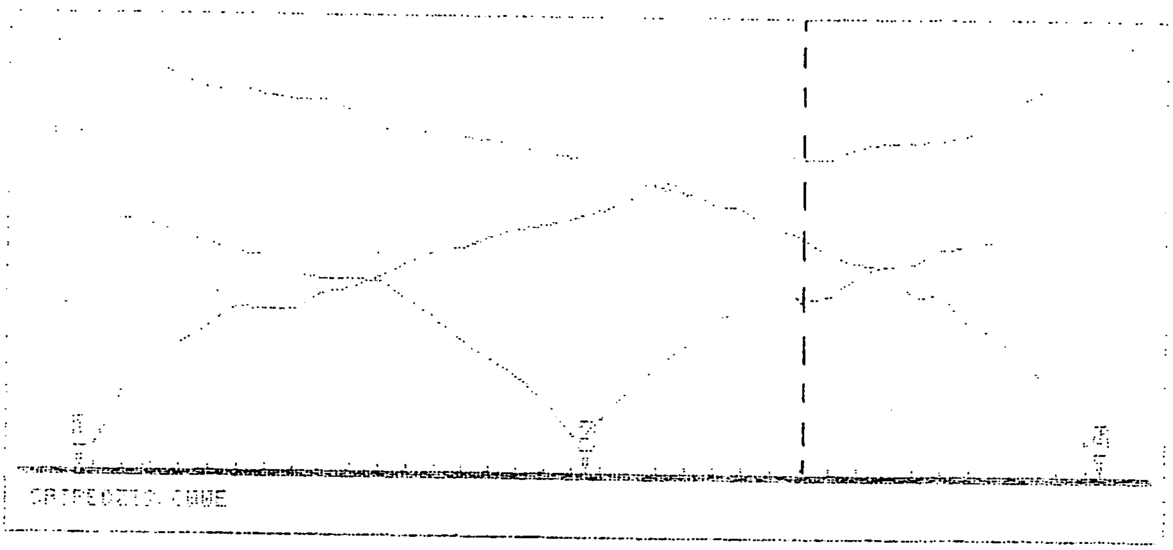



**Fig 40 CHIREDZI 1 W-E**



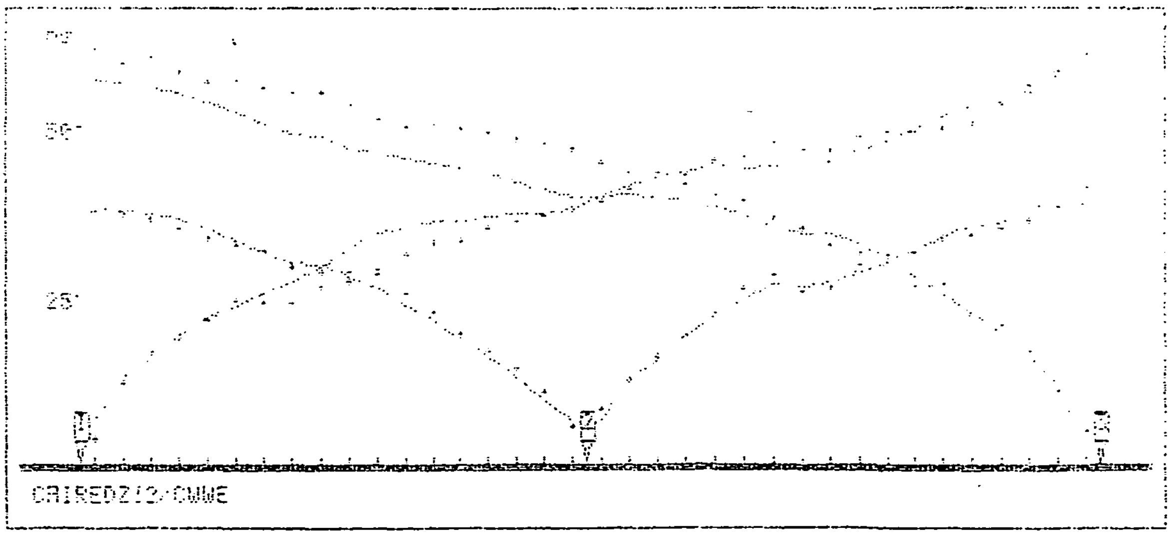




Fig 41 CHIREDZI 2 W-E

Appendix 5. There was no noticeable difference in depth of penetration between the different methods used. The depths of penetration of 10-20 m attained are primarily dependant upon geological conditions present, as shown at site TAMWA 17 where interpreted penetration to 30 m depth was exceptionally achieved. The hammer/steel plate energy source produced the clearest, most readily identifiable sets of first arrival 'picks' that were equalled by use of the 43.5 kg weight/steel plate energy source. However the latter system proved to be too cumbersome for regular survey work out-weighing any small increase in accuracy attained. Sources of interference need to be avoided, an example being recorded at the third geophone at Chiredzi 2 when interference caused by the running of a pump in an adjacent collector well can be recognised mid-way through the profile (Fig 42).

### 7.2 Geological Conditions

Fifteen seismic refraction profiles were undertaken at sites located adjacent to project boreholes. Geological and drilling data obtained from these boreholes have been correlated with the seismic profiling results as presented in Figs 43 to 55 which detail geological and drilling logs, seismic profiling data and analyses, and a best interpretation. The driller used a drag bit to drill through the soil and clay/saprolite regolith, changing to a down the hole air hammer system when the formation became to hard for the drag bit. Drilling continued until it took about 10 minutes to drill 0.75 m, when drilling was halted. Obviously the speed of drill bit penetration will be dependent upon drill rig power capacity and torque rating. The soft formation penetrated by the drag bit can be readily excavated for construction of a hand dug well or collector well system. Excavation will penetrate into the upper part of the saprock where the highest permeability zone occurs, the main target for horizontal drilling within collector well systems. Geological and drilling data from relevant project boreholes are tabulated in Appendix 4 as well as on Figs 43-55. The geological log descriptions were produced by the driller and must be regarded as fairly ambiguous although providing good indication of geological conditions prevailing.

### 7.3 Interpretation of Geology from Seismic Data

Typical seismic velocities for weathered and unweathered granitic rocks produced by Carruthers et al (1993) (Table 1) agree with those produced during this survey. These are:-

1. The upper dry soil horizon 200-300 m/sec.

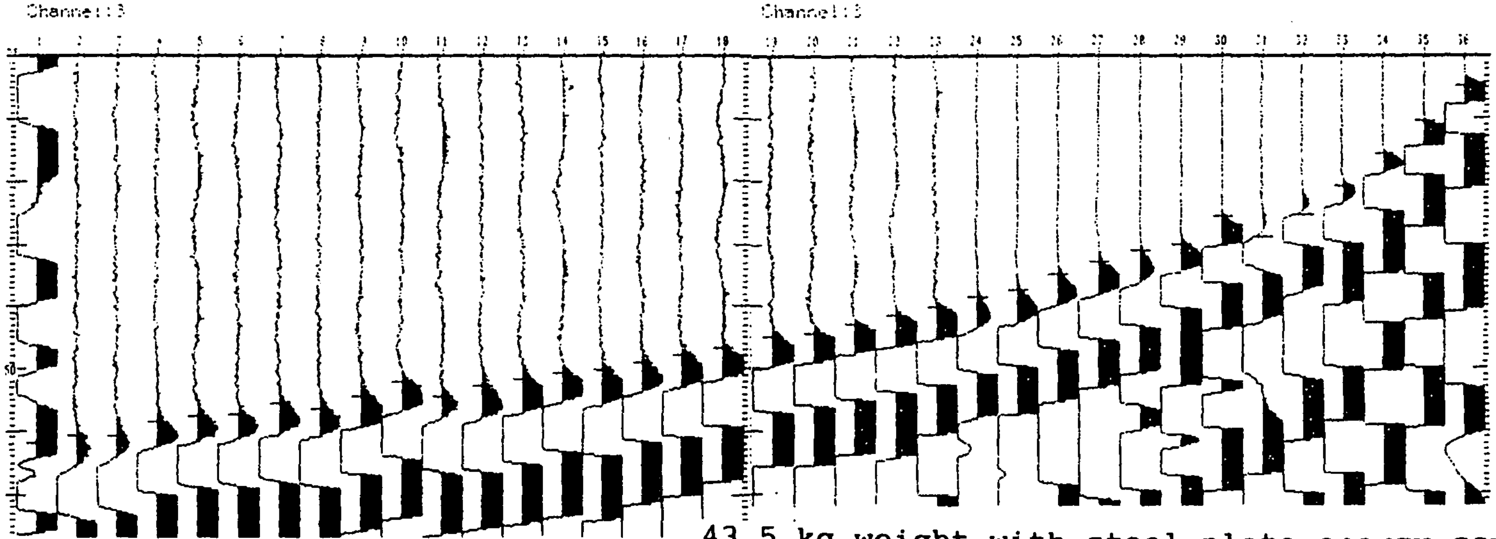
2. The clayey saprolite layer 500 - 1200 m/sec

3. The saprock layer 2400 - 5000 m/sec

4. The bedrock layer >6000 m/sec.

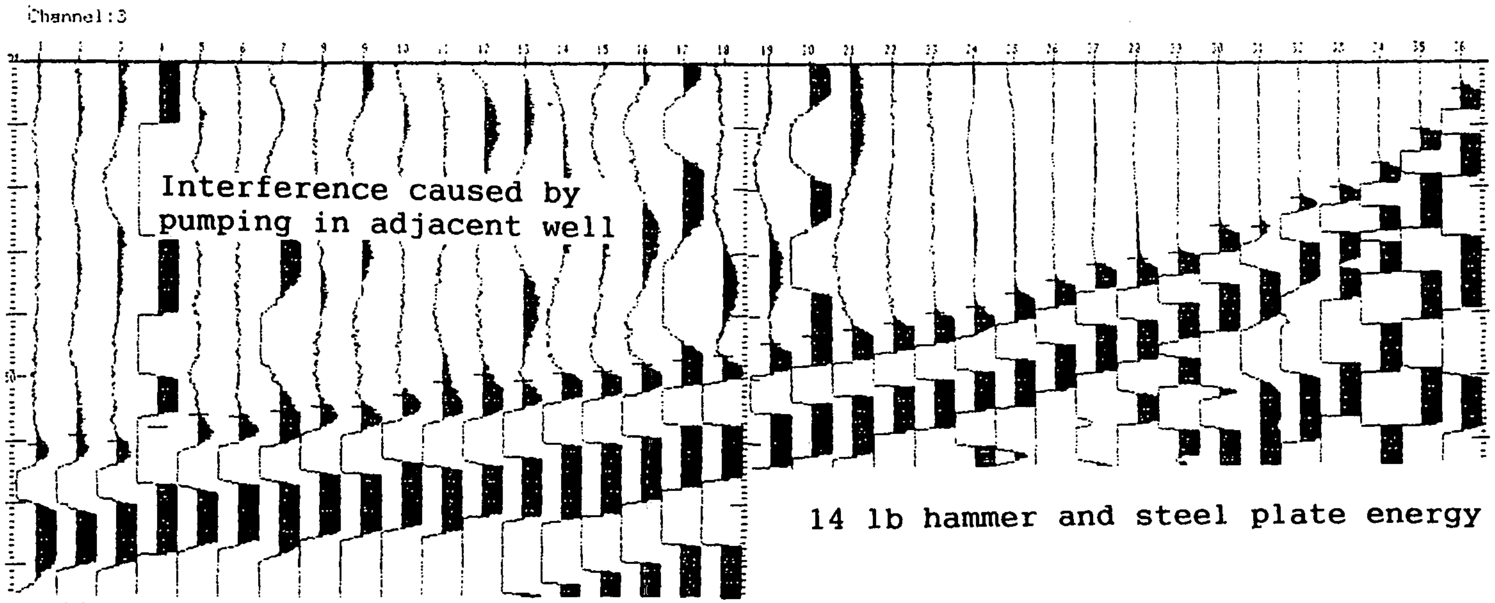
The upper dry soil horizon velocities of 200-300 m/sec are typically too low, reduction to these levels being apparently a function of the distance between the strike plate and the triggering device. The weathered upper saprock velocities are 2400-3400 m/sec

| | | | |
|---|---|---|---|
| Profile ID: | CHIREDZI1/CWWE | Method: | Automatic |
| Project: | BGS | Date: | 94/03/10 |
| Customer: | ODA | Created: | 08:29 |
| Cust. ref.: | ODA | Geoph. spacing: | 54.0 m |
| Operator: | JEFF L | Shot spacing: | 3.0 m |
| Comments: | CLEAR CALM HOT WEIGHT E | Start offset: | 1.5 m |




43.5 kg weight with steel plate energy source

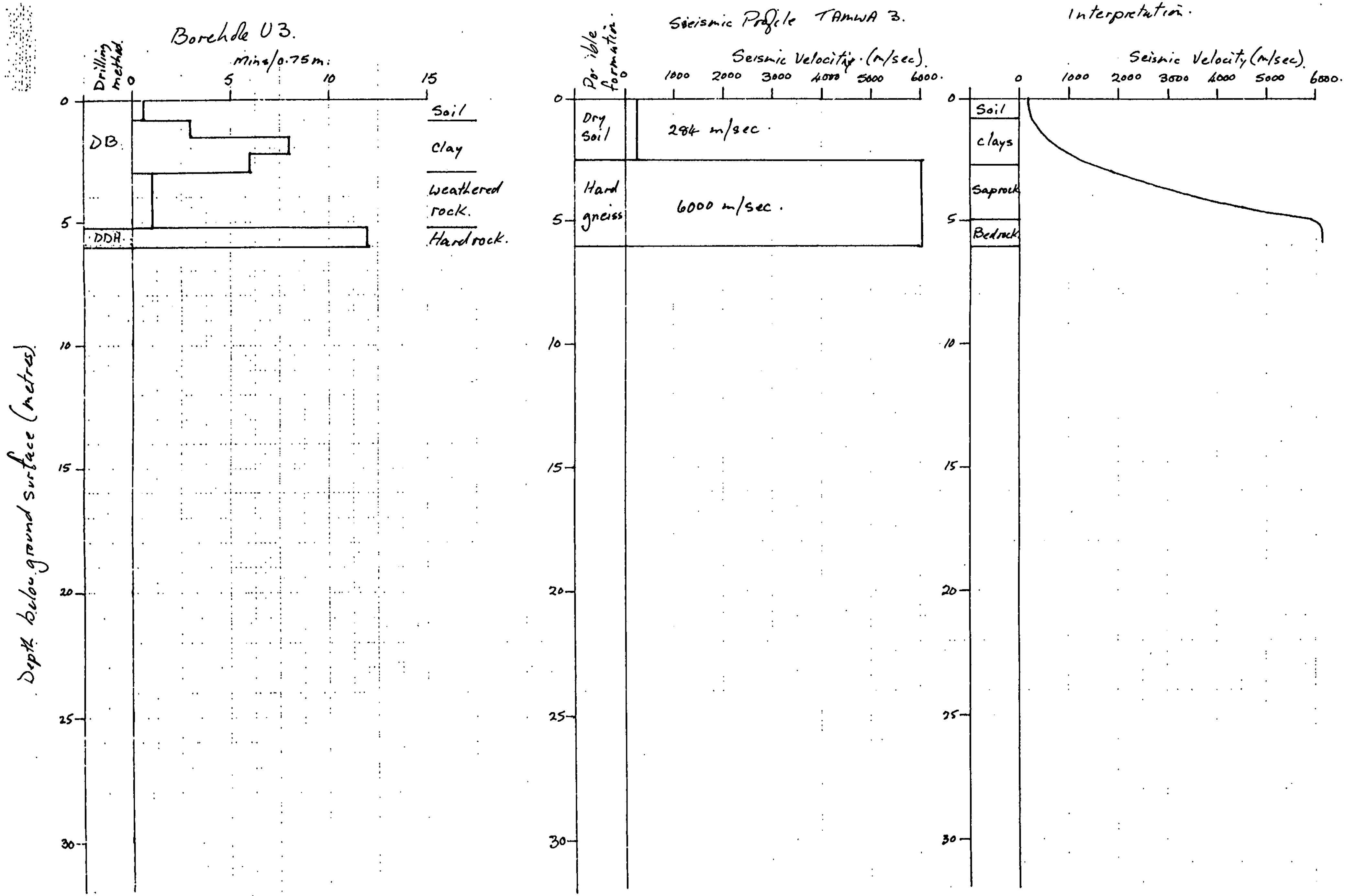
| | | | |
|---|---|---|---|
| Profile ID: | CHIREDZI2/CWWE | Method: | Automatic |
| Project: | BGS | Date: | 94/03/10 |
| Customer: | ODA | Created: | 11:11 |
| Cust. ref.: | ODA | Geoph. spacing: | 54.0 m |
| Operator: | JEFF L | Shot spacing: | 3.0 m |
| Comments: | CLEAR HOT CALM STEEL E | Start offset: | 1.5 m |




14 lb hammer and steel plate energy source

Fig 42 Comparison of seismic trace curves from Chiredzi 1 and Chiredzi 2

TAMWA 3.




DB - drag bit
DDH - down the hole hammer

Fig 43 Interpretation of geophysical and geological data from TAMWA 3.

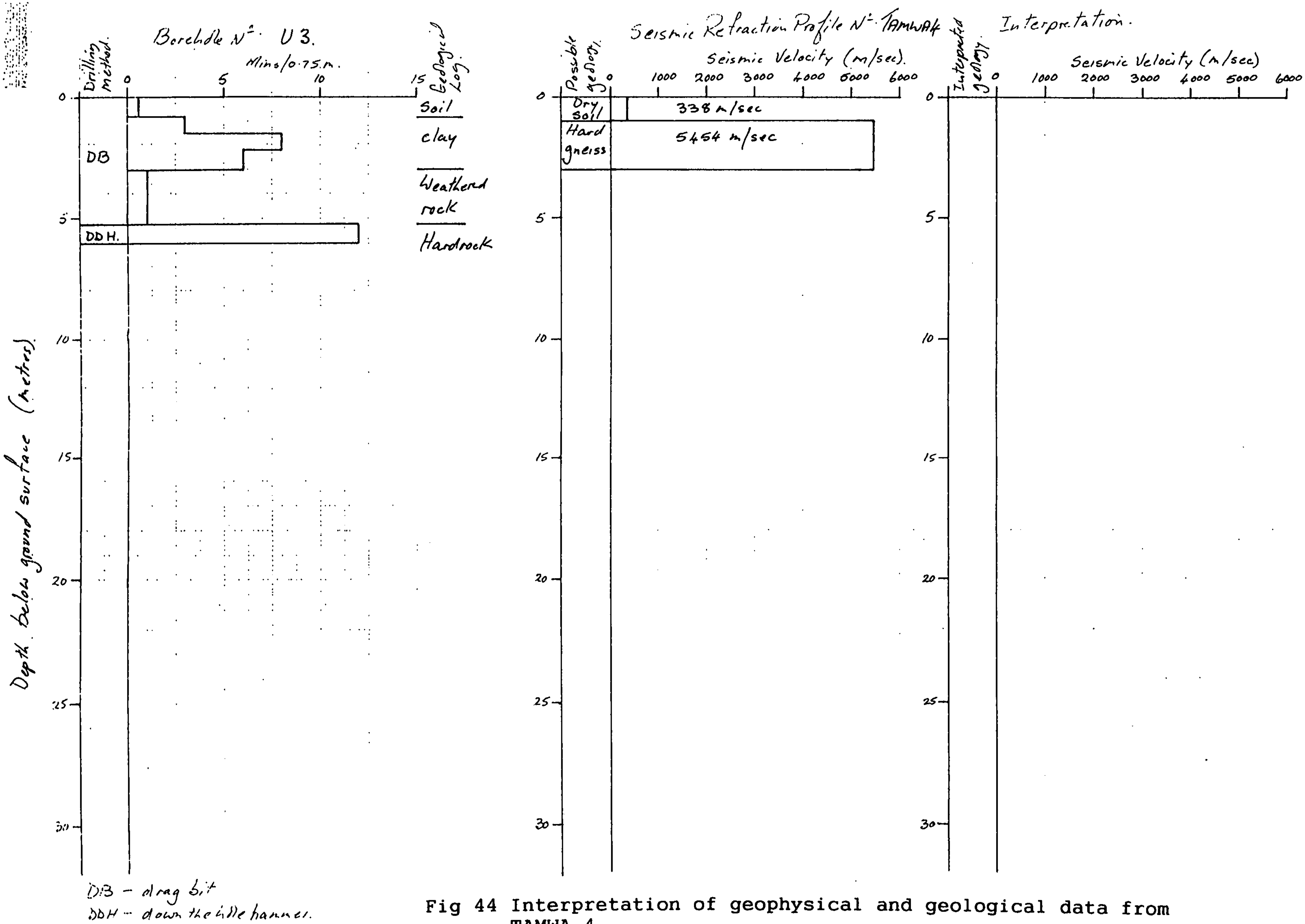



Fig 44 Interpretation of geophysical and geological data from TAMWA 4.

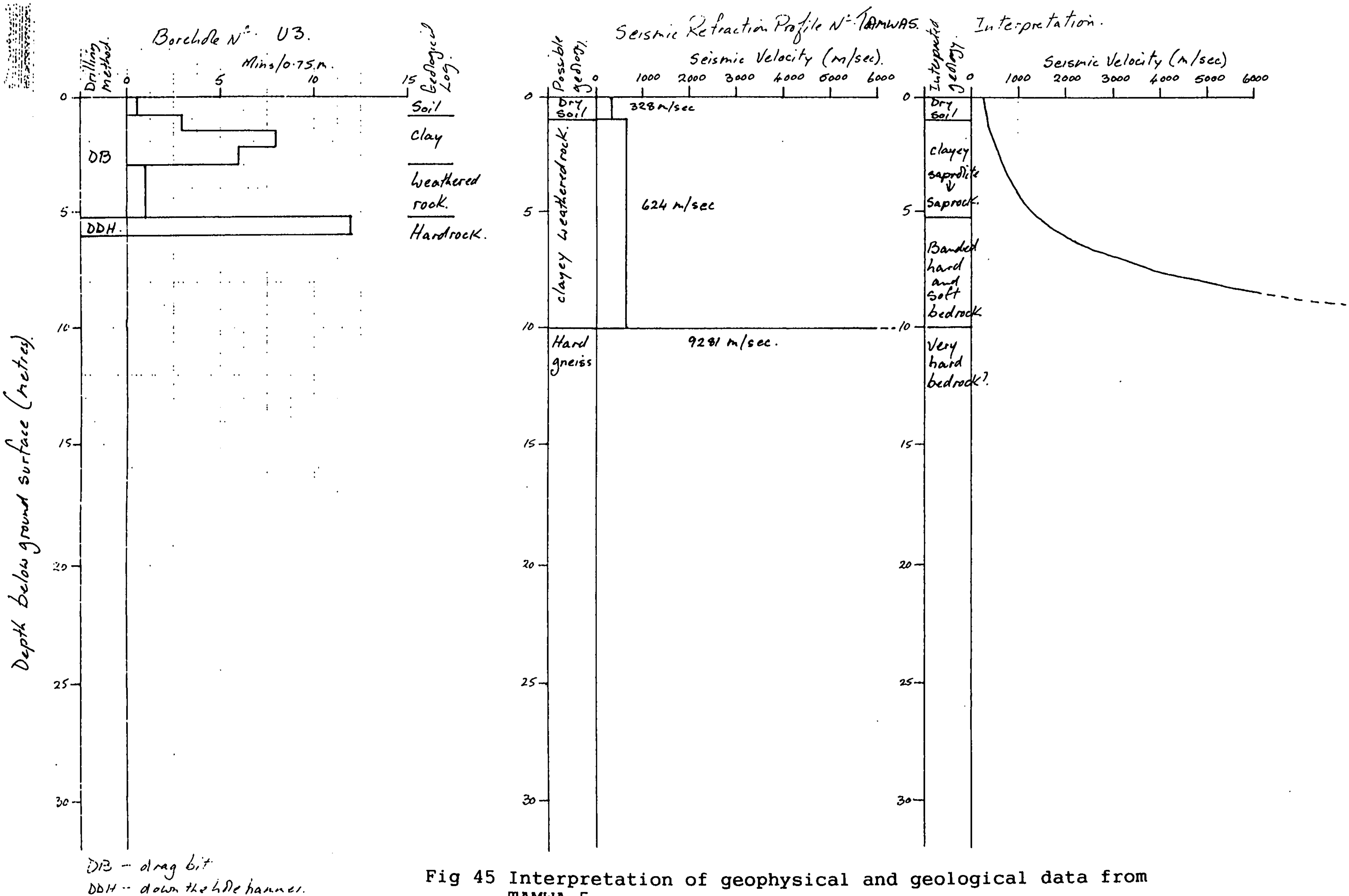
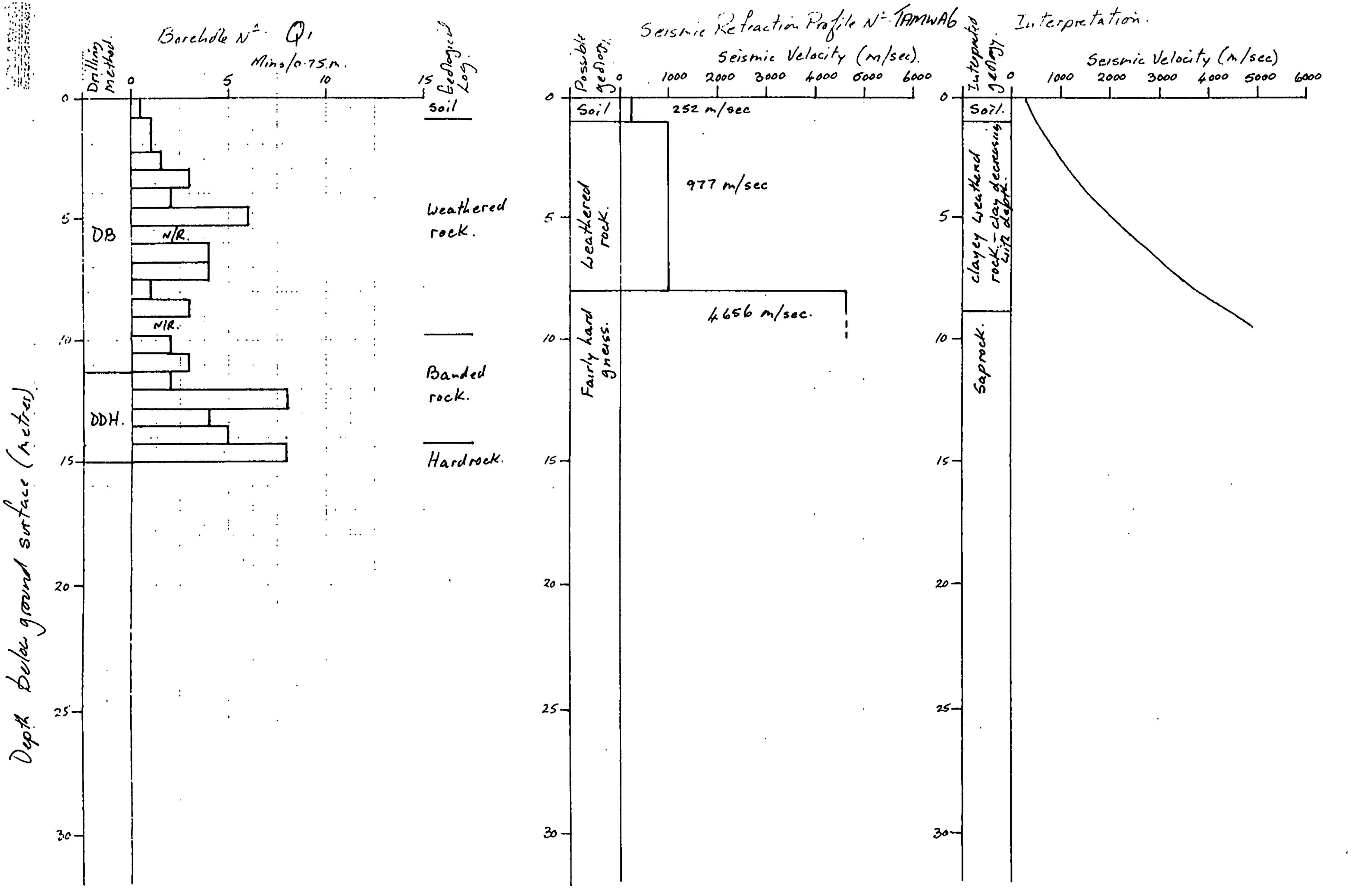



Fig 45 Interpretation of geophysical and geological data from TAMWA 5.




DB -- drag bit
DDH -- down the hole hammer.

Fig 46 Interpretation of geophysical and geological data from TAMWA 6.

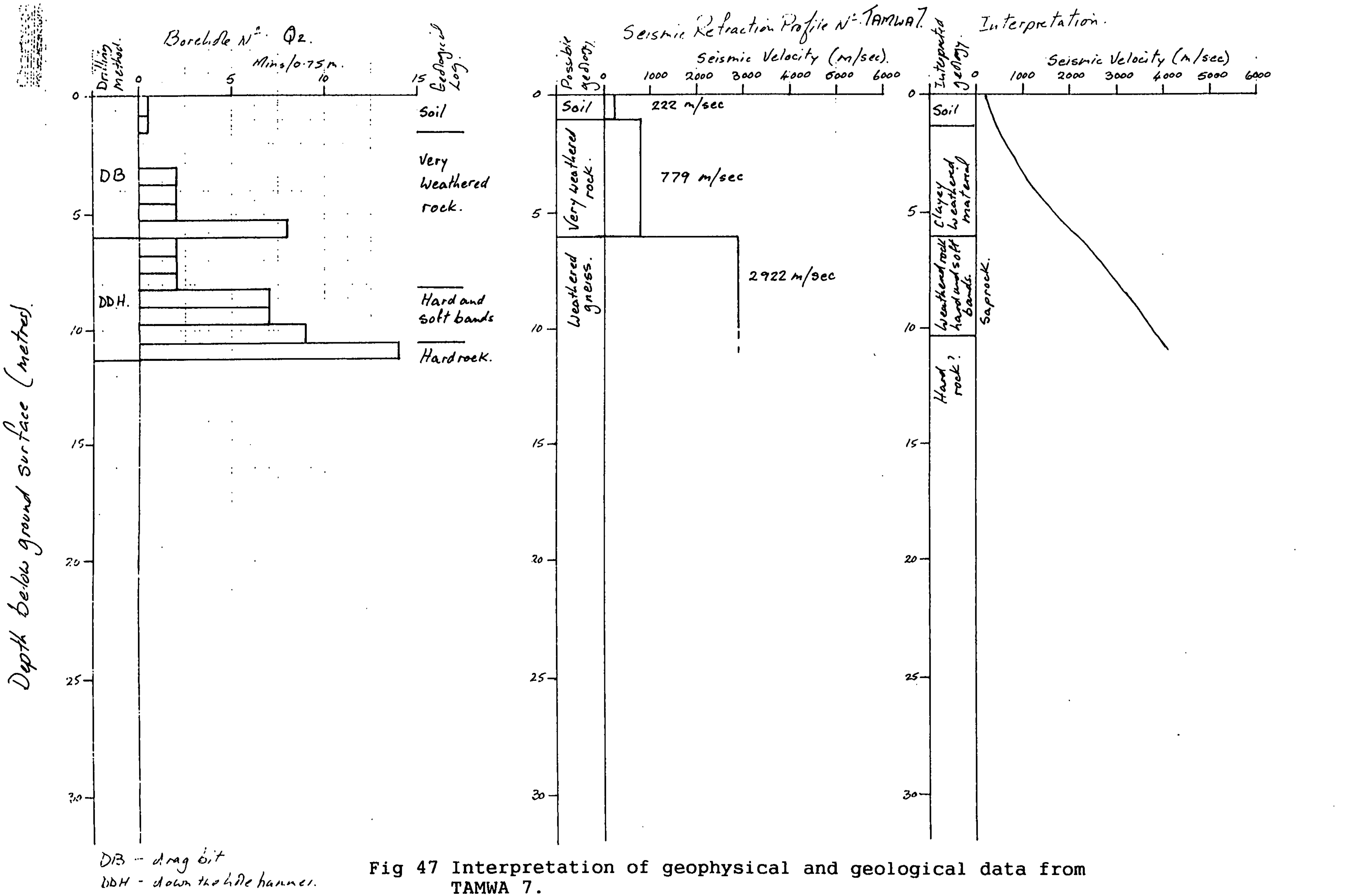



Fig 47 Interpretation of geophysical and geological data from TAMWA 7.

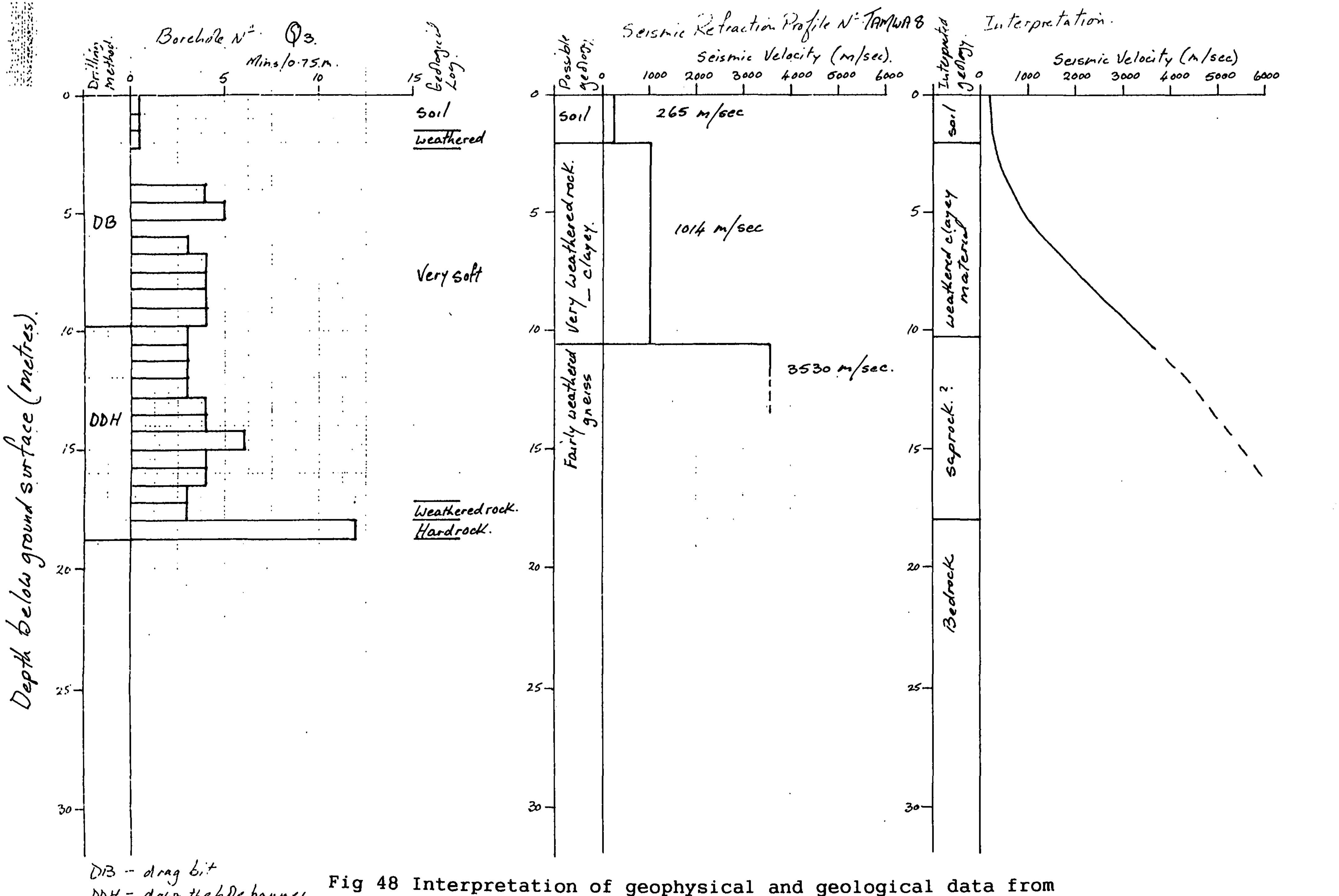



Fig 48 Interpretation of geophysical and geological data from TAMWA 8.

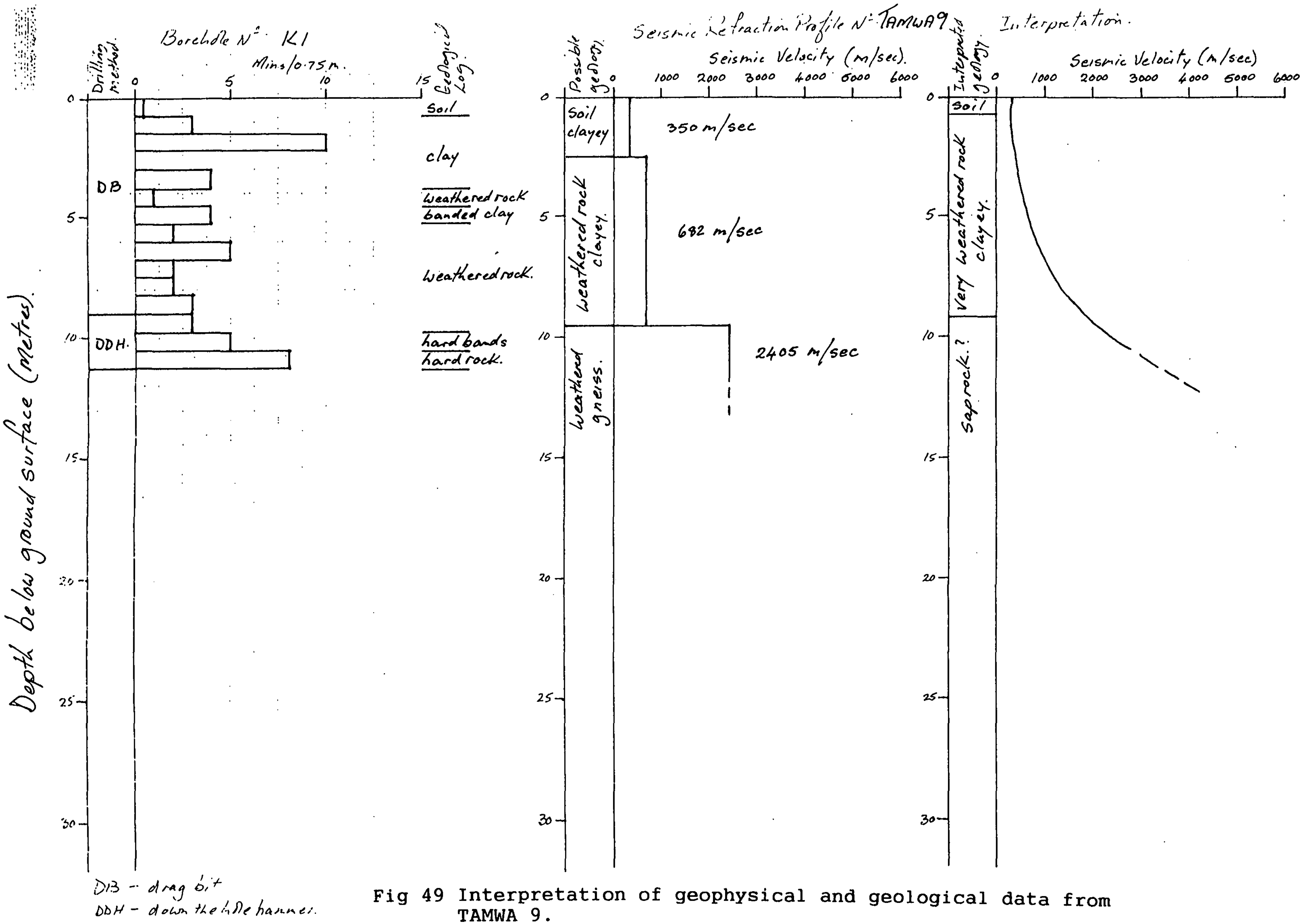



Fig 49 Interpretation of geophysical and geological data from TAMWA 9.

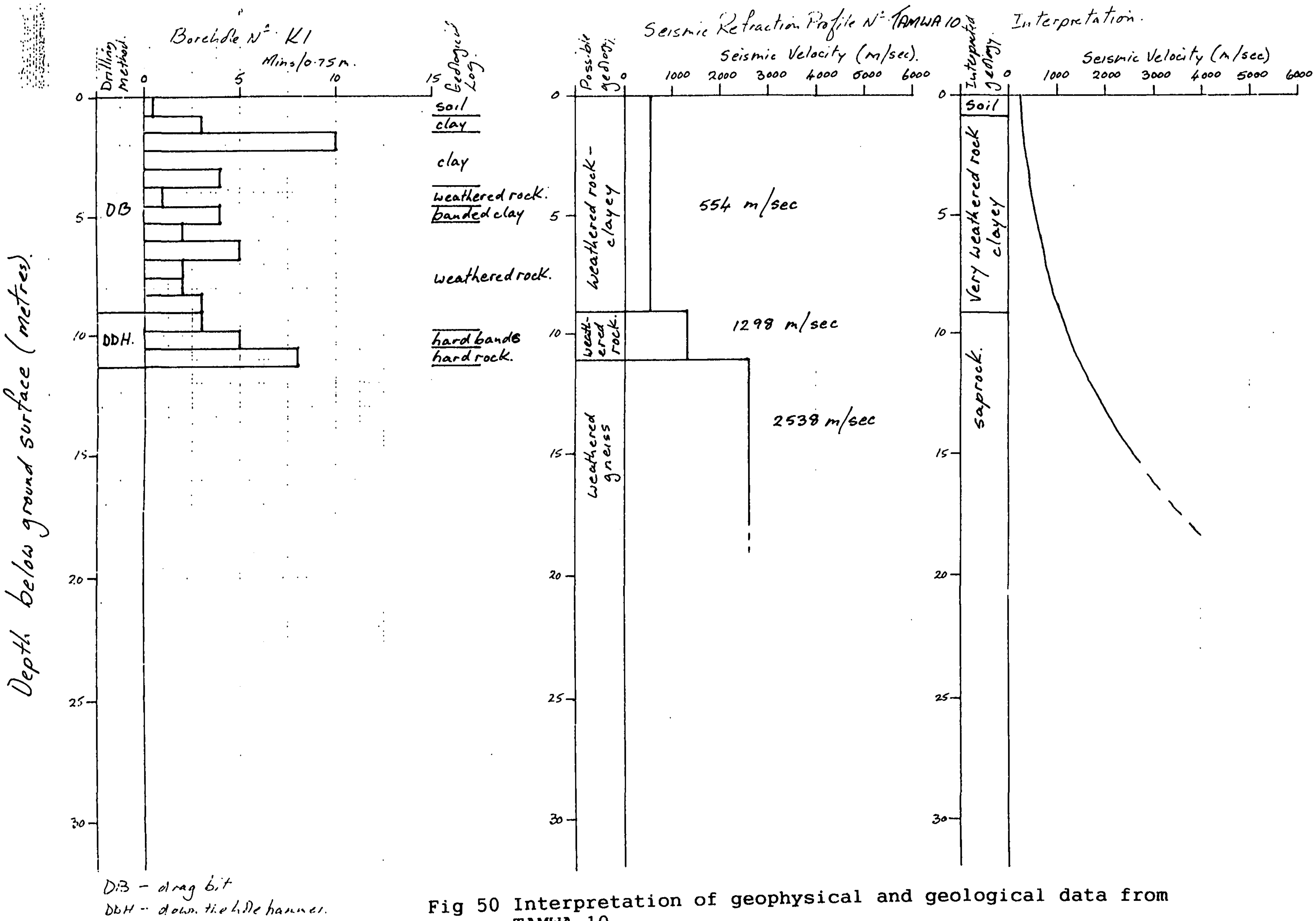



Fig 50 Interpretation of geophysical and geological data from TAMWA 10.

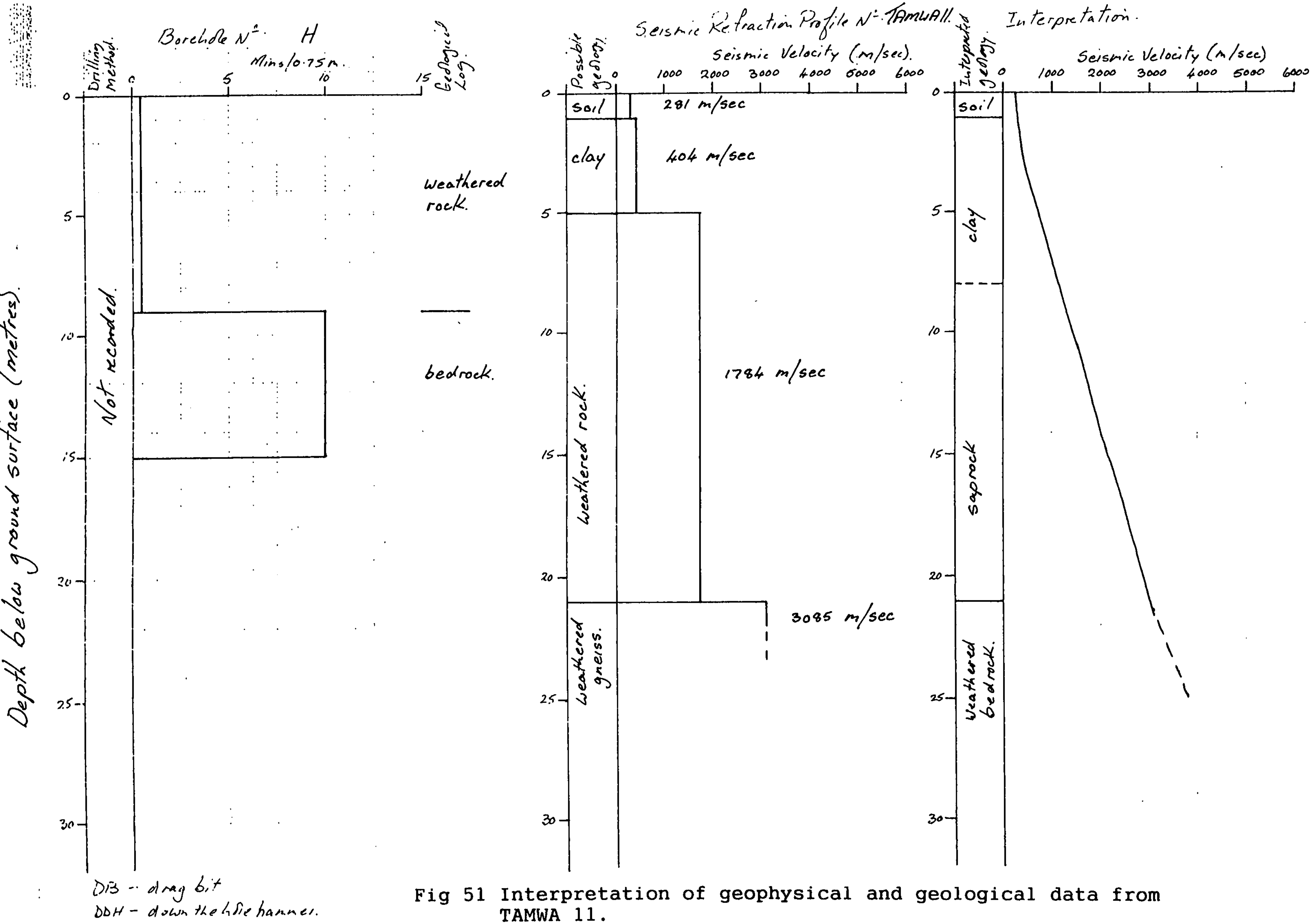



Fig 51 Interpretation of geophysical and geological data from TAMWA 11.

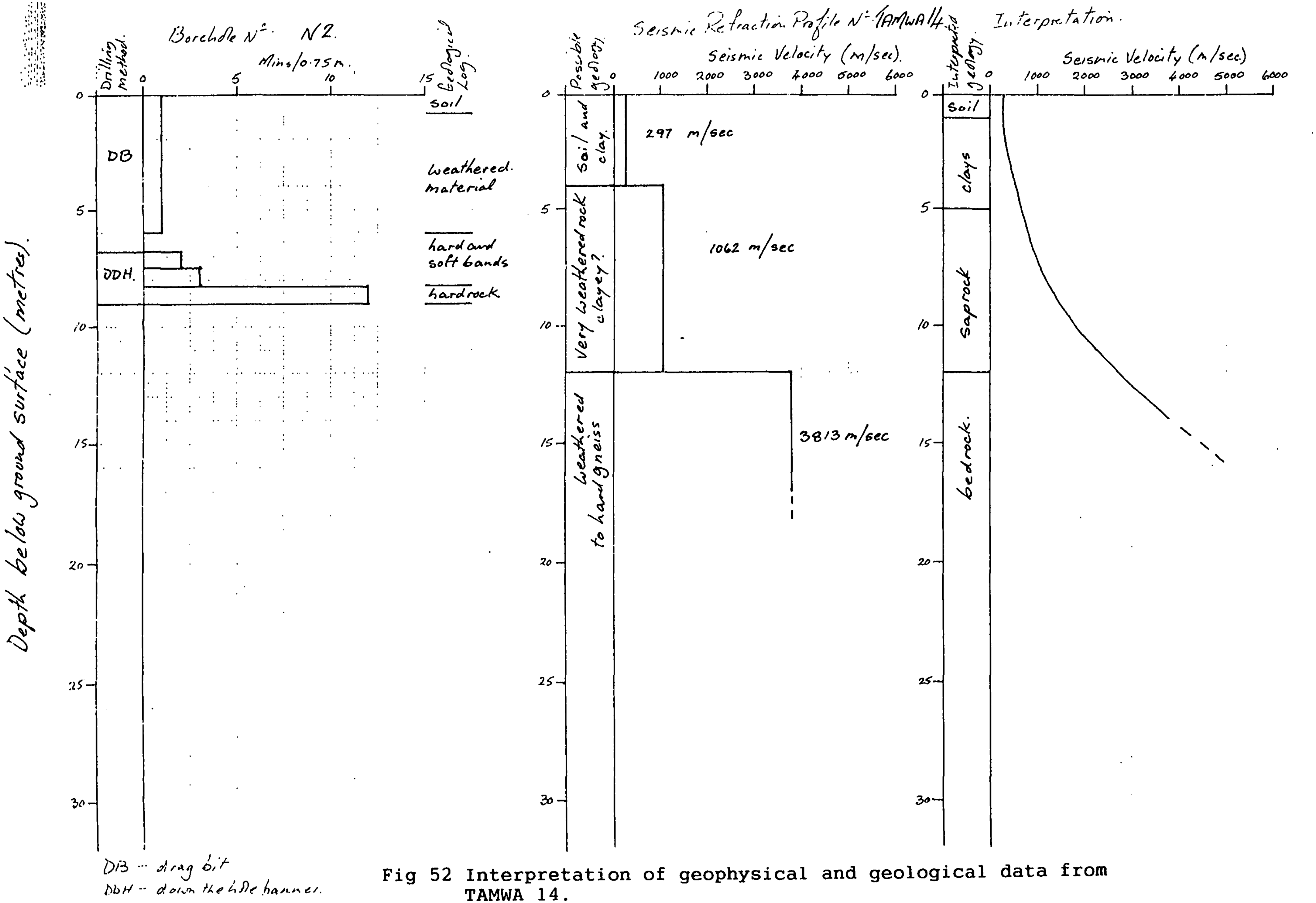



Fig 52 Interpretation of geophysical and geological data from TAMWA 14.

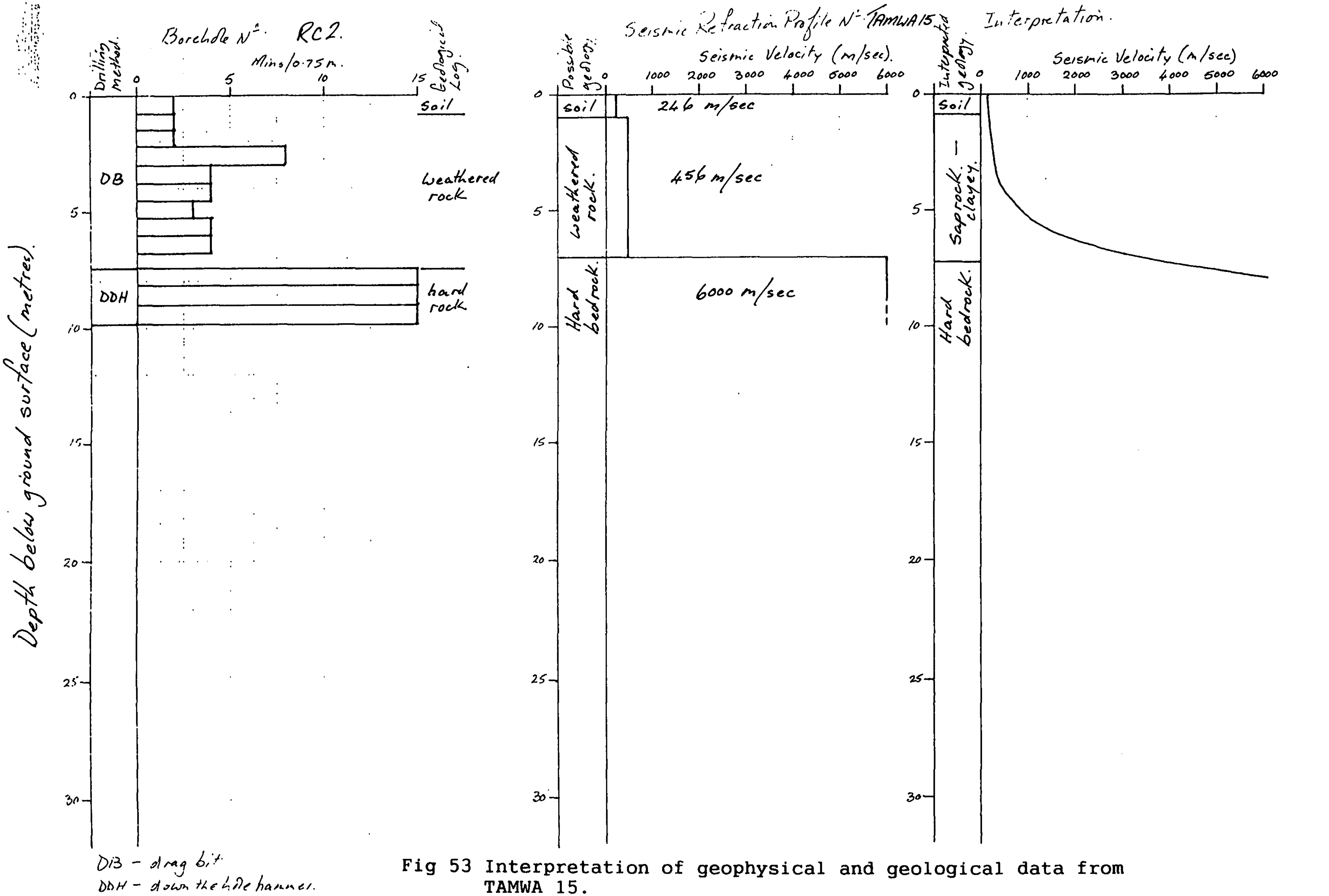



Fig 53 Interpretation of geophysical and geological data from TAMWA 15.

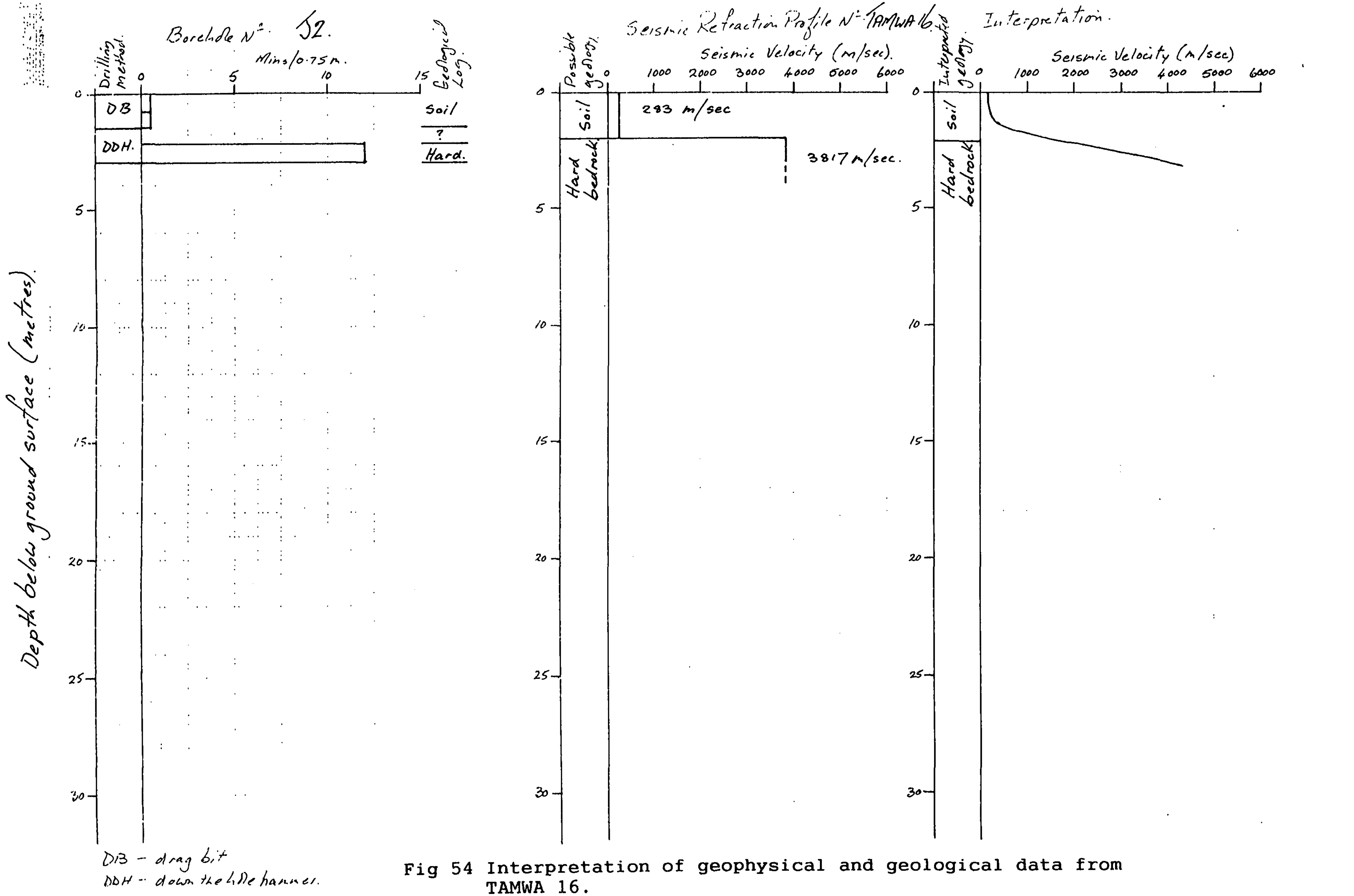



Fig 54 Interpretation of geophysical and geological data from TAMWA 16.

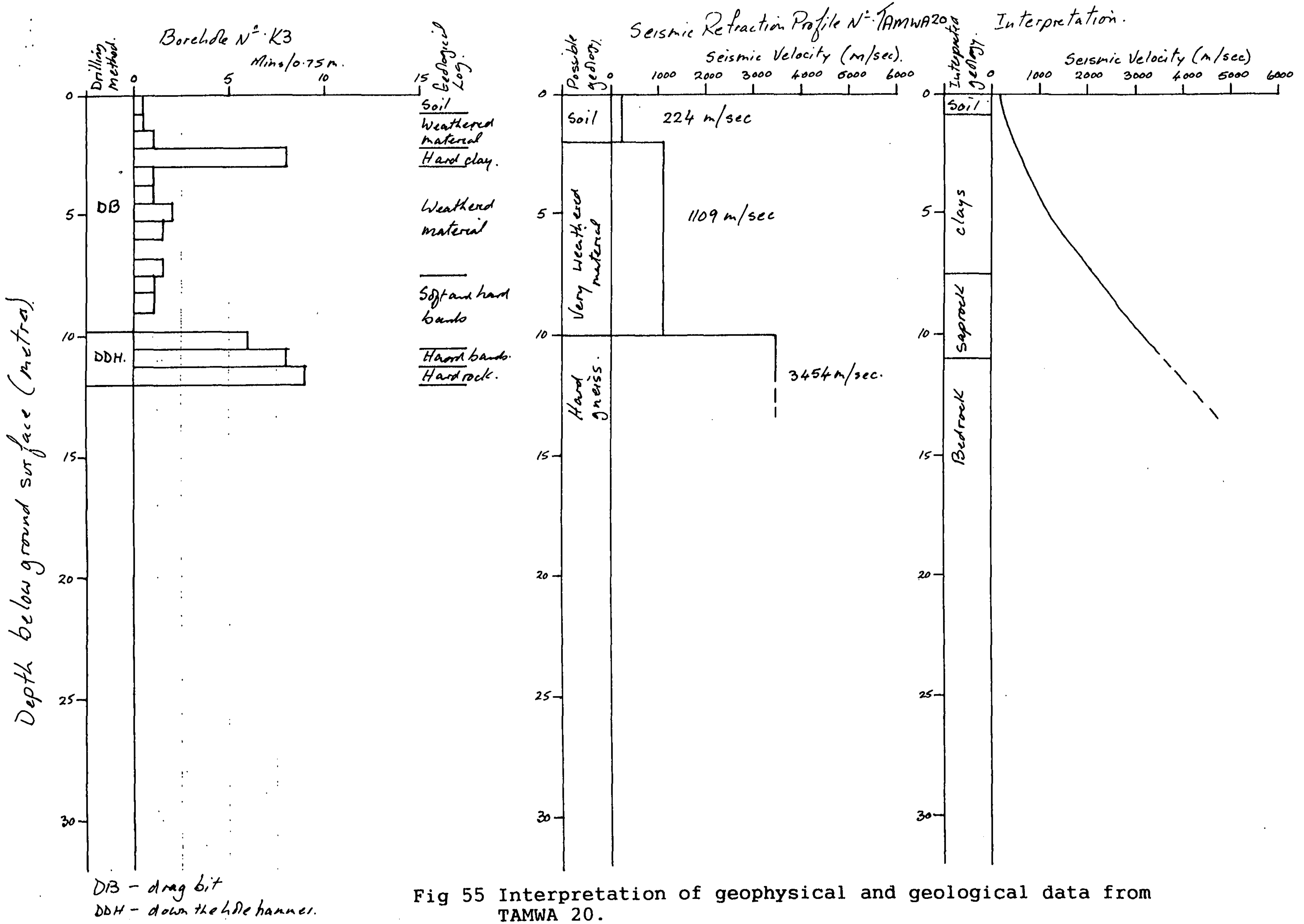



Fig 55 Interpretation of geophysical and geological data from TAMWA 20.

while the less weathered banded lower saprock has velocities of 3500-4500 m/sec. The degree of weathering is often gradational, declining with depth.

Interpretation of the seismic profile results mainly produced three layer solutions with a dry near surface soil overlying a clayey saprolite that in turn overlies saprock. The hard bedrock is only usually identifiable if occurring at shallow depth (<5 m) or exceptionally at depth as at TAMWA 17, where bedrock was determined at 30 m depth. The shape of the time - distance curves produced can be used to indicate sharpness of regolith to saprock/bedrock boundaries as shown in Figs 13 and 18. In areas where the bedrock lies at shallow depth this boundary is sharp, the underlying bedrock being unweathered. In contrast in areas where the saprock was encountered at 10-15 m depth this weathered boundary is gradational the effects of weathering gradually decreasing with depth. In most profiles an interface between the upper clay layer and underlying saprock can be recognised. The depths to saprock interpreted from the seismic profiles agreed very well with the depth of drag bit penetration as shown in Fig 56. The seismic profile data produces reasonably accurate determinations of:-

1. Thickness of soil/clay regolith layer

2. Depth to the clay/saprock interface

3. The nature of the saprock

However it cannot, except in exceptional circumstances, indicate depth to bedrock since either the velocity contrast between the saprock and the hard bedrock is insufficient to permit recognition of the latter, or the interface occurs at depths below the limit of penetration. This result was a disappointment in that the objective of the exercise was to see if depth to bedrock could be identified as a matter of routine. Nevertheless, the ability to find the thickness of the highly weathered material is of great value and dug wells and collector wells can be sited at the greatest found for development of the permeable saprock horizon as defined by Acworth (1989) (Fig 57).

### 7.4 Tentative Interpretation of the Geology of the Tamwa Area

One map, Fig 58 has tentatively been prepared using the results of this study. It shows areas where shallow hard rock of poor development potential with seismic velocities >6000 m/sec occur as well as other areas with good development potential within the Tamwa area. A typical profile of weathering within basement strata is described by Wright (1992) (Fig 59). The distribution pattern of regolith (clays, sands and saprolite) and saprock/bedrock between high ground and dambo/valley bottom are shown in Fig 60 as described by McFarlane (1992). Two geological sections have been drafted using geophysical profile and limited borehole data. The location of these cross-sections are shown on Fig 58. Fig 61 shows cross section A-B that includes the eastern half of the main valley from the water shed in the east to the main dambo/valley in the west. The pattern of weathering is in agreement with the conceptual model of McFarlane. Cross section X-Y shows a weathering pattern modified by the effects of open fractures possibly further intensified by rapid weathering due to the recharge of acidic rainwater from the adjacent bornhardt

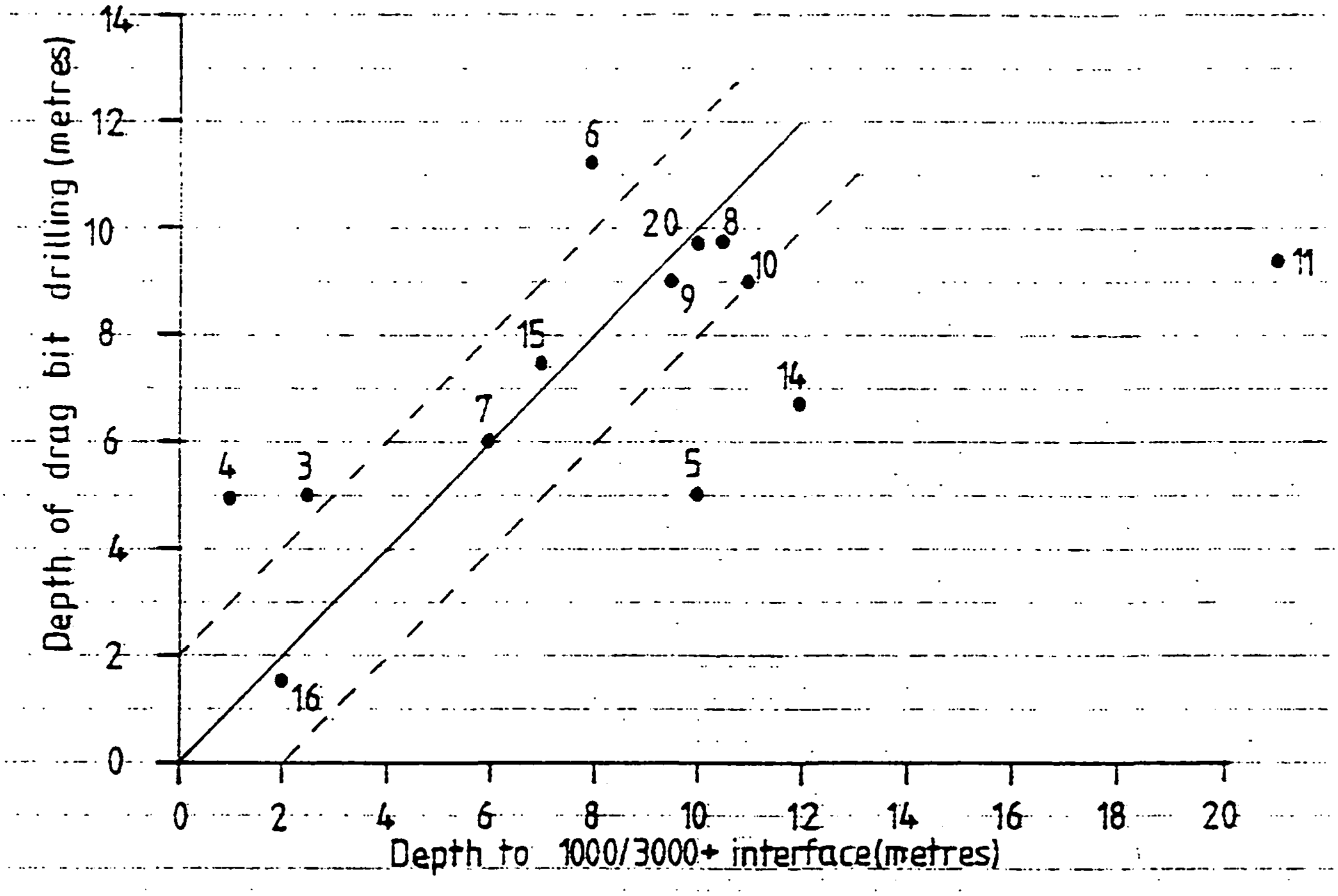



Fig 56 Depth of drag bit drilling verses depth to saprock.

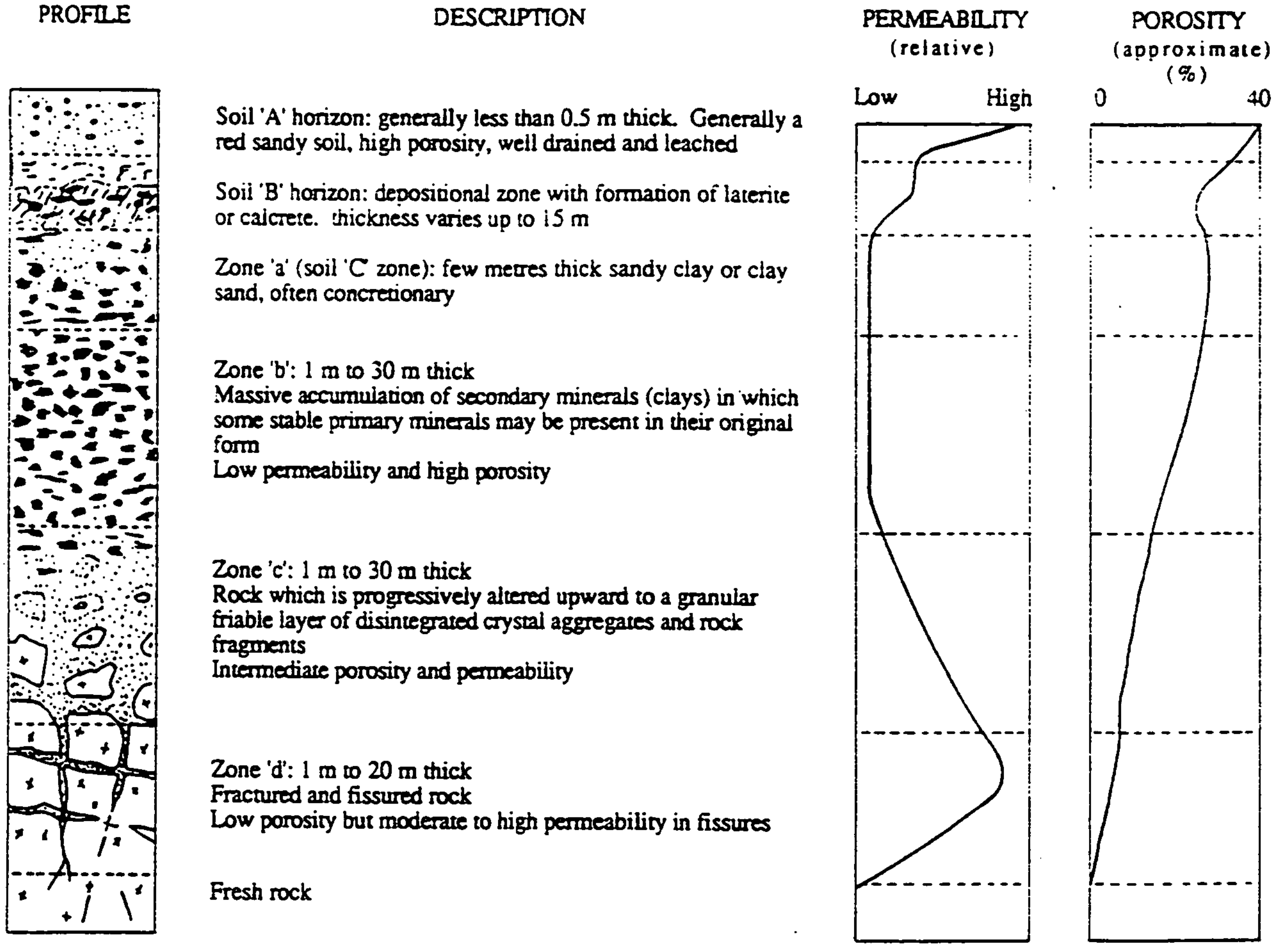



Fig 57 Vertical profile through regolith showing variation of weathering, storage capacity and permeability (after Acworth, 1987)

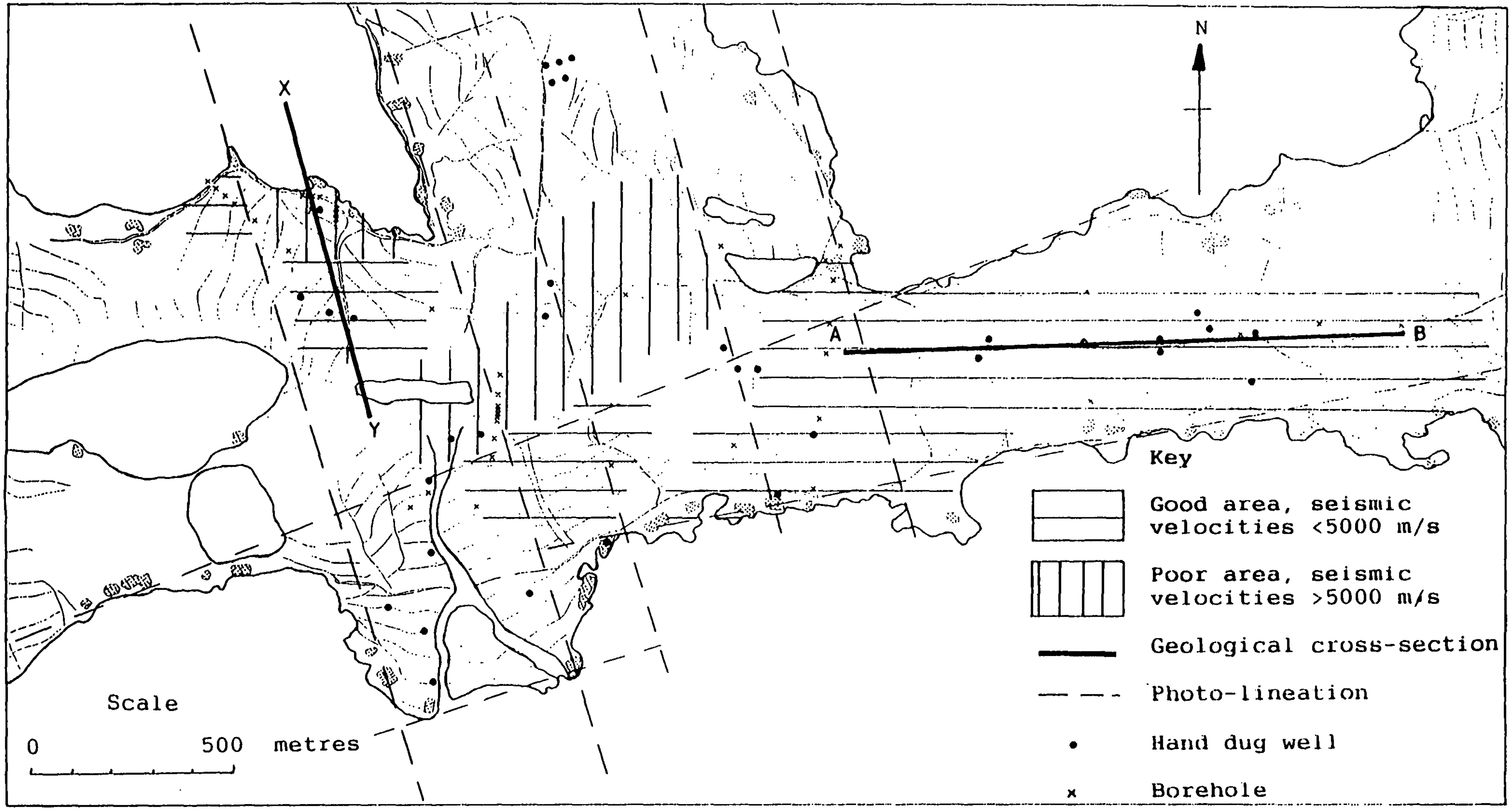
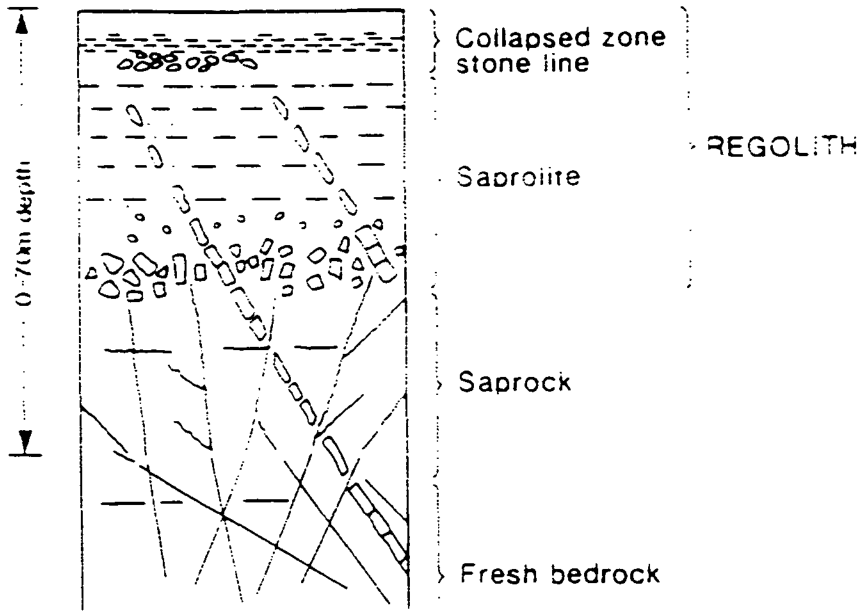



Fig 58 Location of good and poor development potential with cross section locations.




Idealized weathered profile above crystalline basement rocks. (1) Collapsed zone. This may show marked lateral variations being generally sandy on watershed areas with illuviated clay near the base and sometimes a stone line changing to predominantly neoformed clay minerals in valley bottomlands (dambos). Slope bottom laterites may also occur associated with the peripheral dambo clays. (2) Saprolite is derived by in situ weathering but is disaggregated. Permeability and effective porosity tend to decrease at higher levels as a consequence of increase in secondary kaolinite minerals. (3) Saprock is cohesive weathered bedrock.

Fig 59 Idealized weathered profile above crystalline basement rocks (Wright 1992)

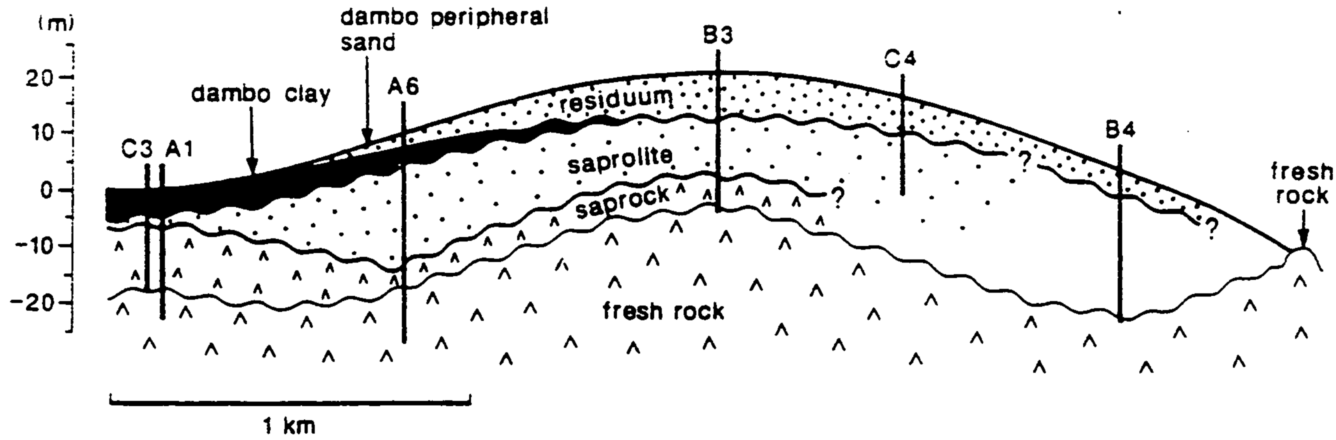



Fig 60 Distribution of weathered strata above basement rocks

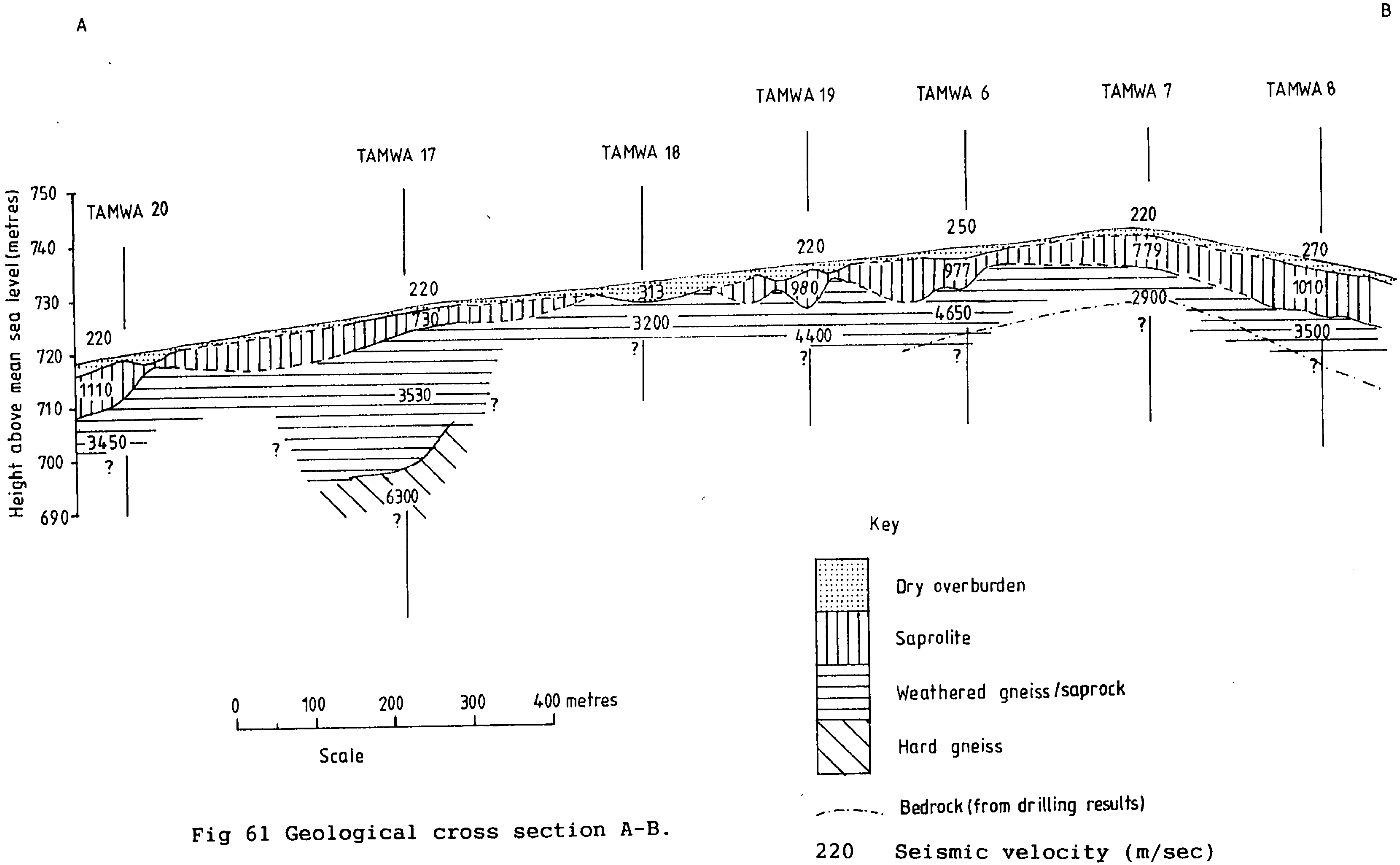



Fig 61 Geological cross section A-B.

producing a deeper than normal zone of saprolite accumulation and associated saprock horizon (Fig 62).

## 8. CONCLUSIONS AND RECOMMENDATIONS

1. The ABEM MINILOC seismic refraction system is easy to use, can be used to quickly produce seismic profiles, and produce reliable data. Unfortunately the raw field data cannot yet be stored for office based analysis at a later date. Data must be analysed in the field, a time consuming operation that may initially cause poor data interpretation by the inexperienced operator. However with experience such field interpretation is to be encouraged if only to field check the validity of the data sets ind interpretations acquired.

2. The depth of penetration of the system is limited to about 20 m, even with the use of a large weight/ steel plate energy source. The routine application of the latter or alternative use of explosives is impractical if the rapidity and mobility of survey and equipment are to be maintained. Essentially operation of the system has to be faster and cheaper than test drilling to be viable. Up to four shallow test boreholes can be drilled per day within a restricted area under highly favourable conditions, whereas three or four seismic profiles can routinely be produced and interpreted per day without the incurring problems associated with rig down time or mobilisation from one site to the next.

3. The seismic data produced can readily be used to identify the thickness of the regolith (soil and saprolite) layer, depth to the saprock layer and the nature of the saprock. The total depth to bedrock is not really required for hand dug well/ collector well system location, since the most permeable horizon is in the upper saprock horizon. The system can therefore produce adequate data from an area where the geology is imperfectly understood. The nature of vertical fracture zones can be indicated, ie whether they are tight or open.

4. Carruthers (personal communication) suggests that additional study needs to be undertaken in several areas to reduce inconsistencies in the acquisition and interpretation of raw data.

   4.1 Improved consistency should be given by ensuring reciprocal times match across the spread before entering 'interpret' mode, either by adjusting first arrival picks or by assuming zero time offset and shifting whole segment by the same amount.

   4.2 Time anomalies reproduced at the same geophone for reversed channel segments must be near surface effects (e.g. Fig 19), possibly related to geophone emplacement (depth, charge and soil compaction) (Ref Figs 15-17 which indicate offsets resulting from buried sources).

   4.3 Unlikely that surface layer with velocities <300 m/sec would extend below 0.5-1 m depth unless in thick, aerated soils. Would usually expect a minimum of three layers with second layer of >500 m/sec, unless first layer is

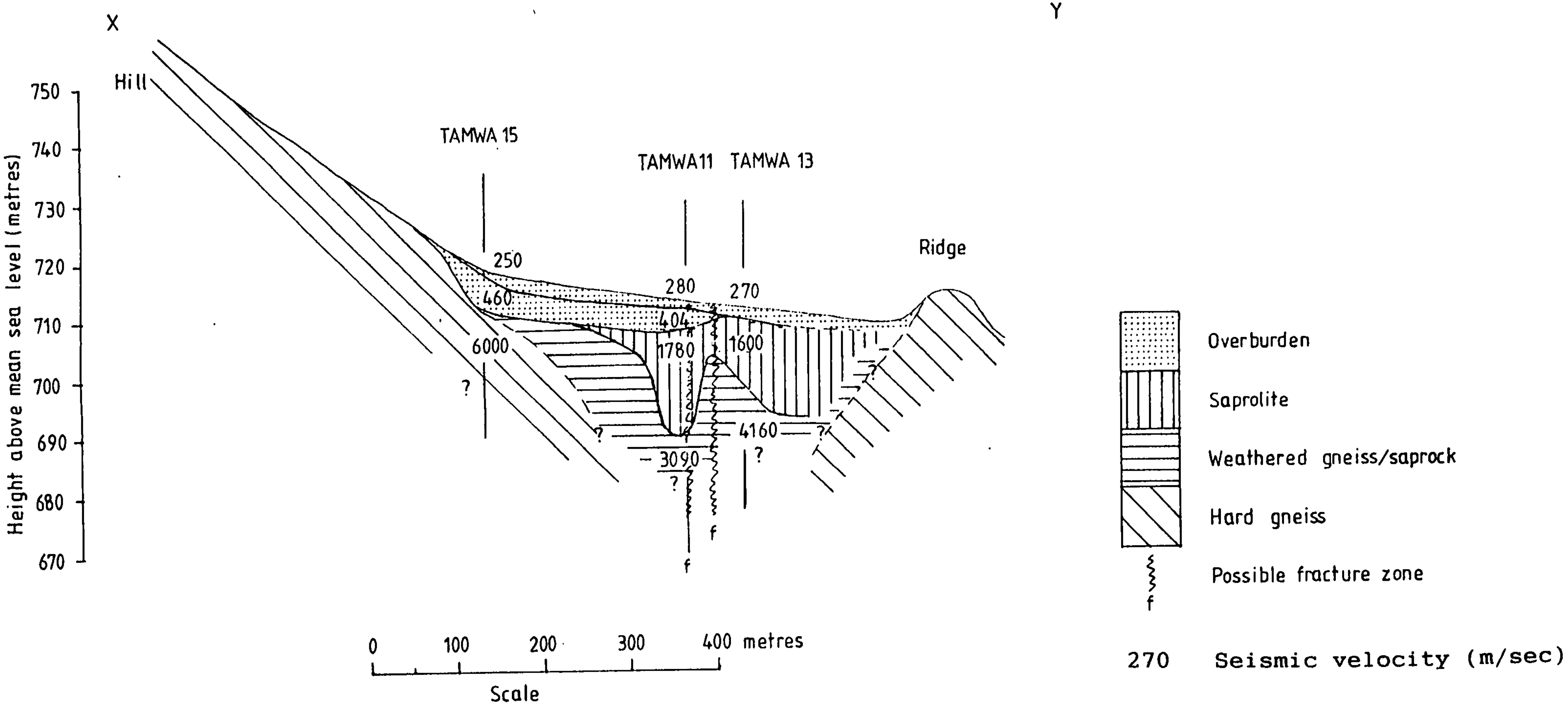



Fig 62 Geological cross section X-Y

>400 m/sec. Note: interpretation forces top layer segment through origin (ie. zero time at geophone location) whereas field data often suggest some offset in most cases, this will lead to an underestimate of layer 1 velocities.

5. It is recommended that the following siting programme be adopted where suitable equipment and facilities exist:-

**LOCATION OF HAND DUG WELL AND COLLECTOR WELL CONSTRUCTION SITES**

Within developing countries rapid reconnaissance methods using the following steps are employed to locate hand dug well and collector well construction sites that are sociologically, economically and hydrogeologically sustainable.

(1) A socio-economic evaluation of an area is undertaken to determine the distribution of a target population, its current and potential water requirements, and its present water resources. Health considerations must be taken into account including the location of such sites well away from potential sources of pollution such as pit latrines.

(2) An agro-economic assessment of a target area will indicate quantities of water required for agricultural activities, the impact of climate upon these activities, how these activities could be modified to utilise excess capacity water given adequate soil conditions, and assessment of the impact of modified groundwater use patterns such as grazing upon the local environment.

The above studies will produce initial target areas and some idea of potential water demand.

(3) An evaluation of aerial photographs of each of the target areas will provide an initial indication of geological conditions including fracture patterns and rock type distributions. Mapping of surface geological features is required to interpret lineaments and rock type distributions identified from aerial photographs.

(4) Rapid surface geophysical surveys using the EM method can be used to survey each target area, to determine the distribution of rock types and fracture patterns at shallow depth below superficial deposits.

(5) Detailed surface geophysical surveys employing seismic refraction or resistivity surveys to locate depth of weathering and nature of fracture patterns. Three 100 metre seismic profiles will be required to fully evaluate a potential drilling target requiring two days of site preparation, survey work and analysis.

(6) An appropriate method is employed to excavate and construct hand dug wells or collector wells to a pre-determined depth that may be proved by exploration drilling at the site selected.

(7) If groundwater is encountered at a depth <10 m then the construction of a collector well system should be considered.

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