THE CRUSTAL STRUCTURE OF NORTHERN ENGLAND

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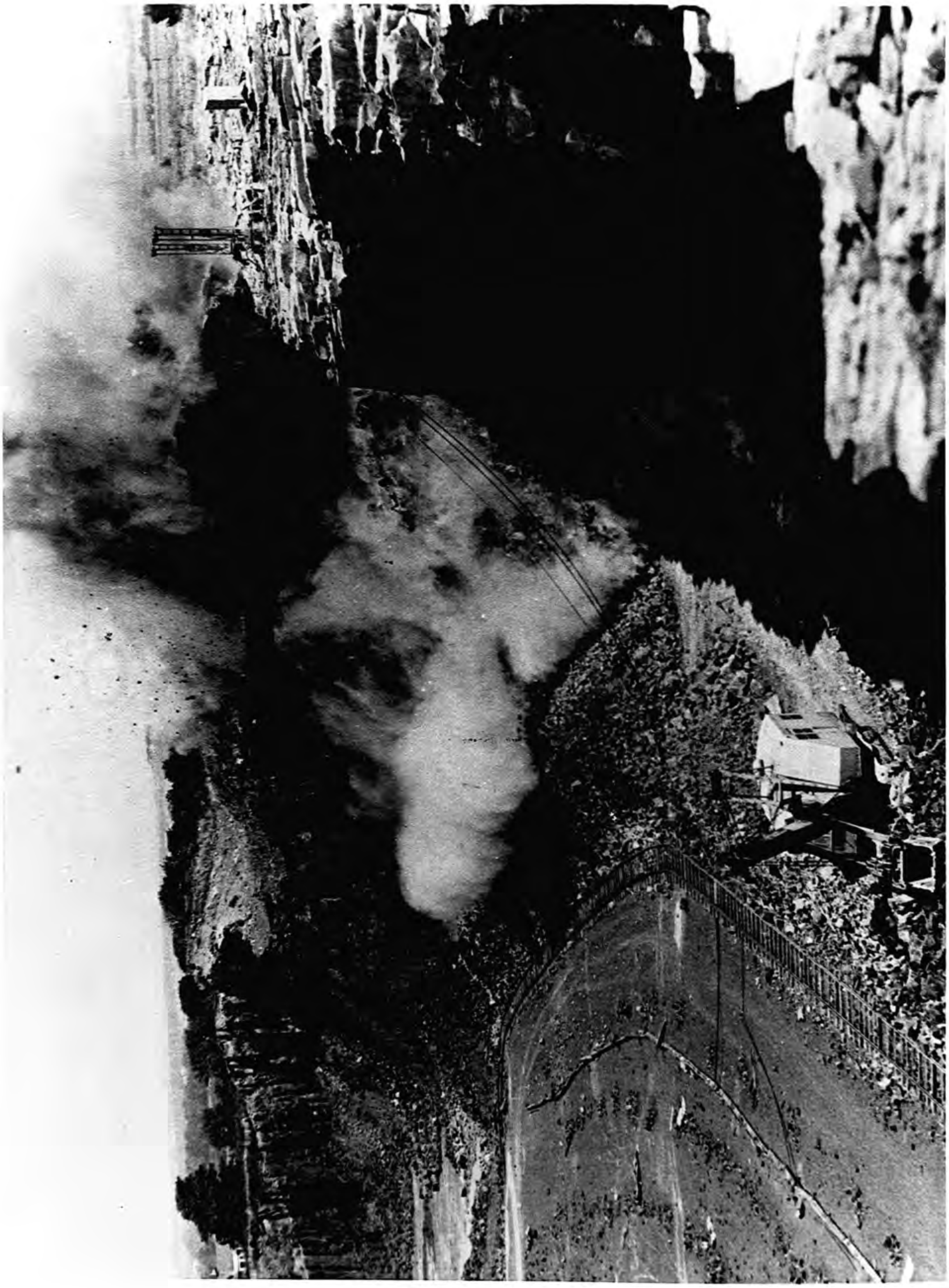

ABSTRACT

The crustal structure of Northern England was examined, using mainly the refraction technique. A three layer crustal model with interfaces at 0 to 3 km, 12 km, and 27 km was interpreted from the data.

The lateral variations in thickness of the sedimentary cover was investigated by measuring Pg travel times from quarry blast sources recorded at mobile stations. The time term method was used to interpret the results and showed that the basement varied from 2½ to 3½ km deep within the sedimentary troughs to less than 1 km beneath the block regions.

The interpretation of apparent velocities of crustal phases across Eskdalemuir and Rookhope arrays, and wide angle reflections, suggested the existence of a lower crust between 12 and 27 km deep, with a velocity of about 6.5 km/sec. The upper crust (Pg about 5.7 km/sec) showed some evidence of velocity increasing with depth, especially the uppermost part of the granite beneath Rookhope array.

A refraction line (N.E.R.L.) recorded the shots of the L.I.S.P.B. project throughout the northern Pennines. This line examined the variation in thickness of the main crustal layers across the principal structural units. It suggested that the Moho was approximately level beneath the region. This indicates that the relative elevation of the blocks was isostatically supported by low density granites. The upper mantle has a Pn velocity of about

8.05 km/sec and the character of the phase suggested a sub-moho structure such as an increase of velocity with depth.

The surface wave dispersion of teleseismic events recorded at Eskdalemuir and Wolverton was examined. The interpretation suggested a crust 30 km thick and a shear velocity of 4.55 km/sec for the upper mantle.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The area of study comprised a region of Northern England, extending from the Scottish Border to Northern Yorkshire. It examined in most detail the crustal structure beneath the Northern Pennines, and specifically the units known as the Northumberland Trough, Alston Block, Stainmore Trough, and Askrigg Block. The general geology and the gravity and magnetic interpretation of the area have been well studied (Bott 1967). The purpose of this study was to complete the interpretation of the structure of the crust, using seismic techniques, by starting from the basement-cover relationships and extending to lower crustal and upper mantle structure.

1.2 General Geology

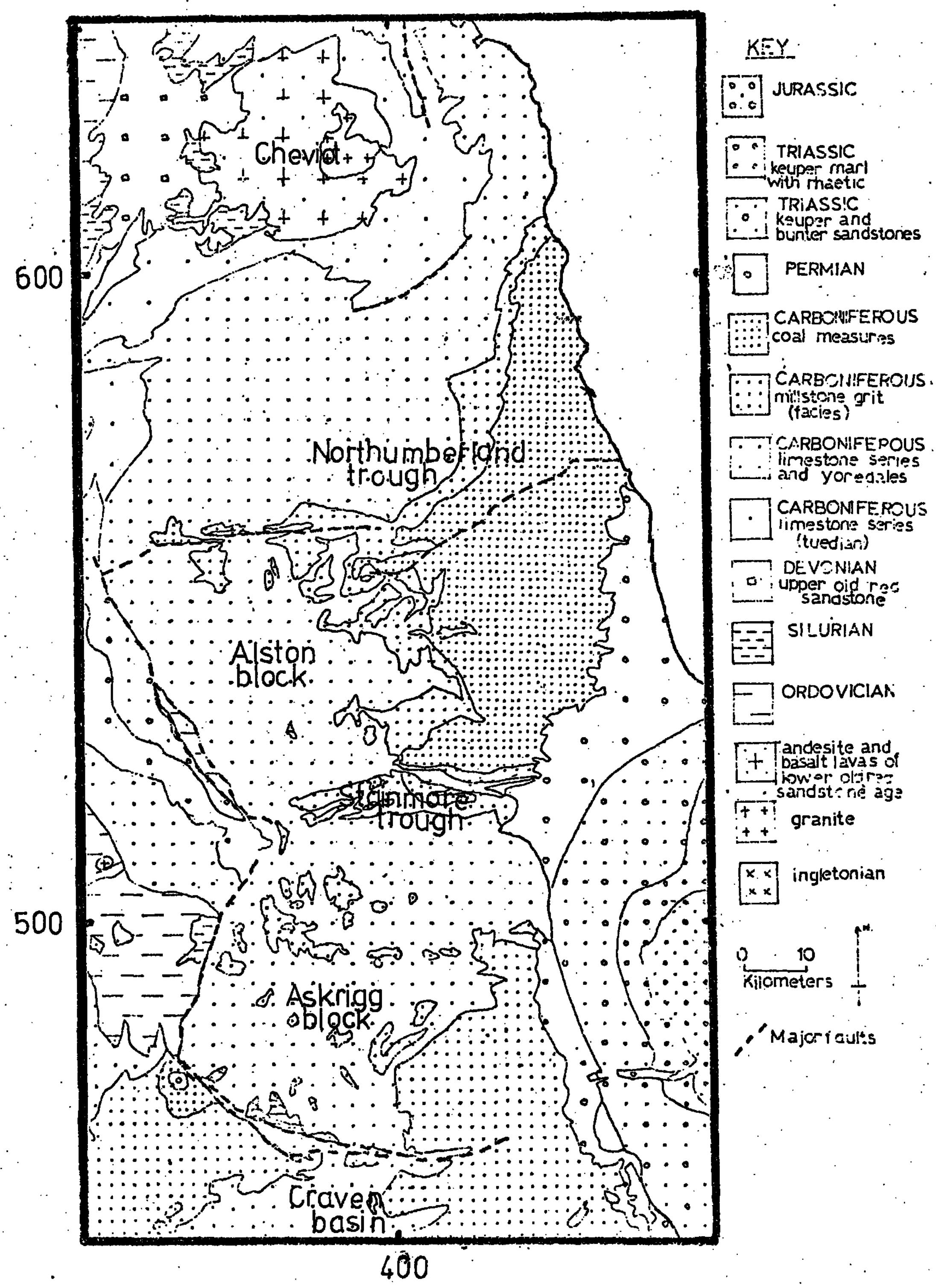
The single most important event in the Phanerozoic geology of Northern England was the emplacement of post-orogenic granite batholiths during the Lower Devonian. On cooling, these batholiths formed block regions which are generally fault bounded and have a thin cover of relatively undeformed sediments. The intervening troughs exhibit abrupt changes in sedimentary thickness, especially in the Lower Carboniferous. An outline of the general geology is shown in figure 1.

1.2.1 Basement Rocks

The oldest known rocks are exposed in inliers within the block regions. The inliers are generally Ordovician

Figure 1

GEOLOGY OF NORTH EASTERN ENGLAND



or Silurian in age, although there remains some doubt as to the age of the Ingletonian of the Chapel le Dale and Horton inliers, which may be pre-Cambrian (cf. Ingham and Rickards 1974). In general these lower Palaeozoic rocks form a thick sequence of highly deformed greywackes, siltstones and mudstones.

All three lithological units of the Ordovician, namely the Skiddaw Slate group, Borrowdale Volcanic group, and the Coniston Limestone group are exposed within the inliers.

The Skiddaw slates are exposed in the Cross Fell and Upper Teesdale inliers, and in the Crook borehole (Woolacott 1923). The widespread outcrop pattern indicates an extensive subsurface distribution. Sedimentologically they are variable, from mudstones to siltstones and graded greywackes, and they range in age from the Tremadoc to upper Llanvirn.

The Borrowdale Volcanic group is seen to rest unconformably on the Skiddaw Slate group in the Cross Fell and Upper Teesdale inliers. They consist primarily of acid and intermediate lavas and tuffs erupted during the Llandeilo.

The rocks of the Coniston Limestone group are lithologically grey calcareous mudstones, and suggest a quiet, muddy, shelf environment. About 600 m. are exposed in the Cautley area (Cautley mudstones) and are equivalent to the Dufton shales of the Cross Fell inlier, being mainly of Caradoc to Ashgill age.

The most complete section of the Silurian is exposed in the Howgate Fells, but graptolitic mudstones and distal turbidites are seen in the Cross Fell and Horton inliers, and they form the base to the Cheviot Volcanic pile.

1.2.2 The Granites

Three separate granite batholiths are known to occur to the east of the Pennines. Geological evidence and Radiometric dating suggest that all three were approximately contemporaneous.

On the Scottish border lies the igneous complex of the Cheviot hills, in which the granite is exposed within its associated volcanic cover and dyke intrusions. The batholith is variable in composition with its margins and central parts being diopside granodiorite with augite xenocrysts, separated by pink pyroxene free granophyres. Gravity interpretation (Spratling, 1973) suggests a denser phase along the northern margin.

The Weardale granite was originally postulated by Dunham (1934) and later substantiated by detailed gravity interpretation (Bott and Masson Smith, 1957), and finally proved at a depth of 1281 feet in the borehole at Rookhope (Dunham et al., 1961, 1965). Petrologically the granite is a foliated, non porphyritic, per aluminous, soda rich granite, with the phases:- albite, K. feldspar, quartz, muscovite, and biotite. Radiometric ages indicate that it was intruded at 394 $\pm$ 34 m.y. (Dunham et al., 1974). Geochemically there is evidence of a discontinuity at about 2,200' (Holland, 1967), of which the evidence suggests a slightly later fraction was intruded below.

From the interpretation of Bouguer anomalies, Myers and Wardell (1967) and Bott (1961) suggested the existence of a granite beneath the Askrigg block, south of Wensleydale. This granite was later confirmed in the borehole at Raydale (Dunham , 1974) and lay directly below Visean beds at a depth of 490 m. It is a medium grained, non porphyritic, unfoliated pink granite, consisting of microperthite, quartz, albite and chlorite. The Rb/Sr ratios indicate an age of 400 ± 10 m.y. with an initial Sr 87/86 of 0.7210 ± 0.0044. This figure is significantly higher than that for the Weardale granite (0.706). The suggestion (Dunham , 1974) is that although the granites were contemporaneous, they were not consanguineous; the Weardale granite being derived from a source such as the upper mantle, while the Wensleydale granite being re-fused crustal material.

1.2.3 <u>The Cover</u>

The only known outcrops of Devonian sediments are exposed round the flanks of the Cheviot volcanic pile. These red beds are mainly of Upper Old Red Sandstone age. It is not known whether any substantial thickness of Devonian occurs at the base of the sedimentary troughs.

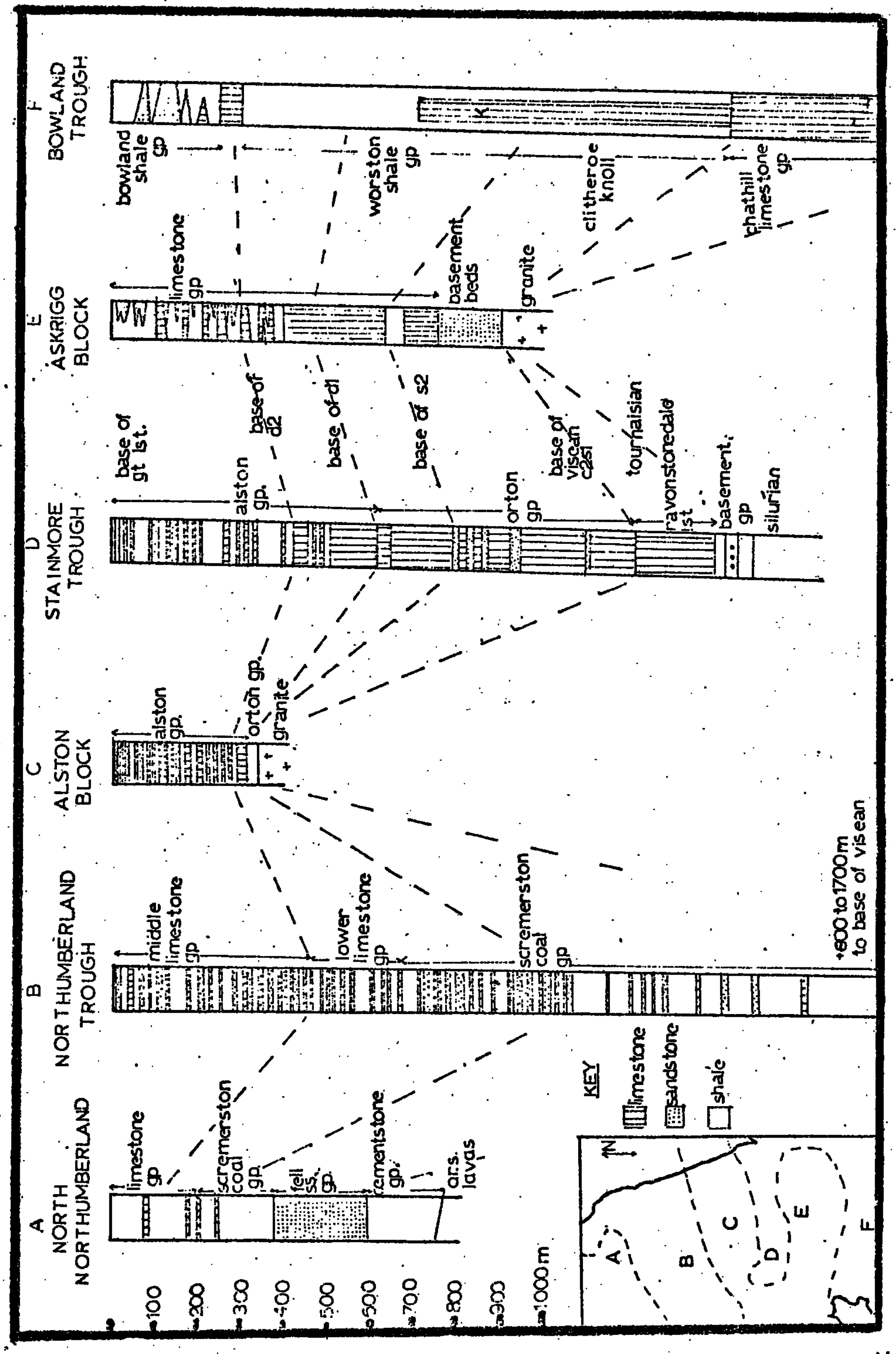
In terms of surface outcrop, and the volume of cover, the Carboniferous is the most important system within the region. Stratigraphically the rocks are divided into two subsystems; the Dinantian or Lower Carboniferous and the Silesian or Upper Carboniferous. The Dinantian is further divided into two series; the Tournaisian below, and the Viséan above. The Dinantian is also known as the Carboniferous Limestone Series. The Upper Carboniferous is represented by the Namurian (Millstone Grit Series) and the Westphalian (Coal Measures).

During the Dinantian, sedimentation was closely controlled by the structural blocks, with considerable lateral variations in thickness. Figure 2 shows the variation in thickness of several kilometers of the Dinantian, between the blocks and troughs. Essentially this was a period of major cyclic sedimentation (Ramsbottom, 1973), in which the transgressive periods were represented by bioclastic limestones or calcareous shales, and the regressive phases by the presence of oolitic or calcitic mudstones, often desiccated and dolomitized, and stromatolites and nodular algae. The most important feature of this cyclic sedimentation was the progressive burial of the block areas. Deposition in the troughs began in the Tournaisian, and in some regions was a continuation of Old Red Sandstone sedimentation. The blocks formed gradually dwindling islands which were not covered till late Visean times (Johnson, 1967). In some areas, individual beds e.g. Roman Fell beds (Burgess and Harrison, 1967) showed marked changes in thickness and facies over hinge lines at the margins of the blocks, and which were due to contemporaneous movement during sedimentation. Reefs formed along the southern margin of the Askrigg block and indicate basement control (Johnson, 1967).

The Namurian is considered to be transitional from the marine-esturine conditions of the Viséan, to the

Figure-2

COMPARATIVE SECTIONS OF LOWER CARBONIFEROUS STRATA



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lagoon-swamp conditions of the Coal Measures, and is characterised by cyclic sedimentation. Lateral thickness variations follow a similar but less pronounced pattern as the Visean. The 'Yoredale' facies consist of a repetitive sequence of limestones, marine shales and subordinate sandstones, similar to the Visean. The second facies of the Namurian is the 'Millstone Grit', characterised by thick, coarse grained, cross bedded sandstones, together with fine-grained sandstones, siltstones and mudstones, in which marine intercalations are comparatively thin. The boundary between these facies originally lay along the Craven faults, but gradually moved northwards over the Alston block.

Cyclic sedimentation continues into the Westphalian, in which the depositional environment is regarded as deltaic. Sedimentation occurred in low lying, paralic plains, occupied by swamps and brackish and freshwater lagoons, in which accumulated muds, silts, and vegetable debris. River distributaries brought deltaic sands with occasional marine incursions.

At 295 $\pm$ 6 m.y. (Fitch and Miller, 1967) a substantial intrusion of quartz dolerite occurred as a sill complex (Whin Sill) and associated dykes. Although not forming any part of the basement, the Whin stone forms a prominent quarried horizon.

During the Permo-Trias substantial thicknesses of marine sediments occurred within the Cleveland Basin of N. Yorkshire and of red beds in the Eden Valley-Carlisle Basin. Both basins lie at the margin of the investigated region.

1.3 Crustal Structure

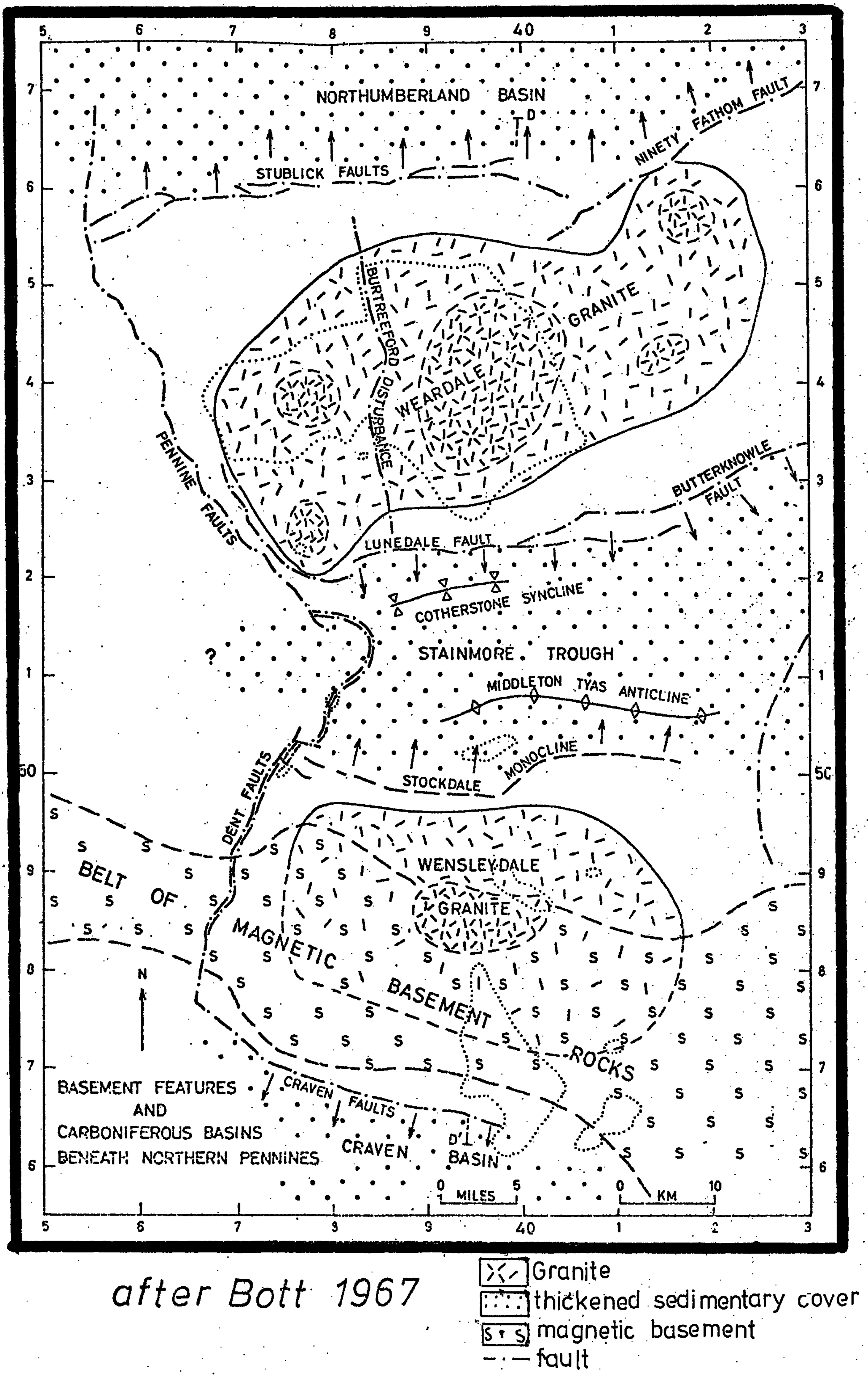
1.3.1 Upper Crustal Structure

The relationship of the cover to the basement structure of the Northern Pennines was interpreted by Bott (1967), from the gravity and magnetic anomalies. Figure 3 shows the suggested basement features of the area.

The most essential feature of the Bouguer anomaly map shown in Figure 4 is the low values associated with the granite batholiths. The best fitting models for the Weardale granite indicate a background density contrast of -110 to -150 kg/ m^3. For a contrast of -130 kg/ m^3, the base to the granite was interpreted at 8.8 km. The Bouger anomalies reach a minimum of -24 Mgall near Rookhope, and have a second derivative which gave a maximum depth to the upper surface of the granite of 1 km (Bott, 1960). The Wensleydale granite has a similar negative anomaly, but is smaller in amplitude and has lower gradients. A base between 5.7 km and 9.5 km for a density contrast of -120 to -80 g/ m^3 is indicated. Spratling (1973) found a minimum value of about -12 Mgall for the Cheviot granite and interpreted the base at least 6 to 7 km deep for a density contrast of -100kg/ m^3.

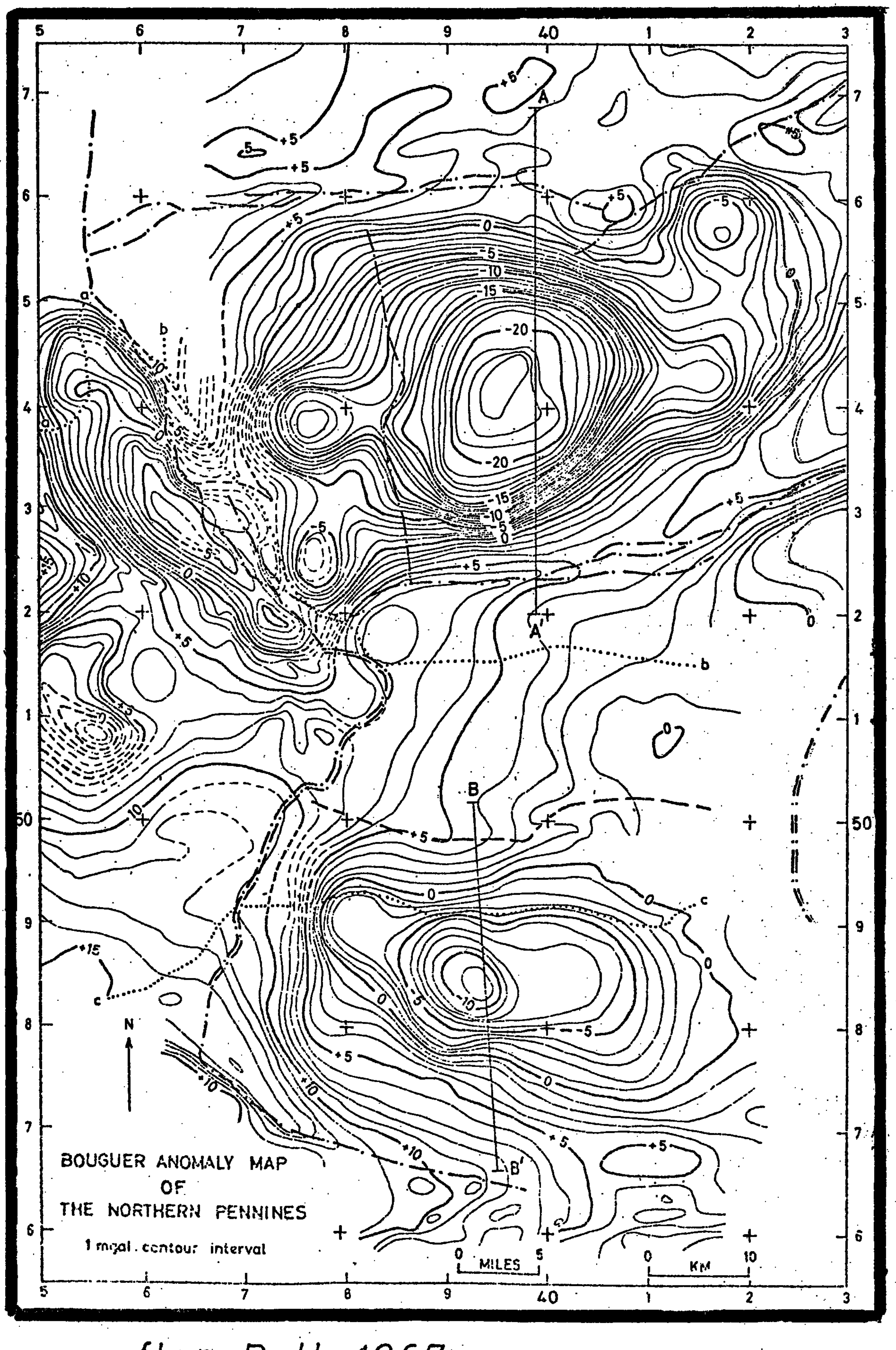
The most striking feature of the total field magnetic anomaly map shown in Figure 5 are the east-west trending belt of magnetic basement rocks found across the Askrigg block. These rocks underlie the Ingletonian and require a susceptibility of at least 6.3×10^{-10} Hm^{-1} (Bott, 1961). Their relationship on the southern flank of the Wensleydale granite suggests that these rocks have formed a

Figure 3



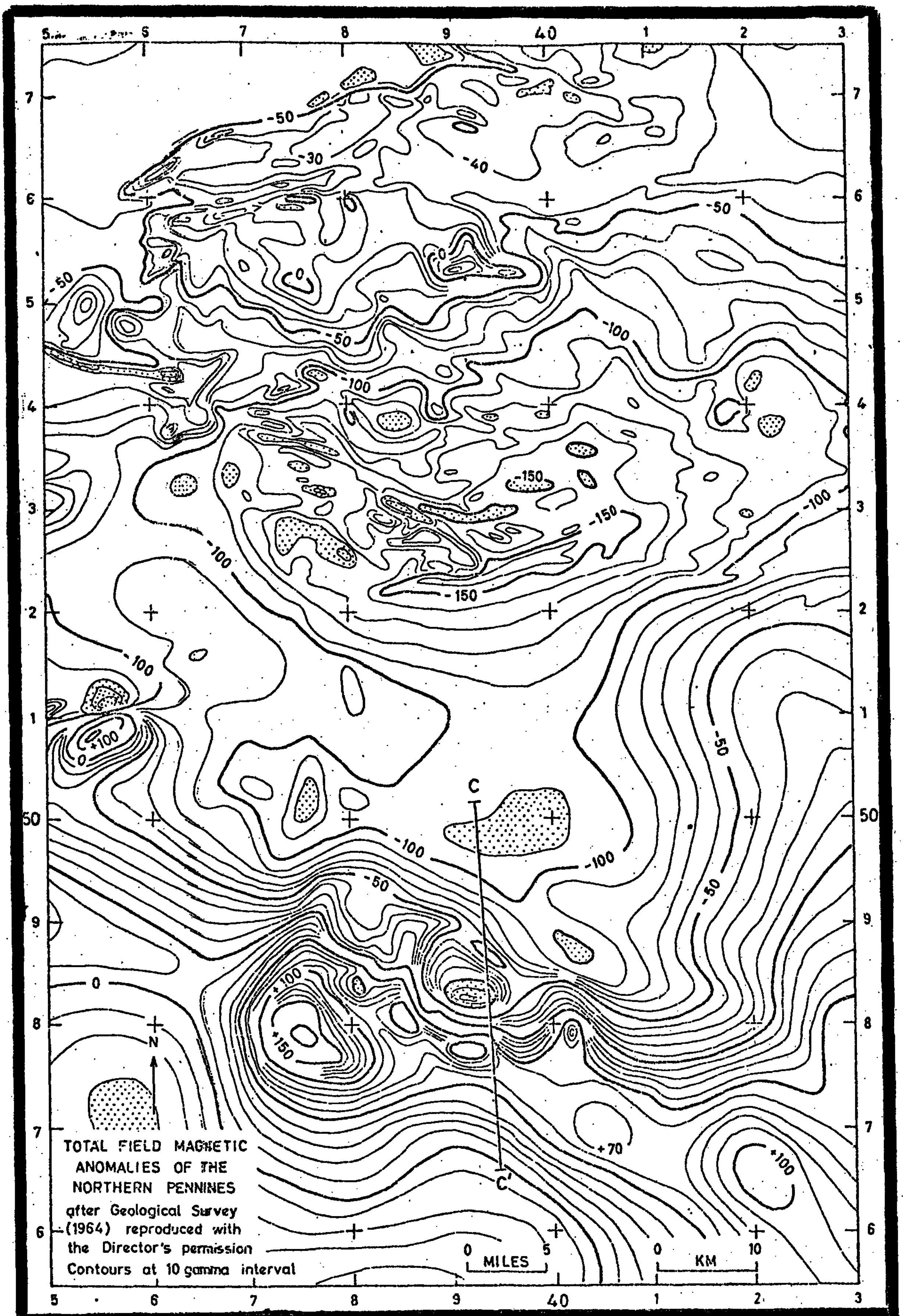
after Bott 1967

Figure 4



after Bott 1967

Figure 5



after Bott 1967

cover through which the granite was intruded. Both granites are only weakly magnetised.

Gravitationally and magnetically, the basement beneath the sedimentary troughs appears to be featureless. Gravity traverses on the margins of the blocks indicate a substantial thickening of low density cover (Bott, 1967). However, these gravity anomalies are partially negated by the effects of the low density granites. This makes the interpretation of the central and western section of the Stainmore Trough and the southern margin of the Northumberland Trough rather difficult. To the east, the anomaly over the Ninety Fathom fault indicates a thickening of 1800 m of low density (-150 kg/m^3) sediments into the Northumberland Trough. Along the Butterknowle-Lunedale fault a thickening of 3050 m of the cover over 8 km for a density contrast of -150 kg/m^3 is indicated towards the Stainmore Trough. To the west, the anomaly becomes confused with the Weardale granite anomaly, but when the residual effects are taken into account, there appears to be a thickening of 1200 to 1500 m of lower Carboniferous with a density contrast of -150 kg/m^3.

In an effort to resolve the ambiguities of the gravity interpretation of the basement-cover relationships, three upper crustal refraction surveys within the region have been attempted.

Archer (1971) investigated the basement-cover structures between Weardale and Berwick upon Tweed. He found a best fitting basement velocity of 5.6 $\pm$ 0.1 km/sec. Although there is some doubt as to the size of the time terms found, and the velocity of the cover, the survey did show a thickening of the cover within the Northumberland Trough and towards the North Sea.

Kidd (1972) attempted to survey to the south of Weardale, over the Stainmore Trough and Askrigg block. The low basement refractor velocity of 5.5 to 5.6 km/sec resulted in small time terms within the Stainmore Trough, but they did indicate a thickening of the cover.

Griffiths (1974) examined the seismic basement of the Stainmore Trough. As this project was undertaken jointly, a detailed interpretation is given in Section 2.7. The survey did find that the cover increased in thickness to about 3 Km within the trough.

The relatively high heat flow at Rookhope, estimated at $89.0\ mWm^{-2}.s^{-1}$. (Bott et al., 1972) may be explained by the high observed radioactivity of the underlying Weardale granite, and a higher contribution from beneath the granite, than in North Yorkshire. The high heat flow of $96.2\ mWm^{-2}.s^{-1}$. recorded at Woodland on the southern edge of the Alston block may be due to the circulation of hydrothermal waters near the Butterknowle fault system.

The previous geophysical interpretations have clearly indicated the subsurface shape of the granite batholiths beneath the blocks, and the lateral variations of the cover within the sedimentary troughs. The suggested upper crustal structure is similar to that interpreted by Powell (1971) beneath Eskdalemuir, of a thick pile of lower Palaeozoic greywackes resting above a pre-Palaeozoic high grade granulite basement, through which the granites have been intruded.

1.3.2. Lower Crustal Structure

Agger and Carpenter (1965) suggested from the interpretation of a refraction experiment between the Irish and North Seas, a single crustal layer 27.1 and 25.1 km thick beneath Eskdalemuir and Rookhope respectively. They found a Pn velocity of 7.99 ± 0.10 km/sec and a Pg velocity of 6.29 ± 0.10 km/sec. However this experiment was not designed to obtain the best velocity determinations using the time term method.

Jacobs (1969) reported two crustal phases recorded at Eskdalemuir; a 'slow' Pg arrival of 5.5 to 6.0 km/sec, and a 'fast' arrival of 6.4 to 6.5 km/sec. He interpreted the fast arrivals as originating from a first order discontinuity at approximately 12 km deep.

Further evidence of a lower crustal, high velocity layer came from the identification of P* arrivals from two British earthquakes recorded at Eskdalemuir (Key, Marshall and MacDowell, 1964). Collette (1970) also identified a lower crustal layer with a velocity of 6.5 to 7.0 km/sec from arrivals recorded at Eskdalemuir, from shots in the North Sea. He further suggested this layer may be anorthositic in composition. Similar phase velocities of about 6.5 km/sec were reported from Central Scotland (Crampin et al., 1970) and in Northern Scotland (Smith, 1974). Blundell and Parks (1969) reported P* arrivals with a velocity of 7.3 km/sec from a refraction experiment in the Irish Sea. They interpreted their results on the basis of three crustal layers with interfaces at 4, 24 and 30 Km.

Jain and Wilson (1967) used the Magneto-Telluric method to examine the crustal structure beneath Eskdalemuir and the Irish Sea. They suggested a lower crustal layer between 12 Km deep and 30 Km deep, with a resistivity of 45 ohm metres.

The geophysical interpretations suggested the existence of a high velocity,low resistivity, lower crust beneath Northern England.

1.4 Aim of the Present Survey

The available geological and geophysical evidence indicated substantial variations in the thickness of sedimentary cover. To solve the uncertainties of the gravity interpretation it was decided to map out these variations in cover, using the refraction technique. This upper crustal survey, using quarry blasts recorded at mobile stations was well suited to the interpretation of Pg arrivals using the time term method. Previous attempts to solve this problem, using the same technique, had poorly connected networks and inadequate velocity determination.

The previous geophysical interpretations did not determine the deep crustal structure in any detail beneath Northern England. In particular, the velocity structure of the upper crust and the existence of a lower crust was to be examined by measuring crustal phase velocities across two arrays:- Rookhope and Eskdalemuir. Systematic variations in the thickness of the main crustal layers across the principal structural units were to be determined by recording along an auxiliary refraction line parallel to the main L.I.S.P. B project. The study of the dispersion of surface waves from teleseismic events, between Eskdalemuir and Wolverton stations, was to ascertain the deep structure of England.

CHAPTER 2

BASEMENT-COVER RELATIONSHIPS OF N.E. ENGLAND

2.1 Introduction

The aim of this study was to examine the variations in thickness of sedimentary cover using the refraction technique, by recording local quarry blasts, and to interpret the arrivals (Pg) by using the time term method. This upper crustal refraction experiment involved the measurement of travel times between the source and mobile recording equipment over a range of 10 to 60 km. As more travel times than stations (sources and recording sites) were measured, a least squares solution was obtained by treating the delay of the refracted wave through the low velocity cover (time term) as a variable for each station.

2.2 Planning

The time term method as introduced by Scheidegger and Willmore (1957) and amplified by Willmore and Bancroft (1960), provides a most powerful interpretive tool for the refraction method. Its greatest use is in obtaining the maximum statistical information from an extended or irregular shot-receiver arrangement, such as that used in this experiment. Meaningful results are only obtained if the limitations and principles (Willmore and Bancroft, 1960) of the method are kept in mind.

It is important that the quarry and recording stations form an extended pattern to provide adequate information on the velocity of the refractor. As many widely dispersed quarries as possible were used, but in regions with few quarries e.g. the Stainmore Trough, recording stations were in a higher density. For economic and geological reasons, quarries tend to be clustered in specific areas, e.g. along the Whin Sill in Northumberland.

The network was closely linked to Rookhope station, at which most of the quarries used in the survey were recorded. Quarries not linked to Rookhope and situated at the fringe of the survey gave inconsistent delay times.

A compromise had to be achieved between waiting for the maximum number of shots to a station, or moving on the recording equipment to form another station. The balance between quality and the number of stations used in the resolution of a structure was achieved by leaving a station to operate for between one and four weeks.

It was impossible to arrange recording equipment at a quarry site because of the high noise levels generated by the plant. Several quarries were situated within well dispersed basement inliers. At the most important link station, Rookhope, the structure was well known from the borehole and the delay term could be measured directly (2.5.4).

Problems concerning the dip and curvature of the refractor (2.5) were minimised by not placing recording sites directly over the hinge lines of the troughs. If a consistent set of time terms were obtained within a given structural unit, then it was reasonable to presume that this reflected a real significance.

2.3 Quarry Blasts as a Seismic Source

It was usually the aim of the quarry manager to crush the maximum amount of rock, using the minimum amount of explosives, and to reduce the level of anti-social ground vibrations. From a seismological point of view this was extremely inefficient.

A typical quarry had between 6 and 24 holes drilled behind the working face, and filled with a mixture of a primary charge of gelignite and ammonium nitrate. Stemming (gravel) was placed in the upper part of the hole to tamp the explosive. The holes were fired either electrically with short delay (20 m.s.) detonators between holes, or using Cordtex detonating line with delaying relays.

The effect of the delays was to propagate a crack along the edge of the face (cf. frontispiece), in a similar mechanism to an earthquake. It has been shown (Willis, 1963) that the maximum ground velocity for compressional and shear waves is independent of the number of holes. Surface wave energy is not so effectively reduced. The seismic efficiency of a quarry blast was then reduced to the equivalent of one hole.

Although the amount of explosives used in the quarries connected with this experiment, varied from two to forty thousand pounds, the amount per hole remained reasonably constant at between 200 to 500 lbs/hole. On a qualitative basis, there seemed to be little difference in amplitude of recorded waves at the same range but from different quarries. Although most energy at the source is in the range 100 to

Figure 6

The Recording Equipment

500 Hz (Willis, 1963), the ground acts as a low pass filter and most energy at the recording site was near to 5 Hz.

Quarry blasts are usually detonated at the end of a working shift e.g. midday or late afternoon. Particular quarries kept to a particular shot time, which made the identification of the source much simpler.

2.4 Data Collection

2.4.1 Logistics

Two sets of mobile recording equipment were transported to preselected sites and left continuously recording. As many quarry blasts as possible were recorded at their sources, so that the travel time could be calculated from the first arrival of the replayed records.

2.4.2 The Recording Equipment

As many as two, three component, F.M. recording sets were used (Long, 1974), c.f. Figure 6.

The recording equipment consisted of three units; a modified ¼" tape deck, a digital clock, and a three channel seismic amplifier and frequency modulator unit. The tape deck was run at a speed of 0.1"/sec, giving up to 4½ days of continuous recording on a 3,600' triple play, 7" reel. The clock generated a modified IRIG C type time code, using a thermally compensated crystal, operating at 5 MHz, to provide a stability of better than 1 part in 10^6. The amplifier had a broad band response. Gain levels were switched electronically by powers of two.

The system recorded frequency modulated signals about a central frequency of 84 Hz, using 8 tracks. A set of three component Willmore MK2 seismometers were recorded with intervening blank tracks to reduce crosstalk. A reference frequency of 100 Hz was recorded so that the replay could be adjusted for flutter compensation. The output from the clock was recorded on another track, and the signal from a 60 KHz M.S.F. radio standard on yet another.

Synchronisation of the clock, using the M.S.F. radio was achieved automatically to allow resetting to 0.1 sec of the minute marker. Further synchronisation was made manually, by observing the relative phases of the radio and clock pulses. The drift of the clock was about 0.3 sec/week. The time code was encoded within ten second blocks. Two digit numbers in successive blocks encoded minutes, hours, days, station number, gain and system mode.

Calibration of the seismometers was achieved by impulses of current to the seismometers. The lower frequency cut-off of the system depended on the natural period of the seismometer, which was set at about 1 Hz. The upper frequency cut-off depended on the system, which in this case was about 20-30 Hz. The response within the passband depended on the system electronics and the damping of the seismometer, which was set at about 0.6.

The equipment was designed for low power consumption, which was less than 0.6 watts. Power was supplied via eight PP9 batteries or through a car accumulator. The system was reasonably compact and portable and entirely self contained. Numerous check-out facilities were provided, the most useful of which was an audio channel via a separate monitor and replay channel to check the F.M. recorded signal.

The recording equipment used to measure the source time consisted of a modified cassette recorder, an M.S.F. radio and a geophone. The input impedance of the recorder was altered to prevent radio pick up. The signal from the geophone and the M.S.F. radio were mixed and recorded directly on the cassette.

2.4.3 Recording sites

The choice of site was always a compromise between optimum noise conditions, e.g. distance from trees and roads, availability of bedrock and easy access. The position of the site was determined from the existing network and the relationship of the site to the structure being investigated.

The recording equipment was usually left running in a farm out-building such as a disused hen coop. Cables were run out to a covered pit, dug to near bedrock, so as to keep wind noise on the three component set of seismometers to a minimum.

It was found that a sufficient signal to noise ratio was achieved when the seismometers were directly coupled to bedrock. When this was not possible, it was found that the noise levels were particularly high during strong winds, especially on thick regolith.

2.4.4 Recording at Quarries

The geophone was placed about 10-20 m behind the first hole to be fired. A screened cable 100 to 200 m long was laid out to a safe recording distance. The recorder was switched on when the warning of the blast was sounded, and left running for several minutes to enable minute markers to be identified.

2.4.5 Rookhope Station

A permanent three component system was in operation throughout the entire period of the project. The output from a set of three component Willmore MK1 seismometers was recorded frequency modulated on a 1" EMI deck, along with the signals from a crystal clock and a radio time standard.

It was hoped during the experiment that it would be necessary to measure the travel time between a quarry and Rookhope once only. From then on it would be necessary to enquire the approximate time of the shot, the origin time being the Rookhope arrival time minus the measured travel time. In practice this rarely worked out, as frequently the quarry blast was not observed at Rookhope.

2.4.6 Replay of Recordings

The ¼" tapes were replayed at 10 times their recording speed. The replay heads were adjusted to achieve the optimum flutter compensation, the signals were demodulated and then passed through Krohn-Hite filters set to a specific bandwidth. A bandwidth of 2 to 10 Hz was judged to give the best signal to noise improvement. The output was replayed on a jet pen recorder and consisted of three filtered and unfiltered seismic channels, with time (clock and M.S.F. radio) channels at both edges of the record. The static offset of each channel of the jet pen was checked by a marker pulse.

The cassette recordings of the quarry blasts were replayed directly through to the jet pen recorder. The one inch Rookhope tapes were replayed through an EMI deck and demodulators, in a similar manner to the ¼" tapes.

2.4.7 Calculation of Travel Times and Distances

From the analogue playback, the onset of the Pg arrival was calculated. This time was normally read off the unfiltered records, using the filtered channels to establish the character of the signal. The accuracy of the initial break of the Pg wave was dependent on the frequency content and signal to noise ratio. This error was judged to be a maximum of about 0.1 seconds.

The quarries and recording stations were positioned on 2½" and 6" Ordnance Survey maps. Little difficulty arose in establishing the grid coordinates of the recording site, as the many reference points of the farm buildings gave accuracies of better than 50 m. The position of the shots was much more difficult to assess, because of the constantly changing position of the working face. The total error in distance between any two stations was judged to be a maximum of 0.2 Km.

2.4.8 The Data

A total of 94 travel time equations were obtained from 22 sources and 29 recording stations. The full data set is given in Table 1, and includes those travel times obtained by Archer (1971), Kidd (1972) and Griffiths (1974).

2.5 The Time Term Method

The travel time of the refracted wave between two stations can be written as:-

Table 1
Time Term Data

DATA CARDS

STATION		NUM	TO	STATION	NUM	TRTRM	ERROR	DIST	ERROR	C	ERROR	ERG	D	ERROR	ERG	RESID	ERROR	ERG
H FORCE	Q	15	TO	KIDDS 6	14	3.98	0.02	19.91	0.12	-0.72	0.26	0.05	-3.98	0.65	0.13	-0.02	0.38	0.05
LEYBRN	Q	16	TO	KIDDS 5	13	5.13	0.10	26.70	0.04	-1.16	0.44	0.12	-6.42	0.54	0.08	-0.04	0.54	0.12
H RIBB	Q	18	TO	KIDDS 9	17	3.87	0.05	20.85	0.12	-4.08	0.44	0.07	-22.82	0.71	0.13	-0.08	0.59	0.09
EAST	Q	8	TO	KIDDS 9	17	9.26	0.05	50.05	0.22	5.77	0.41	0.07	32.14	0.79	0.23	0.14	0.50	0.11
LEYBRN	Q	16	TO	KIDDS 9	17	3.08	0.10	15.82	0.04	-1.69	0.46	0.11	-9.31	0.60	0.07	-0.06	0.58	0.12
NEWL	Q	11	TO	ROOKHOPE	7	1.27	0.02	7.10	0.15	-0.94	0.12	0.03	-5.20	0.35	0.15	-0.03	0.19	0.04
NEWL	Q	11	TO	KIDDS 5	13	4.10	0.05	21.59	0.12	1.16	0.32	0.08	6.42	0.59	0.14	0.04	0.41	0.09
NEWL	Q	11	TO	KIDDS 6A	14	4.74	0.05	24.68	0.12	0.72	0.26	0.07	3.98	0.62	0.13	0.02	0.36	0.07
NEWL	Q	11	TO	KIDDS 2	12	1.45	0.02	7.75	0.12	-0.00	0.22	0.04	-0.00	0.64	0.13	0.00	0.33	0.05
EAST	Q	8	TO	ROCKHOPE	7	1.15	0.10	5.56	0.22	-3.14	0.27	0.10	-17.47	0.47	0.22	-0.07	0.38	0.12
MOCT	Q	3	TO	ROCKHOPE	7	6.67	0.10	33.57	0.12	2.27	0.34	0.11	14.08	0.41	0.13	-0.20	0.39	0.12
MOCT	Q	3	TO	ARCH R8	2	7.37	0.10	35.75	0.12	-3.09	0.59	0.14	-17.65	0.76	0.15	0.01	0.75	0.14
SWINB	Q	5	TO	ROOKHOPE	7	6.65	0.10	34.12	0.10	0.18	0.35	0.12	1.38	0.37	0.12	-0.06	0.41	0.12
EAST	Q	8	TO	ROCKHOPE	7	1.15	0.10	5.56	0.27	-3.14	0.27	0.10	-17.47	0.52	0.27	-0.07	0.39	0.12
EAST	Q	8	TO	ARCH P6	6	3.43	0.10	17.04	0.30	0.00	0.52	0.15	0.00	1.09	0.32	0.00	0.71	0.16
KIRK	Q	4	TO	ROCKHOPE	7	7.62	0.10	41.25	0.16	0.00	0.22	0.14	0.00	0.32	0.19	-0.00	0.28	0.15
EAST	Q	8	TO	ROCKHOPE	7	1.15	0.10	5.56	0.11	-3.14	0.27	0.10	-17.47	0.36	0.11	-0.07	0.36	0.11
EAST	Q	8	TO	ROCK S1	9	0.73	0.10	3.38	0.12	0.00	0.52	0.15	0.00	0.73	0.16	0.00	0.65	0.15
EAST	Q	8	TO	ROCK S2	10	0.94	0.10	4.63	0.11	-0.00	0.52	0.13	-0.00	0.79	0.14	0.00	0.66	0.13
EAST	Q	8	TO	ARCH P8	2	13.43	0.10	74.59	0.12	3.09	0.52	0.13	17.65	0.72	0.15	-0.01	0.62	0.14
EAST	Q	8	TO	ROCKHOPE	7	1.15	0.10	5.56	0.27	-3.14	0.27	0.10	-17.47	0.52	0.27	-0.07	0.39	0.12
EAST	Q	8	TO	ROCK S2	10	0.94	0.10	4.63	0.27	-0.00	0.52	0.13	-0.00	0.95	0.28	0.00	0.69	0.14
LISPB1	S	20	TO	GOFTF 03	21	4.34	0.02	22.59	0.10	-0.64	0.32	0.06	-4.57	0.51	0.11	0.16	0.42	0.06
LISPB1	S	20	TO	HIND 04	22	3.14	0.02	15.49	0.10	0.00	0.29	0.05	0.00	0.58	0.11	0.00	0.39	0.05
LISPB1	S	20	TO	ROCKHOPE	7	8.52	0.03	47.61	0.10	-0.40	0.16	0.04	-2.36	0.29	0.10	0.02	0.22	0.05
LISPB2	S	20	TO	WCLIFF05	23	4.32	0.02	24.20	0.10	0.00	0.29	0.05	0.00	0.58	0.11	0.00	0.39	0.05
LISPB2	S	20	TO	THURST06	24	6.53	0.05	33.55	0.10	0.00	0.35	0.08	0.00	0.58	0.12	-0.00	0.45	0.08
LISPB2	S	20	TO	ROCKHOPE	7	8.58	0.05	47.61	0.10	-0.34	0.18	0.06	-2.36	0.29	0.10	0.08	0.24	0.06
LISPB2	S	20	TO	CGLE C7	25	9.92	0.03	54.47	0.10	0.96	0.37	0.07	5.88	0.59	0.12	-0.08	0.46	0.08
LISPB3	S	20	TO	BED 08	26	12.07	0.03	66.59	0.10	0.81	0.37	0.07	5.77	0.59	0.12	-0.20	0.46	0.08
LISPB3	S	20	TO	ROOKHOPE	7	8.53	0.03	47.61	0.10	-0.39	0.16	0.04	-2.36	0.29	0.10	0.03	0.22	0.05
BARRAS	Q	27	TO	GOFTF 03	21	2.21	0.03	9.32	0.05	0.28	0.40	0.08	1.87	0.48	0.09	-0.05	0.49	0.08
BARRAS	Q	27	TO	ROCKHOPE	7	6.10	0.10	31.81	0.05	0.24	0.31	0.12	1.46	0.26	0.08	-0.02	0.35	0.12
MOCT	Q	3	TO	BED 08 R	26	5.93	0.10	24.58	0.10	-0.81	0.55	0.13	-5.77	0.70	0.13	0.20	0.68	0.13
MOCT	Q	3	TO	CGLE 07R	25	3.49	0.10	12.24	0.10	-0.56	0.55	0.13	-5.88	0.70	0.13	0.08	0.68	0.13
CRAGHL	Q	28	TO	BELFORDR	19	1.26	0.05	3.75	0.05	-0.00	0.75	0.17	-0.00	0.89	0.17	0.00	0.92	0.18
MOOT	Q	3	TO	BELFORDR	19	11.40	0.10	58.09	0.10	0.00	0.66	0.16	0.00	0.79	0.16	-0.00	0.80	0.16
BELFRD	Q	1	TO	ELSDEN R	29	8.87	0.05	46.49	0.10	0.00	0.76	0.17	0.00	0.99	0.19	-0.00	0.94	0.18
L HAUG	Q	30	TO	ELSDEN R	29	7.48	0.02	38.91	0.05	0.00	0.70	0.16	0.00	0.89	0.17	-0.00	0.86	0.16
MOCT	Q	3	TO	ELSDEN R	29	4.41	0.10	18.50	0.10	0.00	0.66	0.16	0.00	0.79	0.16	0.00	0.80	0.16
RAISBY	Q	31	TO	DURHAM R	32	2.51	0.03	10.14	0.05	-0.00	0.46	0.07	-0.00	0.61	0.08	-0.00	0.57	0.07
HARDEN	Q	33	TO	ROOKHOPE	7	11.70	0.10	65.86	0.10	0.00	0.22	0.14	0.00	0.20	0.14	-0.00	0.26	0.14
RAISBY	Q	31	TO	ROCKHOPE	7	8.23	0.10	41.61	0.10	-0.06	0.31	0.11	-1.96	0.35	0.11	0.28	0.38	0.11
MARSDN	Q	35	TO	ROCKHOPE	7	9.60	0.10	51.21	0.05	0.00	0.22	0.14	0.00	0.10	0.11	-0.00	0.24	0.14
BARR	Q	27	TO	EBCHESTR	36	4.91	0.10	23.55	0.10	-0.51	0.53	0.13	-3.32	0.59	0.13	0.07	0.64	0.13
EAST	Q	8	TO	EBCHESTR	36	4.96	0.10	26.10	0.10	1.12	0.49	0.12	6.56	0.63	0.12	-0.03	0.60	0.12

Table 1 (cont.)

MOCT Q	3 TO EBCHESTR	36	4.25	0.10	17.82	0.10	0.29	0.57	0.12	1.81	0.68	0.12	-0.02	0.68	0.12
MOCT Q	3 TO LANCHSTR	37	6.59	0.10	31.46	0.10	2.29	0.58	0.13	13.40	0.69	0.13	-0.06	0.68	0.13
SWNBRN Q	5 TO LANCHSTR	37	7.24	0.10	36.31	0.10	0.87	0.59	0.13	5.01	0.67	0.13	-0.01	0.70	0.14
SWNBRN Q	5 TO EBCHESTR	36	4.98	0.10	22.87	0.10	-1.05	0.57	0.13	-6.38	0.65	0.13	0.07	0.70	0.13
EAST Q	8 TO LANCHSTR	37	4.44	0.10	22.48	0.10	0.25	0.51	0.12	0.89	0.65	0.12	0.09	0.62	0.12
EAST Q	8 TO EBCHESTR	36	4.86	0.10	26.10	0.10	1.02	0.49	0.12	6.56	0.63	0.12	-0.13	0.60	0.12
RAISBY Q	31 TO EBCHESTR	36	6.95	0.10	34.86	0.10	-0.87	0.53	0.12	-5.22	0.64	0.12	0.05	0.65	0.12
RAISBY Q	31 TO LANCHSTR	37	4.77	0.10	22.83	0.10	-3.40	0.55	0.12	-19.30	0.65	0.12	-0.01	0.69	0.13
WALTWN Q	34 TO ROCKHOPE	7	6.71	0.10	35.23	0.10	-0.37	0.28	0.13	-2.70	0.27	0.13	0.11	0.33	0.13
WALTWN Q	34 TO GOFTON R	21	3.51	0.10	17.73	0.05	0.37	0.45	0.13	2.70	0.45	0.10	-0.11	0.52	0.14
HORT Q	18 TO CAVE 01	39	5.41	0.04	52.30	0.05	1.38	0.39	0.06	7.80	0.55	0.07	0.01	0.48	0.07
ARCO Q	38 TO CAVE 01	39	9.80	0.05	53.56	0.05	-1.38	0.33	0.07	-7.80	0.43	0.07	-0.01	0.42	0.07
HORT Q	18 TO CAVE 02	40	9.16	0.04	49.19	0.06	0.12	0.42	0.06	-0.30	0.60	0.08	0.17	0.52	0.07
EAST Q	8 TO DAVE 02	40	3.60	0.05	17.99	0.10	-0.97	0.41	0.07	-5.74	0.62	0.11	0.03	0.52	0.07
SWIND Q	41 TO CAVE 02	40	11.25	0.05	60.35	0.10	-0.07	0.42	0.07	0.29	0.63	0.11	-0.12	0.53	0.07
RAISBY Q	31 TO DAVE 02	40	9.48	0.10	50.03	0.10	0.93	0.50	0.11	5.76	0.63	0.11	-0.08	0.60	0.12
HORT Q	18 TO CAVE 03	42	7.50	0.10	40.14	0.05	-1.86	0.55	0.13	-10.67	0.61	0.10	0.01	0.67	0.13
RAISBY Q	31 TO CAVE 03	42	10.73	0.10	56.26	0.10	1.86	0.56	0.13	10.67	0.65	0.13	-0.01	0.66	0.14
HORT Q	18 TO CAVE 04	43	7.91	0.04	41.99	0.06	-0.74	0.42	0.06	-4.66	0.60	0.08	0.08	0.53	0.07
EAST Q	8 TO DAVE 04	43	5.07	0.05	25.04	0.10	0.89	0.40	0.07	4.15	0.62	0.11	0.16	0.51	0.07
RAISBY Q	31 TO DAVE 04	43	9.22	0.10	48.18	0.10	1.06	0.49	0.11	6.75	0.63	0.11	-0.12	0.59	0.12
SWIND Q	41 TO CAVE 04	43	9.72	0.04	50.99	0.10	-1.21	0.40	0.06	-6.24	0.63	0.11	-0.12	0.52	0.07
HORT Q	18 TO DAVE 05	44	6.48	0.05	34.47	0.06	0.00	0.47	0.08	0.00	0.65	0.09	-0.00	0.58	0.08
SWIND Q	41 TO CAVE 06	45	7.20	0.04	36.37	0.05	-2.85	0.38	0.06	-16.65	0.55	0.07	0.07	0.50	0.07
RAISBY Q	31 TO CAVE 06	45	10.58	0.10	56.62	0.10	3.30	0.47	0.11	19.40	0.60	0.11	-0.10	0.55	0.12
EAST Q	8 TO DAVE 06	45	7.34	0.05	39.74	0.10	4.04	0.38	0.07	23.06	0.59	0.11	-0.01	0.45	0.09
LEYRN Q	16 TO CAVE 06	45	3.76	0.02	18.49	0.05	-0.82	0.35	0.05	-5.41	0.53	0.07	0.13	0.45	0.05
GIGGL Q	46 TO DAVE 06	45	6.52	0.03	34.56	0.05	-3.67	0.36	0.06	-20.40	0.49	0.07	-0.09	0.48	0.07
GIGGL Q	46 TO DAVE 07	47	8.50	0.08	45.37	0.05	0.49	0.42	0.10	2.06	0.50	0.07	-0.01	0.51	0.10
LEBN Q	16 TO CAVE 07	47	1.86	0.02	8.88	0.05	-0.55	0.37	0.05	-2.58	0.53	0.07	-0.09	0.46	0.06
SWIND Q	41 TO CAVE 07	47	7.93	0.05	40.29	0.05	0.06	0.41	0.07	-0.28	0.55	0.07	0.11	0.50	0.07
RAISBY Q	31 TO CAVE 08	48	6.61	0.05	32.55	0.10	-1.58	0.44	0.07	-8.44	0.66	0.11	-0.10	0.57	0.08
HORT Q	18 TO DAVE 08	48	9.93	0.02	53.71	0.10	1.25	0.39	0.05	7.50	0.67	0.11	-0.06	0.50	0.06
SWIND Q	41 TO CAVE 08	48	11.28	0.05	57.73	0.10	0.32	0.41	0.07	0.95	0.66	0.11	0.16	0.52	0.07
RAISBY Q	31 TO DAVE 09	49	8.62	0.07	45.44	0.10	-1.18	0.45	0.09	-5.68	0.64	0.11	-0.18	0.57	0.09
HIGHF Q	15 TO CAVE 09	49	5.12	0.02	26.64	0.05	0.70	0.31	0.05	3.60	0.57	0.07	0.07	0.41	0.05
EAST Q	8 TO CAVE 09	49	6.30	0.05	32.65	0.10	0.48	0.35	0.07	2.08	0.63	0.11	0.12	0.50	0.07
SKIP Q	50 TO ROCKHOPE	7	16.10	0.10	90.17	0.10	0.00	0.22	0.14	0.00	0.20	0.14	0.00	0.26	0.14
EAST Q	8 TO ROCKHOPE	7	1.15	0.05	5.56	0.10	-3.14	0.22	0.06	-17.47	0.35	0.10	-0.07	0.31	0.07
HORT Q	18 TO ROCKHOPE	7	12.68	0.04	71.94	0.05	3.93	0.23	0.05	23.16	0.31	0.06	-0.13	0.25	0.07
GIGGL Q	46 TO ROCKHOPE	7	14.35	0.09	78.84	0.05	3.18	0.22	0.06	17.54	0.25	0.06	0.10	0.23	0.07
ARCO Q	38 TO ROCKHOPE	7	13.28	0.02	73.43	0.05	1.38	0.14	0.04	7.80	0.20	0.06	0.01	0.16	0.04
RAISBY Q	31 TO ROCKHOPE	7	8.20	0.10	41.61	0.10	-0.06	0.31	0.11	-1.96	0.35	0.11	0.28	0.38	0.11
LEBN Q	16 TO ROCKHOPE	7	9.79	0.02	53.97	0.05	4.22	0.19	0.04	23.72	0.28	0.06	0.06	0.20	0.06
SWIND Q	41 TO ROCKHOPE	7	14.79	0.02	81.29	0.05	3.76	0.20	0.04	21.93	0.30	0.06	-0.09	0.22	0.06
HART Q	51 TO ROCKHOPE	7	7.40	0.02	36.73	0.05	0.00	0.06	0.03	0.00	0.10	0.06	-0.00	0.08	0.03
NEWL Q	11 TO ROCKHOPE	7	1.27	0.02	7.10	0.10	-0.94	0.12	0.03	-5.20	0.30	0.10	-0.03	0.18	0.04
HIGHF Q	15 TO ROCKHOPE	7	2.91	0.02	15.86	0.10	0.02	0.14	0.03	0.38	0.34	0.10	-0.04	0.20	0.04

$$t_{ij} = \frac{D_{ij}}{V} + a_i + a_j \qquad (1)$$

where t_{ij} = travel time between stations i and j

D_{ij} = distance measured along the refractor between the normals to the station

V = Velocity of the refractor (constant)

a_i, a_j = the 'time terms' of stations i and j and are defined as the delay of the refracted wave caused by the low velocity cover.

In deriving equation (1), Berry and West (1966) assume that:-

1. The velocity of the refracting horizen is very nearly constant.
2. The regional dip of the refractor is not too large.
3. The curvature of the refractor is slight.
4. The velocity structure beneath any site is a function only of perpendicular depth to the refractor.

The observed travel time, T_{ij}, is different from the hypothetical travel time, t_{ij}, because of measurement errors and the non-ideal behaviour of the refractor.

$T_{ij} = t_{ij} + \delta_{ij}$ where δ_{ij} is the residual time.

If the refractor is approximately level then

$D_{ij} \approxeq X_{ij}$ where X_{ij} is the horizontal distance between the stations.

The measured travel time is given by:-

$$T_{ij} = \frac{X_{ij}}{V} + a_i + a_j + \delta_{ij} \qquad (2)$$

If there are n stations (shots and recording sites), then there is a possibility of up to n(n-1) observations, with n+1 unknowns; the delay times of each station and the velocity of the refractor. If there are more observations than unknowns, the problem can be solved by linear regression.

The m sets (number of data) of equations like (2) can be written in matrix notation:-

$$[A][a] = [T] - \frac{1}{V}[X]$$

where [A] is a m by n coefficient matrix

[a] is a column matrix (n x 1) of unknown delay times

[T] is a column matrix (m x 1) of travel times

[X] is a column matrix (m x 1) of distances

V is the scalar quantity of the velocity of the refractor.

It is convenient to divide matrix [a] such that:-

$$e_i - \frac{1}{V} f_i = a_i$$

The two equations:-

$$[A][e] = [T] \qquad (3)$$

and

$$[A][f] = [X] \qquad (3)$$

are independent of the velocity of the refractor. The solution for the sum of the residuals squared to be a minimum is:-

$$[e] = [A^T A]^{-1}[A^T][T]$$

$$[f] = [A^T A]^{-1}[A^T][X]$$

For each travel time equation a quantity is assigned:-

$$C_{ij} = T_{ij} - e_i - e_j$$

and

$$D_{ij} = X_{ij} - f_i - f_j$$

The residual becomes:-

$$\delta_{ij} = C_{ij} - D_{ij}/V$$

Differentiating the sum of the residuals squared with respect to the velocity of the refractor gives the least squares velocity which is:-

$$V = \frac{\sum_{i=1}^{m} D_{ij}^2}{\sum_{i=1}^{m} C_{ij}D_{ij}}$$

2.5.1 Standard Errors

An estimate of the variance of the solution for the least squares velocity is:-

$$\sigma^2 = \frac{\sum_{i=1}^{m} \delta_{ij}^2}{m-n-1}$$

The standard error of the velocity is given by

$$Se(V) = V^2 \, Se(\tfrac{1}{V})$$

where $$(Se(\tfrac{1}{V}))^2 = \frac{\sigma^2}{\sum_{i=1}^{m} D_{ij}^2}$$

The standard error of the k^{th} time term is given by Berry and West (1966) as:-

$$(Se(a_K))^2 = \frac{\sum_{i=1}^{L} \delta_{iK}^2}{L(L-1)}$$

where L = number of observations to station K.

Alternatively the standard error of a time term can be estimated from the diagonal element of matrix $[Q] = [A^TA]^{-1}$:-

$$(Se(a_K))^2 = Q_{KK} \, \sigma^2$$

The confidence limit for each time term is estimated by multiplying the standard error by the appropriate value in Students t distribution tables (two ended) for L-1 degrees of freedom.

2.5.2 Weighting of the Data

It may be necessary to give prominence to a particular travel time. By this means it is possible to improve on the standard error of the unknowns by emphasising the particular travel times with the least observational error. Weighting was achieved by multiplying entire rows of the matrix equations (3) by a given factor.

2.5.3 Constraining the Data

It is sometimes possible to estimate the value of a particular time term by the position of the station relative to the basement. It is convenient to constrain the solution of a particular time term to this value while still treating it as an unknown. This is simply achieved by adding K constraints to the travel times. The first K rows of matrix [A] have only one figure in the i^{th} column instead of two, where the i^{th} time term is to be constrained. The corresponding value in matrix [T] is the constrained term and the value in matrix [X] is set to zero.

2.5.4 Constraints on the basement

The local geology at Rookhope is well known from the borehole (Dunham et al., 1961, 1965), from which the Weardale granite was discovered at a depth of 390 m. Using a velocity of 4.0 km/sec for the cover and 5.5 km/sec for the granite it was possible to estimate the time term at 0.07 seconds.

As part of a project carried out by U.K.A.E.A. and the University of Durham, a borehole seismometer was constructed and operated in the hope of improving the signal to noise ratio for nuclear detection. As the seismometer lay within the basement, the delay between this instrument and a similar surface seismometer situated at the top of the borehole, was a direct measurement of the delay term at Rookhope. Figure 7 shows the result of the measurement of the delay of a number of local events. These events (Section 3.4.1) were measured by matching waveforms or by picking the difference in onset time directly. This measurement was subject to a large relative inaccuracy and consequently the results showed considerable statistical variance. Although bimodal, the results showed a broad agreement with the expected delay.

Several quarries were situated on or very close to the basement. These quarries included Arcow and Horton quarries at Horton in Ribblesdale, High Force quarry in Upper Teesdale, and Harden quarry in the Cheviots.

2.5.5 Two Velocity Solution

Figure 3 shows the two basement rock types known within the network. It is possible to achieve a solution to the best fitting velocity of each rock type. If the velocity contrast between the granite and basement is small, there will be little refraction at the contact. The distance between the stations was divided into that travelled in the granite and that in the basement, using Figure 3 for the distribution of the two basement rock types.

The travel time equation becomes:-

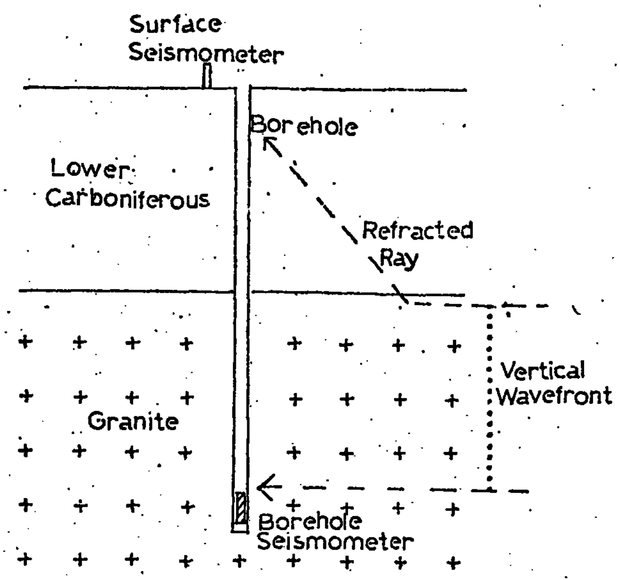
$$T_{ij} = \frac{X1_{ij}}{V1} + \frac{X2_{ij}}{V2} + a_i + a_j + \delta_{ij}$$

where XI_{ij} = distance travelled in basement.

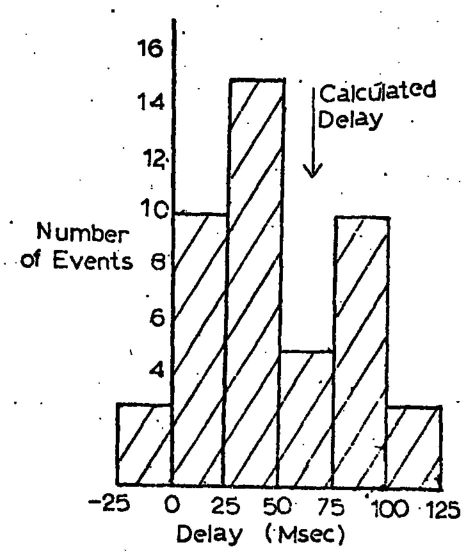
$X2_{ij}$ = distance travelled in granite

Figure 7

Rookhope Delay



Histogram of Delay between Borehole and Surface Seismometers



V1 = velocity of the basement

V2 = velocity of the granite.

Three equations are solved:-

$[A][e] = [t]$

$[A][f1] = [X1]$

$[A][f2] = [X2]$

The time term is given by $a_i = e_i - \frac{f1_i}{V1} - \frac{f2_i}{V2}$

Also defined are:-

$$D1_{ij} = X1_{ij} - f1_i - f1_j$$

$$D2_{ij} = X2_{ij} - f2_i - f2_j$$

The sum of the residuals squared is given by:-

$$I = \sum_{i=1}^{m} \delta_{ij}^2 = \sum_{i=1}^{m} (C_{ij} - D1_{ij}/V1 - D2_{ij}/V2)^2$$

Differentiating I with respect to 1/V1 and 1/V2 gives:-

$$\sum_{i=1}^{m} C_{ij}\, D1_{ij} = \left(\frac{1}{V1}\right) \sum_{i=1}^{m} D1_{ij}^2 + \left(\frac{1}{V2}\right) \sum_{i=1}^{m} D1_{ij}\, D2_{ij}$$

$$\sum_{i=1}^{m} C_{ij}\, D2_{ij} = \left(\frac{1}{V1}\right) \sum_{i=1}^{m} D1_{ij}\, D2_{ij} + \left(\frac{1}{V2}\right) \sum_{i=1}^{m} D2_{ij}^2$$

or in matrix notation

$$\begin{bmatrix} \frac{1}{V1} \\ \\ \frac{1}{V2} \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{m} D1_{ij}^2, & \sum_{i=1}^{m} D1_{ij}\, D2_{ij} \\ \\ \sum_{i=1}^{m} D1_{ij}\, D2_{ij}, & \sum_{i=1}^{m} D2_{ij}^2 \end{bmatrix}^{-1} \begin{pmatrix} \sum_{i=1}^{m} C_{ij}\, D1_{ij} \\ \\ \sum_{i=1}^{m} C_{ij}\, D2_{ij} \end{pmatrix}$$

The standard error for the velocities are:-

$$Se(V1) = V1^2\, Se\left(\frac{1}{V1}\right) \quad \text{where} \quad \left(Se\left(\frac{1}{V1}\right)\right)^2 = \frac{\sigma^2}{\sum_{i=1}^{m} D1_{ij}^2}$$

$$Se\,(V2) = V2^2\, Se(\tfrac{1}{V2}) \text{ where } (Se(\tfrac{1}{V2})) = \frac{\sigma^2}{\sum_{i=1}^{m} D2_{ij}^2}$$

where σ^2 is the estimate of the variance of the solution = I/m-n-2.

2.5.6 Velocity increasing with distance

It is commonly found that velocity increases with distance (c.f. section 3.4.1). If a model of velocity increasing linearly with distance away from the source is proposed:-

$$V = V_o + KX_{ij}$$

where V = velocity at distance X_{ij} away from the source

V_o = initial velocity

K = a factor by which velocity increases.

The travel time is given by:-

$$t_{ij} = \int_i^j (V_o + KX)\, dX = \frac{1}{K}\ln\left(1 + \frac{KX_{ij}}{V_o}\right) = \frac{X_{ij}}{V_o} - \frac{KX_{ij}^2}{2V_o^2} + \frac{K^2X_{ij}^3}{3V_o^3}$$

+ higher terms in K^3 and above.

If K is small e.g. $K = 10^{-3}$ and taking X_{ij} = 70 km; V_o = 5.0 km/sec.

$$\frac{X_{ij}}{V_o} = 14 \text{ sec} \quad \frac{KX_{ij}^2}{2V_o^2} \simeq 10^{-1} \text{ sec} \quad \frac{K^2X_{ij}^3}{3V_o^3} \simeq 10^{-3} \text{ sec which is}$$

below the measurable time accuracy.

Terms in K^2 and above can be neglected and the travel time equation becomes:-

$$T_{ij} = \frac{X_{ij}}{V_o} - \frac{KX_{ij}^2}{2V_o^2} + a_i + a_j + \delta_{ij}$$

Three equations are solved:-

$$[A][e] = [T]$$

$$[A][f1] = [X]$$

$$[A][f2] = [X^2]$$

The time terms are given by:- $a_i = e_i - (\frac{1}{V_o})f1_i + (\frac{K}{2V_o^2})f2_i$

Also defined are:-

$$C_{ij} = T_{ij} - e_i - e_j$$

$$D1_{ij} = X_{ij} - f1_i - f1_i$$

$$D2_{ij} = X_{ij}^2 - f2_i - f2_j$$

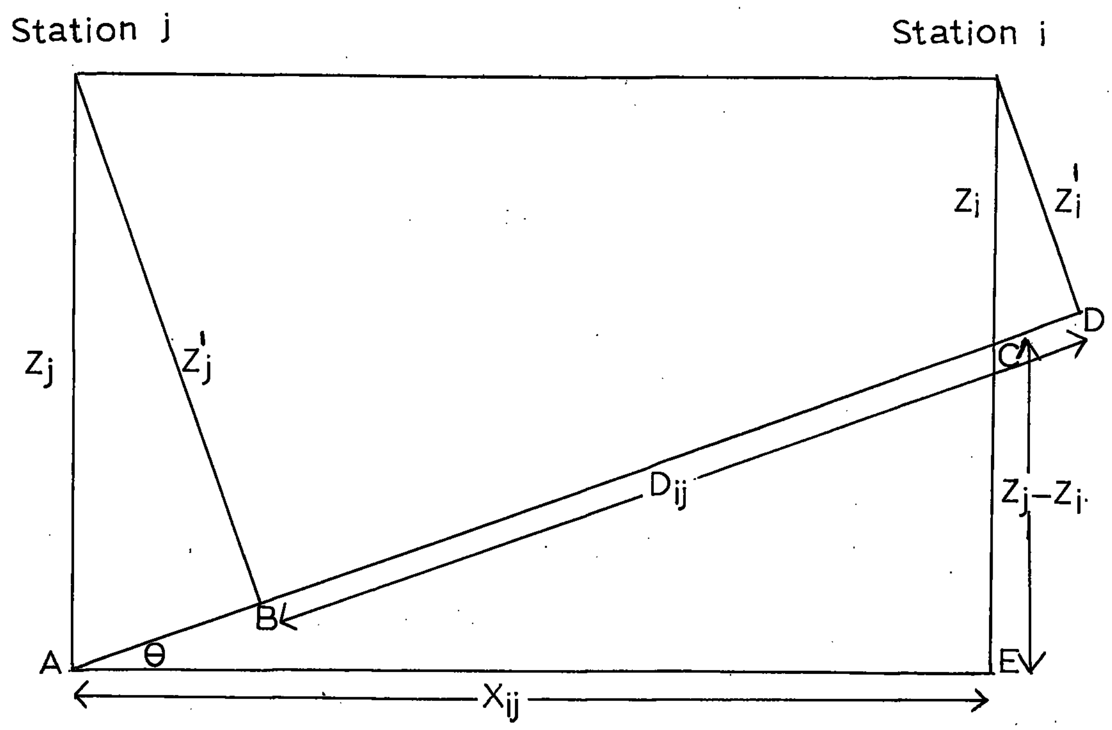
Differentiating the sum of residuals squared with respect to $(\frac{1}{V_o})$ and $(\frac{K}{2V_o^2})$ gives the solution for V_o and K

$$\begin{pmatrix} (\frac{1}{V_o}) \\ (\frac{K}{2V_o^2}) \end{pmatrix} = \begin{bmatrix} \sum_{i=1}^{m} D1_{ij}^2, & -\sum_{i=1}^{m} D1_{ij}\, D2_{ij} \\ \sum_{i=1}^{m} D1_{ij}\, D2_{ij}, & -\sum_{i=1}^{m} D2_{ij}^2 \end{bmatrix}^{-1} \begin{pmatrix} \sum_{i=1}^{m} C_{ij}\, D1_{ij} \\ \sum_{i=1}^{m} C_{ij}\, D2_{ij} \end{pmatrix}$$

When values of V_o and K have been solved, it was possible to use the Weichert inversion (Section 3.4.2) to establish the velocity-depth relationship for the model.

2.5.7 Dipping Layer Iteration

One of the assumptions of the time term method was that the angle of dip of the refractor was small and consequently $X_{ij} \simeq D_{ij}$. For a dipping refractor:-



Z_i and Z_j are the perpendicular depths to the refractor

Z_i' and Z_j' are the normal depths to the refractor

θ is the angle of dip of the refractor.

$D_{ij} = BD = AC + CD - AB$

$$AC = \frac{X_{ij}}{\cos\theta} \qquad AB = Z_j \sin\theta \qquad Z_j - Z_i = X_{ij}\tan\theta$$

$$CD = Z_i \sin\theta$$

$$D_{ij} = \frac{X_{ij}}{\cos\theta} - \sin\theta\,(Z_j - Z_i) = \frac{X_{ij}}{\cos\theta} - \frac{\sin^2\theta}{\cos\theta}X_{ij} = X_{ij}\cos\theta$$

$$\text{then } Z_j = \frac{Z_j'}{\cos\theta} \qquad Z_i = \frac{Z_i'}{\cos\theta}$$

In the first iteration the angle θ was set to zero and the time terms calculated in the normal way. These time terms were inverted to depths (Z_i' and Z_j') and then the dip of refractor between two stations could be calculated (from Z_i and Z_j). A new value of D_{ij} is calculated from:-

$$D_{ij} = X_{ij}\cos\theta_{ij} = \frac{X_{ij}^2}{(X_{ij}^2 + (Z_j-Z_i)^2)^{\frac{1}{2}}}$$

2.5.8 Tests on Model Networks

It was found that the dipping layer iteration gave only a slight improvement in the determination of the refractor velocity over a single solution. It was found that for structurally complex models, and for poorly reversed models, the solution became unstable. This instability is a common feature of iterative time term analyses (Bamford, 1973), and is caused by the interaction of the delay terms with the velocity of the dipping layer. As θ becomes larger, D_{ij} becomes smaller and a_i and a_j become larger, which causes θ to increase.

It was generally found that if the velocity of the refractor was known and constrained, or if good reversed coverage was available, a single solution gave reliable time terms, except at the margins of the network. The problem of the marginal time terms was caused by poor reversal of velocity (Willmore and Bancroft, 1960).

2.6 Time Term Solutions

2.6.1 Single Velocity Solution

The best fitting velocity to the solution was 5.70 ± 0.045 Km/sec. The solution was obtained by constraining the time term at Rookhope to 0.1 sec. Table (2) shows a list of time terms obtained for the least squares velocity. The distribution of the stations are shown in Figure 8 and the details of the station are listed in Table 3.

Incorporated throughout the solution was an estimate of errors. The observational error was considered in two

Table 2

Time Term Solution

SOLUTION USING A VELOCITY OF 5.70
SUM OF RESIDULES SQUARED IS 0.76
STANDARD ERROR OF THE SOLUTION IS 0.13

STATION	E	ERROR	ERG	F	ERROR	ERG	TTERM	ERROR	ERG	B,W ST.ERR	95 CONF	NUM DATA
1	8.76	0.38	0.12	47.48	0.49	0.15	0.43	0.40	0.16	0.0	3.06	1
2	6.16	0.26	0.08	33.91	0.35	0.10	0.21	0.27	0.11	0.01	0.51	2
3	4.30	0.23	0.05	19.49	0.29	0.06	0.58	0.25	0.07	0.04	0.12	8
4	7.52	0.11	0.10	41.25	0.16	0.16	0.29	0.08	0.14	0.0	2.38	1
5	6.37	0.24	0.06	32.74	0.27	0.07	0.63	0.24	0.10	0.04	0.29	3
6	-0.76	0.26	0.10	-5.99	0.55	0.31	0.29	0.37	0.12	0.0	2.45	1
7	0.10	0.01	0.01	0.00	0.00	0.00	0.10	0.01	0.01	0.02	0.05	27
8	4.18	0.16	0.03	23.02	0.25	0.06	0.15	0.17	0.06	0.02	0.07	18
9	-3.46	0.26	0.10	-19.64	0.37	0.13	-0.01	0.36	0.11	0.0	2.45	1
10	-3.24	0.26	0.08	-18.39	0.44	0.16	-0.02	0.37	0.09	0.00	0.51	2
11	2.11	0.09	0.02	12.30	0.20	0.07	-0.05	0.11	0.04	0.01	0.18	5
12	-0.66	0.11	0.03	-4.55	0.32	0.14	0.14	0.17	0.04	0.0	2.59	1
13	0.83	0.18	0.06	2.88	0.27	0.08	0.32	0.22	0.06	0.04	0.53	2
14	1.91	0.12	0.03	8.41	0.30	0.10	0.44	0.16	0.04	0.02	0.53	2
15	2.79	0.11	0.02	15.48	0.24	0.07	0.07	0.13	0.04	0.03	0.30	3
16	5.47	0.16	0.03	30.25	0.23	0.04	0.16	0.16	0.07	0.04	0.18	5
17	-0.70	0.20	0.05	-5.11	0.33	0.10	0.20	0.27	0.05	0.07	0.29	3
18	8.65	0.18	0.03	48.78	0.26	0.05	0.10	0.16	0.11	0.03	0.12	8
19	7.10	0.33	0.11	38.60	0.39	0.12	0.33	0.34	0.14	0.00	0.61	2
20	8.82	0.12	0.03	45.97	0.19	0.05	0.05	0.08	0.11	0.03	0.11	9
21	-3.83	0.18	0.05	-22.90	0.22	0.06	0.18	0.25	0.07	0.08	0.30	3
22	-5.68	0.14	0.03	-34.49	0.29	0.11	0.37	0.25	0.08	0.0	2.52	1
23	-4.50	0.14	0.03	-25.77	0.29	0.11	0.02	0.23	0.07	0.0	2.52	1
24	-2.29	0.17	0.06	-16.43	0.29	0.11	0.59	0.25	0.07	0.0	2.52	1
25	0.15	0.22	0.06	-1.38	0.30	0.08	0.39	0.27	0.06	0.08	0.52	2
26	2.44	0.22	0.06	10.85	0.30	0.08	0.54	0.25	0.07	0.20	0.52	2
27	5.76	0.20	0.06	31.35	0.21	0.05	0.44	0.19	0.09	0.04	0.29	3
28	-5.84	0.39	0.12	-34.64	0.44	0.13	0.27	0.51	0.14	0.0	3.06	1
29	0.11	0.33	0.11	-0.99	0.39	0.12	0.29	0.40	0.11	0.30	0.37	3
30	7.37	0.35	0.11	39.90	0.44	0.13	0.37	0.37	0.14	0.0	3.06	1
31	8.16	0.20	0.04	43.57	0.25	0.04	0.52	0.18	0.10	0.05	0.10	11
32	-5.65	0.23	0.05	-33.42	0.30	0.07	0.21	0.33	0.09	0.0	2.48	1
33	11.60	0.11	0.10	65.86	0.10	0.10	0.05	0.03	0.17	0.0	2.38	1
34	6.58	0.17	0.08	37.93	0.17	0.07	0.32	0.14	0.11	0.11	0.52	2
35	9.50	0.11	0.10	51.21	0.05	0.05	0.52	0.04	0.15	0.0	2.38	1
36	-0.34	0.23	0.05	-3.48	0.28	0.05	0.27	0.29	0.05	0.03	0.15	6
37	0.01	0.25	0.06	-1.44	0.30	0.06	0.26	0.30	0.06	0.03	0.21	4
38	11.80	0.11	0.03	65.63	0.15	0.04	0.29	0.03	0.14	0.01	0.53	2
39	-0.62	0.17	0.04	-4.28	0.24	0.05	0.13	0.22	0.04	0.01	0.54	2
40	0.39	0.20	0.04	0.71	0.28	0.06	0.27	0.24	0.04	0.07	0.21	4
41	10.93	0.17	0.03	59.36	0.25	0.04	0.52	0.12	0.13	0.05	0.15	6
42	0.71	0.26	0.08	2.03	0.30	0.07	0.35	0.31	0.08	0.01	0.52	2
43	-0.00	0.19	0.04	-2.13	0.28	0.06	0.37	0.25	0.04	0.07	0.21	4
44	-2.17	0.23	0.06	-14.31	0.32	0.08	0.34	0.31	0.07	0.0	2.53	1
45	-0.88	0.17	0.04	-6.35	0.24	0.05	0.23	0.23	0.04	0.04	0.17	5
46	11.07	0.16	0.04	61.30	0.20	0.04	0.32	0.13	0.14	0.06	0.29	3
47	-3.06	0.19	0.04	-18.78	0.25	0.04	0.23	0.26	0.06	0.06	0.30	3
48	0.02	0.19	0.04	-2.57	0.30	0.07	0.48	0.24	0.04	0.08	0.29	3
49	1.63	0.18	0.04	7.55	0.29	0.07	0.31	0.22	0.04	0.09	0.29	3
50	16.00	0.11	0.10	90.17	0.10	0.10	0.19	-0.01	0.22	0.0	2.38	1
51	7.30	0.03	0.02	36.73	0.05	0.05	0.86	-0.02	0.08	0.0	2.38	1

CONSTRAINT CARDS

STATION	NUM	TIME TERM	ERROR
ROCKHOPE	7	0.10	0.01

Figure 8

Distribution of Stations in Northern England

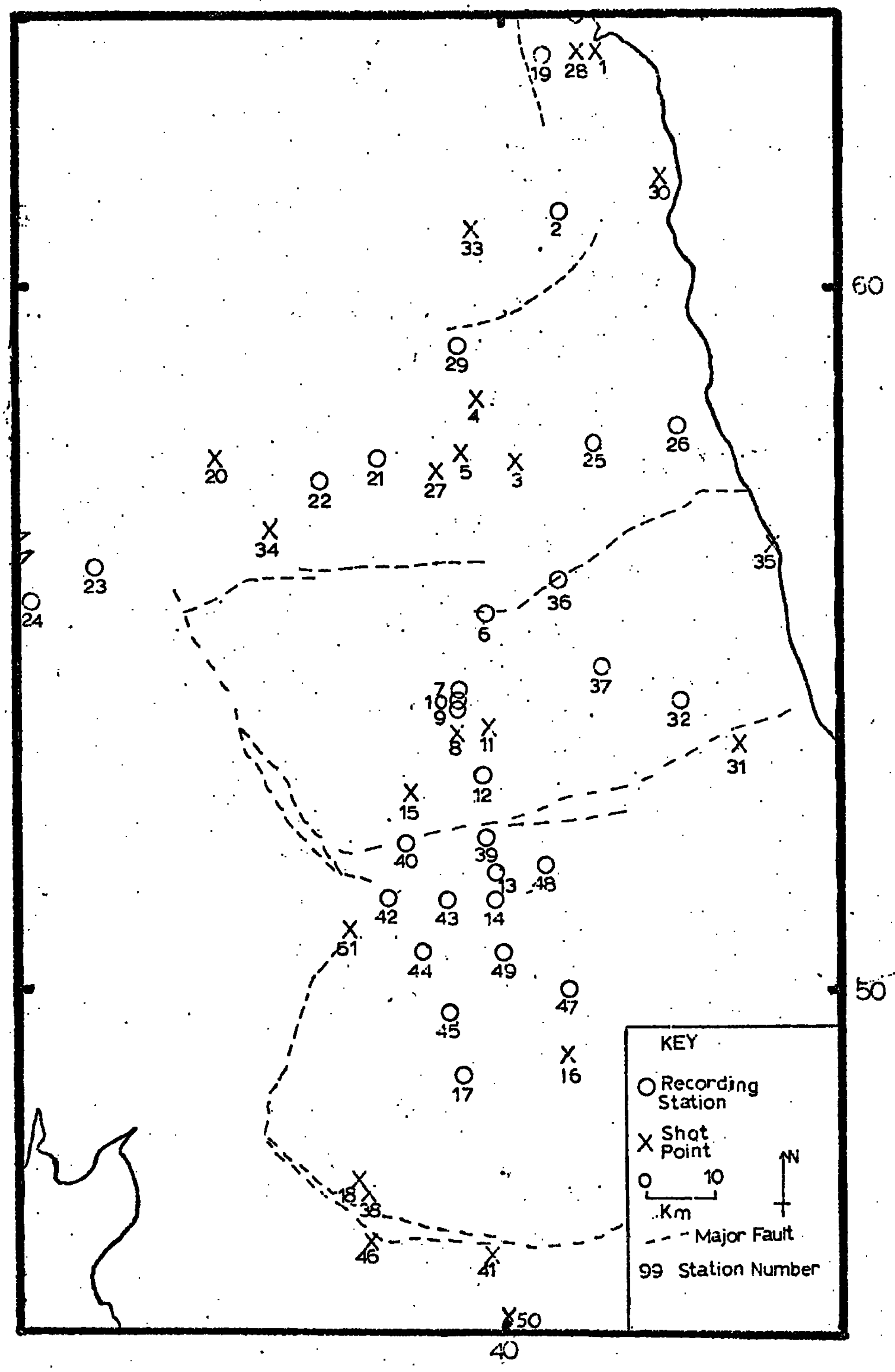


Table 3

Details of Stations

STATION NUMBER	NAME	O.S. COORD. EAST	NORTH
1	Belford Quarry	413.16	634.18
2	Archers R8	408.49	610.42
3	Mootlaw Quarry	402.10	575.25
4	Kirkwhelpington Quarry	397.60	583.80
5	Swinburne Quarry	394.88	576.83
6	Archers R6	397.96	553.84
7	Rookhope S3	393.76	542.73
8	Eastgate Quarry	394.30	537.20
9	Rookhope S1	393.56	540.50
10	Rookhope S2	393.98	541.82
11	Newlandside Quarry	398.82	537.75
12	Kidds 2	397.54	530.11
13	Kidds 5	399.85	516.18
14	Kidds 6A	399.11	513.07
15	High Force Quarry	387.33	528.23
16	Leyburn Quarry	409.65	491.34
17	Kidds 9	394.39	487.15
18	Horton Quarry	379.70	472.35
19	Belford	407.55	633.08
20	Spadeadam Shot	359.60	575.90
21	Gofton	382.10	575.57
22	Hindley Steel	374.74	572.65
23	West Cliff	341.22	560.16
24	Thurston	332.14	556.63
25	Ogle	414.03	577.97
26	Bedlington	426.00	580.98
27	Barrasford Quarry	391.35	574.45
28	Craghill Quarry	411.00	634.55
29	Elsden	393.94	591.85
30	Little Haughton Quarry	423.75	616.85
31	Raisby Quarry	434.70	535.30
32	Durham Observatory	426.71	541.55
33	Harden Quarry	395.85	608.56
34	Walltown Quarry	367.10	566.11
35	Marsden Quarry	395.85	608.56
36	Ebchester	408.95	558.80
37	Lanchester	414.78	546.46
38	Arcow Quarry	380.35	470.62
39	Hunderthwaite D01	398.30	521.08
40	Lunedale D02	386.80	520.85
41	Swinden Quarry	398.03	461.55
42	Barras D03	383.34	512.13
43	Stainmore D04	392.40	512.23
44	Tan Hill D05	388.99	505.38
45	Muker D06	392.55	497.50
46	Giggleswick Quarry	381.03	464.92
47	Marske D07	409.65	500.13
48	Stainton D08	406.75	518.62
49	Stang D09	400.68	505.18
50	Skipton Rock Quarry	401.38	452.80
51	Hartley Quarry	379.82	508.75

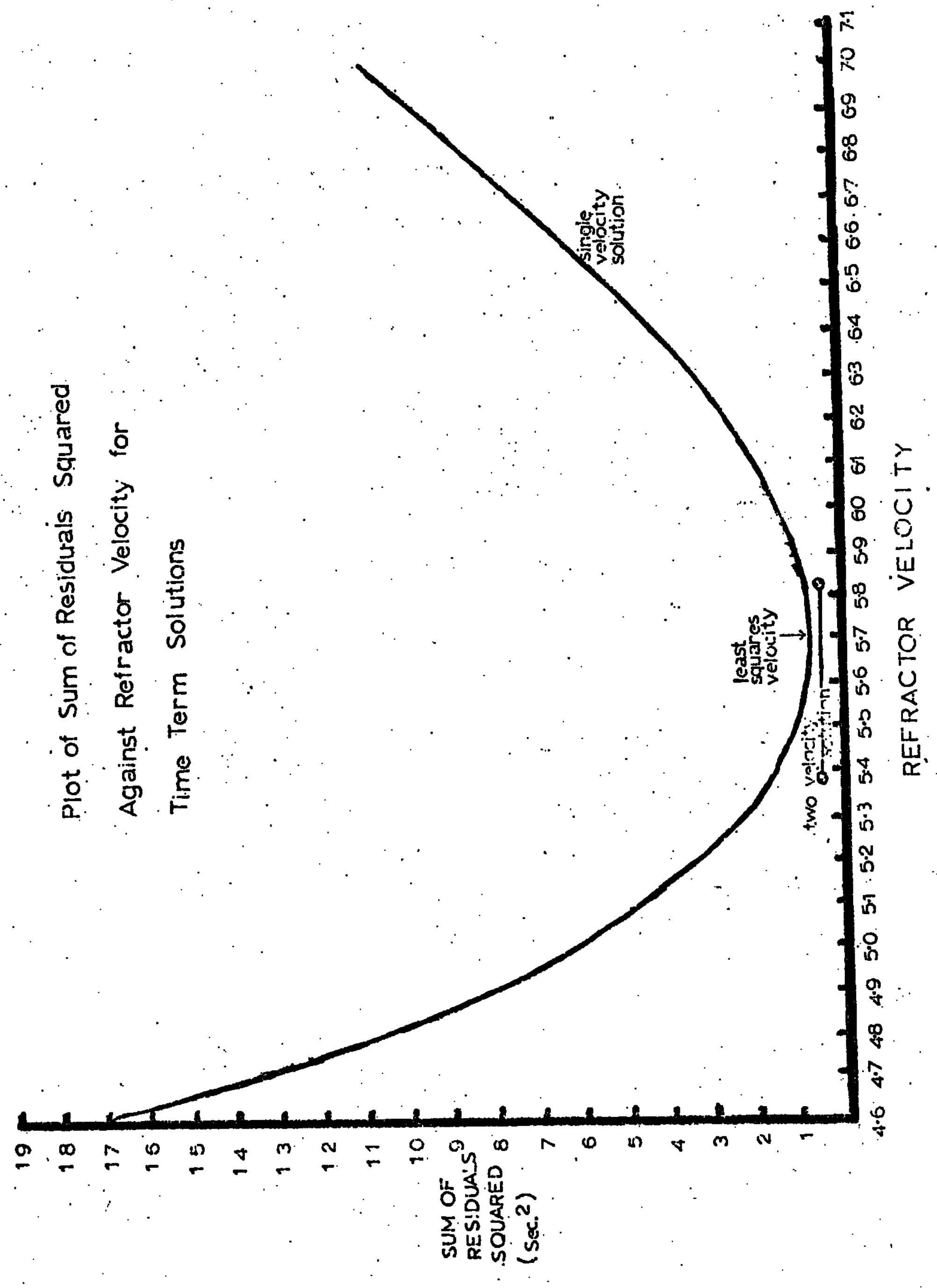
manners. First, it was considered as an error bar, within which the real value must lie. The accumulation of error limits of the unknown is shown in the column headed 'ERROR'. Secondly the observational error was considered to be normally distributed about the true value. This type of error accumulates differently from the first type, and this error is given in the column titled 'ERG'. As can be seen in Table 2, the error in the time terms caused by observational errors are smaller by the second consideration and generally amount to about 0.1 seconds.

Table 2 lists the values of e_i and f_i found at each station. These terms give respectively the part of the time term independent and dependent on the velocity of the refractor. By glancing at these values it is possible to say which time terms will be most effected by a change in velocity. Standard errors are obtained for the time terms using the formulas given by Berry and West (1966) and by matrix inversion. The number of data to each station is also shown.

Figure 9 shows the variation of the sum of residuals with the basement velocity. It shows a gently curved minimum in the region of 5.7 Km/sec. This curve shows the quality of the data in the determination of the velocity of the basement.

Figure 10 shows a plot of the residuals against travel distance. The plot will show any substantial variation in velocity with distance if it exists (Willmore and Bancroft, 1960). As the residuals appear to be evenly distributed with distance, there appears to be little

Figure 9

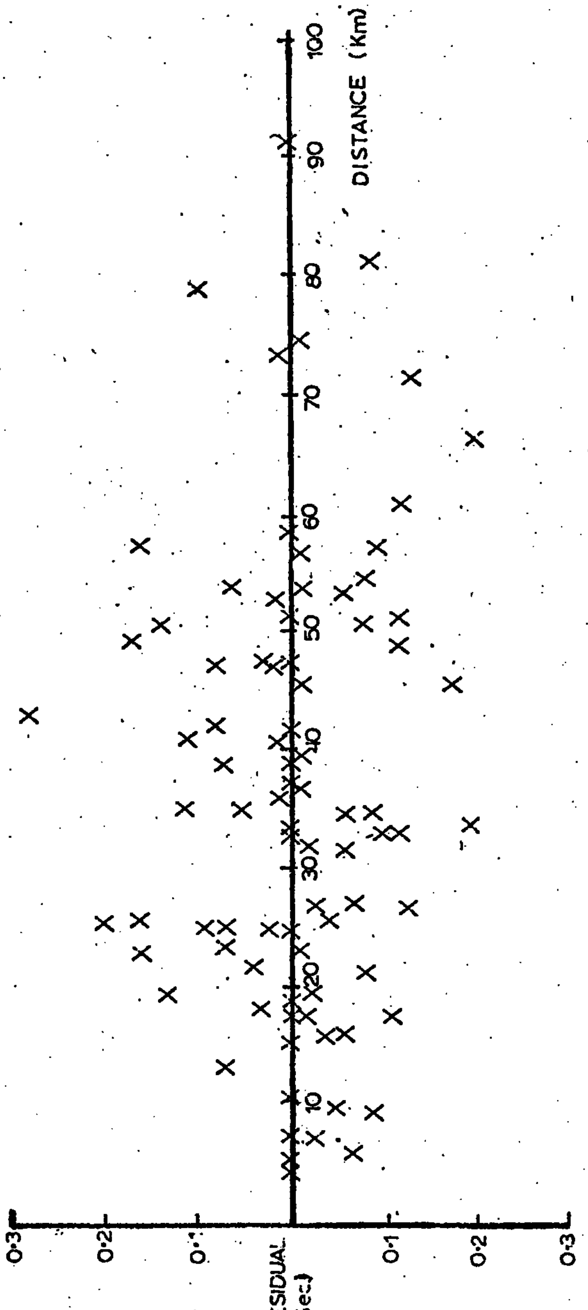


Plot of Sum of Residuals Squared Against Refractor Velocity for Time Term Solutions
SUM OF RESIDUALS SQUARED (Sec.2)
REFRACTOR VELOCITY
single velocity solution
least squares velocity
two velocity solution
19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
4·6 4·7 4·8 4·9 5·0 5·1 5·2 5·3 5·4 5·5 5·6 5·7 5·8 5·9 6·0 6·1 6·2 6·3 6·4 6·5 6·6 6·7 6·8 6·9 7·0 7·1

Figure 10

Plot of Residuals against Distance

Single Velocity Time Term Solution



evidence of velocity changing substantially with distance.

2.6.2 Two Velocity Solution

A substantial improvement of 0.76 sec^2 to 0.55 sec^2 in the sum of the residuals squared was achieved by treating the granite basement with a separate velocity. The distribution of granite basement was taken from Figure 3. The least squares velocity for the granite was 5.39 ± 0.077 Km/sec and for the basement 5.81 ± 0.046 Km/sec.

2.6.3 Velocity Increasing with Distance

This solution showed a reduction in the sum of residuals squared from 0.76 sec^2 for the single solution to 0.64 sec^2. The least squares velocity was V_o = 5.35 km/sec, increasing linearly away from the source by 0.00414 Km/sec/km.

2.6.4 Iterative Solution

The dipping layer iterative solution showed very little change in the sum of residuals squared (0.76 sec^2 to 0.75 sec^2) and no change in the least squares velocity.

2.7 Interpretation

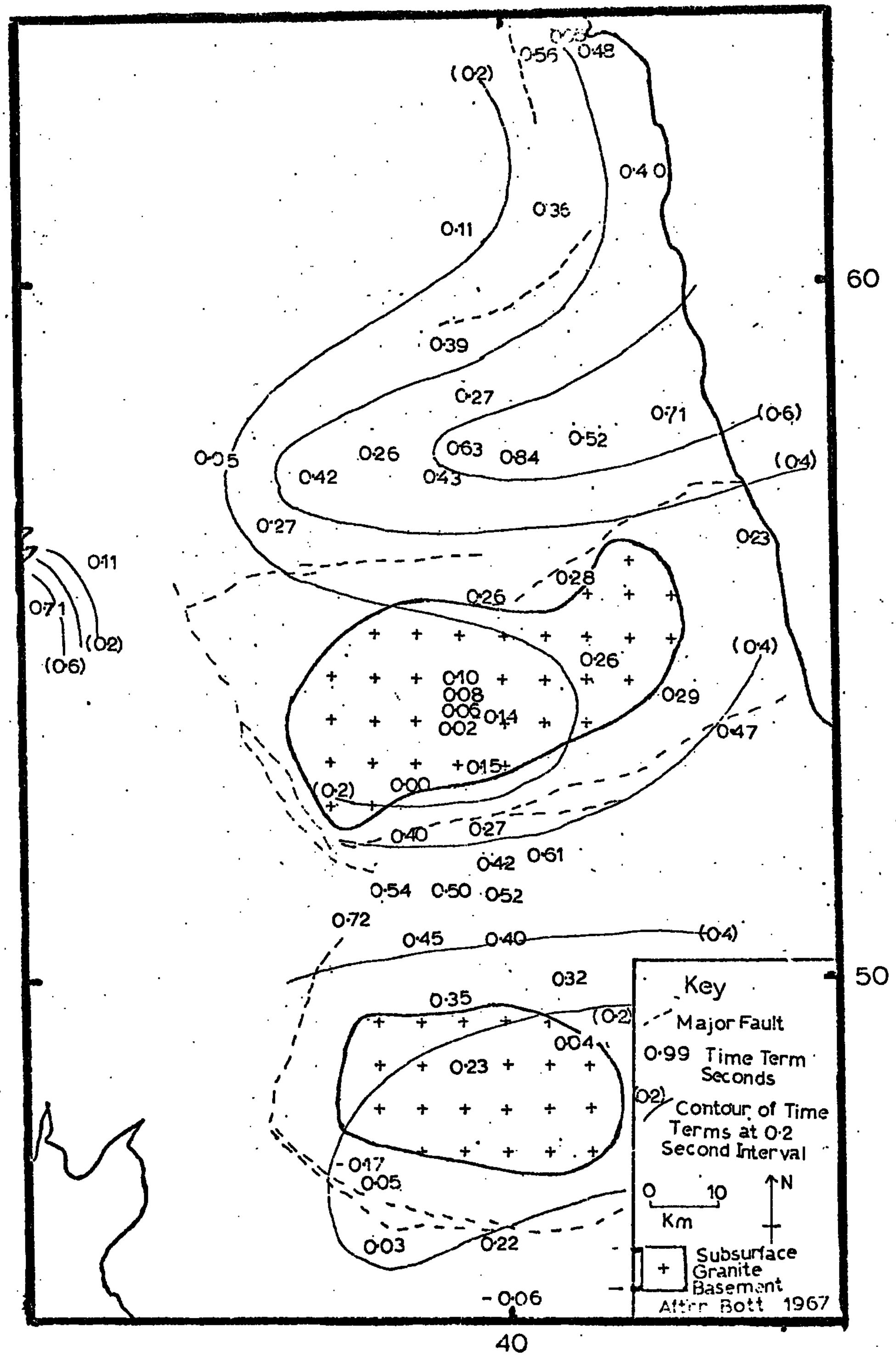
2.7.1 Distribution of Time Terms

The distribution of time terms is shown in Figure 11. The time terms were obtained with the two velocity basement structure which gave the least sum of residuals squared and is based on the most reasonable geological premise.

In general, the time terms were smallest over the blocks where substantial areas had less than 0.2 sec. delay time. Over the Alston block, time terms appeared to increase to the northern and southern margins and towards

Figure 11

Distribution of Time Terms in Northern England
Two Velocity Basement Solution



the North Sea. Over the Askrigg block the distribution of stations was less extensive, but still showed low time terms. In northern Northumberland time terms were generally below 0.2 sec., but increased markedly towards the North Sea.

The Northumberland Trough showed delay terms of greater than 0.6 seconds and which decreased markedly to the west. Delay terms in the Stainmore Trough showed a maximum of about 0.5 seconds with no east-west lateral variation. One value of 0.71 seconds was obtained in the Carlisle basin but as with time terms on the edge of the Craven basin, were of little significance because of their proximity to the margin of the network.

2.7.2 Dependence of Time Terms on the Type of Solution

There was no major redistribution of time terms whichever solution was employed.

Because of the lower velocity of the granite, the time terms within the blocks were slightly reduced compared to the single velocity solution. A similar effect was noticed for the solution with velocity increasing with distance, because most quarries were situated on the blocks. The exact significance of the rather large K factor of 0.00414 Km/sec/Km was doubtful because travel distances tended to be smaller on the blocks with the low velocity granite refractor.

2.7.3 Velocity of the Cover

As part of the evaluation of Rookhope borehole, a seismometer was lowered within the hole, while several shots were fired at the surface. The results of this experiment are shown in Table 4. They indicate a mean velocity in the

Table 4

Velocity of the Cover

ROOKHOPE BOREHOLE

COVER

DEPTH (m)	TRAVEL TIME (ms)	VELOCITY (km/s)
194	46	4.21
258	67	3.85
388	97	4.00

Mean velocity of the cover (viséan) = 4.00 Km/s

GRANITE

797	167	5.84

DIRECT ARRIVALS

QUARRY	RECORDING SITE	DIST.	VELOCITY	STRAT.
Craghill	Belford	4.25	3.70	Viséan
Raisby	Durham	9.99	3.52	Coal Measures
Barrasford	Gofton	9.40	3.60	Viséan

Visean of 4.0 Km/sec. On a few records, close to the blast, a high frequency second arrival was interpreted as the direct wave. The velocity appeared to be 3.50 to 3.70 Km/sec. and was independent of the stratigraphical position. For this reason, the cover was presumed to have a constant velocity of 3.7 Km/sec.

2.7.4 Inversion of Time Terms to Depths to the Basement

The delay time is dependent on both the velocity of the refractor and the velocity structure of the cover, and is given by:-

$$a_K = \int_o^h \frac{(V_r^2 - V(Z)^2)^{\frac{1}{2}}}{V_r V(Z)} \, dZ$$

where V_r = velocity of the refractor

$V(Z)$ = velocity function of the cover with depth

h = thickness of cover.

For a constant velocity of the cover:-

$$h = \frac{a_K V_r V_c}{(V_r^2 - V_c^2)^{\frac{1}{2}}}$$

where V_c = velocity of the cover.

Berry and West (1966) showed that if V_c was the mean velocity of the cover, then a good approximation to the depth to the basement was given by the constant velocity formulae. Taking V_c = 3.7 km/sec., for the two velocity solution then:-

h granite = $5.09 \times a_K$

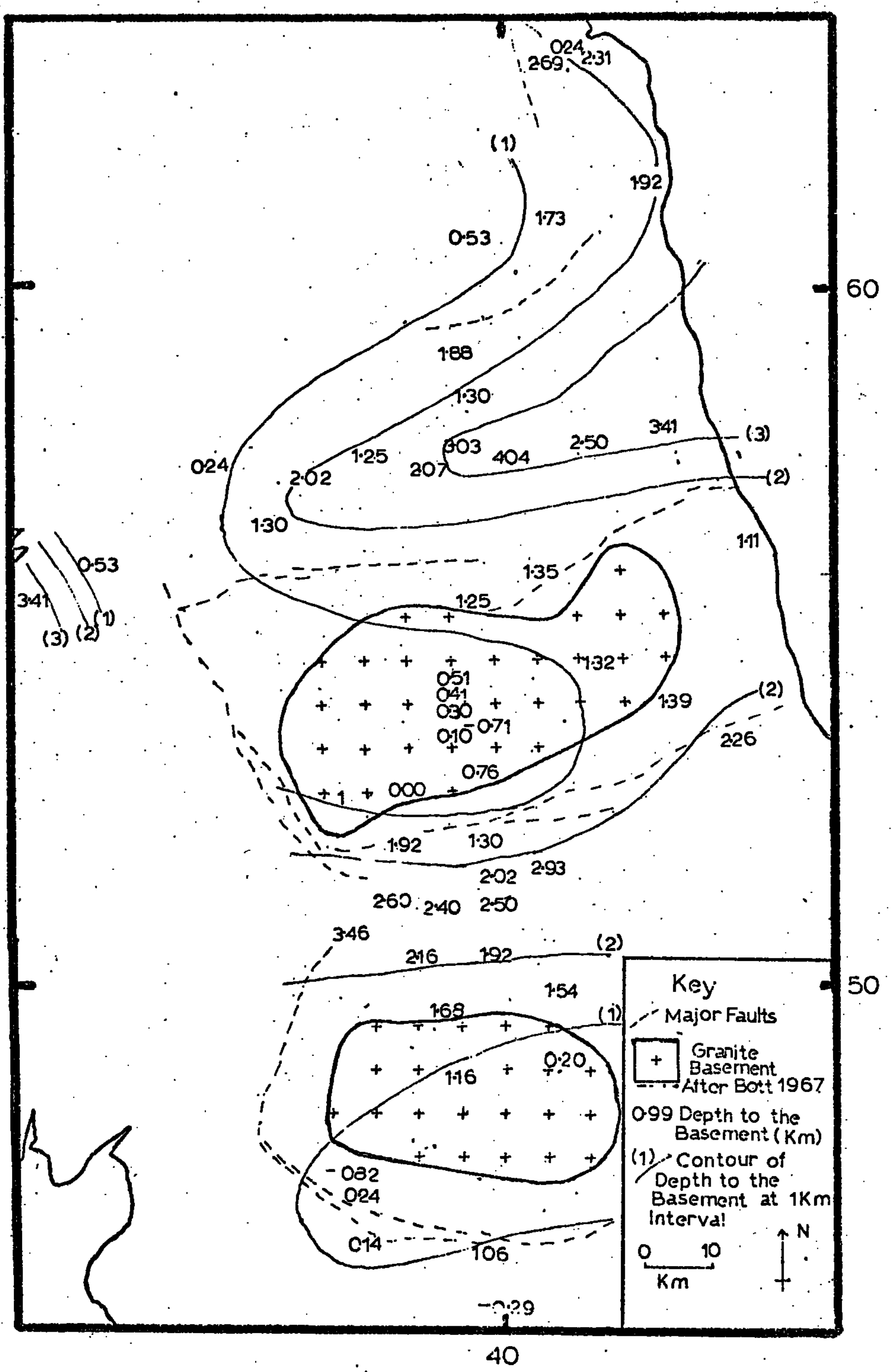
h basement = $4.80 \times a_K$

2.7.5 Depth to the Basement in Northern England

Figure 12 shows the interpreted depth to the basement of Northern England, based on the two velocity basement

Figure 12

Depth to the Basement in Northern England
Two Basement Time Term Solution



solution and a constant velocity sedimentary cover.

The most noticeable feature of the map is the thin cover over the blocks, with much thicker accumulation of sediments in the intervening troughs. Cover appeared to thicken generally towards the North Sea.

Northern Northumberland showed a relatively thin cover of less than 1 km of sediments, which increased towards the Northumberland Trough. The axial region of the Northumberland Trough appeared to have a maximum of 3 to 4 km of cover, which agreed well with the gravity interpretation (Bott, 1967). The trough shoaled gradually towards Cumbria.

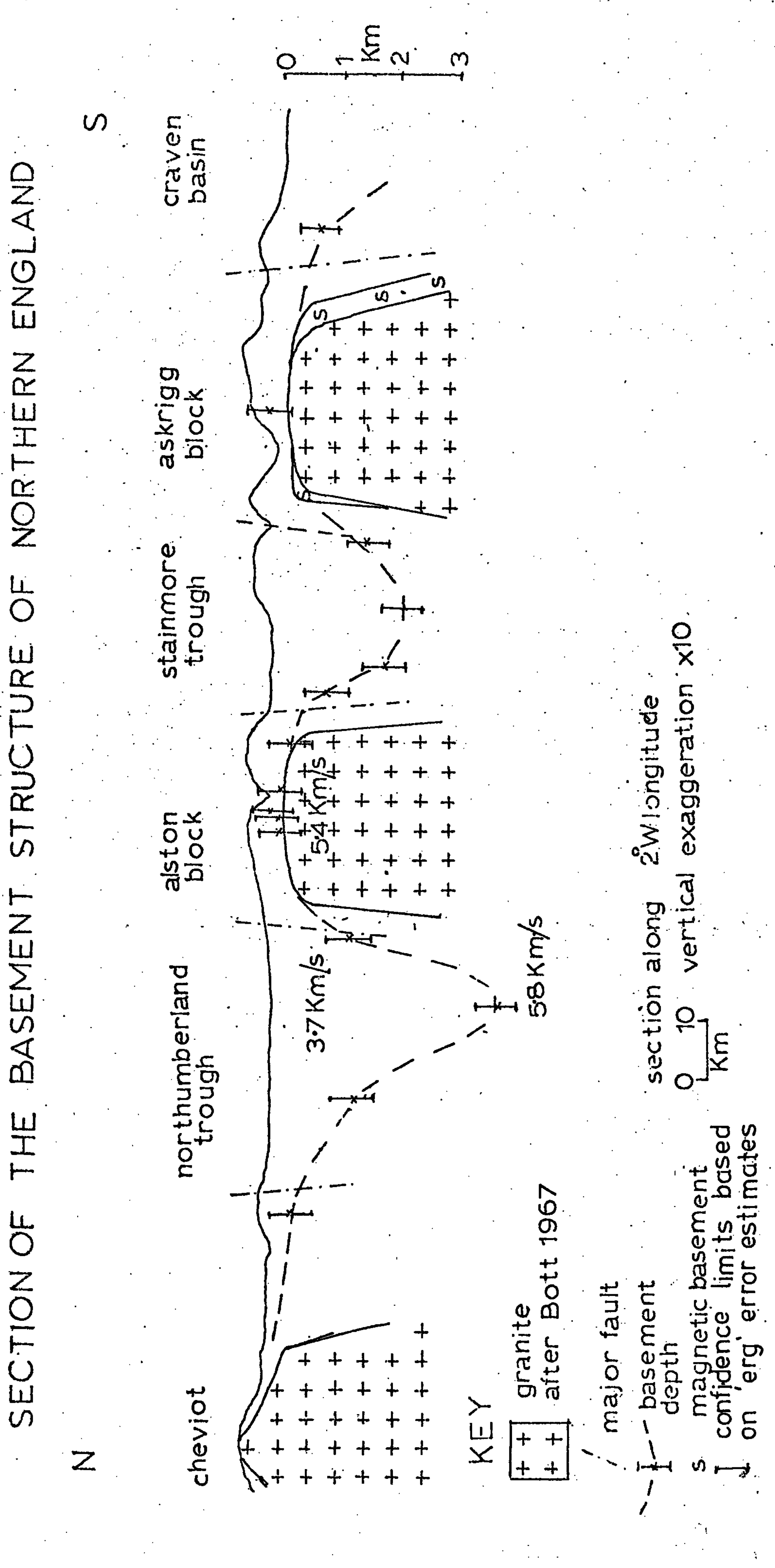
The Alston block showed a thinning of cover to a minimum in the Rookhope area. The cover increased to the margins of the blocks.

The Stainmore Trough showed a depth to the basement of about 2½ km. The region was discussed in detail by Griffiths (1974). There appeared to be no evidence of cover thinning to the west.

Over the Askrigg block, the cover appeared to thin substantially. The asymmetric nature of the sedimentary cover (thinnest in the south) was reflected on the map. Station coverage over the southern margin was not well defined.

To synthesise the regional picture, Figure 13 shows a section along the 2^{O}W longitude which lies central to the structural units. The section shows the interpreted relative disposition of basement-cover relationships as outlined.

Figure 13



SECTION OF THE BASEMENT STRUCTURE OF NORTHERN ENGLAND
N
S
cheviot
northumberland trough
alston block
stainmore trough
askrigg block
craven basin
0
1
2
3
Km
3·7 Km/s
5·4 Km/s
5·8 Km/s
s
KEY
granite after Bott 1967
major fault
basement depth
s
magnetic basement confidence limits based on 'erg' error estimates
section along 2°W longitude
vertical exaggeration x10
0 10
Km

2.7.6 Precision of the Results

The largest error in the time terms was caused by the uncertainty in picking the first arrival. Both the travel time and the distance between two sites could be measured to a high relative accuracy (better than 1%), but as the difference between the travel time and the distance divided by the velocity was usually small, the relative error of this difference was large. For small delay terms (about 0.5 seconds), the error made during measurement may be greater than 25%. The problem was further aggravated by changes in the velocity of the refractor. The observational error was in general much larger than the standard error calculated from the residuals.

The precision of the depth estimates due to observational error was about 0.5 Km, but may be greater, for example at stations situated at the margin of the network. This inaccuracy meant that the basement topography within each unit could not be resolved. Nor was it possible to distinguish any velocity distribution at depth within the cover. Because of the very low time terms obtained within the Lower Palaeozoic inliers, it was presumed that the seismic refractor was indeed the geological basement.

The margins of the troughs may be more abrupt than has been indicated. The hinge lines were avoided because of the problem of the dip and curvature of the refractor (2.2).

2.8 Conclusions

The time term method has proved a most useful tool in the investigation of basement-cover relationships in Northern England. The limitations to the interpretation due to the initial assumptions and observational error must be treated with care. The survey has shown that the measurement of travel times to continuous recording mobile stations was feasible.

The experiment has shown substantial lateral variations of the thickness of sedimentary cover. In particular, the basements beneath the Northumberland and Stainmore Troughs have been estimated at between 2½ to 3½ Km deep. This contrasted with the intervening block regions where less than 1 Km of cover was indicated.

It was hoped that the survey would solve some of the uncertainties of previous geophysical and geological interpretation. The network can stand as a building block for extending to neighbouring areas or for more detailed investigations within each unit. It also aids the interpretation of the deep structure by allowing for the correction of the cover.

CHAPTER 3

APPARENT VELOCITY OF CRUSTAL PHASES ACROSS ROOKHOPE AND ESKDALEMUIR ARRAYS

3.1 Introduction

Although the recording of quarry blasts at mobile stations provided useful data for the interpretation of the onset of Pg, using the time term method, it did not allow for the identification and correlation of later phases between records. Because of the abundance of quarry blast sources, it was decided to examine records from two short period crossed arrays; namely Rookhope in Weardale and Eskdalemuir in Southern Scotland. The purpose of this study was to deduce the sub-basement, crustal velocity structure.

3.2 The Scope of the Study

Initially the apparent velocity of Pg arrivals across Rookhope array was examined to investigate the velocity of the basement refractor and compare this with the value obtained from the time term survey of Northern England (Chapter 2). As the work progressed it became clear that a distinctive velocity structure of the upper crust beneath Rookhope existed. Because the array had been dismantled before the quarry blasts used in Chapter 2 were recorded, only the apparent velocity across the array could be established. It was possible to invert the measured velocity-distance function for Pg, to form the velocity-depth structure, by using the Wiechert integral.

Eskdalemuir array station was operated throughout the period of the experiment described in Chapter 2. Because the origin time was known it was possible to calculate the apparent velocity and travel times for each phase and to construct a record section. The array was situated at the northern margin of the network of quarries, and because of the greater ranges involved (40 to 160 Km) it was ideally placed to investigate the deep crustal structure. The identification of later arrivals and in particular of wide angle reflections was only possible from the correlation of all the records.

3.3 Data Collection

At both arrays it was of fundamental importance to calculate the apparent velocity for the identification of phases and for the interpretation directly. Linear regression of the onset time at a pit on distance was used. At Rookhope array it was first necessary to locate the event by calculating the best fitting azimuth and by using the P-S time to estimate the distance to the source. The location of the source was taken as the nearest worked quarry, and was confirmed by its distinctive blasting time (Section 2.3). The source locations of the events recorded at Eskdalemuir were known, but in practise regression with unknown azimuth was employed to check for systematic azimuthal anomalies.

3.3.1 Rookhope Array

Rookhope array was established in 1969 by the University of Durham. It was situated on Namurian strata of the

'Yoredale' facies, close to the centre of the Alston block. The array had linear crossed arms with a total of nine pits, spread at intervals of approximately 1 Km. A three component pit and borehole seismometer (2.5.4) were operated to the south of the cross-over point. The distribution of pits and their relationship to the local geology is shown in Figure 14 and the list of pit coordinates is given in Table 5.

The instrumentation of the station was similar to that described by Long (1968). Vertical Willmore MK.1 seismometers were used at the pits, where the signal was amplified and frequency modulated. The signal was transmitted, via land lines, with transformer terminations, to the central recording unit. An EMI deck recorded the F.M. signals on 1" wide tape on up to 24 tracks, along with the output from a digital clock with binary coding, a radio time standard, and a reference frequency for flutter compensation.

The main source of cultural noise was generated by a mineral washing plant situated to the south east of the array (Halls, 1964), and was of a similar frequency (near 6 Hz) to the signals from local events.

3.3.2 <u>Eskdalemuir Array</u>

The array station was operated by the United Kingdom Atomic Energy Authority (U.K.A.E.A.), primarily for the detection and identification of underground nuclear explosions. Although designed to investigate teleseismic events, it does however provide a most useful tool in the examination of local events.

Figure 14

ROOKHOPE ARRAY

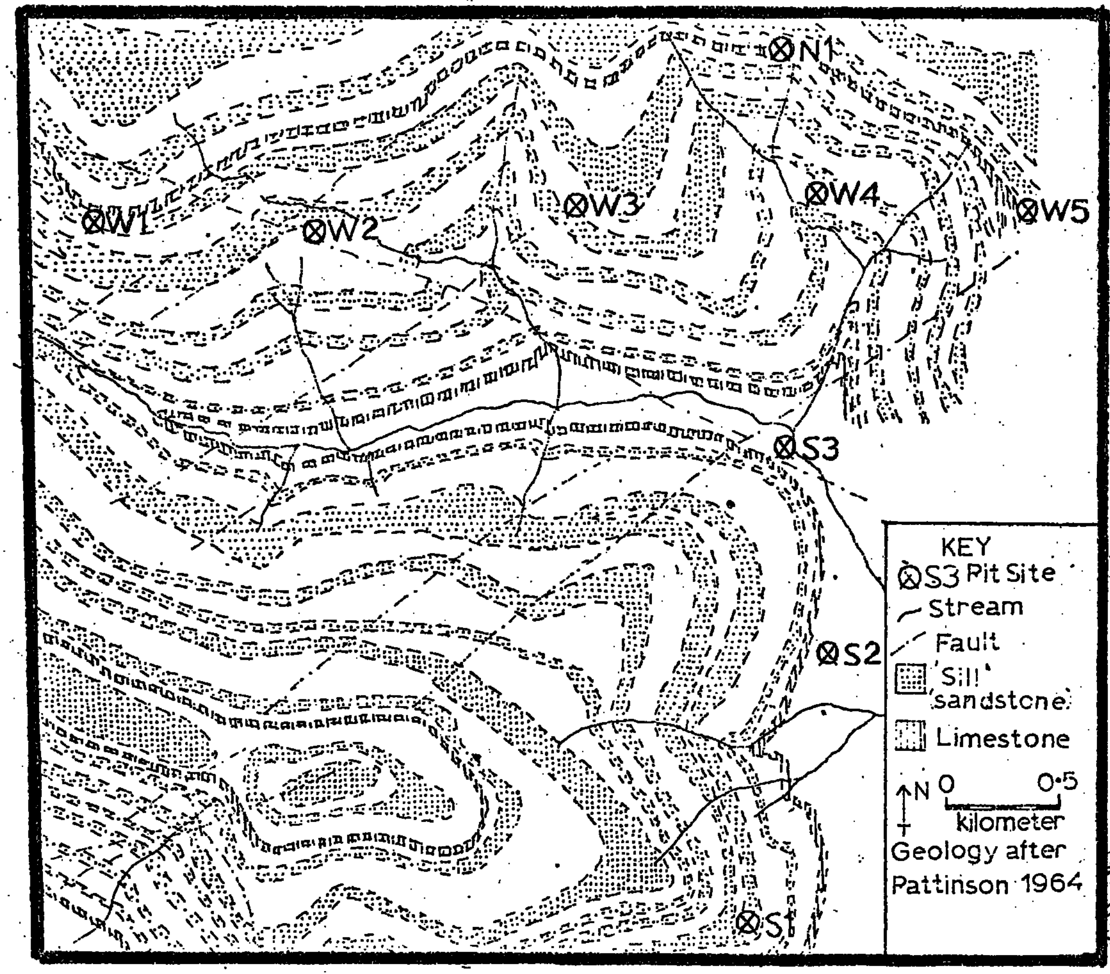


Table 5

Pit Coordinates at Rookhope

PIT	X Coord.	Y Coord.	Alt.
W1	-3.274	0.153	0.118
W2	-2.344	0.079	0.074
W3	-1.140	0.158	0.068
W4	0.0	0.0	0.0
W5	0.892	0.021	0.082
S1	-0.380	-3.152	0.022
S2	0.032	-1.811	-0.042
S3	-0.169	-0.956	-0.048
N1	-0.264	0.781	0.077

X Coordinate is positive eastwards.

Y Coordinate is positive northwards.

Coordinates and altitude are relative to W4 pit, and are in kilometers.

W4 pit is at O.S. 393.93 543.69

The array was sited at Llandovery rocks of Silurian age. The main rock types were grits, shales, mudstones, greywackes and conglomerates.

The array consisted of two linear crossed arms, each with ten pits containing Willmore MK.2 seismometers (Truscott, 1965). The distribution of pits is shown on Figure 15 and the coordinates are listed in Table 6. The signals were recorded, frequency modulated on 24 channel tape decks, using 1" wide tape. Timing was obtained from a quartz clock, calibrated from radio broadcasts.

3.3.3 Replay of Recordings

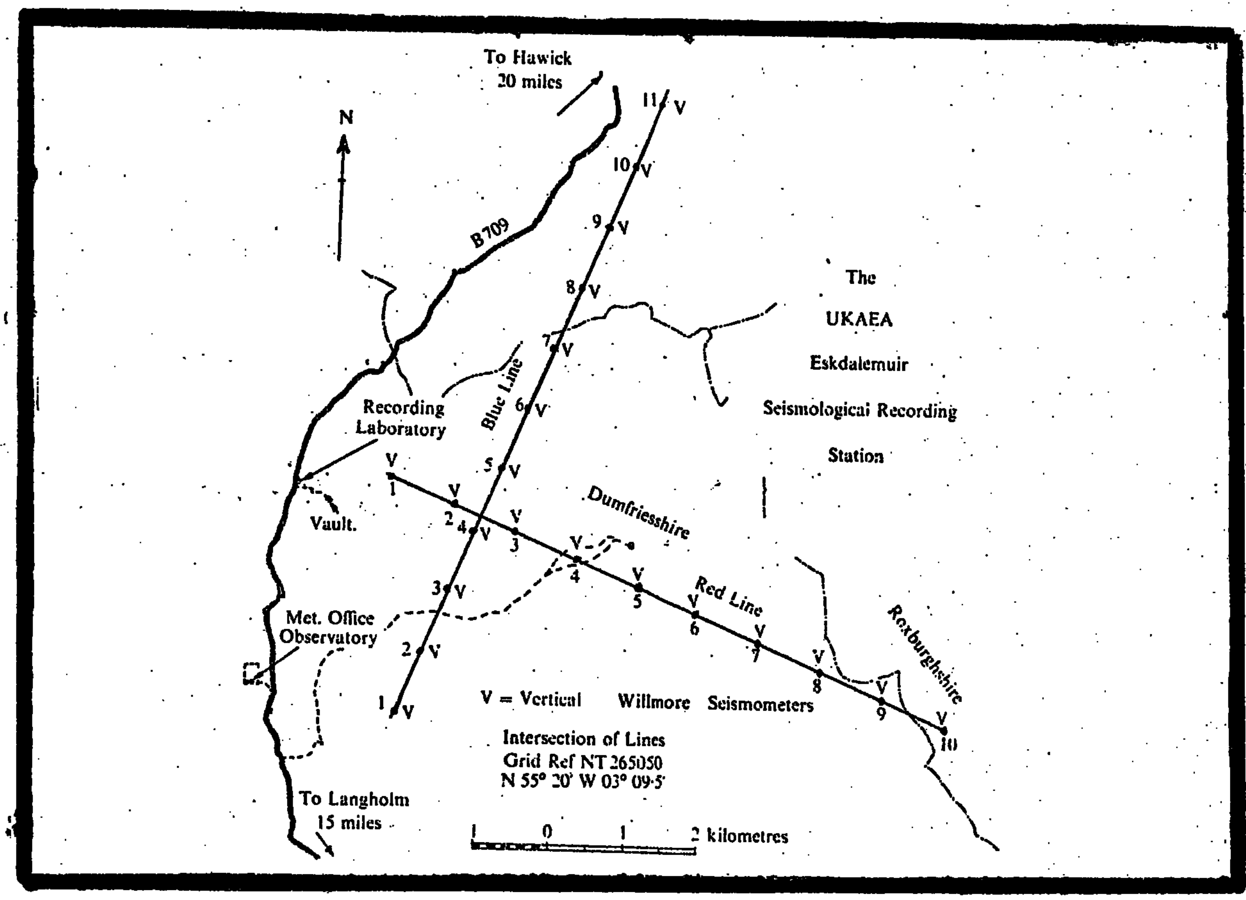
The Rookhope tapes were initially replayed with a single demodulated channel recorded on a heliocorder, from which local events were distinguished. The tapes from both Rookhope and Eskdalemuir were replayed in a similar manner to Section 2.4.6. The signals were demodulated, filtered and played out onto a jet pen recorder. A record speed of 25 to 50 mm/sec. was chosen as a compromise between accurate time measurement and the preservation of the waveform.

3.3.4 Calculation of Onset Times

The relative delay between pits was measured by matching waveforms. A waveform for a particular phase was chosen near to the cross-over point of the array, and traced. The reference trace was moved along the record till a visual best fit was obtained, and the offset from a particular time reference was measured.

Figure 15

Eskdalemuir Array



after Truscott 1965

Table 6

Pit Coordinates at Eskdalemuir

PIT	X COORD.	Y COORD.	ALT.
R1	-1.174	0.471	0.127
R2	-0.342	0.136	0.121
R3	0.489	-0.199	0.093
R4	1.320	-0.534	0.109
R5	2.151	-0.869	0.078
R6	2.983	-1.204	0.166
R7	3.814	-1.539	0.119
R8	4.645	-1.874	0.190
R9	5.477	-2.210	0.200
R11	7.140	-2.880	0.122
B1	-1.049	-2.659	0.046
B2	-0.719	-1.829	0.084
B3	-0.521	-0.952	0.083
B4	-0.056	-0.168	0.070
B5	0.276	0.662	0.081
B6	0.606	1.493	0.108
B7	0.937	2.323	0.207
B8	1.313	3.281	0.176
B9	1.529	5.645	0.114

X coordinate is positive eastwards.
Y coordinate is positive northwards.
Coordinates and altitude are relative to the cross over point and are in kilometers.
Cross over point is at 55 19 59.0N and at 229m.
3 9 33.0W

3.4 Apparent Velocity Across an Array

3.4.1 Known Azimuth

If the shot location is known, then the problem of the best fitting velocity to the curved wavefront across an array reduces to the linear regression of onset time on distance to the event.

The arrival time at pit (i) is given by:-

$$T_i = T_o + \left(\frac{1}{V}\right) X_i + \varepsilon_i + \delta_i \qquad (1)$$

where T_i is the onset time.

T_o is an arbitrary origin time.

X_i is the distance between the pit and the shot.

ε_i is the site and height correction term.

δ_i is the residual at the pit.

V is the apparent velocity across the array.

For the sum of residuals squared to be a minimum then:-

$$V = \frac{\sigma^2_{XX}}{\sigma^2_{XT}}$$

where σ^2_{XX} is the variance of the distances

σ^2_{XT} is the covariance of distances and onset times.

$$\sigma^2_{XX} = \frac{1}{m-1} \sum_{i=1}^{m} X_i^2 - \frac{1}{m}\left(\sum_{i=1}^{m} X_i\right)^2$$

where there are m onset times.

$$\sigma^2_{XT} = \frac{1}{m-1} \sum_{i=1}^{m} X_i T_i - \frac{1}{m}\left(\sum_{i=1}^{m} X_i\right)\left(\sum_{i=1}^{m} T_i\right)$$ (Topping 1972)

3.4.2 Confidence Limits

A particular level of significance (γ) was chosen e.g. 95%. The solution to the equation:- $F(C) = \frac{1}{2}(1+\gamma)$ was found from a table of Students t distribution for m - 2 degrees of freedom. The confidence limit of $\left(\frac{1}{V}\right)$ was found from:-

$$Se(\frac{1}{V}) = C \left[\frac{Q}{\sigma_{XX}^2 \, (m - 2)(m - 1)} \right]^{\frac{1}{2}}$$

where $Q = (m - 1)(\sigma_{TT}^2 - (\frac{1}{V})^2 \, \sigma_{XX}^2)$

and σ_{TT}^2 is the variance of the onset times.

The confidence limit of the apparent velocity was found from:-

$$Se(V) = V^2 Se\,(\frac{1}{V})$$

3.4.3 Solution for a Constrained Velocity

If the apparent velocity is constrained, the only unknown in equation (1) is T_o, which for the condition of least squares gives:-

$$T_o = \frac{1}{m} \sum_{i=1}^{m} T_i - \frac{1}{m} (\frac{1}{V}) \sum_{i=1}^{m} X_i$$

The standard error of the solution is given by:-

$$Se(Sol.) = \frac{1}{m-1} \sum_{i=1}^{m} (T_i - T_o - (\frac{1}{V})\, X_i)^2$$

The log value of the standard error of the solution was plotted against a set of constrained velocities about the least squares velocity. This proved useful to assess the quality of the data for the determination of velocity. Figure 16 shows the fit of velocity (Pg) to a blast from Eastgate quarry across Rookhope array, and displays a well defined minimum at 5.14 Km/sec.

3.4.4 Site Corrections

The height correction of the pit is given by:-

$$\frac{h_i \, (V^2 - V_c^2)^{\frac{1}{2}}}{V \, V_c}$$

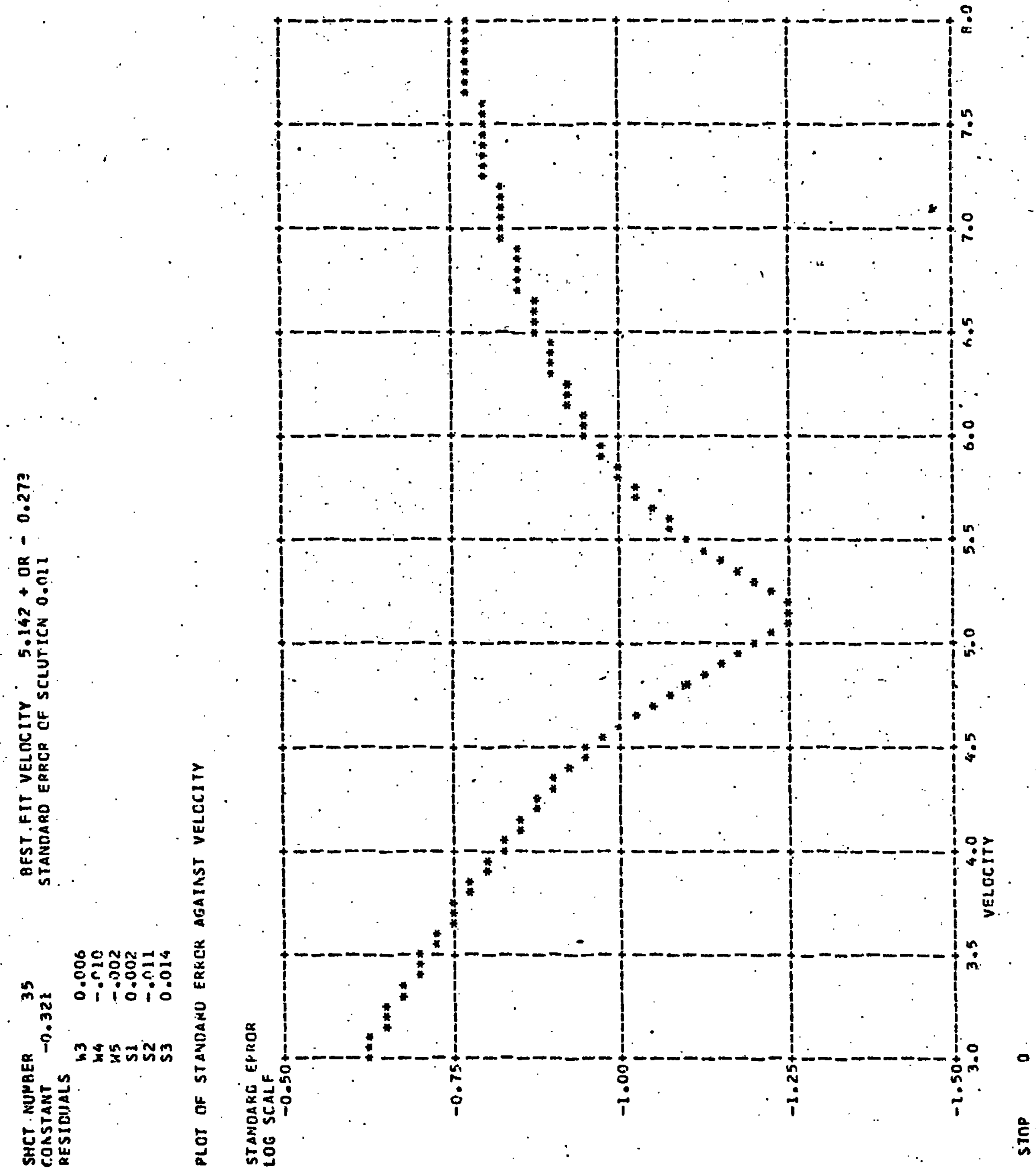
where h_i is the height above a common reference point e.g. cross over point.

V is the apparent velocity across the array.

V_c is the velocity of the cover.

Figure 16

Fit of Onset Times to Apparent Velocity
Across Rookhope Array



Because this formula contains the unknown (velocity), the solution becomes non linear. If h_i is small (less than 0.2 Km), the correction can be replaced by (h_i/V_c), which is different from the exact solution by an amount less than the observational error, for real cases. A site correction can also be applied for known systematic changes in geological structure.

3.4.5 Unknown Azimuth

The arrival time at a pit with coordinates (x_i, y_i), references to the cross-over point, for a ray with a plane wavefront is given by

$$T_i = T_o - x_i \left(\frac{\sin \alpha}{V}\right) - y_i \left(\frac{\cos \alpha}{V}\right) + \varepsilon_i + \delta_i \qquad (2)$$

where T_i is the onset time

T_o is the intercept time

ε_i is the site correction

δ_i is the residual at the pit

α is the azimuth of the ray with velocity V measured clockwise from the Y arm.

At least three onset times are required to solve the unknowns $[T_o, \alpha, V]$. The set of m equation of the type (2) can be written in matrix notation:-

$$[T] = [A][S]$$

where [T] is the column matrix (m x 1) of onset times

[S] is the column matrix of unknowns = $\begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} T_o \\ \sin \alpha/V \\ \cos \alpha/V \end{pmatrix}$

[A] is an m x 3 matrix of coordinates $\begin{pmatrix} \vdots & \vdots & \vdots \\ 1 & -x_i & -y_i \\ \vdots & \vdots & \vdots \end{pmatrix}$

For the sum of residuals to be a minimum the solution is:-

$$[S] = [A^TA]^{-1}[A^T][T]$$

The velocity is given by:- $V = \frac{1}{(S2^2 + S3^2)^{\frac{1}{2}}}$

The azimuth is $\alpha = \tan^{-1} (\frac{S2}{S3})$

3.4.6 Standard Error on the Unknowns

The variance on each of the unknowns is estimated from

$$\sigma_i^2 = \frac{Q_{ii} \sum_{i=1}^{m} \delta_i^2}{m - 3}$$

where Q_{ii} is the i^{th} diagonal element of $[A^TA]^{-1}$

The standard error of S_i = Se $(S_i) = \sqrt{\sigma_i^2}$

Velocity and azimuth are functions of S2 and S3:-

$$V = f\,(S2,\ S3)$$

$$\alpha = g(S2,\ S3)$$

The standard error of velocity is given by:-

$$(Se(V))^2 = (\frac{\partial f}{\partial S2})^2\ (Se(S2))^2 + (\frac{\partial f}{\partial S3})^2\ (Se(S3))^2$$

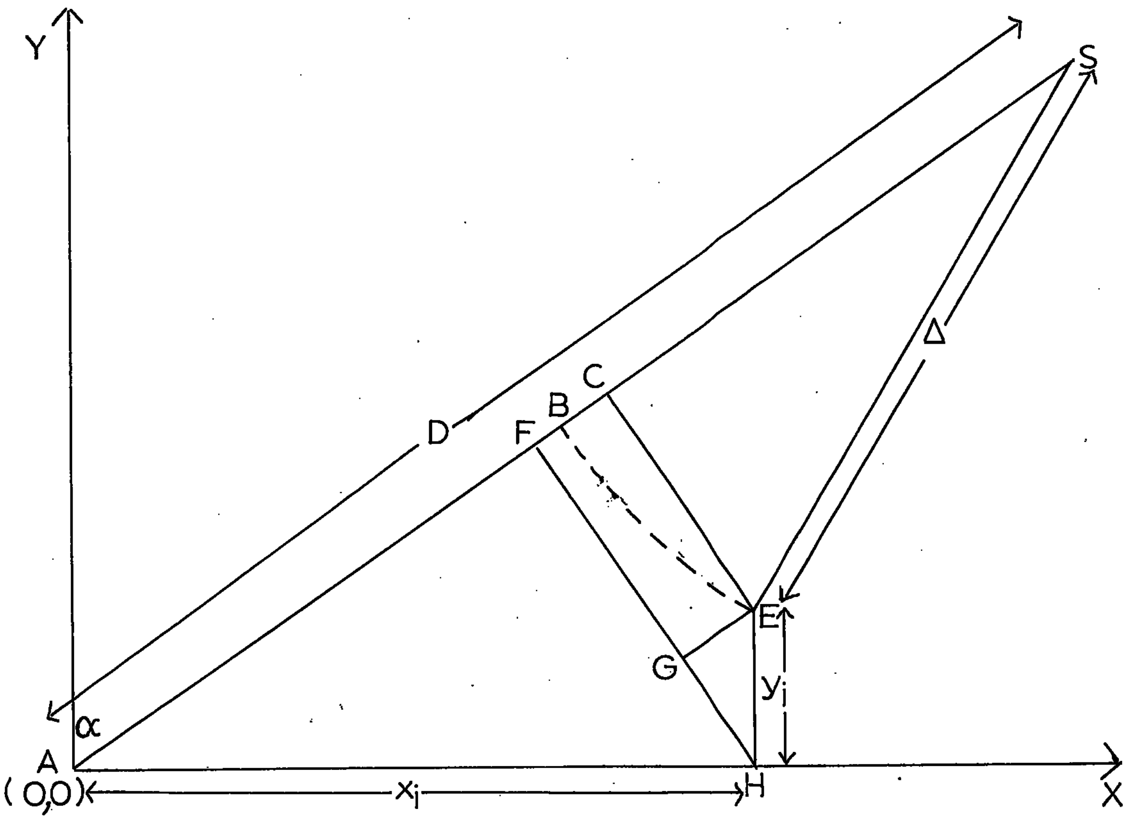
and similarly for azimuth.

Then $(Se(V))^2 = \frac{S2^2\ (Se(S2))^2 + S3^2\ (Se(S3))^2}{(S2^2 + S3^2)^3}$

and for azimuth $(Se(\alpha))^2 = \frac{S2^2\ (Se(S3))^2 + S3^2(Se(S2))^2}{(S2^2 + S3^2)^2}$

To calculate the confidence limit of V and α, a level of significance was chosen e.g. 95%, and the appropriate value from a table of students t distribution (two ended) for m - 3 degrees of freedom was multiplied by the standard error.

3.4.7 Correction for a Circular Wavefront



The distance from the source to the pit is given from the cosine rule:- $\Delta = (D^2 + x_i^2 + y_i^2 - 2\,D\,(\,x_i \sin\alpha + y_i \cos\alpha))^{\frac{1}{2}}$ where D is the distance from the cross over point to the source.

$$CE = FG = FH - GH = x_i \cos\alpha - y_i \sin\alpha$$

$$BC = BS - CS = \Delta - (\Delta^2 - (x_i \cos\alpha - y_i \sin\alpha)^2)^{\frac{1}{2}}$$

and is the extra distance travelled by the circular wavefront. The site correction in equation (2) (3.4.5) becomes

$$\varepsilon_i = \frac{A - (A^2 - (x_i \cos\alpha - y_i \sin\alpha)^2)^{\frac{1}{2}}}{V} + \frac{h_i\,(V^2 - V_c^2)^{\frac{1}{2}}}{V\,V_c}$$

The second term is the height correction. Because both velocity and azimuth are required to calculate the site correction, the problem becomes non linear and is solved by iteration. The distance D of the source to the cross over point can be calculated if the shot position is known, or it can be estimated from the P - S time. The iterative procedure is continued till the values of the site correction changes by less than a particular value (10^{-3} seconds) which is less than the accuracy of measurement of the onset time. In practise ε_i is small compared to T_i (especially for D greater than 50 Km) and the solution quickly converges.

3.5 The Upper Crustal Structure of Rookhope

3.5.1 The Data

A total of 140 local events were examined during a period from September-December 1969. Of these, the source of 49 events was located and are listed in Table 7.

Figure 17 shows the results of the measurement of apparent velocities plotted against the distance to the source. The weighted mean and confidence limits for repeated measurement of apparent velocity from the same quarry were calculated by using weights inversely proportional to the square of the standard error for individual measurement (Topping, 1972). The consistent low apparent velocities recorded for the Pg phase at Heights quarry and especially at Eastgate quarry, meant that the low apparent velocities (about 5.0 Km/sec) recorded at short ranges (below 8 Km) was of real statistical significance. Beyond 8 Km range, the apparent velocity (about 5.7 Km/sec) was commensurate with that obtained from the time term analyses (Chapter 2). The apparent velocity appeared to be independent of the azimuth of the source. The large confidence limits for

Table 7
Events used to Calculate Apparent Velocities across Rookhope Array

SOURCE	PHASE	DIST.	VARIABLE AZIMUTH VELOCITY	FIXED AZIMUTH VELOCITY
W4 Shot	Pg	0.121	7.88± 6.75	5.06± 0.76
Crooks Alter	Pg	4.294	4.36± 0.15	4.82± 1.09
Northgate	Pg	3.437	4.89± 0.16	5.49± 0.70
Eastgate	Pg	6.501	5.04± 1.27	5.46± 0.97
Eastgate	Pg	6.501	5.21± 0.35	5.24± 0.31
Frosterly	Pg	11.766	5.38± 0.76	5.48± 0.41
Frosterly	Pg	11.766	6.03± 0.74	6.10± 0.87
Heights	Pg	4.999	4.62± 0.80	5.25± 1.01
Eastgate	Pg	6.501	5.12± 0.87	5.44± 0.71
Shap	Pg	46.342	5.61± 0.22	5.62± 0.50
Newlandside	Pg	7.394	5.76± 1.06	4.90± 0.62
Mootlaw	Pg	32.600	5.75± 1.11	5.75± 0.74
Mootlaw	Pg	32.600	5.87± 1.19	5.86± 0.75
Shap	Pg	46.342	5.27± 0.85	5.49± 0.54
Buxton	Pm	171.190	6.27± 0.81	6.58± 2.42
Leyburn	Pg	54.832	5.92± 0.56	6.23± 0.71
Leyburn	Pg	54.832	5.89± 0.21	5.81± 0.48
Taprain	Pm	135.962	6.61± 0.35	6.49± 0.92
Newlandside	Pg	7.394	5.49± 1.27	5.25± 1.07
Eastgate	Pg	6.501	5.07± 0.29	5.14± 0.27
Mootlaw	Pg	32.600	5.86± 0.37	5.81± 0.39
Taprain	Pm	135.962	6.58± 0.44	6.70± 0.87
Newlandside	Pg	7.394	5.79± 0.31	5.90± 0.61
Shap	Pg	46.342	5.66± 0.17	5.72± 0.49
Horton	Pg	72.899	5.44± 0.53	5.55± 0.97
Mootlaw	Pg	32.600	6.02± 1.56	6.04± 1.12
Shap	Pg	46.342	5.82± 2.28	5.74± 1.40
Newlandside	Pg	7.394	4.92± 0.21	5.43± 0.55
Eastgate	Pg	6.501	4.80± 0.11	5.00± 0.48
Newlandside	Pg	7.394	5.77± 0.63	5.69± 0.42
Mootlaw	Pg	32.600	5.39± 1.41	5.47± 1.61
Belford	P*	92.511	6.48± 0.22	6.42± 0.79
Heights	Pg	4.999	4.95± 0.26	5.11± 0.35
Heights	Pg	4.999	4.86± 0.44	5.36± 0.73
Newlandside	Pg	7.394	5.39± 1.36	5.95± 0.65
Shap	Pg	46.342	5.08± 1.06	5.22± 0.81
Mootlaw	Pg	32.600	5.04± 1.38	5.24± 1.63
Swinden	Pg	82.242	5.97± 0.99	6.12± 1.17
Newlandside	Pg	7.394	5.13± 1.47	5.47± 1.59
Shap	Pg	46.342	5.28± 0.52	4.93± 1.05
Eastgate	Pg	6.501	5.28± 0.47	5.56± 0.51
Eastgate	Pg	6.501	4.17± 1.23	5.38± 1.60
Belford	P*	92.511	6.75± 0.30	6.79± 0.62
Kirkudbright	Pm	109.088	7.43± 1.53	7.40± 1.41
Mootlaw	Pg	32.600	5.95± 0.84	5.83± 1.00
Hartley	Pg	37.681	6.34± 0.56	6.49± 0.55
Eastgate	Pg	6.501	5.09± 0.24	5.11± 0.24
Newlandside	Pg	7.394		5.43± 0.46
Eastgate	Pg	6.501	5.32± 2.55	5.48± 2.98

Confidence limits are 95 per cent.

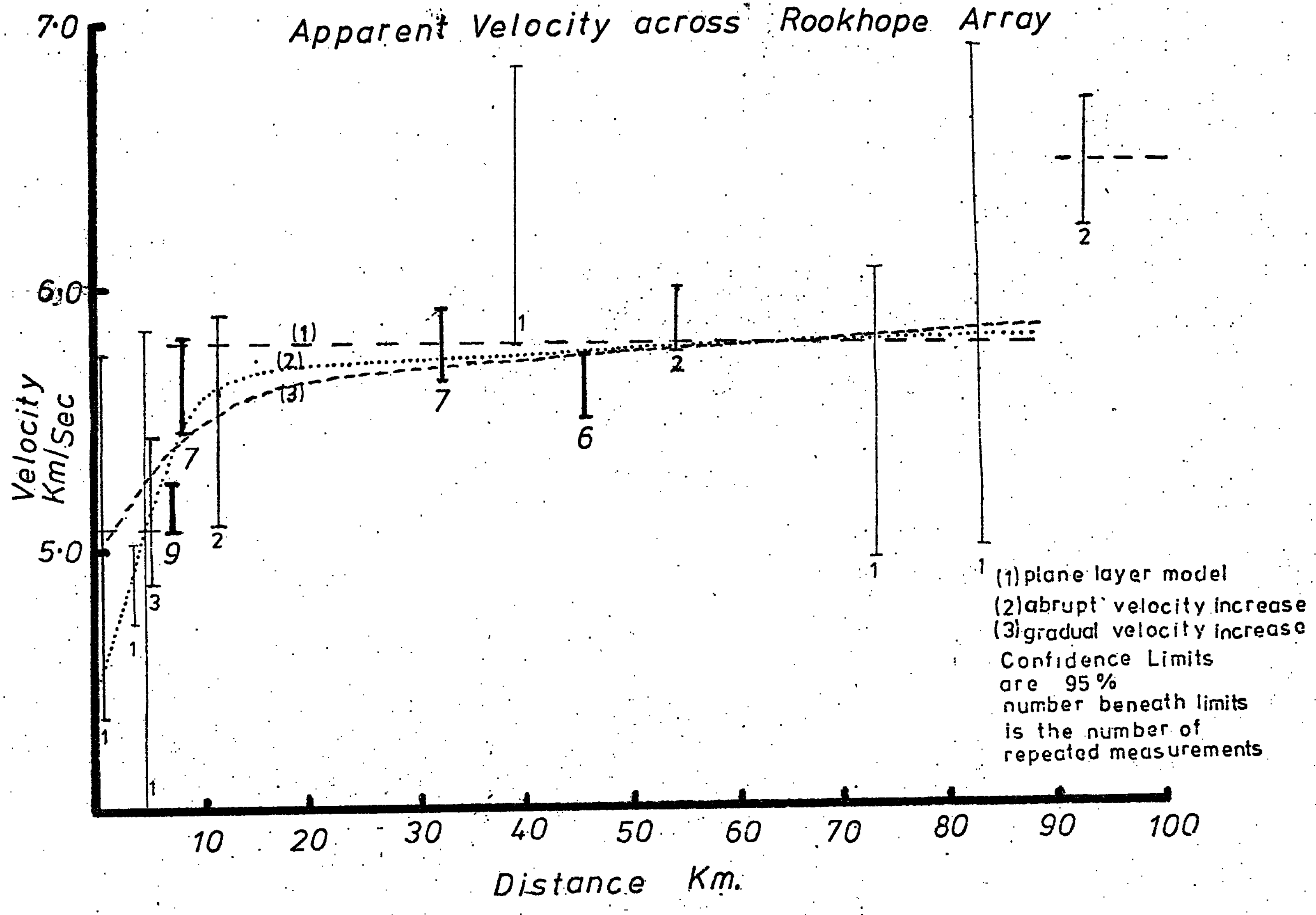

Apparent Velocity across Rookhope Array
Velocity Km/Sec
7·0
6·0
5·0
Distance Km.
10
20
30
40
50
60
70
80
90
100
(1)
(2)
(3)
(1) plane layer model
(2) abrupt velocity increase
(3) gradual velocity increase
Confidence Limits are 95%
number beneath limits is the number of repeated measurements

Figure 17

single events made it difficult to assess the exact velocity-distance function. Three separate functions were proposed to explore the range of possible solutions; two continuous and one discontinuous function.

An apparent velocity of about 6.5 km/sec was observed as a first arrival beyond 90 km and was interpreted as P* phase. Pm reflections were observed to have an apparent velocity of about 6.6 km/sec at large ranges (more than 130 km).

3.5.2 Inversion Procedure

The continuous velocity-distance functions were inverted to the velocity-depth structure by using the Wiechert integral:-

$$Z(V1) = \frac{1}{\pi} \int_0^{\Delta_1} \cosh^{-1}\left(\frac{V1}{V(\Delta)}\right) d\Delta \quad \text{(e.g. Slichter, 1932)}$$

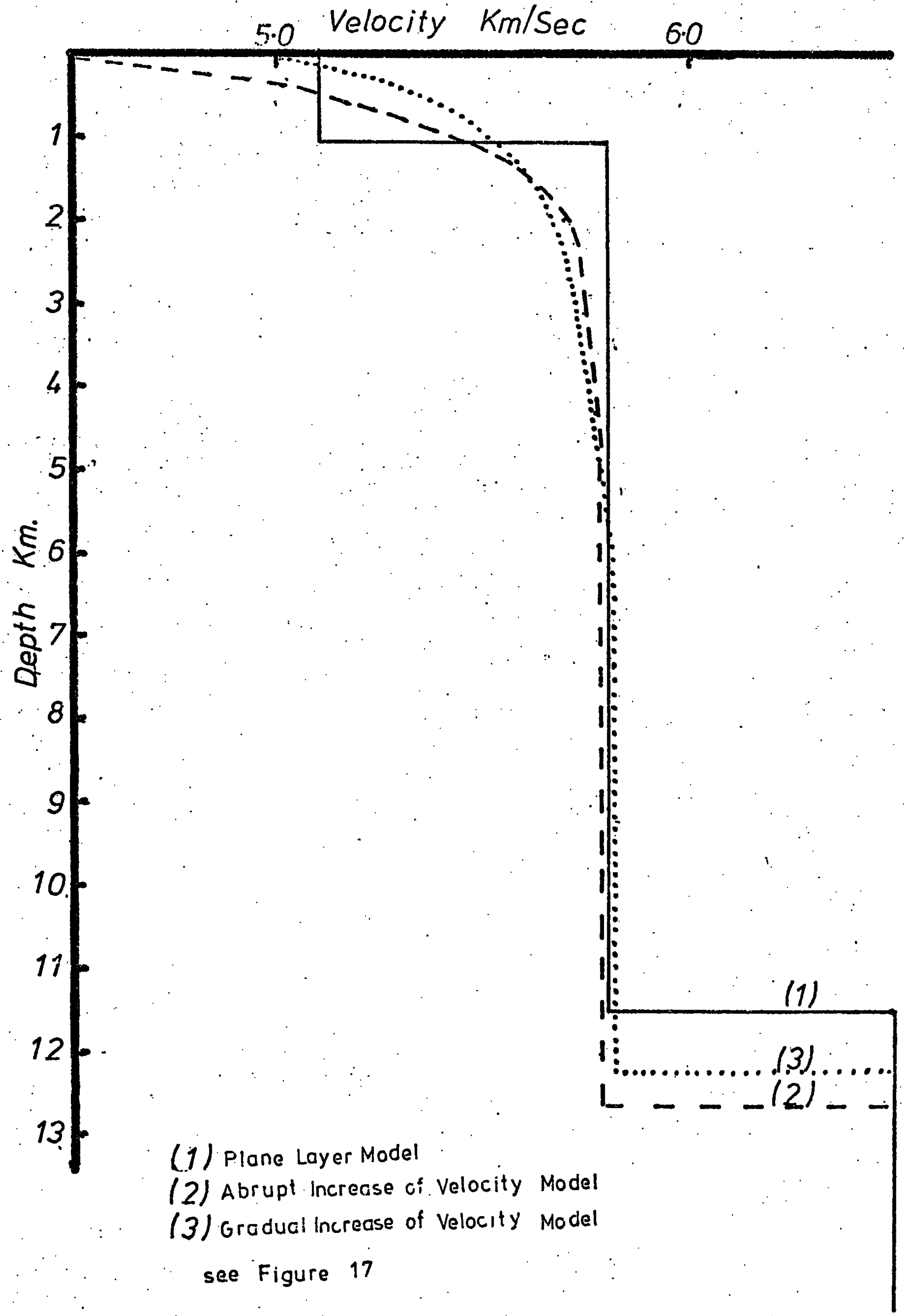
The inversion integral assumes that velocity increases continuously with depth, with no abrupt changes causing triplication of the velocity-depth function. The discontinuous function of apparent velocity was inverted by assuming plane layers, from which the depth to the higher velocity refractor was calculated.

3.5.3 The Velocity Structure of the Upper Crust beneath Rookhope

Figure 18 shows the result of the inversion of the three velocity-distance relationships. All three velocity-depth structures exhibit a low Pg velocity in the topmost 1 km of the granite beneath Rookhope, even though the nature of the transition to the underlying material could not be determined.

Figure 18

Velocity Structure of the Upper Crust at Rookhope



see Figure 17

It would be doubtful whether the observed velocity-distance relationship was caused by a laterally varying cylindrical structure. Whether the low velocity of the granite near the surface was due to compositional changes (Holland, 1967), or the result of deep weathering cannot be stated.

3.5.4 Depth to the Lower Crust

Beyond 90 km a P* phase with an apparent velocuty of 6.5 km/sec was observed. Further evidence for a lower crust comes from the velocity of the Pm phase at large distances, which becomes asymptotic to the same velocity.

At the cross-over distance the travel time of the Pg and P* waves are equal. Assuming plane layering, the delay time to the P* refractor is given by:

$$a = \frac{X_c}{2} \left(\frac{1}{V_{pg}} - \frac{1}{V_{p*}}\right) + a_1$$

where X_c is the cross-over distance

V_{pg} is the velocity of the Pg phase at the cross-over point

V_{p*} is the velocity of the P* phase

a_1 is the delay time relative to V_{pg} and can be calculated from the Wiechert integral:-

$$\int_o^h \frac{(V_{pg}^2 - V(z)^2)^{\frac{1}{2}}}{V_{pg}\, V(z)} \, dz \qquad (3)$$

where V(z) is the velocity distribution to depth h.

The estimate of the delay time to the P* refractor beneath Rookhope varied from 0.95 to 1.04 seconds depending on which model was chosen. The delay of the refracted wave to the depth h can be calculated from (3) by replacing V_{pg} with V_{p*}. Assuming a constant velocity (V_{pg})

beneath depth h, the depth to the P* refractor was estimated between 11.3 and 12.7 Km. If velocity increases below h, then this value was a minimum estimate.

3.5.5 Residuals at Rookhope

The mean and standard deviation of the residuals at each pit was calculated for the events listed in Table 7, both for fixed and variable azimuth. The distribution of residuals as shown in Figure 19 are not significantly different from zero. There is no apparent correlation with elevation, suggesting that the velocity of the cover (3.7 Km/sec) was correctly chosen.

3.5.6 Amplitude of the Pg phase Recorded at Rookhope

On a qualitative basis it was observed that the amplitude of Pg arrivals from sources just beyond the sub-surface boundary of the Weardale granite was very low. This may be explained by diffraction at the outward sloping contacts of the low velocity granite. The effect was not so noticeable at larger ranges, and may be due to a smaller velocity contrast at depth.

3.6 Interpretation of Eskdalemuir Records

3.6.1 Apparent Velocities across Eskdalemuir Array

First, and distinctive high amplitude second (Pm) arrivals from a number of known quarry blast sources, were used to calculate apparent velocities across Eskdalemuir. The events used and the results are shown on Table 8.

Figure 20 shows the results of the measurement of apparent velocities across the array. Because no events were located within 35 Km range, it was not possible to

Figure 19

PIT RESIDUALS AT ROOKHOPE ARRAY

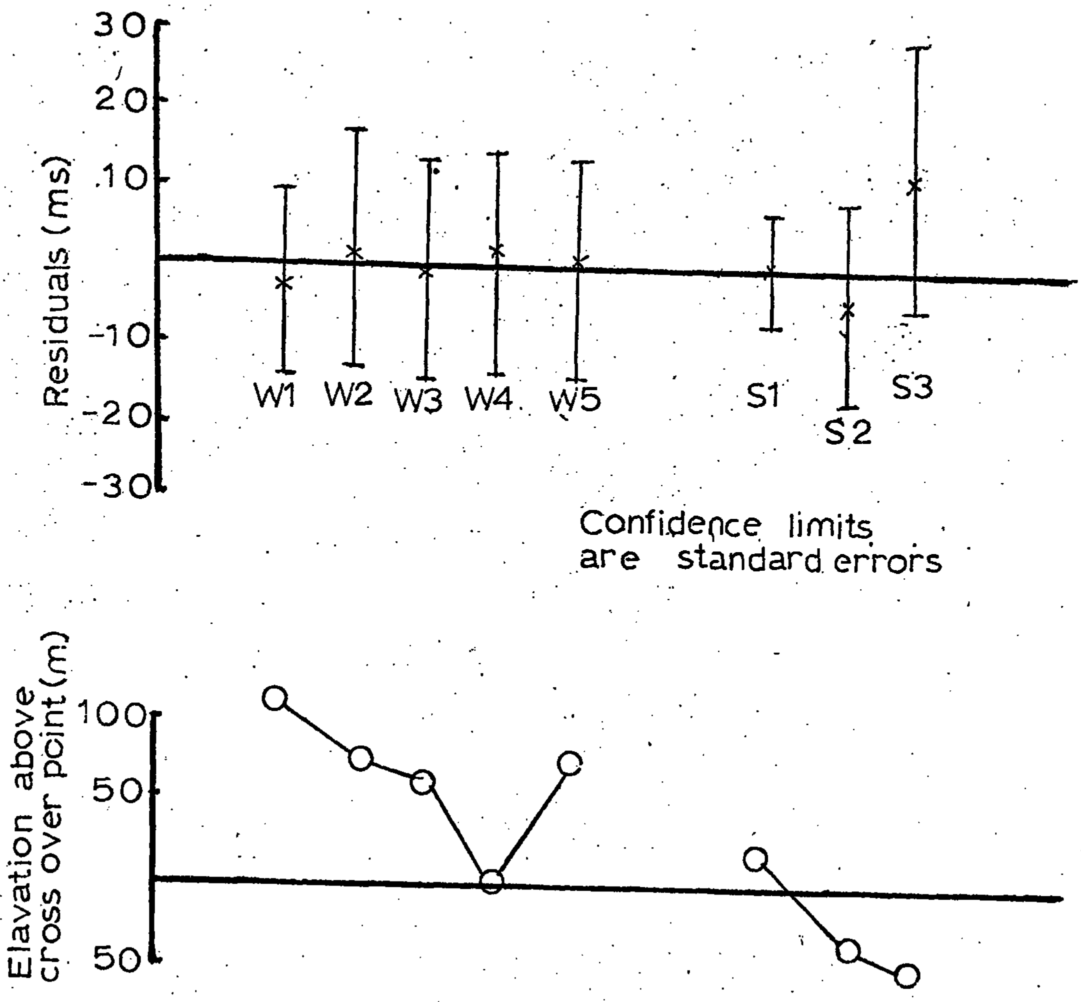


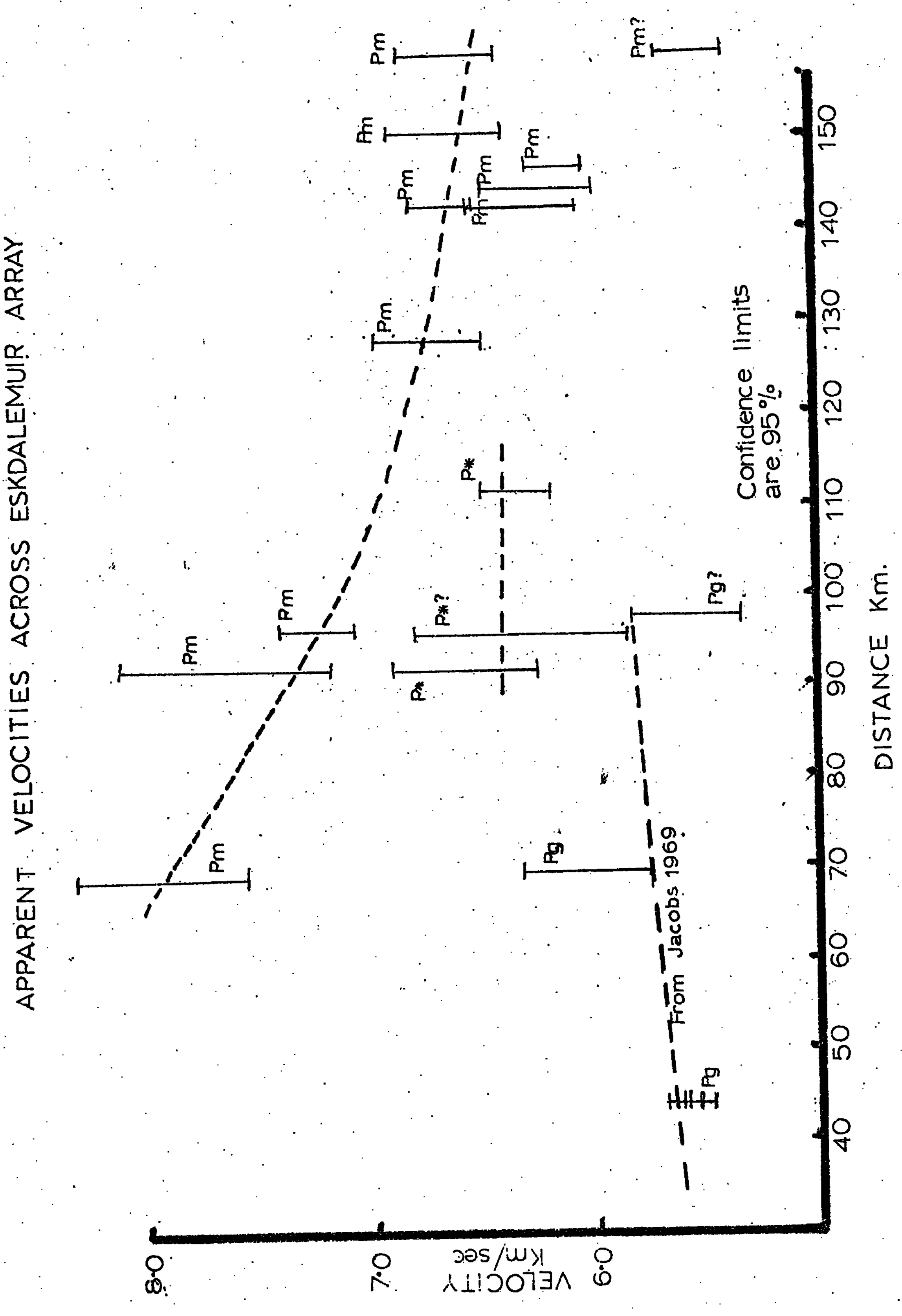
Table 8

Events used to Calculate Apparent Velocities across Eskdalemuir Array

SOURCE	DATE	DIST	PHASE	APPARENT VELOCITY
Belford	6/7/73	91.45	P*	6.57± 0.33
			Pm	7.66± 0.47
Little Haughton	10/7/73	97.97	Pm	9.69± 0.47
Harden	8/8/73	69.44	Pg	6.08± 0.27
			Pm	7.92± 0.39
Eastgate	9/8/73	95.87	P*?	6.33± 0.47
			Pm	7.25± 0.18
Raisby	9/8/73	126.85	Pm	6.72± 0.22
			Sm	4.00± 0.32
Spadeadam	27/8/73	44.06	Pg	5.61± 0.07
	28/8/73		Pg	5.57± 0.06
	29/8/73		Pg	5.58± 0.07
Horton	13/5/74	143.13	Pm	6.88± 0.73
	28/5/74		Pm	6.62± 0.17
	10/6/74		Pm	6.26± 0.25
Leyburn	5/6/74	141.06	Pm	6.09± 0.13
Giggleswick	6/6/74	150.30	Pm	6.59± 0.28
Swinden	7/6/74	160.28	Pm	5.55± 0.19
	15/7/74		Pm	6.60± 0.22
Arcow	19/6/74	143.13	Pm	6.26± 0.25
Hartley	26/6/74	110.02	P*	6.32± 0.18
High Force	19/7/74	97.93	Pg	5.56± 0.22

Confidence limits are 95 per cent.

Figure 20

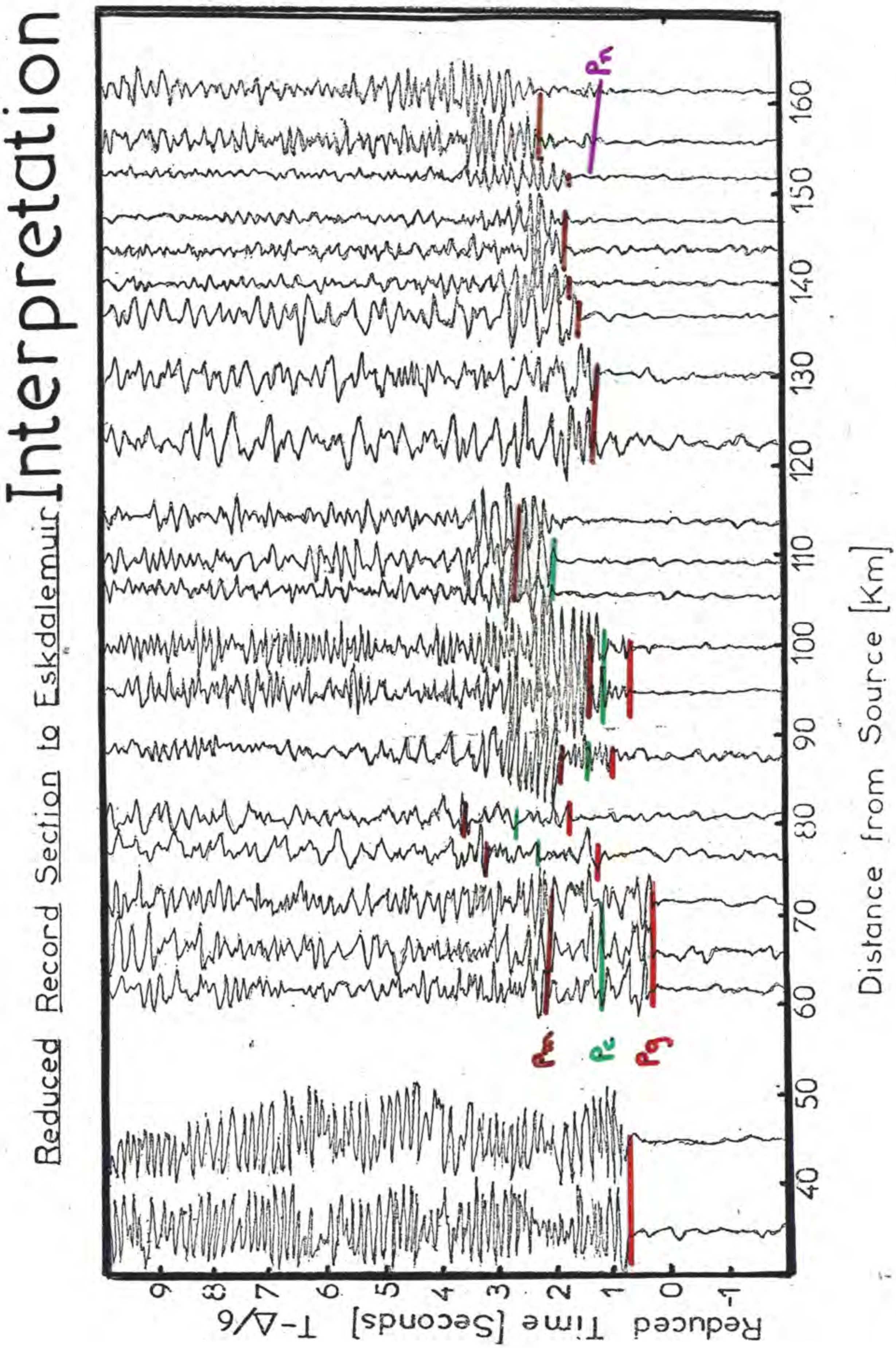

APPARENT VELOCITIES ACROSS ESKDALEMUIR ARRAY
Pm
Pm?
P*
P*?
Pg
Pg?
From Jacobs 1969
Confidence limits are 95%
DISTANCE Km.
40
50
60
70
80
90
100
110
120
130
140
150
VELOCITY Km/sec
6.0
7.0
8.0

invert the velocity-distance function for the Pg phase, but the velocities do agree with those obtained by Jacob (1969). A P* first arrival was observed beyond 90 km, and Jacob (1969) attributes this 'fast' phase to a discontinuity at about 12 Km beneath Eskdalemuir. The Pm phase shows a decreasing velocity with distance and becomes asymptotic to a velocity of about 6.6 km/sec at large ranges. The critical distance is estimated at 65 ± 5 km for an assumed Pn velocity of 8.0 km/sec (Agger and Carpenter, 1965). None of the phases from the sources used, showed any significant azimuthal anomaly.

3.6.2 Record Section to Eskdalemuir

Figure 21 shows a record section of quarry blasts recorded at Eskdalemuir, reduced to a velocity of 6.0 km/sec. Only a fraction of the total records are shown to preserve clarity. Because the events were recorded from different azimuths (east to south of the array), records at the same range but on different structures show a variable delay to the onset of the first arrival. This was particularly noticeable for quarries in the Northumberland Trough (at 75 to 85 km) and in the Stainmore Trough (at 105 to 115 km), which show a reduced time of the first arrival of about 1.5 seconds. Quarries from the block regions show a reduced time of less than one second for the first arrival. A high amplitude Pm phase was observed from one to two seconds after the Pg arrival. This phase persists to beyond 120 km where it can be easily mistaken for a first arrival. Only beyond 160 km was it possible to detect to the Pn phase, and at which distance the amplitude of Pm

Figure 21



Reduced Record Section to Eskdalemuir Interpretation
Pm
Pc
Pg
Pn
40
50
60
70
80
90
100
110
120
130
140
150
160
Distance from Source [Km]
9
8
7
6
5
4
3
2
1
0
-1
Reduced Time [Seconds] T-Δ/6

decreased slightly. Occurring at 1.0 to 0.5 seconds after the Pg phase, was a rather indistinct, but noticeable phase which was interpreted as a wide angle reflection from an intra-crustal discontinuity, and is here called the Pc phase.

3.6.3 Interpretation of Wide Angle Reflections

The interpretation of wide angle reflections was achieved by comparing the observed travel times with those calculated from plane layered crustal models. Assuming Snell's law, then for any ray the parameter, $p = \left(\frac{\sin i}{V(z)}\right)$ is constant. The travel time along the ray between depths z_1 and z_2 is given by:-

$$t = \int_{z_1}^{z_2} \frac{dz}{V(z)\sqrt{1 - p^2V^2(z)}}$$

The horizontal distance is given by:-

$$x = \int_{z_1}^{z_2} \frac{V(z)\, dz}{\sqrt{1 - p^2V^2(z)}}$$

To calculate the travel time for the reflected wave it was necessary to reckon the parameter p of the ray. A Newton iterative solution for the parameter was found from the distance integral. For n plane layers

$$X = \sum_{i=1}^{n} x_i = 2\sum_{i=1}^{n} \frac{p\, D_i\, V_i}{\sqrt{1 - p^2V_i^2}}$$

$$T = \sum_{i=1}^{n} t_i = 2\sum_{i=1}^{n} \frac{D_i}{V_i\sqrt{1 - p^2V_i^2}}$$

where D_i is the thickness of the i^{th} layer; V_i is the velocity of the i^{th} layer

$$\frac{dX}{dp} = \sum_{i=1}^{n} \frac{dx_i}{dp} = 2\sum_{i=1}^{n} \frac{D_i\ V_i}{(1 - p^2\ V_i^2)^{3/2}}$$

For layers with uniformly increasing velocity with depth:-

$$X = \sum_{i=1}^{n} x_i = 2\sum_{i=1}^{n} \frac{1}{pK_i}\left[(1 - Vo_i^2\ p^2)^{\frac{1}{2}} - (1 - Vt_i^2\ p^2)^{\frac{1}{2}}\right]$$

$$T = \sum_{i=1}^{n} t_i = 2\sum_{i=1}^{n} \frac{1}{K_i}\left[\cosh^{-1}\left(\frac{1}{p\ Vo_i}\right) - \cosh^{-1}\left(\frac{1}{p\ Vx_i}\right)\right]$$

$$\frac{dx}{dp} = \sum_{i=1}^{n} \frac{dx_i}{dp} = 2\sum_{i=1}^{n} \frac{1}{p\ K_i}\left[\frac{1}{(1 - p^2 Vt_i^2)^{\frac{1}{2}}} - \frac{1}{(1 - p^2\ Vo_i^2)^{\frac{1}{2}}}\right]$$

where K_i is the linear increase of velocity with depth in the i^{th} layer.

Vo_i is the velocity at the top of the i^{th} layer

Vt_i is the velocity at the bottom of the i^{th} layer

$$Vt_i = Vo_i + K_i\ D_i$$

During the Newton iterative process, an estimate p_j of the parameter of the reflected ray is made. A better estimate of the parameter is given by:-

$$p_{j+1} = p_j - \frac{X(p_j)}{\frac{dX(p_j)}{dp}}$$

At super critical distances the angle of emergence of the reflected and refracted rays is similar. The measurement of the time difference between the refracted and reflected waves is almost independent of the delay of the cover. In practice a small correction is applied.

3.6.4 Interpretation of Pc Reflections at Eskdalemuir

Figure 22 shows the fit of the observed Pc reflection travel times to a discontinuity at a variable depth. A single layered model was used with a velocity of V = 5·7 Km/

Figure 22

Interpretation of Pc Reflections

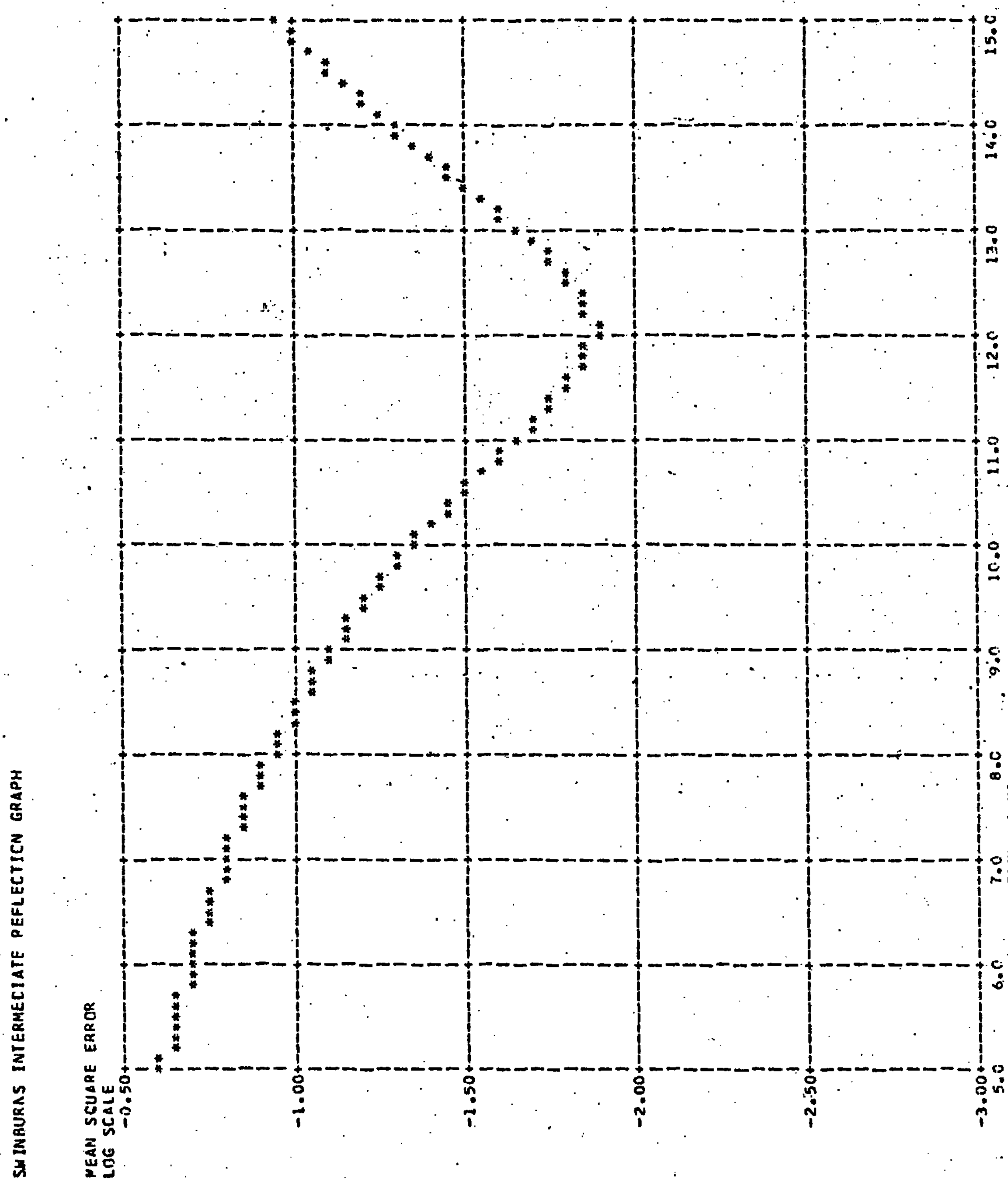


Figure 23

Interpretation of Pm Reflections

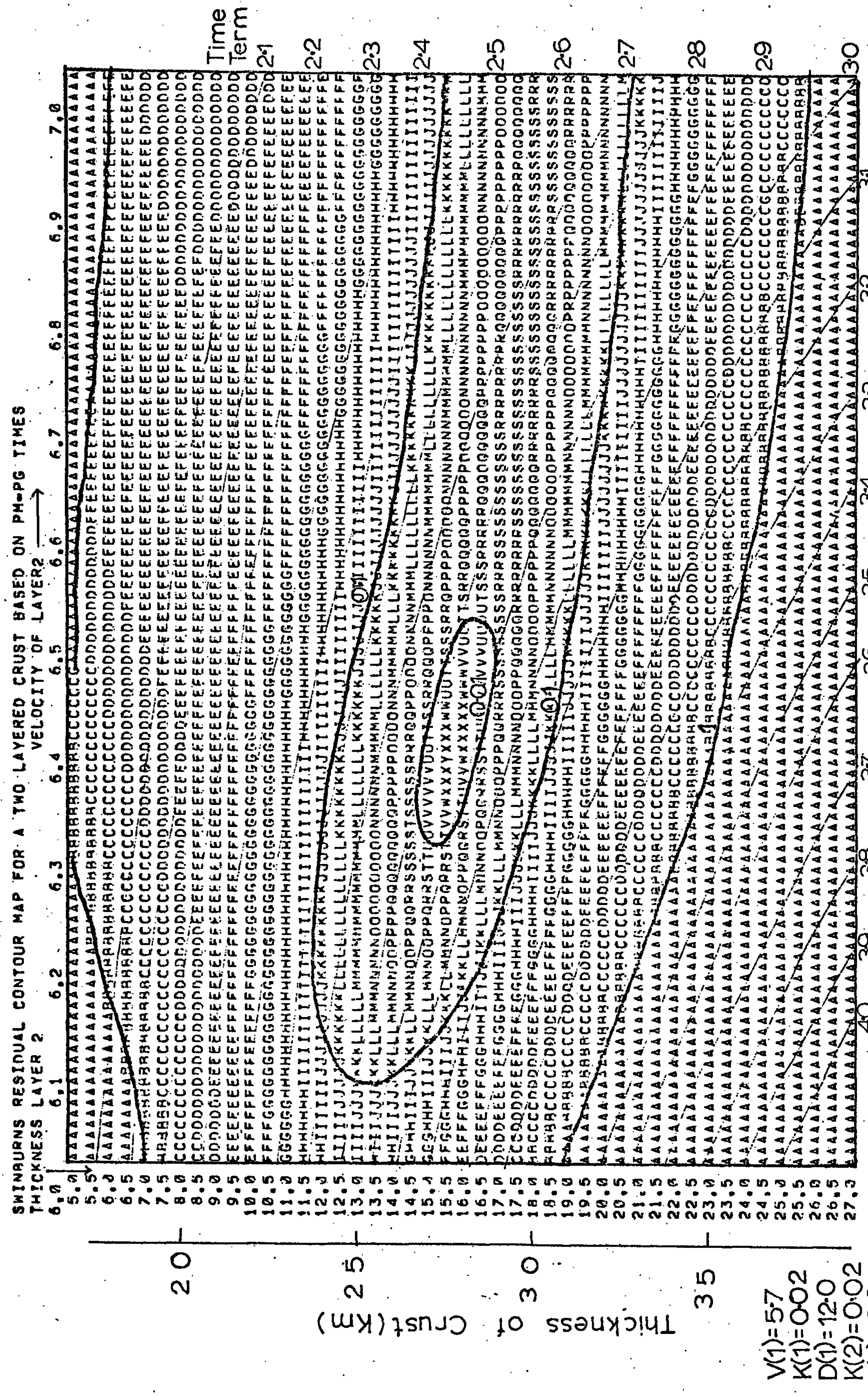
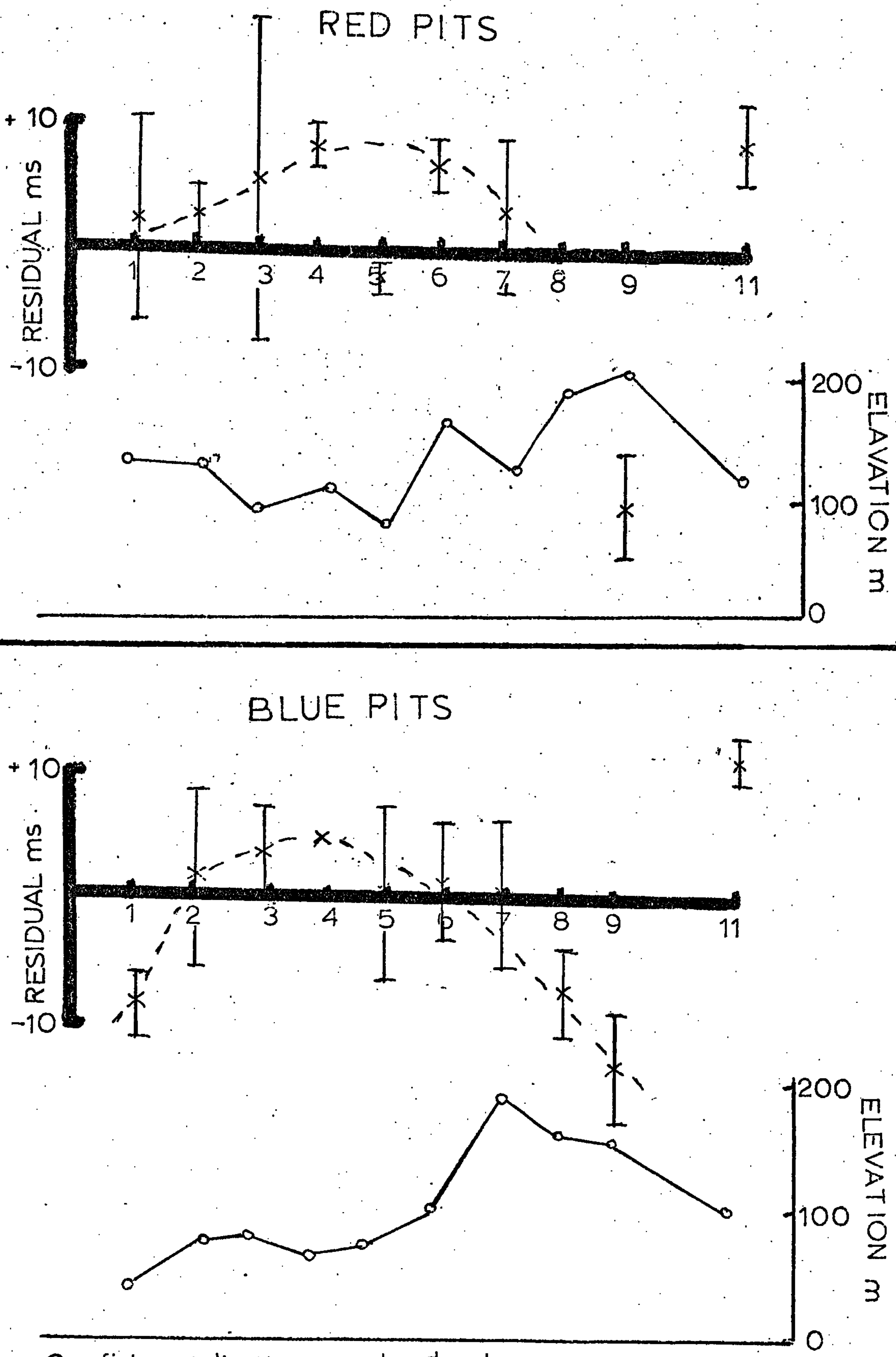


Figure 24

PIT RESIDUALS AT ESKDALEMUIR ARRAY



Confidence limits are standard errors

sec and K = 0·01 Km/sec/Km. The fit suggests a discontinuity at a depth of about 12 Km, which agrees well with the estimate made by Jacob (1969).

3.6.5 Interpretation of Pm Reflections to Eskdalemuir

Figure 23 shows the fit of a two layered crust to the observed Pm travel times. The thickness of the upper crust was constrained to 12 Km, and the velocity and thickness of the lower crust was varied. The best fitting model suggests a velocity of about 6.5 Km/sec at the top of the lower crust, and a depth of 27 Km to the Moho. The model has a time term of 2.85 seconds which closely corresponds to the value suggested by Agger and Carpenter (1965).

3.6.6 Residuals at Eskdalemuir

Figure 24 shows the mean and standard deviation of the residuals at each pit at Eskdalemuir array for three Pg arrivals with high signal to noise ratios. There appeared to be little correlation of the residuals with elevation, suggesting the cover velocity of 4.7 Km/sec (Agger and Carpenter, 1965) was approximately correct.

3.7 Conclusions

An analysis of the apparent velocities for crustal phases across Eskdalemuir and Rookhope array suggests that:-

1) There was an indication that velocity increased with depth in the upper crust. This was especially noticeable near the surface of the Weardale granite beneath Rookhope.
2) From both the reflected and refracted phases, there was evidence of a discontinuity at a depth of 12 to 13 Km beneath Eskdalemuir and Rookhope. Beneath this discon-

tinuity the velocity of the lower crust was about 6.5 Km/sec.

3) The interpretation of Pm reflections suggested that the Mohorovicic discontinuity was at a depth of about 27 Km beneath Eskdalemuir.

CHAPTER 4

NORTHERN ENGLAND REFRACTION LINE (N.E.R.L.)

4.1 Introduction

The N.E.R.L. experiment was a subsidiary refraction line, displaced 30 to 60 Km to the east of the main L.I.S.P.B. project (Lithosphere Seismic Profile in Britain), shot during the summer of 1974. The recording line, which was approximately 130 Km long, stretched from Skipton in North Yorkshire to near Rothbury in Northumberland, and straddled the 2^{o}W meridian. The shot distribution of the main experiment dictated that the line would give essential information about the deep crustal and upper mantle. The project was a joint venture between the Universities of Durham and Cambridge.

4.2 Planning

4.2.1 The L.I.S.P.B. Project

The L.I.S.P.B. project was designed to investigate the lithospheric structure of Britain. A series of four large spreads with eighty recording stations each, were moved to give an even coverage along the length (north-south) of Britain. Land and shallow marine shots were distributed along the line, and were detonated during the first phase from 23rd July to 1st August. During this phase the spreads were moved progressively northwards. During the second phase, from 4th to 15th August, large sea shots were detonated off N.W. Scotland and in the English Channel, as the spreads were moved southwards.

4.2.2 The N.E.R.L. Line in Relation to the L.I.S.P.B. Project

The position of the N.E.R.L. line in relation to the L.I.S.P.B. project is shown in Figure 25. The position of spread gamma of the L.I.S.P.B. project was determined by the two terminal shot points at Buxton (Derbyshire) and Spadeadam (Northumberland). The planned line lay along the western margins of the Askrigg and Alston blocks. The proximity to the Dent and Pennine faults, both of which are major crustal dislocations, meant that this line may not reflect the true structure of the main units. It was decided to operate a separate recording line, parallel to spread gamma, but displaced to the east.

4.2.3 Planning of N.E.R.L.

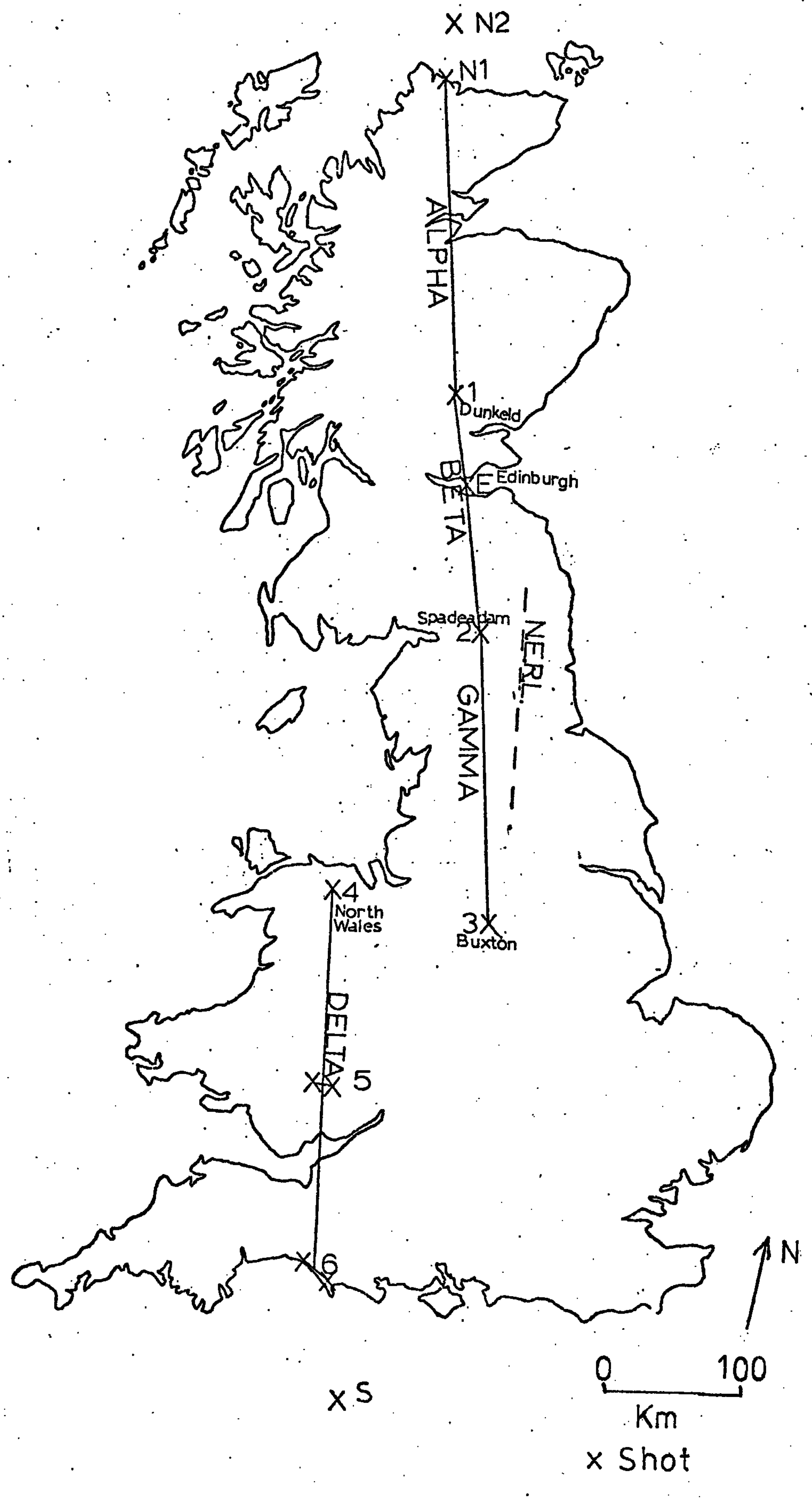
The position of the N.E.R.L. recording line was chosen so that it lay central within the structural units. The profile was designed to cover the Northumberland trough, Alston block, Stainmore trough, and the Askrigg block. This line coincided with the most intensely investigated region of the upper crustal structure (Chapter 2). A north-south line parallel to the main experiment meant that the maximum information about the velocity structure of the crust could be extracted.

4.2.4 Logistics

It was thought that the most information could be obtained if the design of the experiment mirrored the logistics of the main experiment. Because of the small size of the planned shots off Weymouth and in South Wales, it was decided not to include these shots. The N.E.R.L.

Figure 25

The Position of Recording Spreads on the L.I.S.P.B. experiment



line was divided into three spreads which mirrored the movements of lines Alpha, Beta and Gamma (Figure 25) of the main experiment. The relationship of the experiment to the structure of Northern England is shown on Figure 26. The spreads from south to north were designated A, B and C.

The A spread stretched from near Skipton to Wensleydale and covered most of the Askrigg block and its margin onto the Craven basin to the south. The B spread lay from Wensleydale to Weardale. This covered the northern margin of the Askrigg block, the Stainmore trough and the southern edge of the Alston block. The C spread extended from Weardale to near Rothbury in northern Northumberland. The spread lay over the northern edge of the Alston block and covered the Northumberland trough.

A total of 13 mobile recording sets were used on each spread. Cambridge sites were interleaved between Durham stations, so that if a particular system failed, complete, though less detailed coverage would exist. The permanent station at Rookhope was operated throughout the experiment.

It was hoped that the Buxton and Spadeadam shots would give useful upper crustal data, while the Edinburgh, Dunkeld, North Wales and sea shots (Figure 25) would yield information on the variation in crustal thickness.

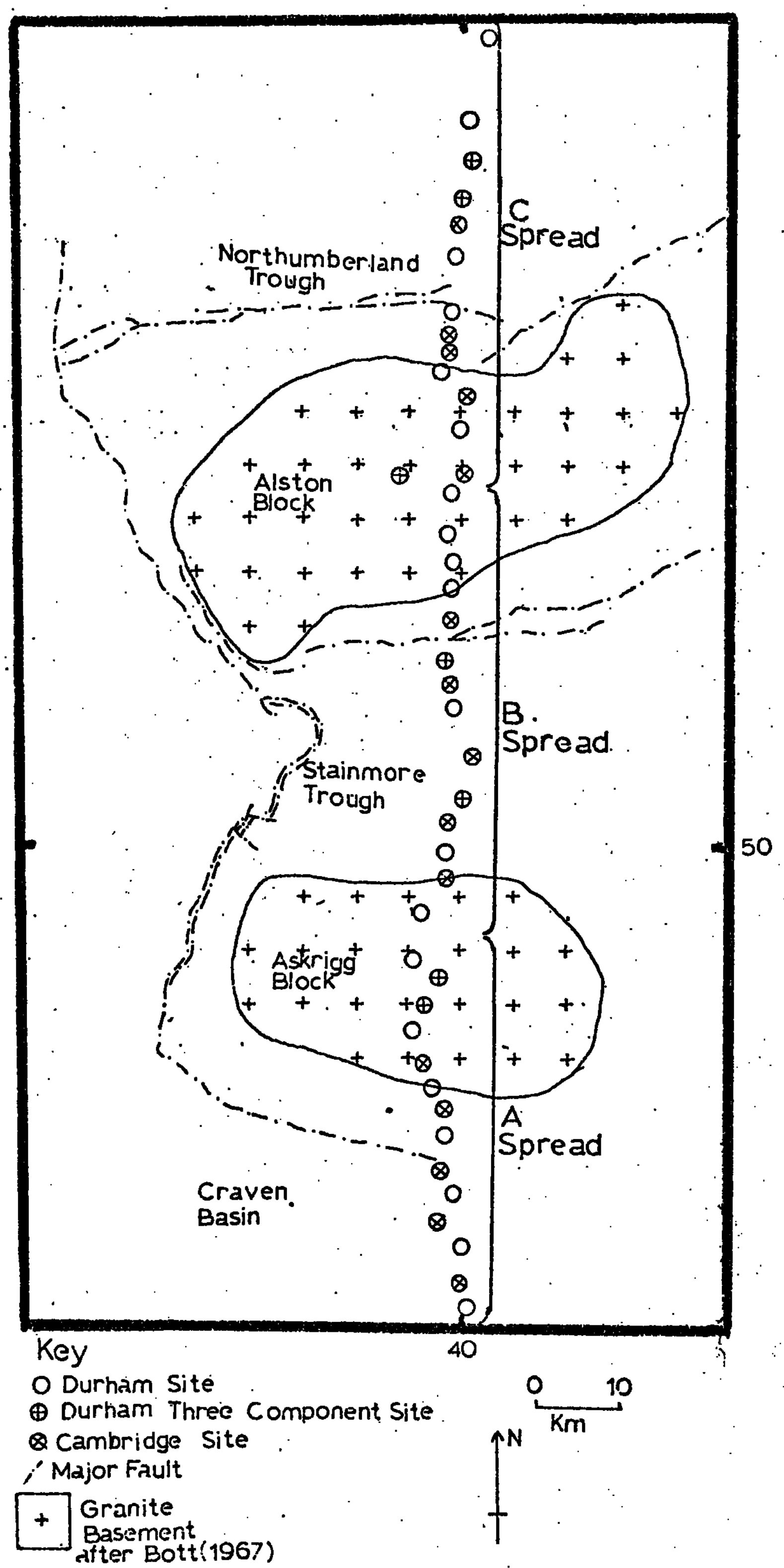
4.3 Data Collection

4.3.1 Recording Sites

Recording stations were selected for easy access by road to low noise sites, on drift free land with good exposure for direct coupling of the seismometers to bedrock.

Figure 26

NERL. Sites in Relation to the Major Structures of the Northern Pennines



Sites were spaced at intervals of approximately 3½ Km along the spreads, with a minimum lateral offset. A small hole was dug sufficiently deep to cover the seismometer, so that wind noise was reduced.

4.3.2 Equipment

The Durham equipment consisted of six portable cassette recording systems, two mobile three component sets, and the permanent station at Rookhope. Cambridge University employed five portable sets.

The tape decks of the six portable Durham sets were Uher stereo cassette recorders, operated at 1⅞ i.p.s. and using C90 or C120, CrO_2 cassettes. One channel recorded M.S.F. time signal directly, the other a frequency modulated siesmic signal. The recorder had an audio monitor to check the system was functioning normally. A separate amplifier-modulator was connected to the recorder. The gain level of the single channel seismic amplifier was switched electronically by powers of two by means of an internal thumbswitch. Calibration pulses were switched automatically when the power from the recording deck was switched on. A single vertical seismometer was connected by about 100 m of screened cable, so that the operator would not disturb the recordings. Five sets used Willmore Mk2 instruments, while the remaining unit used a Willmore Mk3. The recording system was placed in a large polythene bag for weatherproof operation.

The two three component sets were identical to those previously described (2.4.2). Willmore Mk1 seismometers were used as the horizontal components, and a Willmore Mk2 as the vertical for each set.

The Cambridge University equipment was similar to the Durham mobile sets, and used Uher ¼" four track decks, an amplifier-modulator unit and a quartz driven digital clock. Synchronisation of the clocks was achieved by recording M.S.F. radio time signals at the beginning of each recording and by the distinctive speech bursts of B.B.C. radio 2. Gain was switched by powers of two and separate recordings of the single vertical Willmore Mk2 seismometers were made at two gain levels.

4.3.3 Field Operation

A window of 20 to 45 minutes was allocated to each shot, which was usually detonated just after the hour at 07.00, 15.00, 19.00, and 21.00 hours B.S.T.

The three component sets were moved into position on their respective spreads before the appropriate shot was to be fired. A spare day existed between the movement of each spread to enable this to be performed.

Before each shot window, a group of six operators would depart from Durham, each with a mobile recording set, and with watches synchronised. The operators and equipment were unloaded at different sites along a spread. At the beginning of each shot window the operator switched the recording system and made a note of any signals heard through the audio monitor. After the end of the shot window, the systems were dismantled, and the operators and equipment were transported back to Durham. The system allowed for flexible operation depending on any changes in the shot firing programme.

The Cambridge group was based in three field headquarters on each spread. Liaison between each group and the L.I.S.P.B. headquarters at Birmingham and Edinburgh was by telephone.

4.3.4 Replay of the Recordings

The records from the three component sets and Rookhope were replayed as in Section 2.3.7. The cassettes were replayed on the Uher decks. The time channel was fed directly to the jet pen recorder. The signal channel was demodulated and the output filtered using a low pass 50 Hz and 10 Hz (5 Hz for the marine shots) filter. The filtered and unfiltered signals were interleaved with time channels on the jet pen at a playout speed of 25 mm/sec. The Cambridge recordings were similarly replayed, except the clock channel was demodulated before output.

4.3.5 Calculation of Travel Times and Distances

For the time term analyses it was necessary to calculate the travel time and distances for the refracted arrivals between the shots and receiver stations. From the paper playout, the onset time of the refracted wave was picked along with an estimate of the error involved. This error was greater for the marine shots because of their low frequency content. The travel time was obtained by subtracting the time of the shot instance.

For the land shots, the distance to the receiver was calculated by using the O.S. grid coordinates. The positions of the sea shots were given in geographical coordinates. The O.S. grid coordinates of the receiving stations were converted to geographical coordinates, and the travel distances were computed. Briefly, the geographical coordinates were converted to geocentric coordinates and the radius vectors calculated. The geocentric angle between the radius vectors was calculated and the interstation distances reckoned using the cosine rule. The error in distances for the land shots was estimated at about 0.1 km and not more than 0.2 km for the marine shots.

4.4 The Data

The records from the Buxton and Spadeadam shots were stacked at a reduced velocity of 6.0 km/sec. The remaining records were stacked at 8.0 km/sec. From these sections the main phases were identified. First arrivals for refracted phases (Pg and Pn) were picked so that the travel times could be interpreted by using the time term method.

4.4.1 Record Section of the Spadeadam Shots

Figure 27 shows the reduced section of the Spadeadam shots. It displays the broad frequency band of the records, which was typical of the land shots. The main phases identified were:-

a) The Pg phase was seen as a low amplitude first arrival along most of the section. Although the amplitude of this phase decreased markedly beyond 60 km, it was still identifiable to beyond 100 km range. As this phase appeared almost horizontal on the section, its apparent velocity was approximately 6.0 km/sec. A significant feature of this phase was a slight delay of up to 0.4 seconds in the range 70 to 90 km. As this range coincided with the position of the Stainmore trough it was reasonable to assume that this

Interpretation

N.E.R.L. Reduced Section for Spadeadam Shots

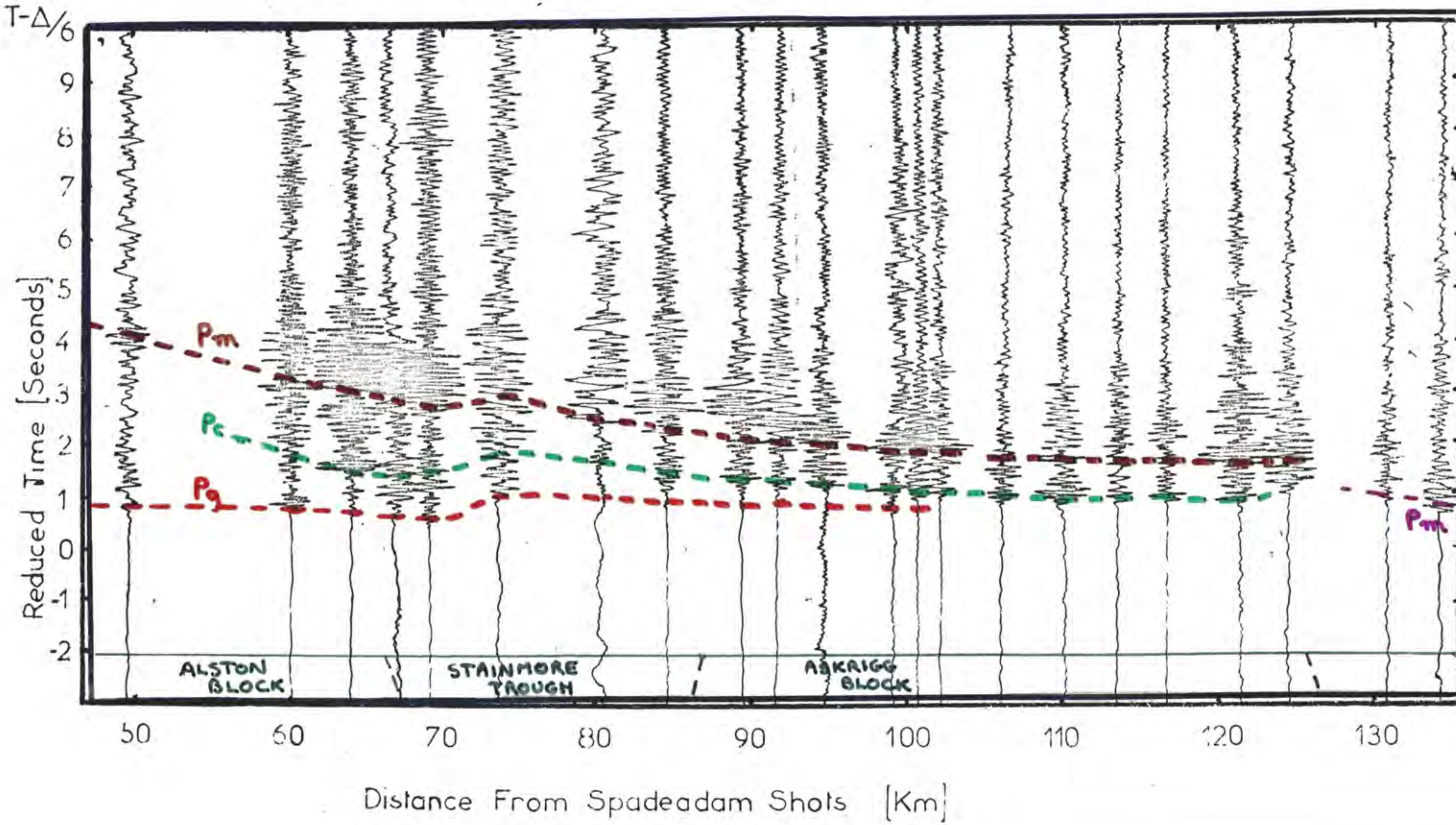


Figure 27

Interpretation

N.E.R.L. Reduced Section for Buxton Shots

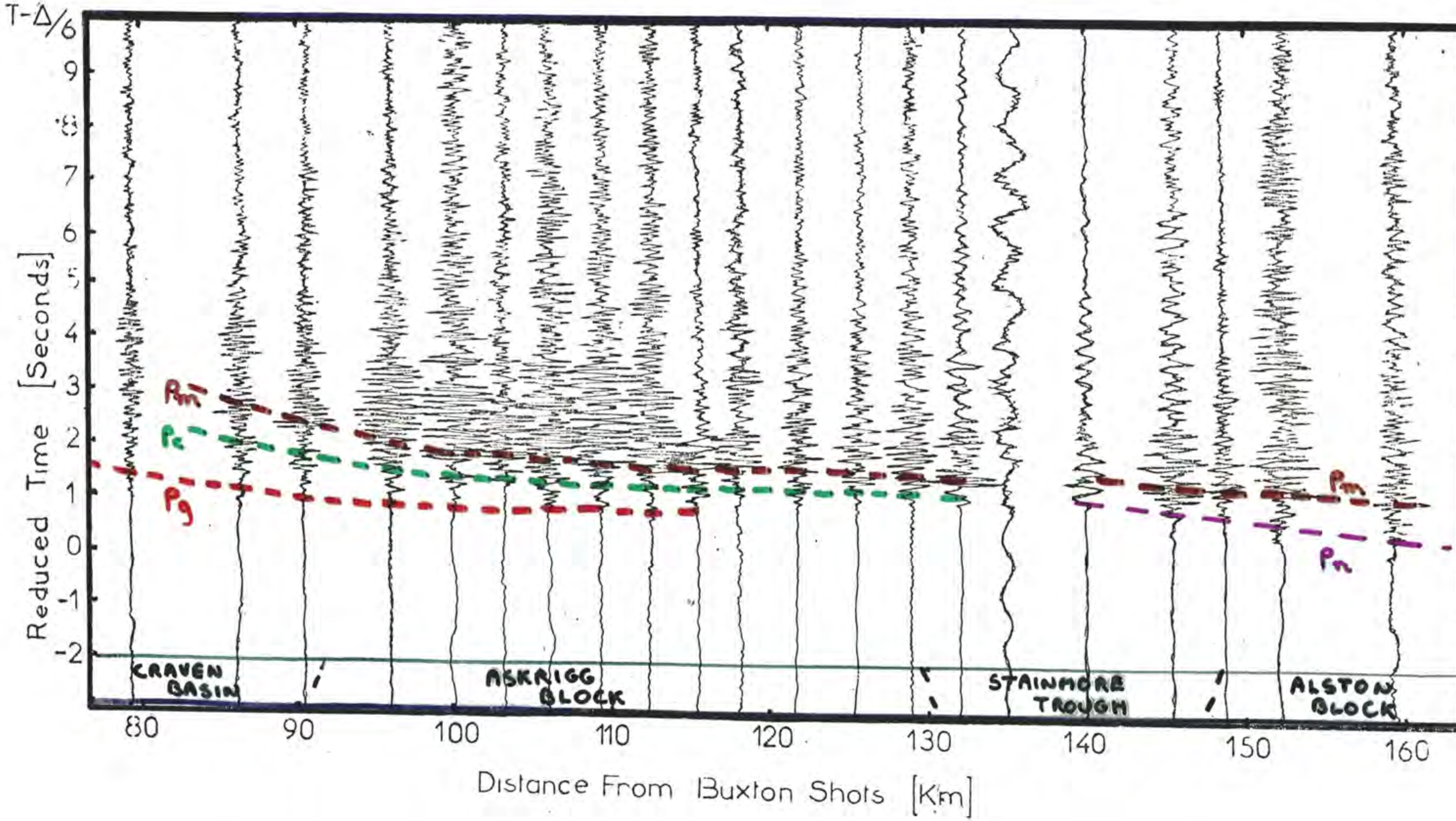


Figure 28

Figure 29

Interpretation

N.E.R.L. Reduced Section of North Wales Shot

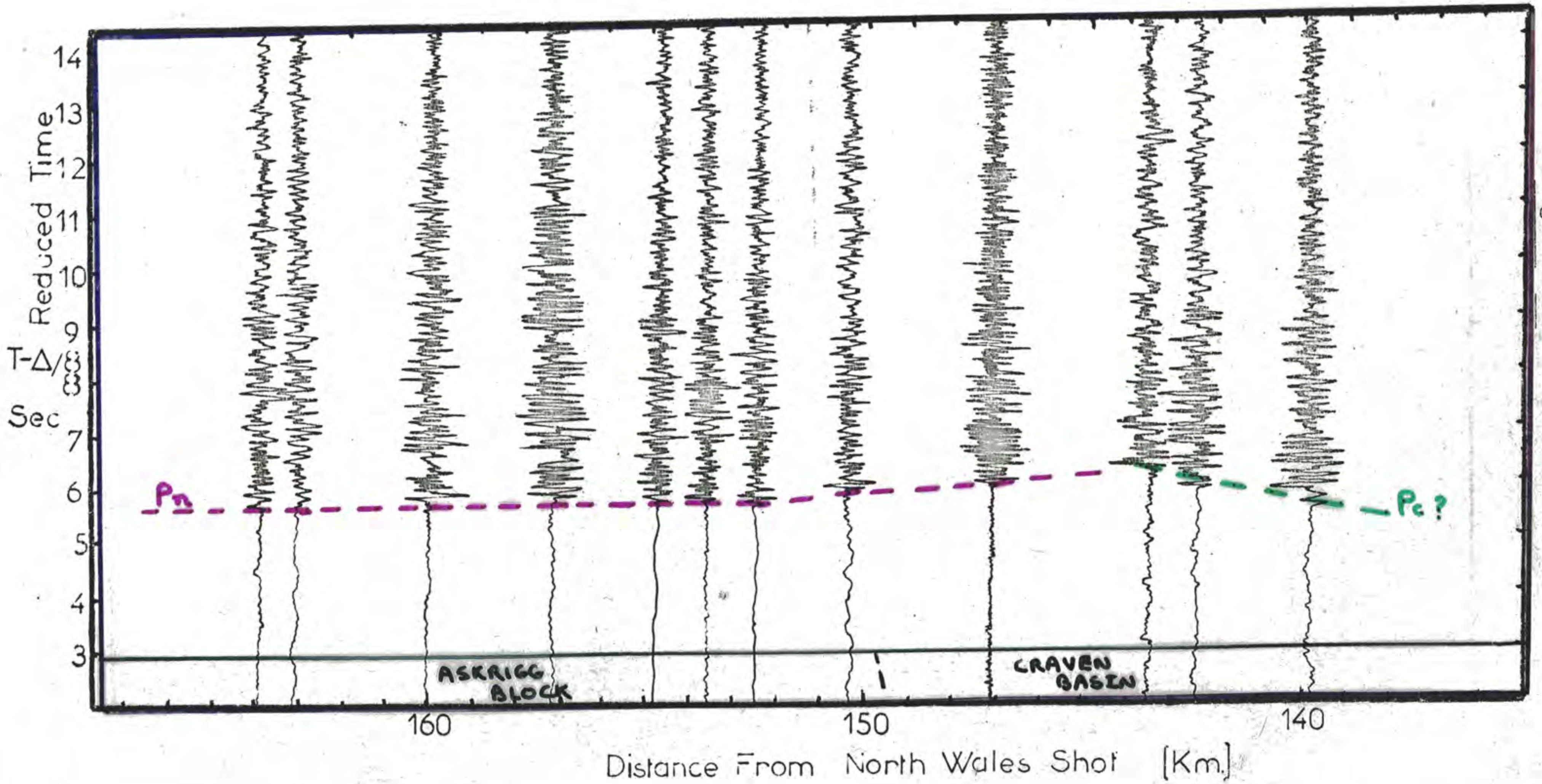
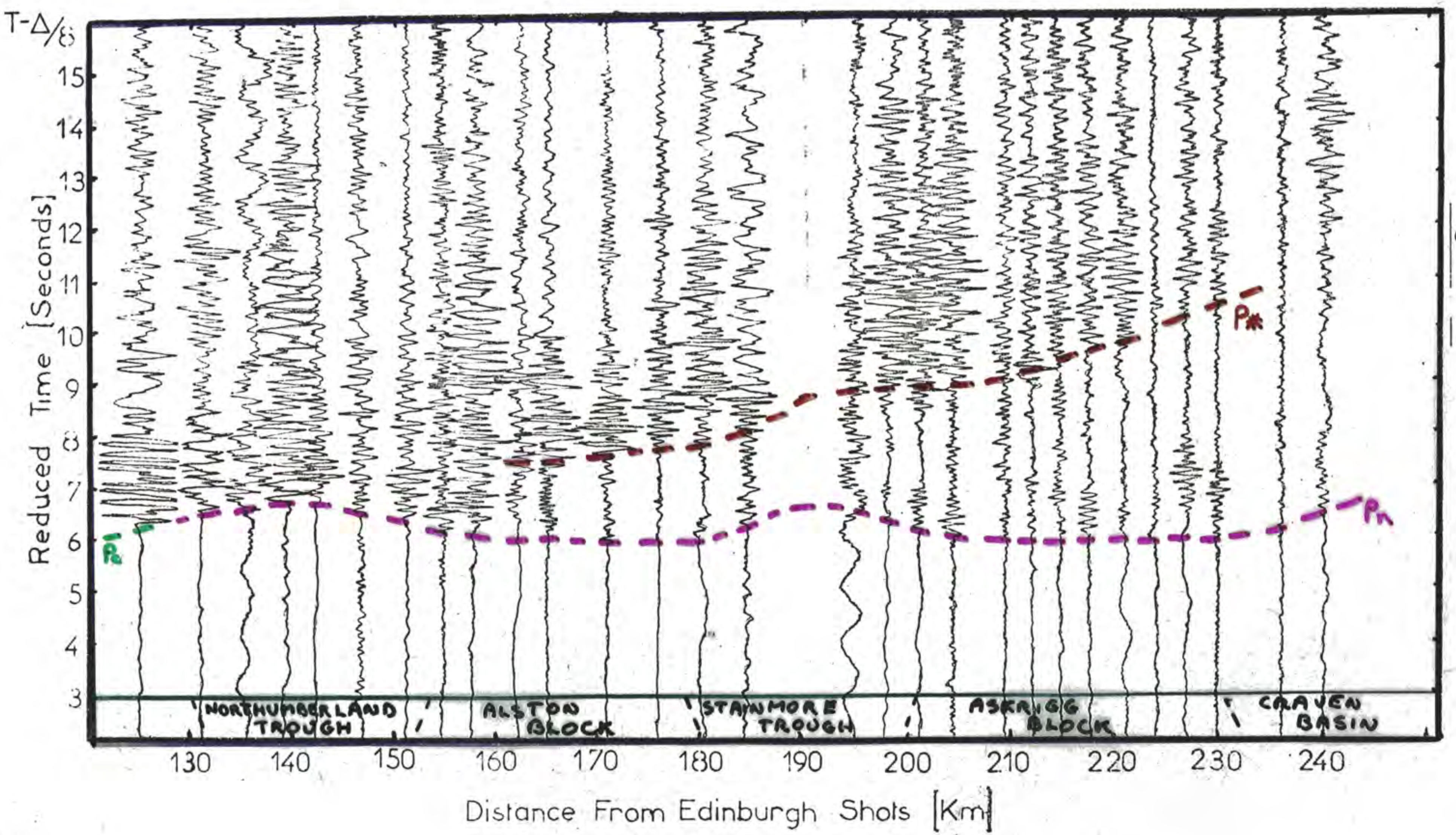


Figure 30

Interpretation

N.E.R.L. Reduced Section of Edinburgh Shots



Interpretation

N.E.R.L. Reduced Section for N1 Shots

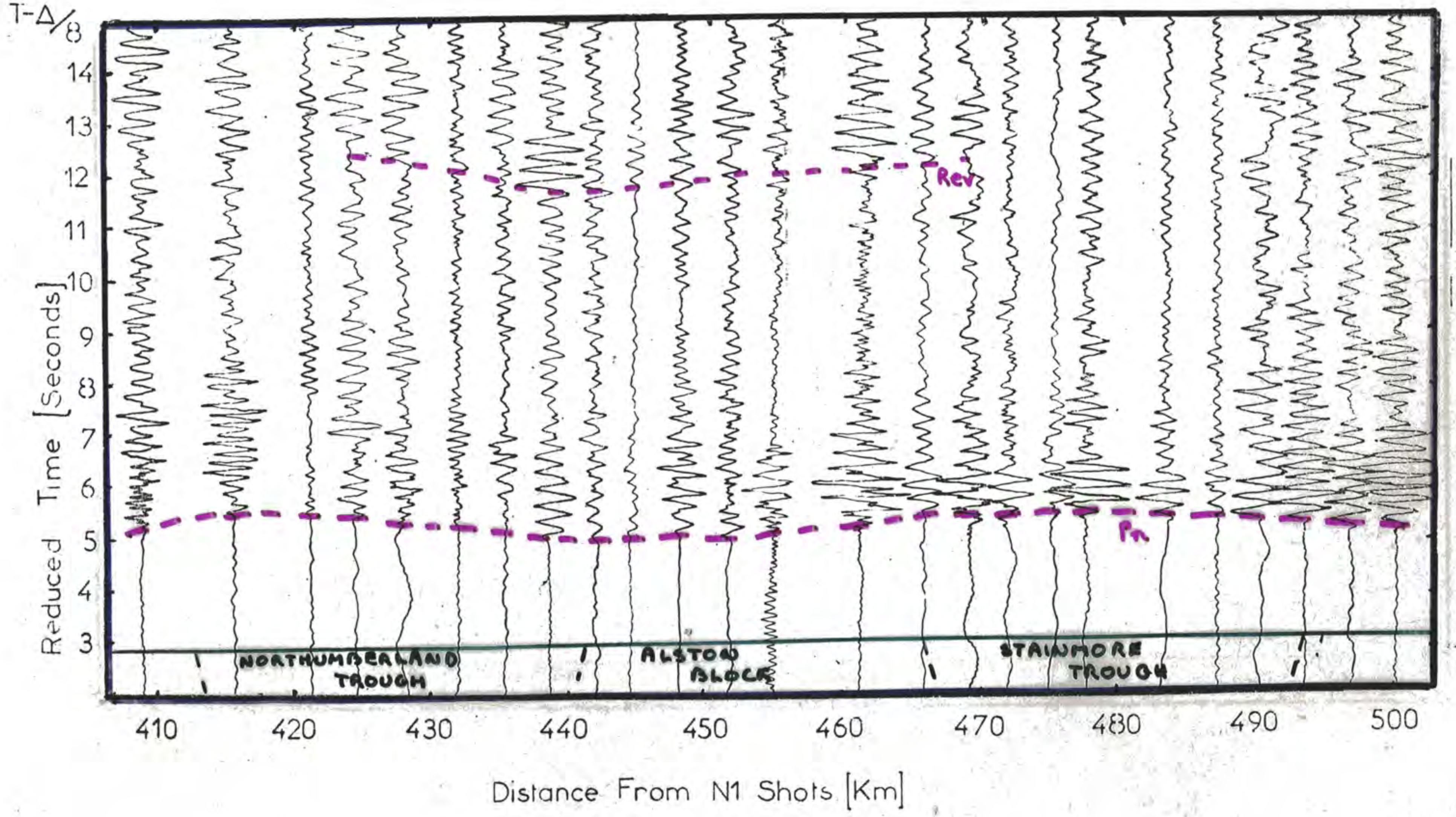


Figure 31

Interpretation

N.E.R.L. Reduced Section for N2 Shots

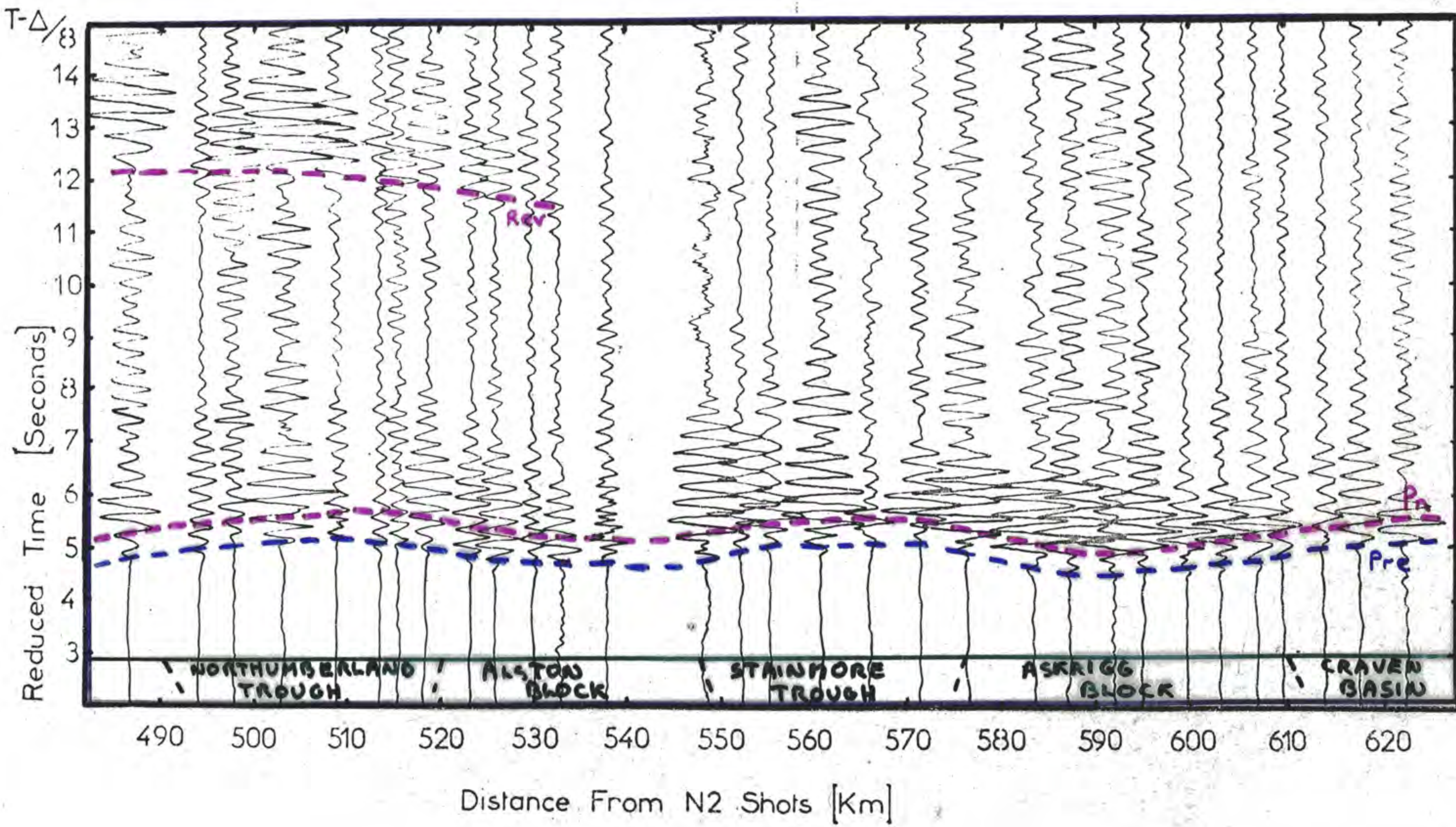


Figure 32

Interpretation

N.E.R.L. Reduced Section for S2 Shots

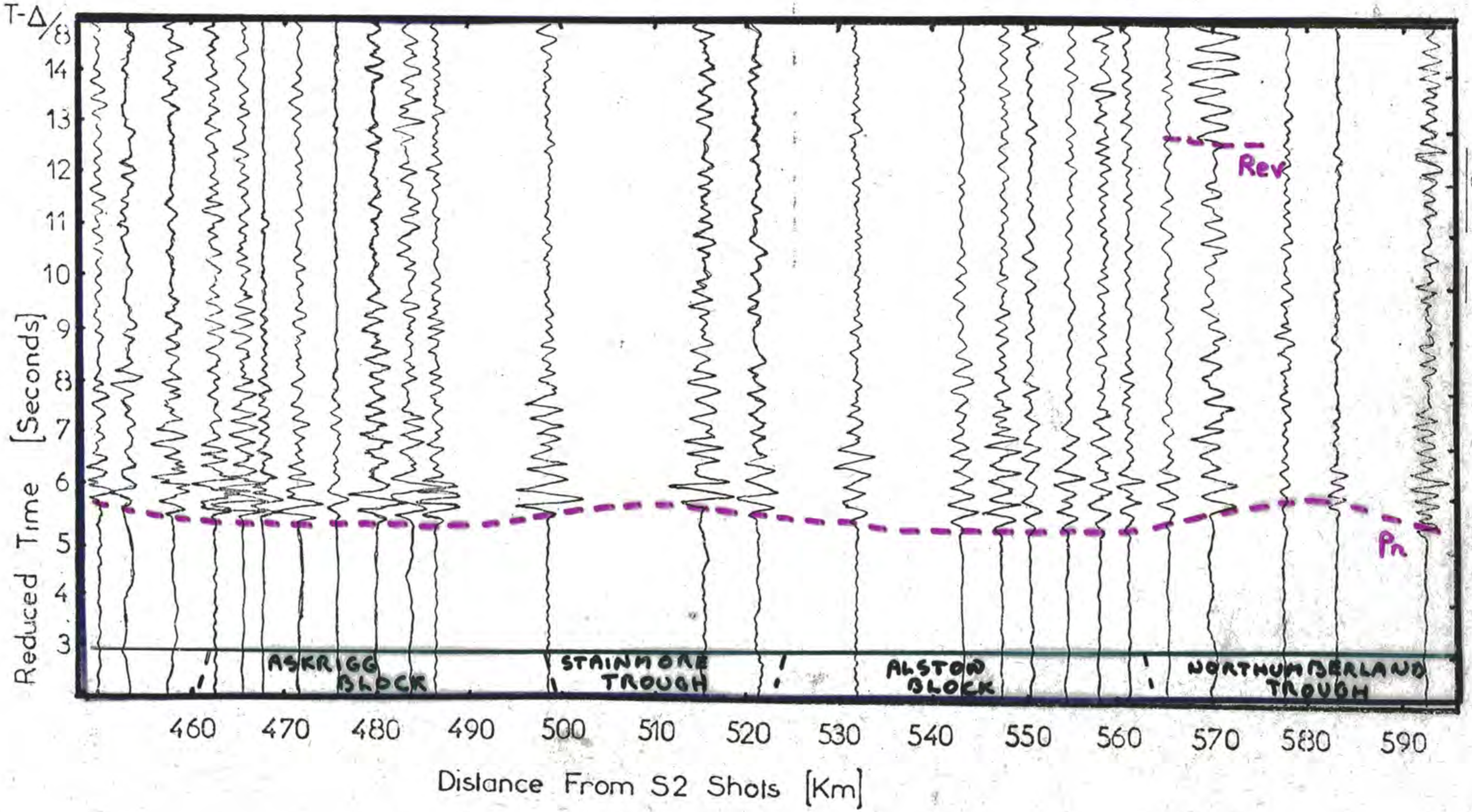


Figure 33

delay was caused by a thickening of low velocity cover.

b) The Pc phase occurred as a high amplitude arrival about 0.8 to 0.4 seconds after Pg. The phase achieves a maximum amplitude between 65 and 100 Km and has an apparent velocity of approximately 6.0 Km/sec. This phase was interpreted as a wide angle reflection off an intra-crustal discontinuity (c.f. Section 6.2.3).

c) The Pm phase appeared about 1.6 to 0.9 seconds behind the first arrival (Pg) and has a maximum amplitude in the range 70 to 100 Km. It was interpreted as a wide angle reflection from the Mohorovičić discontinuity.

d) The Pn phase was seen as a first arrival at ranges in excess of 130 Km.

4.4.2 Record Section of the Buxton Shots

The records from the Buxton shots are shown in Figure 28 reduced to a velocity of 6.0 Km/sec. The section covered the same range and had similar phases to the reduced section of the Spadeadam shots (4.4.1). The main phases were:-

a) A low amplitude Pg phase was seen as a first arrival in the range 80 to 115 Km, with an apparent velocity close to 6.0 Km/sec. There appeared to be a delay of up to 0.5 seconds on the records closest to the shot (below 90 Km range), which corresponds to the margin of the Craven basin.

b) The Pc phase appeared on the records at about 0.6 to 0.4 seconds after Pg. It has a particularly well defined, high amplitude onset at about 100 Km range, within the Askrigg block.

c) The Pm phase appeared 1.5 to 0.7 seconds after Pg and has a particularly large amplitude in the range 95 to 115 Km, where there was substantial 'ringing' for over one second.

d) At distances beyond 130 Km the Pn phase was seen as a low amplitude first arrival.

4.4.3 Record Section for the North Wales Shots

Figure 29 shows the records for the North Wales shot reduced to a velocity of 8.0 Km/sec. The main phases were:-

a) The Pn phase was seen as a first arrival beyond 145 Km and had an apparent velocity of about 8.0 Km/sec. The records at 150 and 147 Km showed a slight delay and were situated close to the margin of the Craven basin.

b) Below 144 Km the first arrival had an apparent velocity of less than 8.0 Km/sec. It was unlikely that this apparent velocity was due to a time term effect, as the stations were situated within the Craven Basin, and from geological evidence would be expected to give a higher apparent velocity. This phase was interpreted as a crustal phase such as P* or Pc.

4.4.4 Record Section of the Edinburgh Shots

Figure 30 shows the record section for the Edinburgh shots, reduced to a velocity of 8.0 Km/sec. The section covered the entire profile in the range 125 to 240 Km.

a) The Pn phase appeared as a first arrival beyond 140 Km, with an apparent velocity of about 8.0 Km/sec. In the ranges 140 to 155 Km, 180 to 200 Km, and beyond 230 Km, the arrivals were delayed by up to 0.5 seconds. These delayed ranges corresponded to the positions of the sedimentary troughs.

b) A high amplitude second arrival with an apparent velocity of about 6.5 Km/sec. was observed over the entire section. It was interpreted as a lower crustal wave similar to P*, and was most distinguishable in records from the block regions.

4.4.5 Record Section of the N1 Shots

The reduced section for the N1 shots, recorded along the northern two spreads (B and C) is shown in Figure 31. The low frequency bandwidth content of the marine shots was evident from the section, by comparison with the band shots.

a) The only phase identified on the section was the Pn phase which had an apparent velocity of about 8.0 km/sec. Between the ranges of 410 to 440 km and 470 to 490 km, the arrivals were delayed by up to 0.5 seconds. These ranges corresponded to the Northumberland and Stainmore troughs respectively. There was some evidence for an arrival with a similar apparent velocity, appearing about 6 seconds after Pn (6.2.2).

4.4.6 Record Section of the N2 Shots

Figure 32 shows the reduced section for the N2 shots recorded over the entire profile. These records were similar in character and frequency content to those from the smaller N1 shots.

a) The Pn phase was recorded with an apparent velocity of about 8.0 km/sec. In the ranges 495 to 520 km, 550 to 575 km and beyond 610 km, the arrivals were delayed by up to 0.5 seconds. As with the N1 shots, these delayed arrivals were recorded in the sedimentary troughs.

A low amplitude, emergent precursor to Pn was recorded over the entire profile, but was most clearly observed from records on the Askrigg block (575 to 610 km range). It was probable that this phase was present, but undetected on similar smaller shots (6.2.1).

A phase with a similar apparent velocity occurred about 6 seconds after Pn. It was interpreted as a Pn reverberated phase (6.2.2).

4.4.7 Record Section of the S2 Shots

These marine shots gave reversed coverage of Pn over the same range as the N1 and N2 shots and the records are shown in Figure 33.

a) Pn arrivals had an apparent velocity of about 8.0 km/sec and showed a similar delay effect to the northern shots over the sedimentary troughs. The amplitude of the Pn phase was similar to the smaller N1 shots over the same range, and exhibits a less complicated character (less ringing), with no evidence of a precursor phase. At the northern end of the profile there was some evidence of a reverberated Pn phase (6.2.2).

4.4.8 Spectral Content of the Signals

Several records were digitised to examine the difference in velocity spectra between the land and sea shots, which was evident by visual inspection of the record sections.

The records were digitised manually at 0.01 second intervals for the first 2.56 seconds of the record, which included most of the first arrival waveform. The vertical component (Willmore Mk2) was used from the three component sets.

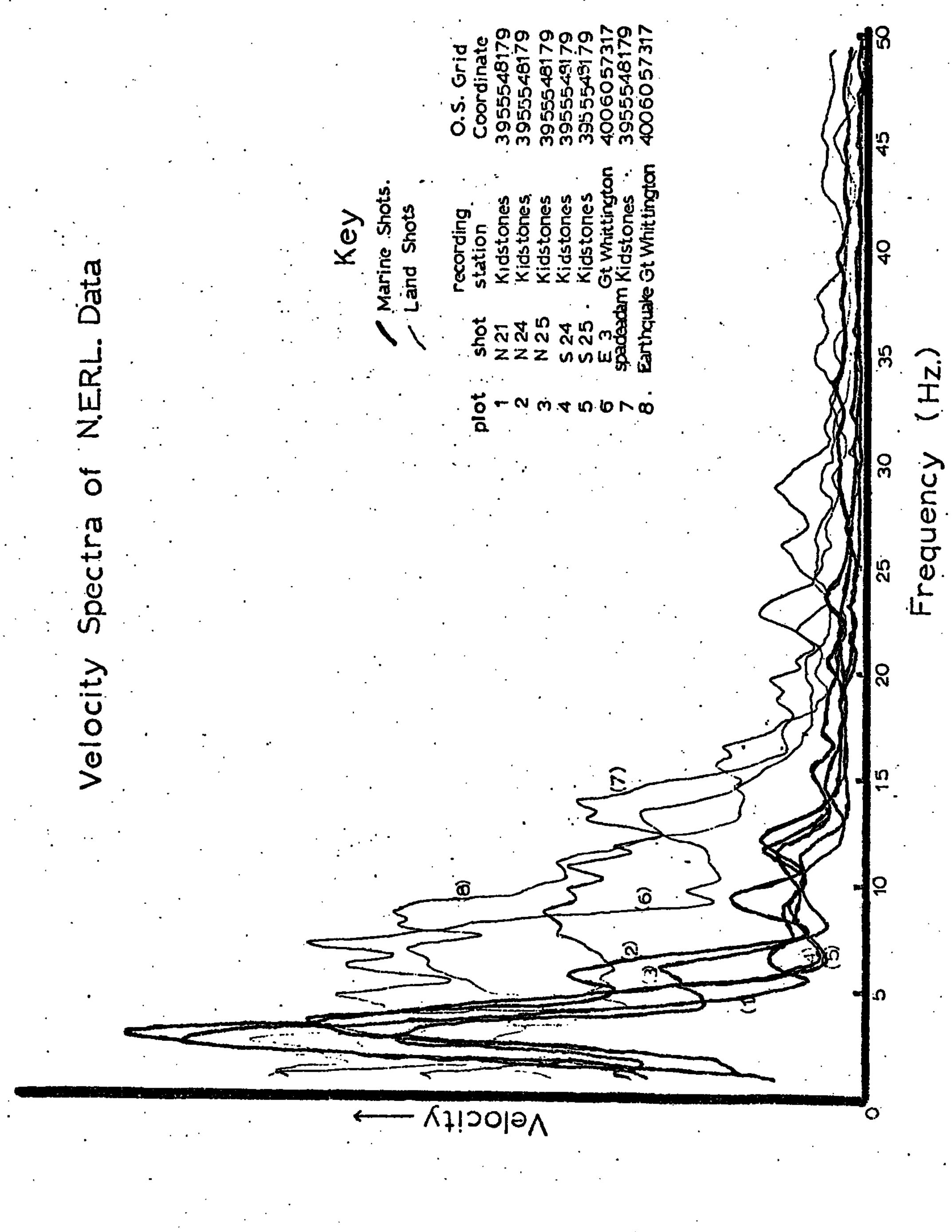
The digitised records were cosine tapered, fitted to a mean baseline and fourier transformed (5.3). The spectra were uncorrected for instrument response. Figure 34 shows the recorded spectra. The most important point was the narrow frequency content of the marine shots which showed a peak of energy at 3 to 4 Hz, with subsidiary side-bands. The land shot (Spadeadam) and to a lesser extent the shallow marine (Edinburgh) shot showed a broader spectral band of up to 1 to 15 Hz. An earthquake, with an epicentre near N.W. Scotland recorded during the project showed a very broad spectral band of 0.5 to 12 Hz. As the distance to this event was similar to the sea shots, it was unlikely that the narrow spectral content of the latter was due to transmission losses.

The analysis confirmed the narrow spectral content of the marine shots in comparison with the broadband content of the land and earthquake records.

4.4.9 <u>Spectral Content of the Noise</u>

Two records from the vertical component (Willmore Mk2) of the three component sets were digitised manually at 0.01 second intervals for 2.56 seconds. Figure 35 shows the uncorrected velocity spectra, which indicates a relatively white noise spectra within the recording passband. Two Cambridge records were digitised at intervals of 0.04 seconds for 10.24 seconds. These records were taken from sites in the Stainmore Trough (spread B) during a micro-seismic storm on 1st August, and show a pronounced peak of energy at about 0.5 Hz. The corrected energy peak may be at a considerably lower frequency, due to the low frequency

Figure 34



Velocity Spectra of N.E.R.L. Data
Key
Marine Shots.
Land Shots
plot shot recording station O.S. Grid Coordinate
1 N 21 Kidstones 3955548179
2 N 24 Kidstones 3955548179
3 N 25 Kidstones 3955548179
4 S 24 Kidstones 3955548179
5 S 25 Kidstones 3955548179
6 E 3 Gt Whittington 4006057317
7 spadeadam Kidstones 3955548179
8 Earthquake Gt Whittington 4006057317
Velocity
Frequency (Hz.)
0 5 10 15 20 25 30 35 40 45 50

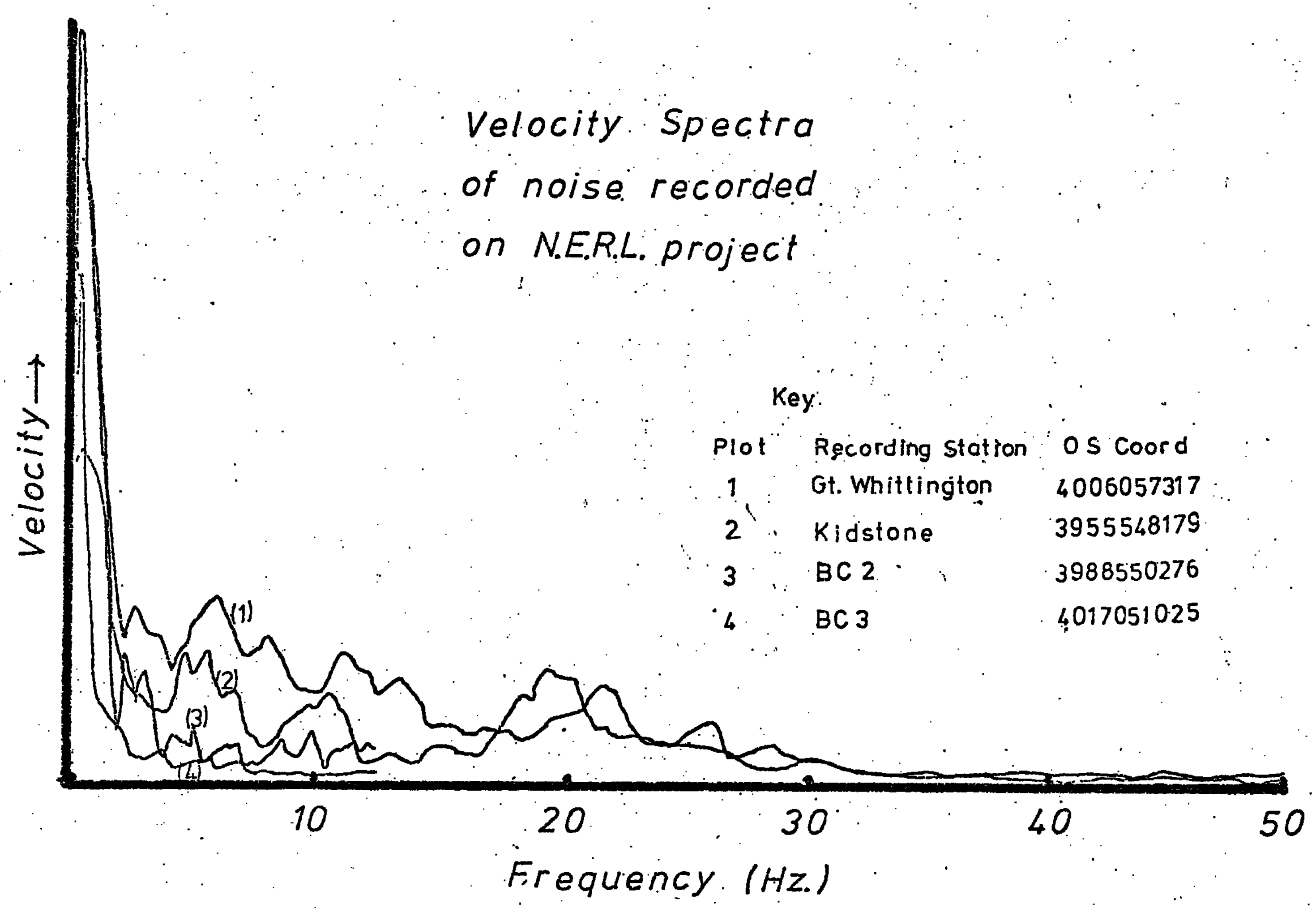

Velocity Spectra
of noise recorded
on N.E.R.L. project
Velocity →
Frequency (Hz.)
10
20
30
40
50
(1)
(2)
(3)
(4)
Key
Plot Recording Station OS Coord
1 Gt. Whittington 4006057317
2 Kidstone 3955548179
3 BC 2 3988550276
4 BC 3 4017051025

Figure 35

cut-off of the seismometer.

4.4.10 Time Term Data

The time term data are divided into three sets and these are listed in Tables 9, 10 and 11.

The Pg travel time data covered only the southern two spreads (A and B). The shots used (Spadeadam and Buxton) provided reversed coverage in the range 60 to 110 Km. It was not possible to distinguish the P* phase at large ranges, but the absence of large residuals at either end of the line militates against a P* first arrival. The data consisted of 29 travel times from 2 shots and 21 recording stations.

The Pn time term data consisted of 130 travel times from 6 shots, recorded at all 40 recording sites along the profile. The shots used were the N1, N2, S2, Edinburgh, North Wales and Dunkeld explosions (Figure 25) and they covered a range of 140 to 610 Km.

A time term solution was proposed to the precursor phase because of the constant and similar apparent velocity to the Pn arrivals. The first arrivals from the N2 shots were recorded at 29 stations, giving 41 travel times.

4.5 Time Term Solution of N.E.R.L. Data

4.5.1 Suitability of the Data for Time Term Analyses

Although not a pre-requisite for time term analyses, the reversed linear refraction line does give the optimum information on the velocity of the refractor, and well determined time terms. As there was no condition of interchange between shot and receiver planned, it was necessary to constrain all the solutions by specifying at least one

Table 9
NERL Time Term Data for the Pg Phase

DATA CARDS

STATION	NUM	TO	STATION	NUM	TRTRM	ERROR	DIST	ERROR	C	ERROR	ERG	D	ERROR	ERG	RESID	ERROR	ERG
31	22	TO	BRADLEY	21	14.13	0.12	77.40	0.10	0.00	0.71	0.23	0.00	0.80	0.22	0.00	0.85	0.23
31	22	TO	AC2	20	15.42	0.08	86.78	0.10	-2.48	0.55	0.17	-14.65	0.69	0.18	0.01	0.66	0.20
31	22	TO	CRACCE	19	15.83	0.08	90.28	0.10	-1.57	0.55	0.17	-11.49	0.69	0.18	-0.02	0.66	0.19
31	22	TO	CONISTCN	18	17.07	0.06	97.15	0.10	-0.75	0.52	0.16	-4.68	0.69	0.18	0.04	0.64	0.17
31	22	TO	AC4	17	17.43	0.06	99.78	0.10	-0.35	0.53	0.17	-2.09	0.69	0.18	0.01	0.65	0.17
31	22	TO	AC5	15	18.19	0.06	104.92	0.10	0.49	0.53	0.17	3.23	0.69	0.18	-0.06	0.65	0.17
31	22	TO	CRAY	14	19.03	0.08	109.20	0.10	1.28	0.54	0.17	7.59	0.69	0.18	-0.02	0.65	0.18
31	22	TO	KIDSTONE	13	19.48	0.08	111.69	0.10	1.66	0.55	0.17	9.82	0.69	0.18	-0.01	0.66	0.19
31	22	TO	BISHOPDL	12	20.01	0.08	114.62	0.10	2.13	0.56	0.18	12.29	0.69	0.19	0.04	0.67	0.20
21	23	TO	ROOKHOPE	1	8.51	0.10	47.79	0.10	0.00	0.20	0.14	0.00	0.20	0.14	-0.00	0.23	0.14
22	23	TO	EGGLESTN	2	10.94	0.06	61.25	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.39	0.17
22	23	TO	BC5	3	11.28	0.06	63.64	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.39	0.17
22	23	TO	HUND	4	12.05	0.08	67.26	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
22	23	TO	BC4	5	12.41	0.06	69.45	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.39	0.17
22	23	TO	BOWES	6	12.95	0.08	72.02	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
22	23	TO	STANG	7	14.70	0.08	81.89	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
22	23	TO	LOW ROW	8	15.31	0.08	86.46	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
22	23	TO	BC1	9	15.52	0.08	88.64	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
22	23	TO	ASKRIGG	10	16.06	0.08	91.33	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.43	0.18
21	23	TO	SEMER W	11	16.73	0.06	95.22	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.39	0.17
21	23	TO	BISHOPDL	12	17.23	0.08	98.83	0.10	-2.13	0.42	0.17	-12.29	0.49	0.18	-0.04	0.50	0.20
21	23	TO	KIDSTONE	13	17.64	0.06	100.84	0.10	-1.66	0.39	0.16	-9.82	0.49	0.18	0.01	0.47	0.18
21	23	TO	CRAY	14	17.96	0.04	102.80	0.10	-1.28	0.36	0.15	-7.59	0.49	0.18	0.02	0.44	0.17
21	23	TO	AC5	15	18.69	0.08	107.25	0.10	-0.49	0.41	0.17	-3.23	0.49	0.18	0.06	0.49	0.18
21	23	TO	KETTLEWL	16	19.11	0.06	109.71	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.39	0.17
21	23	TO	CONISTCN	18	20.06	0.06	115.30	0.10	0.75	0.38	0.16	4.68	0.49	0.18	-0.04	0.46	0.17
21	23	TO	AC4	17	19.61	0.08	112.75	0.10	0.35	0.41	0.17	2.09	0.49	0.18	-0.01	0.49	0.17
21	23	TO	CRACOE	19	21.25	0.06	122.05	0.10	1.57	0.39	0.16	11.49	0.49	0.18	0.02	0.47	0.18
21	23	TO	AC2	20	21.87	0.06	124.86	0.10	2.48	0.39	0.16	14.65	0.49	0.18	-0.01	0.47	0.19

Table 10

NERL Time Term Data for the Pn Phase

DATA CARDS STATION	NUM	TO	STATION	NUM	TRTRM	ERROR	DIST	ERROR	C	ERROR	ERG	Q	ERROR	ERG	RESID	ERRCR	ERG
N21	41	TO	KHEATON	3	67.81	0.10	497.95	0.20	-0.91	0.74	0.18	-7.79	1.23	0.25	0.06	0.89	0.19
N22	41	TO	KHEATON	3	67.82	0.10	498.10	0.20	-0.90	0.74	0.18	-7.64	1.23	0.25	0.05	0.89	0.19
N22	41	TO	CORBRDGE	6	68.92	0.08	508.68	0.20	-6.24	0.76	0.17	-49.38	1.32	0.25	-0.10	0.93	0.18
N22	41	TO	EDMUNDBY	12	70.79	0.08	525.79	0.20	-3.77	0.70	0.17	-30.52	1.23	0.25	0.03	0.86	0.17
N25	41	TO	EDMUNDBY	12	70.91	0.10	527.42	0.20	-3.65	0.72	0.18	-28.89	1.23	0.25	-0.06	0.88	0.18
N21	41	TO	CC1	14	71.23	0.08	529.86	0.20	-4.20	0.69	0.17	-33.38	1.20	0.25	-0.06	0.84	0.18
N23	41	TO	CRAWL SD	15	71.61	0.08	532.27	0.20	-2.34	0.70	0.17	-18.73	1.18	0.25	-0.02	0.84	0.18
N23	41	TO	BOLLIHPE	16	72.57	0.08	539.47	0.20	-3.86	0.74	0.17	-31.49	1.31	0.25	0.05	0.90	0.18
N23	41	TO	FLNDTHWT	18	74.03	0.08	550.11	0.20	-2.76	0.69	0.17	-22.28	1.20	0.25	0.00	0.84	0.17
N22	41	TO	BC4	19	74.40	0.08	552.27	0.20	-2.31	0.74	0.17	-19.12	1.34	0.25	0.07	0.90	0.18
N23	41	TO	BOWES	20	74.79	0.06	555.21	0.20	-2.37	0.66	0.16	-19.73	1.20	0.25	0.09	0.81	0.16
N22	41	TO	BC3	21	75.53	0.08	561.26	0.20	-2.48	0.76	0.17	-20.51	1.32	0.25	0.07	0.92	0.18
N23	41	TO	STANG	22	76.02	0.08	565.92	0.20	-2.26	0.70	0.17	-18.06	1.18	0.25	-0.02	0.84	0.18
N23	41	TO	LOW ROW	24	76.53	0.06	571.22	0.20	-1.25	0.70	0.16	-9.75	1.31	0.25	-0.03	0.86	0.16
N22	41	TO	BC1	25	76.84	0.08	573.41	0.20	-2.18	0.68	0.17	-18.30	1.18	0.25	0.10	0.82	0.17
N24	41	TO	BISHOPD	28	78.09	0.08	584.87	0.20	1.32	0.72	0.17	11.05	1.25	0.25	-0.05	0.87	0.17
N25	41	TO	BISHOPD	28	78.19	0.08	585.97	0.20	1.42	0.72	0.17	12.15	1.25	0.25	-0.09	0.87	0.17
N25	41	TO	KIDSTNS	29	78.47	0.08	588.18	0.20	1.76	0.70	0.17	14.31	1.25	0.25	-0.02	0.86	0.17
N24	41	TO	KIDSTNS	29	78.34	0.08	587.14	0.20	1.63	0.70	0.17	13.27	1.25	0.25	-0.02	0.86	0.17
N24	41	TO	CRAY	30	78.56	0.08	589.23	0.20	1.36	0.70	0.17	11.73	1.22	0.25	-0.10	0.85	0.17
N23	41	TO	AC5	31	79.12	0.10	593.28	0.20	2.32	0.73	0.18	19.10	1.24	0.25	-0.05	0.89	0.18
N24	41	TO	AC5	31	79.19	0.08	593.68	0.20	2.39	0.71	0.17	19.50	1.24	0.25	-0.03	0.87	0.17
N24	41	TO	AC4	33	79.95	0.08	599.14	0.20	3.10	0.71	0.17	24.67	1.24	0.25	0.03	0.86	0.17
N23	41	TO	AC4	33	79.87	0.08	598.74	0.20	3.02	0.71	0.17	24.27	1.24	0.25	0.00	0.86	0.17
N24	41	TO	CONISTON	34	80.24	0.08	601.71	0.20	2.97	0.72	0.17	24.09	1.22	0.25	-0.02	0.87	0.17
N23	41	TO	AC3	35	80.81	0.08	605.35	0.20	5.86	0.74	0.17	47.26	1.30	0.25	-0.01	0.90	0.18
N24	41	TO	CRACOE	36	81.24	0.08	608.52	0.20	5.17	0.75	0.18	41.68	1.36	0.25	-0.01	0.92	0.16
N24	41	TO	AC2	37	81.77	0.08	611.42	0.20	4.57	0.71	0.17	36.32	1.23	0.25	0.05	0.87	0.18
N23	41	TO	AC2	37	81.73	0.08	611.02	0.20	4.53	0.71	0.17	35.92	1.23	0.25	0.06	0.87	0.18
S24	43	TO	BRADLEY	40	61.97	0.10	448.89	0.20	0.00	0.81	0.20	0.01	1.40	0.27	-0.00	0.99	0.21
S23	43	TO	AC1	39	62.11	0.10	450.45	0.20	-1.88	0.79	0.18	-15.14	1.34	0.25	-0.00	0.96	0.19
S24	43	TO	AC1	39	62.26	0.10	451.61	0.20	-1.73	0.79	0.18	-13.98	1.34	0.25	0.00	0.96	0.19
S23	43	TO	AC2	37	62.78	0.10	456.88	0.20	-6.84	0.73	0.18	-54.75	1.23	0.25	-0.04	0.89	0.19
S24	43	TO	AC2	37	62.94	0.08	458.02	0.20	-6.68	0.71	0.17	-53.61	1.23	0.25	-0.02	0.87	0.18
S24	43	TO	AC3	35	63.62	0.06	464.10	0.20	-3.75	0.72	0.16	-30.52	1.30	0.25	0.05	0.88	0.17
S24	43	TO	CRACOE	36	63.31	0.08	461.68	0.20	-5.18	0.75	0.18	-41.69	1.35	0.25	0.01	0.92	0.18
S23	43	TO	AC3	35	63.45	0.06	462.96	0.20	-3.92	0.72	0.16	-31.66	1.30	0.25	0.02	0.88	0.17
S24	43	TO	CONISTN	34	64.06	0.06	468.50	0.20	-5.63	0.70	0.16	-45.65	1.21	0.25	0.05	0.85	0.17
S24	43	TO	AC4	33	64.31	0.08	471.11	0.20	-4.96	0.70	0.17	-39.89	1.23	0.25	-0.01	0.86	0.18
S23	43	TO	AC4	33	64.17	0.06	469.96	0.20	-5.10	0.68	0.16	-41.04	1.23	0.25	-0.00	0.84	0.17
S23	43	TO	AC5	31	64.75	0.08	474.91	0.20	-4.47	0.71	0.17	-35.80	1.23	0.25	-0.02	0.87	0.17
S24	43	TO	AC5	31	64.91	0.08	476.05	0.20	-4.31	0.71	0.17	-34.66	1.23	0.25	0.00	0.87	0.17
S24	43	TO	CRAY	30	65.43	0.08	480.20	0.20	-4.19	0.70	0.17	-33.83	1.21	0.25	0.01	0.85	0.17

Table 10 (cont.)

S25	43	TO	KIDSTONE	29	65.72	0.08	482.63	0.20	-3.41	0.70	0.17	-27.77	1.24	0.25	0.04	0.86	0.17
S24	43	TO	KIDSTONE	29	65.66	0.08	482.84	0.20	-3.47	0.70	0.17	-27.56	1.24	0.25	-0.04	0.86	0.17
S25	43	TO	BISHOPDL	28	66.17	0.10	485.73	0.20	-3.02	0.74	0.18	-24.62	1.24	0.25	0.04	0.89	0.18
S24	43	TO	BISHOPDL	28	66.14	0.10	485.95	0.20	-3.05	0.74	0.18	-24.40	1.24	0.25	-0.02	0.89	0.18
S23	43	TO	LOW ROW	24	67.90	0.08	499.04	0.20	-2.29	0.72	0.17	-18.46	1.31	0.25	-0.00	0.88	0.17
S23	43	TO	BOWES	20	70.16	0.08	516.05	0.20	0.58	0.68	0.17	4.58	1.19	0.25	0.01	0.83	0.17
S23	43	TO	HUNDTHWT	18	70.72	0.08	521.03	0.20	1.51	0.69	0.17	12.11	1.19	0.25	0.00	0.84	0.17
S23	43	TO	BOLLIHPE	16	71.88	0.10	532.43	0.20	3.03	0.76	0.18	24.94	1.31	0.25	-0.07	0.92	0.19
S21	43	TO	CC1	14	73.14	0.10	542.79	0.20	5.29	0.71	0.18	43.02	1.19	0.25	-0.06	0.86	0.19
S2	43	TO	EDMUNDBY	12	73.89	0.08	548.21	0.20	6.82	0.70	0.17	55.37	1.23	0.25	0.03	0.86	0.18
S21	43	TO	CC2	11	74.05	0.08	549.99	0.20	5.11	0.70	0.17	41.07	1.18	0.25	0.00	0.85	0.18
S25	43	TO	BLANCHLD	10	74.69	0.08	554.81	0.20	3.80	0.77	0.18	30.62	1.34	0.26	-0.01	0.94	0.19
S21	43	TO	CC3	8	75.20	0.08	557.56	0.20	0.00	0.77	0.18	0.01	1.40	0.26	-0.00	0.95	0.19
S2	43	TO	RIDING M	7	75.64	0.10	561.23	0.20	6.73	0.73	0.19	54.85	1.18	0.26	-0.09	0.88	0.20
S2	43	TO	CORBRDGE	6	76.49	0.10	566.14	0.20	8.91	0.78	0.18	71.55	1.32	0.25	0.02	0.95	0.20
S21	43	TO	CC5	5	76.98	0.10	570.00	0.20	8.20	0.70	0.18	66.26	1.18	0.25	-0.03	0.85	0.20
S2	43	TO	KHARTE	2	78.61	0.08	582.74	0.20	11.16	0.71	0.17	89.31	1.22	0.25	0.06	0.86	0.20
S2	43	TO	GRNLGHTN	1	79.46	0.06	591.95	0.20	12.63	0.67	0.16	101.39	1.22	0.25	0.03	0.82	0.19
N11	42	TO	GRNLGHTN	1	56.42	0.08	408.64	0.20	-3.75	0.70	0.17	-29.68	1.24	0.25	-0.06	0.85	0.17
N12	42	TO	GRNLGHTN	1	56.51	0.10	408.82	0.20	-3.66	0.72	0.18	-29.50	1.24	0.25	0.01	0.87	0.18
N12	42	TO	KHARTE	2	57.70	0.12	416.48	0.20	-3.09	0.75	0.19	-24.72	1.24	0.25	-0.02	0.91	0.20
N11	42	TO	KHARTE	2	57.68	0.10	416.30	0.20	-3.11	0.73	0.18	-24.90	1.24	0.25	-0.02	0.89	0.19
N11	42	TO	GT WHIT	4	58.64	0.10	424.05	0.20	0.93	0.69	0.18	8.09	1.16	0.25	-0.08	0.84	0.19
N11	42	TO	CC5	5	59.02	0.08	426.72	0.20	-3.10	0.69	0.17	-24.79	1.20	0.25	-0.02	0.84	0.18
N11	42	TO	CORBRDGE	6	59.57	0.12	431.16	0.20	-1.35	0.81	0.20	-11.20	1.33	0.25	0.04	0.98	0.20
N12	42	TO	CORBRDGE	6	59.60	0.12	431.34	0.20	-1.32	0.81	0.20	-11.02	1.33	0.25	0.05	0.98	0.20
N12	42	TO	RIDING M	7	60.02	0.12	435.79	0.20	-2.24	0.76	0.20	-18.35	1.20	0.26	0.05	0.91	0.20
N12	42	TO	BLANCHLD	10	60.44	0.12	441.38	0.20	-3.79	0.81	0.20	-30.58	1.35	0.26	0.01	0.98	0.21
N11	42	TO	CC2	11	60.89	0.12	445.68	0.20	-1.40	0.75	0.20	-11.01	1.20	0.25	-0.03	0.90	0.20
N11	42	TO	EDMUNDBY	12	61.29	0.08	448.20	0.20	0.97	0.71	0.17	7.60	1.24	0.25	0.03	0.86	0.17
N12	42	TO	EDMUNDBY	12	61.26	0.06	448.38	0.20	0.94	0.69	0.16	7.78	1.24	0.25	-0.02	0.84	0.16
N11	42	TO	CC1	14	61.76	0.08	452.39	0.20	0.56	0.70	0.17	4.85	1.20	0.25	-0.04	0.85	0.17
N13	42	TO	CRAWLEYS	15	62.14	0.10	454.67	0.20	2.42	0.72	0.18	19.37	1.19	0.25	0.02	0.87	0.19
N13	42	TO	BOLLIHPE	16	63.02	0.06	461.84	0.20	0.83	0.72	0.16	6.58	1.32	0.25	0.01	0.89	0.17
N13	42	TO	BC5	17	63.84	0.08	467.91	0.20	1.37	0.67	0.17	10.52	1.16	0.25	0.06	0.81	0.18
N13	42	TO	HUND	18	64.56	0.08	472.44	0.20	2.00	0.69	0.17	15.76	1.20	0.25	0.05	0.84	0.17
N13	42	TO	BC4	19	64.78	0.06	474.80	0.20	2.31	0.72	0.17	19.11	1.35	0.25	-0.07	0.89	0.17
N13	42	TO	BOWES	20	65.16	0.06	477.54	0.20	2.24	0.66	0.16	18.31	1.20	0.25	-0.03	0.81	0.16
N13	42	TO	STANG	22	66.60	0.10	488.23	0.20	2.55	0.72	0.18	19.95	1.19	0.25	0.07	0.87	0.19
N13	42	TO	BC2	23	66.68	0.08	490.00	0.20	1.55	0.72	0.17	12.52	1.21	0.25	-0.00	0.87	0.18
N13	42	TO	BC3	21	65.94	0.06	483.79	0.20	2.17	0.75	0.17	17.73	1.33	0.25	-0.03	0.91	0.17
N13	42	TO	LOW ROW	24	67.08	0.06	493.51	0.20	3.54	0.71	0.16	28.24	1.32	0.25	0.03	0.87	0.17
N13	42	TO	BC1	25	67.28	0.08	495.89	0.20	2.50	0.68	0.17	19.88	1.19	0.25	0.03	0.83	0.17
N13	42	TO	ASKRIGG	26	67.64	0.08	499.13	0.20	0.00	0.79	0.18	0.00	1.43	0.26	-0.00	0.96	0.19

Table 10 (cont)

E3	44 TO GRNLGHTN	1	22.11	0.04	125.85	0.10	-5.20	0.44	0.15	-42.04	0.72	0.18	0.02	0.53	0.16
E3	44 TO KHARTE	2	23.01	0.05	131.25	0.10	-4.93	0.47	0.16	-39.52	0.72	0.18	-0.02	0.56	0.16
E3	44 TO KHEATON	3	23.43	0.10	135.05	0.10	1.81	0.53	0.18	15.44	0.72	0.18	-0.11	0.62	0.19
E3	44 TO GT WHIT	4	23.54	0.06	137.50	0.10	-0.92	0.44	0.16	-8.04	0.65	0.18	0.08	0.52	0.17
E3	44 TO CC5	5	24.17	0.06	139.64	0.10	-5.10	0.46	0.16	-41.44	0.68	0.18	0.05	0.54	0.17
E3	44 TO RIDING M	7	24.91	0.12	147.24	0.10	-4.49	0.55	0.20	-36.47	0.68	0.19	0.04	0.63	0.20
E3	44 TO CC4	9	24.98	0.10	150.38	0.10	0.00	0.40	0.20	0.00	0.40	0.20	0.00	0.45	0.20
E3	44 TO CC2	11	25.72	0.10	156.22	0.10	-3.71	0.52	0.18	-30.04	0.68	0.18	0.02	0.60	0.19
E3	44 TO ECMUNDBY	12	26.03	0.08	158.78	0.10	-1.43	0.50	0.17	-11.40	0.73	0.18	-0.01	0.59	0.17
E1	44 TO ROCKHOPE	13	26.12	0.10	159.46	0.10	0.00	0.20	0.14	0.02	0.20	0.14	0.00	0.22	0.14
E2	44 TO CRAWLEYS	15	26.78	0.10	164.21	0.10	-0.08	0.51	0.18	-0.66	0.68	0.18	0.00	0.59	0.18
E3	44 TO CC1	14	26.69	0.08	162.62	0.10	-1.65	0.49	0.17	-14.49	0.69	0.18	0.15	0.57	0.17
F2	44 TO BC5	17	28.26	0.06	176.49	0.10	-1.36	0.43	0.16	-10.47	0.65	0.18	-0.06	0.51	0.16
E2	44 TO HUND	18	28.55	0.08	180.65	0.10	-0.75	0.48	0.17	-5.60	0.69	0.18	-0.05	0.57	0.17
E2	44 TO BOWES	20	29.60	0.08	185.63	0.10	-0.46	0.47	0.17	-3.17	0.69	0.18	-0.07	0.56	0.17
E2	44 TO STANG	22	30.90	0.10	195.95	0.10	-0.29	0.51	0.18	-1.90	0.68	0.18	-0.05	0.59	0.18
E2	44 TO BC2	23	31.04	0.08	197.43	0.10	-1.23	0.51	0.17	-9.63	0.70	0.18	-0.03	0.59	0.17
E2	44 TO BC1	25	31.60	0.06	203.98	0.10	-0.32	0.45	0.16	-1.60	0.68	0.18	-0.13	0.53	0.16
E1	44 TO SEMER W	27	32.42	0.10	209.86	0.10	0.00	0.40	0.20	0.00	0.40	0.20	0.00	0.45	0.20
E1	44 TO BISHOPDL	28	33.09	0.08	213.47	0.10	3.32	0.51	0.17	25.79	0.74	0.18	0.12	0.60	0.17
E1	44 TO KIDSTONE	29	33.09	0.06	215.48	0.10	3.48	0.48	0.16	27.74	0.74	0.18	0.03	0.57	0.16
F1	44 TO CRAY	30	33.31	0.06	217.41	0.10	3.20	0.48	0.16	26.04	0.71	0.18	-0.03	0.57	0.16
E1	44 TO AC5	31	33.91	0.08	221.87	0.10	4.21	0.51	0.17	33.82	0.73	0.18	0.00	0.60	0.17
E1	44 TO AC4	33	34.60	0.06	227.38	0.10	4.84	0.48	0.16	39.04	0.73	0.18	-0.01	0.57	0.16
F1	44 TO CONISTON	34	34.93	0.08	229.91	0.10	4.76	0.51	0.17	38.42	0.71	0.18	-0.02	0.60	0.17
E1	44 TO AC2	37	36.45	0.10	239.35	0.10	6.34	0.53	0.18	50.38	0.73	0.18	0.08	0.62	0.19
42	45 TO AC1	39	23.62	0.05	139.77	0.10	3.62	0.79	0.16	29.14	1.31	0.18	-0.00	0.95	0.17
41	45 TO AC2	37	23.73	0.05	142.42	0.10	-1.90	0.73	0.16	-14.25	1.20	0.18	-0.13	0.88	0.16
42	45 TO EMBSAY	38	24.02	0.08	143.05	0.10	0.00	0.87	0.19	0.00	1.35	0.20	0.00	1.04	0.19
41	45 TO AC3	35	24.36	0.05	147.14	0.10	0.99	0.76	0.16	7.48	1.27	0.18	0.06	0.92	0.16
42	45 TO AC3	35	24.19	0.08	147.14	0.10	0.82	0.79	0.17	7.48	1.27	0.18	-0.11	0.95	0.17
42	45 TO CONISTON	34	24.62	0.12	150.74	0.10	-1.08	0.81	0.19	-8.45	1.19	0.18	-0.03	0.96	0.19
41	45 TO CONISTCN	34	24.67	0.12	150.74	0.10	-1.03	0.81	0.19	-8.45	1.19	0.18	0.02	0.96	0.19
41	45 TO AC4	33	24.84	0.05	152.54	0.10	-0.44	0.72	0.16	-3.50	1.20	0.18	-0.01	0.87	0.16
42	45 TO AC4	33	24.84	0.05	152.54	0.10	-0.44	0.72	0.16	-3.50	1.20	0.18	-0.01	0.87	0.16
42	45 TO KETTLEWL	32	24.98	0.06	153.80	0.10	-0.04	0.83	0.17	0.01	1.35	0.18	-0.04	1.00	0.17
41	45 TO KETTLEWL	32	25.07	0.07	153.80	0.10	0.05	0.84	0.17	0.01	1.35	0.18	0.05	1.01	0.17
42	45 TO AC5	31	25.14	0.05	154.80	0.10	-0.09	0.73	0.16	-0.95	1.20	0.18	0.03	0.88	0.16
41	45 TO AC5	31	25.17	0.05	154.80	0.10	-0.06	0.73	0.16	-0.95	1.20	0.18	0.06	0.88	0.16
42	45 TO CRAY	30	25.43	0.04	157.08	0.10	-0.20	0.71	0.15	-1.99	1.19	0.18	0.05	0.86	0.16
41	45 TO CRAY	30	25.45	0.06	157.07	0.10	-0.18	0.73	0.16	-2.00	1.19	0.18	0.07	0.88	0.16
11	46 TO BC3	21	39.12	0.12	259.01	0.10	0.31	0.92	0.22	2.84	1.34	0.20	-0.04	1.09	0.22
11	46 TO BC2	23	39.85	0.12	264.77	0.10	-0.31	0.87	0.22	-2.82	1.22	0.21	0.04	1.03	0.22

Table 11
NERL Time Term Data for the Precursor Phase

DATA CARDS STATION	NUM	TO	STATION	NUM	TRTRM	ERROR	DIST	ERROR	C	ERROR	ERG	C	ERROR	ERG	RESID	ERROR	ERG
N22	1	TO	GREENLTN	2	65.54	0.08	485.53	0.10	-0.11	0.35	0.17	-0.81	0.40	0.18	-0.01	0.40	0.17
N25	1	TO	GREENLTN	2	65.77	0.06	487.56	0.10	0.12	0.33	0.16	0.82	0.40	0.18	0.01	0.38	0.16
N25	1	TO	KHARTE	3	66.95	0.06	495.32	0.10	0.17	0.33	0.16	0.84	0.40	0.18	0.06	0.38	0.16
N22	1	TO	KHARTE	3	66.62	0.08	493.69	0.10	-0.16	0.35	0.17	-0.79	0.40	0.18	-0.06	0.40	0.17
N22	1	TO	KHEATON	4	67.32	0.10	498.10	0.10	-0.02	0.40	0.19	0.08	0.40	0.19	-0.03	0.45	0.19
N21	1	TO	KHEATON	4	67.37	0.10	497.95	0.10	0.03	0.40	0.19	-0.07	0.40	0.19	0.03	0.45	0.19
N21	1	TO	GT WHIT	5	67.68	0.08	501.37	0.10	-0.02	0.35	0.17	-0.07	0.40	0.18	-0.01	0.40	0.17
N22	1	TO	GT WHIT	5	67.72	0.06	501.51	0.10	0.02	0.33	0.16	0.07	0.40	0.18	0.01	0.38	0.16
N22	1	TO	CORBRDGE	6	68.64	0.08	508.68	0.10	0.00	0.36	0.18	0.80	0.40	0.19	0.00	0.41	0.18
N25	1	TO	RDG MILL	7	69.32	0.08	514.78	0.10	0.11	0.36	0.17	0.83	0.40	0.18	0.01	0.41	0.17
N22	1	TO	RDG MILL	7	69.10	0.08	513.15	0.10	-0.11	0.36	0.17	-0.80	0.40	0.18	-0.01	0.41	0.17
N21	1	TO	CC3	8	69.35	0.06	515.31	0.10	0.00	0.32	0.16	0.00	0.40	0.18	0.00	0.37	0.17
N21	1	TO	CC2	9	70.07	0.08	523.11	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N22	1	TO	EDMUNDBY	10	70.30	0.08	525.79	0.10	-0.04	0.37	0.17	-0.81	0.40	0.18	0.06	0.42	0.18
N25	1	TO	EDMUNDBY	10	70.38	0.10	527.42	0.10	0.04	0.39	0.18	0.82	0.40	0.18	-0.06	0.44	0.19
N21	1	TO	ROOKHOPE	11	70.58	0.10	527.89	0.10	0.00	0.20	0.14	0.03	0.20	0.14	0.00	0.22	0.14
N21	1	TO	CC1	12	70.73	0.08	529.86	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N23	1	TO	CRAWL SD	13	71.13	0.08	532.21	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N23	1	TO	BOLLIHP	14	72.11	0.08	539.47	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N23	1	TO	HUNDERTH	15	73.53	0.08	550.11	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N22	1	TO	BC4	16	73.83	0.08	552.27	0.10	0.00	0.36	0.18	0.00	0.40	0.19	-0.00	0.41	0.18
N23	1	TO	BOWES	17	74.28	0.06	555.21	0.10	0.00	0.32	0.16	0.00	0.40	0.18	-0.00	0.37	0.17
N22	1	TO	BC3	18	75.02	0.08	561.26	0.10	0.00	0.36	0.18	0.01	0.40	0.19	0.00	0.41	0.18
N23	1	TO	LOW ROW	19	76.18	0.06	571.22	0.10	0.00	0.32	0.16	0.00	0.40	0.18	0.00	0.37	0.17
N22	1	TO	BC1	20	76.36	0.08	573.41	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N24	1	TO	BISHOPDL	21	77.65	0.08	584.87	0.10	-0.07	0.36	0.17	-0.55	0.40	0.18	-0.00	0.41	0.17
N25	1	TO	BISHOPDL	21	77.79	0.08	585.97	0.10	0.07	0.36	0.17	0.55	0.40	0.18	0.00	0.41	0.17
N25	1	TO	KIDSTONE	22	78.11	0.08	588.18	0.10	0.07	0.36	0.17	0.52	0.40	0.18	0.00	0.41	0.17
N24	1	TO	KIDSTONE	22	77.98	0.08	587.14	0.10	-0.06	0.36	0.17	-0.52	0.40	0.18	-0.00	0.41	0.17
N24	1	TO	CRAY	23	78.20	0.08	589.23	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N23	1	TO	AC5	24	78.76	0.10	593.28	0.10	0.00	0.39	0.18	-0.18	0.40	0.18	0.02	0.44	0.19
N24	1	TO	AC5	24	78.76	0.08	593.68	0.10	0.00	0.37	0.17	0.22	0.40	0.18	-0.02	0.42	0.18
N24	1	TO	AC4	25	79.45	0.08	595.14	0.10	0.06	0.36	0.17	0.20	0.40	0.18	0.04	0.41	0.17
N23	1	TO	AC4	25	79.33	0.08	598.74	0.10	-0.06	0.36	0.17	-0.20	0.40	0.18	-0.04	0.41	0.17
N24	1	TO	CONISTNE	26	79.79	0.08	601.71	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N23	1	TO	AC3	27	80.25	0.08	605.35	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N24	1	TO	CRACOE	28	80.78	0.08	608.52	0.10	0.00	0.36	0.18	0.00	0.40	0.19	0.00	0.41	0.18
N24	1	TO	AC2	29	81.27	0.08	611.42	0.10	0.01	0.36	0.17	0.20	0.40	0.18	-0.01	0.41	0.17
N23	1	TO	AC2	29	81.25	0.08	611.02	0.10	-0.01	0.36	0.17	-0.20	0.40	0.18	0.01	0.41	0.17
N23	1	TO	AC1	30	82.10	0.10	617.97	0.10	-0.02	0.40	0.19	-0.20	0.40	0.19	-0.00	0.45	0.19
N24	1	TO	AC1	30	82.15	0.10	618.37	0.10	0.03	0.40	0.19	0.20	0.40	0.19	0.00	0.45	0.19

time term. The experiment was not designed to resolve the absolute values of the time terms, but to give information on the variation of the time terms along the profile.

4.5.2 The Pg Solution

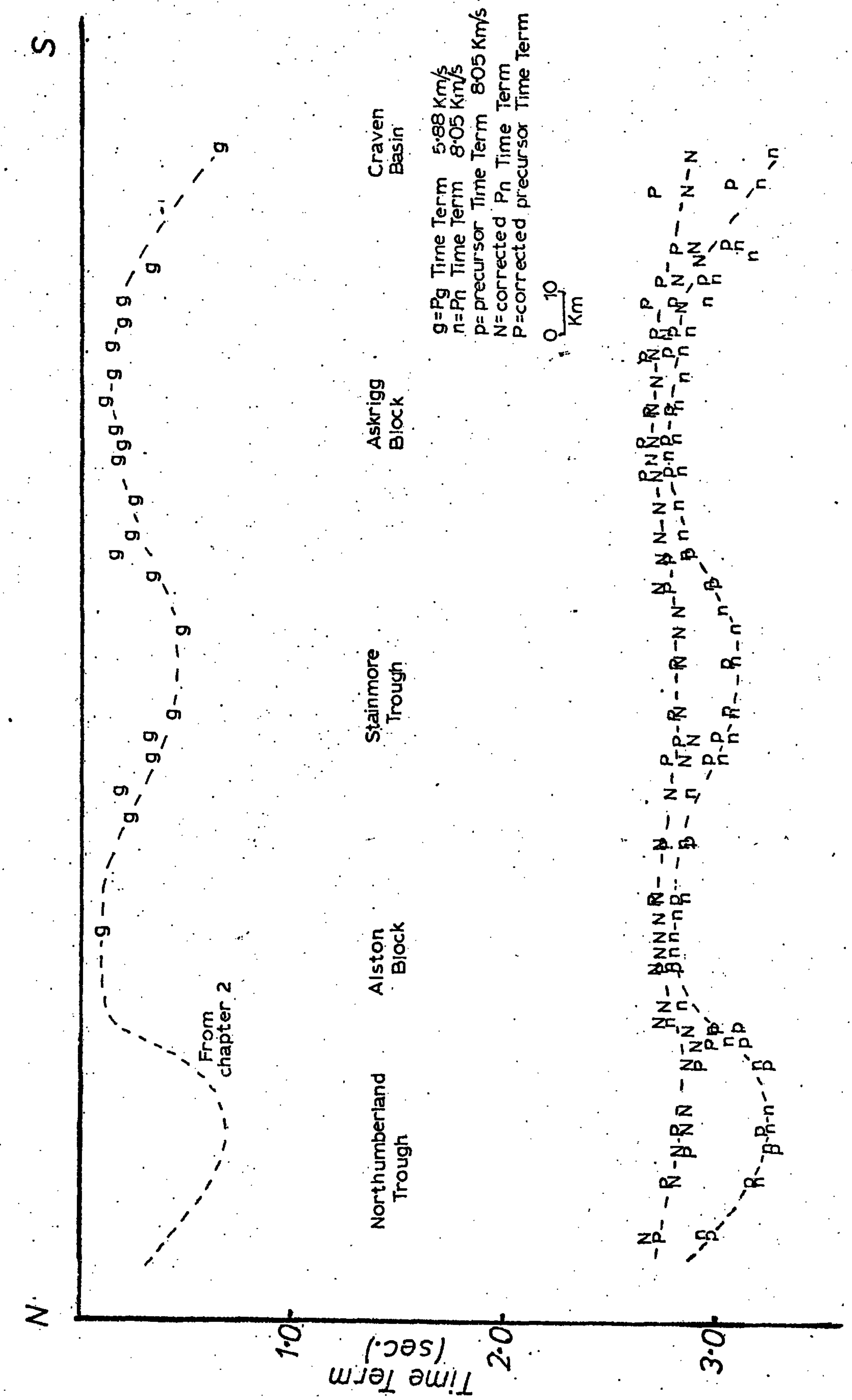
The time term at Rookhope station was constrained to a value of 0.1 seconds. The least squares velocity of 5.88 ±0.047 km/sec was significantly higher than that obtained in the upper crustal refraction survey (2.6.1). This may be explained by the larger ranges involved in this solution, and increasing velocity with depth. The results are listed in Table 12 and are shown in Figure 36.

The main conclusion was that time terms within the sedimentary troughs were greater than on the blocks. The time terms within the Stainmore Trough were about 0.4 to 0.5 seconds, compared with values of about 0.1 to 0.2 seconds on the adjoining block regions. Along the southern end of the profile an increase of time terms was observed for stations in the Craven basin. The values of the time terms were consistent with the distribution of Pg time terms in Section 2.6.1.

4.5.3 The Pn Solution

The results of the Pn solution are listed in Table 13 and are shown in Figure 36. Rookhope station was constrained to a value of 2.80 seconds (Agger and Carpenter, 1965). The best fitting velocity was 8.05 ± 0.012 km/sec. The results showed that the delay times were up to 0.5 seconds greater for the crust within the sedimentary troughs than in the adjoining block regions. These differences are comparable with the values of the time terms obtained from

Figure 36



Distribution of Time Terms along the NERL profile

Table 12

NERL Time Term Solution for the Pg Phase

SOLUTION USING A VELOCITY OF 5.88
SUM OF RESIDULES SQUARED IS 0.01
STANDARD ERROR OF THE SOLUTION IS 0.05

STATION	F	ERROR	ERG	F	ERROR	ERG	TTERM	ERROR	ERG	B,W ST.ERR	95 CONF	NUM DATA
1	0.10	0.00	0.00	-0.00	0.00	0.00	0.10	0.00	0.00	0.0	0.63	1
2	2.53	0.16	0.12	13.46	0.20	0.14	0.24	0.19	0.15	0.0	1.10	1
3	2.87	0.16	0.12	15.85	0.20	0.14	0.18	0.19	0.16	0.0	1.10	1
4	3.64	0.18	0.13	19.47	0.20	0.14	0.33	0.21	0.19	0.0	1.10	1
5	4.00	0.16	0.12	21.66	0.20	0.14	0.32	0.19	0.19	0.0	1.10	1
6	4.54	0.18	0.13	24.23	0.20	0.14	0.42	0.21	0.22	0.0	1.10	1
7	6.29	0.18	0.13	34.10	0.20	0.14	0.49	0.21	0.27	0.0	1.10	1
8	6.90	0.18	0.13	38.67	0.20	0.14	0.33	0.21	0.30	0.0	1.10	1
9	7.11	0.18	0.13	40.85	0.20	0.14	0.16	0.21	0.32	0.0	1.10	1
10	7.65	0.18	0.13	43.54	0.20	0.14	0.25	0.21	0.33	0.0	1.10	1
11	8.32	0.16	0.12	47.43	0.20	0.14	0.26	0.19	0.36	0.0	1.10	1
12	10.95	0.24	0.12	63.33	0.29	0.12	0.18	0.29	0.46	0.04	0.24	2
13	10.89	0.23	0.11	62.87	0.29	0.12	0.20	0.28	0.46	0.01	0.24	2
14	10.63	0.22	0.11	62.60	0.29	0.12	0.18	0.27	0.46	0.02	0.24	2
15	10.77	0.23	0.11	62.69	0.29	0.12	0.11	0.28	0.46	0.06	0.24	2
16	10.70	0.16	0.12	61.92	0.20	0.14	0.17	0.19	0.45	0.0	1.10	1
17	10.85	0.23	0.11	62.87	0.29	0.12	0.16	0.28	0.46	0.01	0.24	2
18	10.90	0.22	0.11	62.83	0.29	0.12	-0.21	0.27	0.46	0.04	0.24	2
19	10.87	0.23	0.11	62.77	0.29	0.12	0.20	0.28	0.46	0.02	0.24	2
20	10.98	0.23	0.11	62.42	0.29	0.12	0.36	0.28	0.46	0.01	0.24	2
21	7.20	0.36	0.16	38.39	0.40	0.15	0.67	0.43	0.32	0.0	1.14	1
22	6.93	0.24	0.11	39.01	0.30	0.11	0.30	0.29	0.30	0.01	0.06	9
23	8.41	0.10	0.10	47.79	0.10	0.10	0.28	0.12	0.35	0.00	0.03	20

CONSTRAINT CARDS

STATION	NUM	TIME TERM	ERROR
ROCKHOPE	1	0.10	0.0

Table 13

NERL Time Term Solution for the Pn Phase

SOLUTION USING A VELOCITY OF 8.05
SUM OF RESIDULES SQUARED IS 0.32
STANDARD ERROR OF THE SOLUTION IS 0.06

STATION	E	ERROR	ERG	F	ERROR	ERG	TTERM	ERROR	ERG	B.W ST.ERR	95 CONF	NUM DATA
1	4.00	0.30	0.11	8.47	0.52	0.14	2.94	0.37	0.11	0.02	0.13	4
2	4.62	0.32	0.11	11.35	0.52	0.14	3.21	0.38	0.11	0.02	0.13	4
3	-1.69	0.33	0.12	-39.81	0.52	0.14	3.26	0.39	0.13	0.06	0.17	3
4	1.54	0.28	0.12	-13.89	0.45	0.15	3.27	0.34	0.12	0.08	0.30	2
5	5.95	0.30	0.11	21.66	0.48	0.14	3.26	0.36	0.11	0.03	0.17	3
6	4.75	0.38	0.11	12.51	0.62	0.15	3.20	0.45	0.12	0.04	0.13	4
7	6.08	0.33	0.12	24.29	0.48	0.14	3.06	0.39	0.12	0.04	0.17	3
8	12.37	0.39	0.13	75.47	0.70	0.23	2.99	0.48	0.15	0.0	1.38	1
9	1.66	0.20	0.14	-9.04	0.20	0.14	2.79	0.22	0.14	0.0	1.36	1
10	8.06	0.38	0.13	42.11	0.64	0.18	2.83	0.46	0.13	0.01	0.30	2
11	6.11	0.32	0.12	26.84	0.48	0.14	2.78	0.38	0.12	0.02	0.17	3
12	4.15	0.32	0.11	10.75	0.53	0.13	2.81	0.38	0.11	0.01	0.09	6
13	2.80	0.00	0.00	0.01	0.00	0.00	2.80	0.00	0.00	0.0	0.78	1
14	5.02	0.31	0.11	17.69	0.49	0.14	2.83	0.37	0.11	0.05	0.13	4
15	3.55	0.31	0.11	5.45	0.48	0.14	2.87	0.37	0.12	0.01	0.17	3
16	6.02	0.35	0.11	25.41	0.61	0.16	2.86	0.42	0.12	0.04	0.18	3
17	6.30	0.27	0.11	27.54	0.45	0.15	2.88	0.33	0.12	0.06	0.30	2
18	6.38	0.30	0.11	26.83	0.49	0.14	3.05	0.36	0.11	0.02	0.13	4
19	6.30	0.35	0.11	25.83	0.63	0.18	3.09	0.43	0.12	0.07	0.30	2
20	6.75	0.29	0.11	29.38	0.49	0.14	3.10	0.35	0.11	0.03	0.13	4
21	7.60	0.37	0.11	36.21	0.62	0.16	3.10	0.45	0.12	0.04	0.18	3
22	7.88	0.31	0.11	38.43	0.48	0.14	3.10	0.37	0.12	0.04	0.17	3
23	8.96	0.33	0.12	47.63	0.50	0.14	3.04	0.39	0.13	0.02	0.18	3
24	7.37	0.34	0.11	35.42	0.61	0.16	2.96	0.41	0.12	0.02	0.18	3
25	8.61	0.29	0.11	46.16	0.48	0.14	2.87	0.35	0.12	0.07	0.17	3
26	11.47	0.39	0.13	65.27	0.71	0.23	2.86	0.48	0.15	0.0	1.38	1
27	9.10	0.20	0.14	50.44	0.20	0.14	2.84	0.23	0.15	0.0	1.36	1
28	6.36	0.33	0.11	28.26	0.54	0.13	2.85	0.40	0.11	0.04	0.11	5
29	6.30	0.32	0.11	28.32	0.54	0.13	2.78	0.39	0.11	0.02	0.11	5
30	6.79	0.32	0.11	31.94	0.51	0.12	2.82	0.38	0.11	0.03	0.11	5
31	6.39	0.33	0.11	28.63	0.53	0.12	2.83	0.39	0.11	0.01	0.08	7
32	6.19	0.42	0.11	26.66	0.67	0.13	2.87	0.50	0.12	0.04	0.31	2
33	6.44	0.32	0.10	28.91	0.53	0.12	2.85	0.38	0.11	0.01	0.08	7
34	6.86	0.33	0.11	32.07	0.51	0.12	2.87	0.40	0.12	0.01	0.11	5
35	4.54	0.35	0.11	12.53	0.60	0.13	2.58	0.43	0.11	0.03	0.11	5
36	5.66	0.37	0.12	21.29	0.65	0.18	3.01	0.45	0.12	0.01	0.30	2
37	6.80	0.33	0.11	29.54	0.53	0.12	3.12	0.39	0.11	0.03	0.09	6
38	5.18	0.43	0.13	15.92	0.67	0.15	3.20	0.52	0.13	0.0	1.40	1
39	1.16	0.38	0.11	-16.50	0.64	0.15	3.21	0.46	0.12	0.00	0.18	3
40	-0.86	0.41	0.14	-33.20	0.70	0.23	3.27	0.49	0.15	0.0	1.38	1
41	70.41	0.31	0.10	545.55	0.50	0.11	2.61	0.38	0.58	0.01	0.03	29
42	56.17	0.31	0.10	425.85	0.51	0.11	2.75	0.38	0.46	0.01	0.04	26
43	62.83	0.31	0.10	492.08	0.50	0.11	2.92	0.38	0.51	0.01	0.03	32
44	23.31	0.10	0.10	159.42	0.10	0.10	3.50	0.12	0.19	0.01	0.04	26
45	18.84	0.35	0.10	127.13	0.57	0.11	3.04	0.43	0.17	0.02	0.05	15
46	31.21	0.43	0.14	219.96	0.62	0.15	3.87	0.51	0.27	0.04	0.31	2

CONSTRAINT CARDS

STATION	NUM	TIME TERM	ERROR
ROCKHOPE	13	2.80	0.0

the Pg solution.

4.5.4 The Precursor Solution

To obtain a time term solution to the precursor phase of Pn, the velocity as well as the Rookhope delay time term had to be constrained. The results of the solution are listed in Table 14 and shown in Figure 36. A velocity of 8.05 Km/sec (least squares velocity for the Pn solution) was used to constrain the data because of the similar apparent velocity of the precursor phase. A least squares velocity from the data was obtained because of the slight changes in the position of the N2 shots. Because $\sum^{m} D^2_{ij}$ was low, the velocity (7.7 Km/sec) had a high standard error (1.04 Km/sec) and was too inaccurate to be of significance. The distribution and values of the time terms were similar to those obtained from the Pn solution.

4.5.5 Correction of Pn Time Terms

It is useful to correct the Pn time terms for the effect of the sedimentary cover to examine how the crust varies in its delay properties. The extra delay of the cover compared to the upper crustal material and relative to the Pn refractor is:

$$a\left[\frac{(V_n^2 - V_c^2)^{\frac{1}{2}} V_g - (V_n^2 - V_g^2)^{\frac{1}{2}} V_c}{(V_g^2 - V_c^2)^{\frac{1}{2}} V_n} \right]$$

where a is the Pg time term

V_n is the velocity of the Pn phase

V_g is the velocity of the Pg phase

V_c is the velocity of the cover.

Table 14

NERL Time Term Solution for the Precursor Phase

SOLUTION USING A VELOCITY OF 8.05
SUM OF RESIDULES SQUARED IS 0.02
STANDARD ERROR OF THE SOLUTION IS 0.04

STATION	E	ERROR	ERG	F	ERROR	ERG	TTERM	ERROR	ERG	B,W ST.ERR	95 CONF	NUM DATA
1	67.77	0.10	0.10	527.84	0.10	0.10	2.20	0.11	0.10	0.00	0.02	41
2	-2.12	0.17	0.11	-41.10	0.20	0.12	2.99	0.19	0.11	0.01	0.21	2
3	-0.99	0.17	0.11	-33.36	0.20	0.12	3.15	0.19	0.11	0.06	0.21	2
4	-0.43	0.20	0.12	-25.82	0.20	0.12	3.28	0.22	0.12	0.03	0.21	2
5	-0.07	0.17	0.11	-26.40	0.20	0.12	3.21	0.19	0.11	0.01	0.21	2
6	0.87	0.18	0.13	-19.17	0.20	0.14	3.25	0.20	0.13	0.0	0.96	1
7	1.43	0.18	0.11	-13.89	0.20	0.12	3.16	0.20	0.12	0.01	0.21	2
8	1.58	0.16	0.12	-12.54	0.20	0.14	3.13	0.18	0.12	0.0	0.96	1
9	2.30	0.18	0.13	-4.74	0.20	0.14	2.88	0.20	0.13	0.0	0.96	1
10	2.57	0.19	0.12	-1.24	0.20	0.12	2.72	0.21	0.12	0.06	0.21	2
11	2.80	0.00	0.00	0.02	0.00	0.00	2.80	0.00	0.00	0.0	0.56	1
12	2.96	0.18	0.13	2.01	0.20	0.14	2.71	0.20	0.13	0.0	0.96	1
13	3.36	0.18	0.13	4.36	0.20	0.14	2.81	0.20	0.13	0.0	0.96	1
14	4.34	0.18	0.13	11.62	0.20	0.14	2.89	0.20	0.13	0.0	0.96	1
15	5.76	0.18	0.13	22.26	0.20	0.14	2.99	0.20	0.13	0.0	0.96	1
16	6.06	0.18	0.13	24.42	0.20	0.14	3.02	0.20	0.13	0.0	0.96	1
17	6.51	0.16	0.12	27.36	0.20	0.14	3.11	0.18	0.12	0.0	0.96	1
18	7.25	0.18	0.13	33.41	0.20	0.14	3.09	0.20	0.13	0.0	0.96	1
19	8.41	0.16	0.12	43.38	0.20	0.14	3.02	0.18	0.12	0.0	0.96	1
20	8.59	0.18	0.13	45.56	0.20	0.14	2.93	0.20	0.13	0.0	0.96	1
21	9.95	0.18	0.11	57.58	0.20	0.12	2.79	0.20	0.12	0.00	0.21	2
22	10.27	0.18	0.11	59.82	0.20	0.12	2.84	0.20	0.12	0.00	0.21	2
23	10.43	0.18	0.13	61.38	0.20	0.14	2.80	0.20	0.13	0.0	0.96	1
24	10.98	0.19	0.12	65.62	0.20	0.12	2.83	0.21	0.12	0.02	0.21	2
25	11.62	0.18	0.11	71.10	0.20	0.12	2.78	0.20	0.12	0.04	0.21	2
26	12.02	0.18	0.13	73.86	0.20	0.14	2.84	0.20	0.13	0.0	0.96	1
27	12.48	0.18	0.13	77.50	0.20	0.14	2.85	0.20	0.13	0.0	0.96	1
28	13.01	0.18	0.13	80.67	0.20	0.14	2.98	0.20	0.13	0.0	0.96	1
29	13.49	0.18	0.11	83.38	0.20	0.12	3.13	0.20	0.12	0.01	0.21	2
30	14.35	0.20	0.12	90.33	0.20	0.12	3.13	0.22	0.12	0.00	0.21	2

CONSTRAINT CARDS

STATION	NUM	TIME TERM	ERROR
ROCKHOPE	11	2.80	0.0

For Vn = 8.05 km/sec, Vg = 5.88 km/sec, and Vc = 3.7 km/sec, then the delay is equal to 0.59 x a. The corrected Pn time terms are related to the depth to the Moho, measured from the surface, and are shown on Figure 36. It was apparent that the corrected delay time was constant within the limits of experimental error (± 0.1 sec) along the entire profile.

4.5.6 Inversion and Precision of the Time Terms

The depth to the basement was calculated from the Pg time terms by assuming a constant velocity of 3.7 km/sec for the cover. The depth to the Moho was calculated from the corrected Pn time terms by assuming a constant velocity of 5.88 km/sec for the upper crust and 6.6 km/sec for the lower crust. The time term for the upper crust (12 km thick) was calculated and subtracted from the observed Pn time terms, from which the thickness of the lower crust was calculated.

The observational error for the Pg and Pn time terms was about 0.1 seconds. This meant an uncertainty of about 0.5 km for the depth to the basement, and 1.1 km to the depth to the Moho. In practise the uncertainty in thickness of the crust may be considerably greater due to the uncertainty arising from the sedimentary cover correction and from the assumption of the depth to the lower crust. It was thought that this error was about 2 km.

4.6 Interpretation of Wide Angle Reflections

4.6.1 Interpretation of Pc Reflections

The fit of the Pc travel times to a single layer with an assumed uniform velocity of 5.88 km/sec, indicates a discontinuity at about 12 km for the records from both the Buxton and Spadeadam shots. This suggests that this discontinuity was approximately level beneath the profile.

4.6.2 Interpretation of Pm Reflections

The best fitting two layered model to the observed Pm reflection times for the Buxton and Spadeadam shots, indicates a velocity of 6.5 km/sec for the lower crust, and a depth to the Moho of 27 km. The upper crust was constrained to a thickness of 12 km, and a uniform velocity of 5.88 km/sec.

4.7 The Crustal Structure Beneath the N.E.R.L. Profile

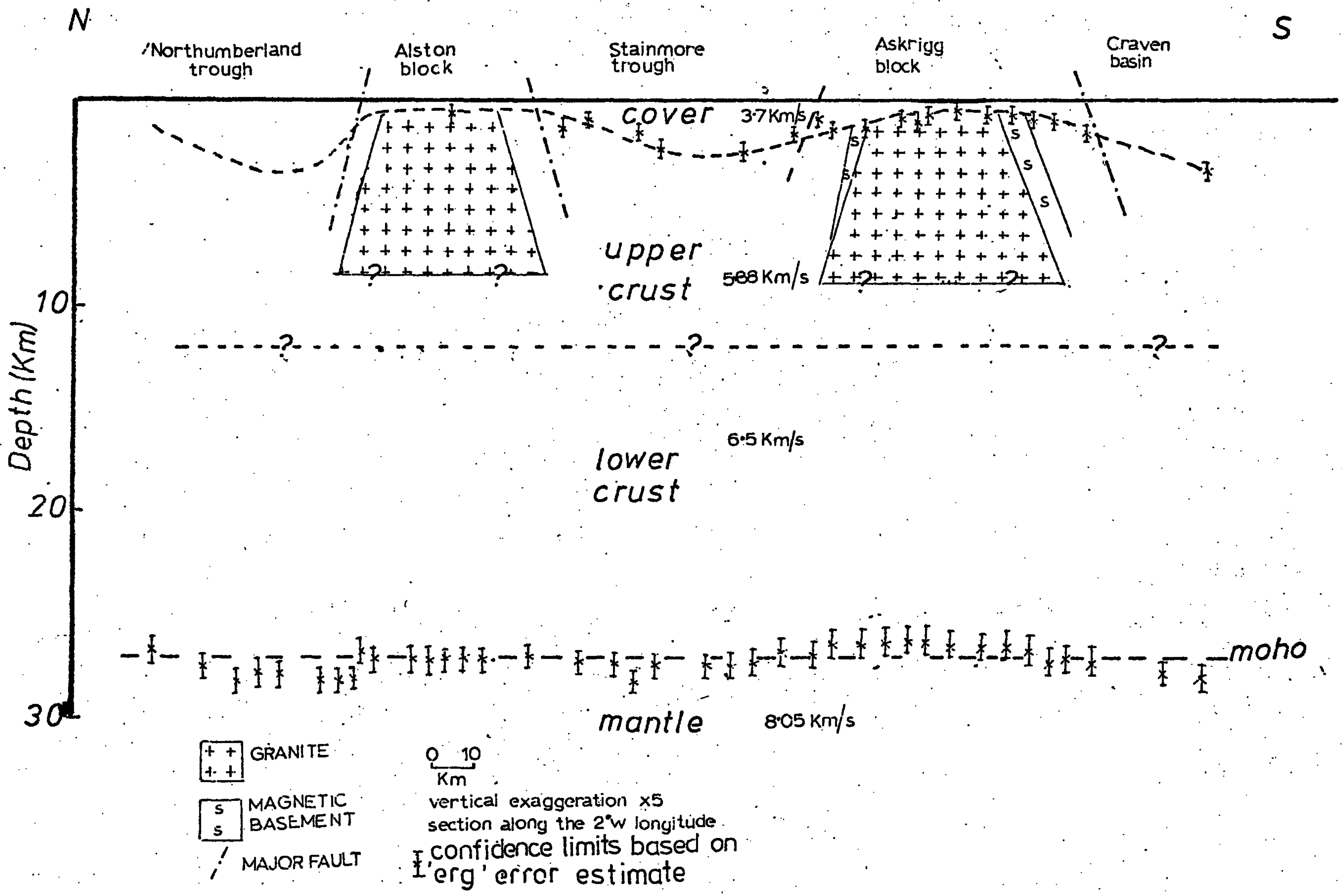
This chapter has summarised a description of the data recorded on the N.E.R.L. project and given an initial interpretation of the crustal structure of the Northern Pennines (c.f. Figure 37). A more detailed interpretation of the data will be possible when the source structures are known from the interpretation of the L.I.S.P.B. project. The main conclusions are:-

1) The delay properties of the cover increased within the sedimentary troughs. The depths to the basement along the profile were entirely consistent with the previously determined basement-cover relationships (2.6.5).

2) There was evidence for the existence of a discontinuity at a depth of approximately 12 km. The velocity of the

Figure 37

Interpretation of the Crustal Structure of the Northern Pennines



crust increased from at least 5.88 km/sec to more than 6.5 km/sec.

3) The Mohorovičić discontinuity lies at a depth of 27 ± 2 km and within the precision of the experimental error appeared to be level. Beneath the Moho the velocity of Pn was 8.05 ± 0.012 km/sec.

CHAPTER 5

SURFACE WAVE DISPERSION OF ENGLAND

5.1 Introduction

The interstation Rayleigh wave, phase and group velocity dispersion for the station pair EKA (Eskdalemuir) and WOL (Wolverton) was examined. Because only a vertical instrument was operated at WOL, the Love wave dispersion could not be calculated.

The station pair EKA-WOL was ideally placed to examine the deep structure of the Pennines and Midlands of England. In this respect, the interstation line followed closely the refraction profiles of the L.I.S.P.B. and N.E.R.L. experiments. The joint interpretation of the surface wave and body wave data was hoped to be a useful tool in the examination of the deep structure of England.

5.2 Data Collection

5.2.1 Data Selection

Five earthquakes along the interstation great circle were used in the analyses and are listed in Table 15 and shown in Figure 38. The G.E.D.E.S.S. earthquake lists were scanned by a search programme with the criteria that the difference in azimuth between the great circle and earthquake paths was less than 4°, and that the body or surface wave magnitude was greater than 5.5.

There was an abundance of earthquakes from the Alaska and Kodiak Island areas with epicentres along the northern extension of the great circle between the station pairs.

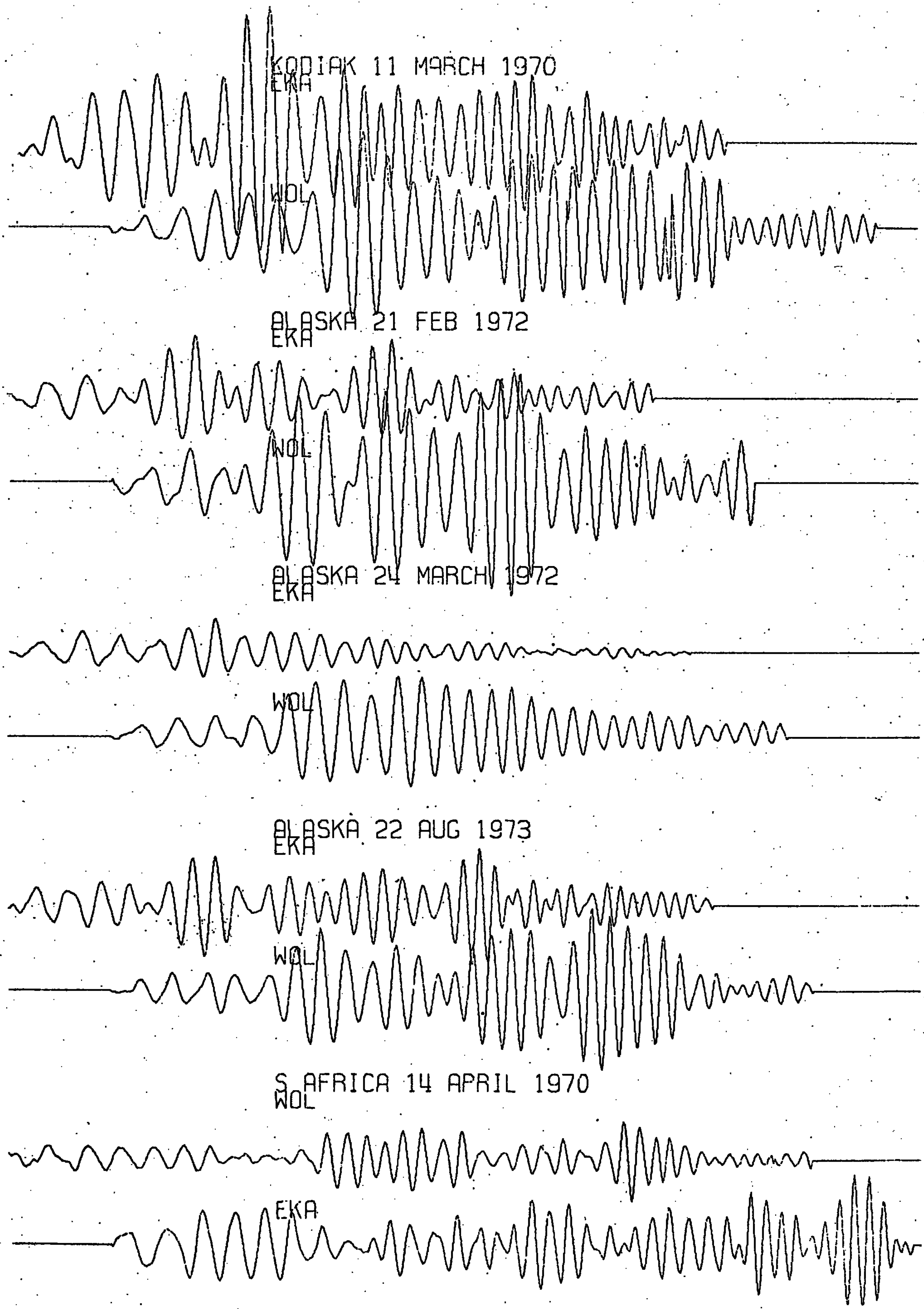
Table 15

List of Events used in Surface Wave Dispersion Analyses

EVENT	DATE	EPICENTRE	LAT	LONG	ORIGIN TIME H	M	S	MAGNITUDE MS	MB	DEPTH	RANGE EKA	WOL	AZIMUTH EKA	WOL
A	11/3/70	Kodiak Is.	57.465N	153.918W	22	38	34.6	6.0	6.0	29	65.1	69.3	343.1	344.6
B	14/4/70	S Africa	33.299S	19.218E	19	8	21.3	5.4	5.7	33	90.3	86.2	161.4	163.0
C	21/2/72	Alaska	55.902N	158.265W	19	34	50.9	/	5.7	60	67.3	71.5	345.1	346.6
D	24/3/72	Alaska	56.142N	157.180W	3	38	27.1	/	6.0	69	66.9	71.1	344.5	346.1
E	22/8/73	Kodiak Is.	57.067N	154.101W	18	14	37.2	5.6	5.9	38	65.5	69.7	343.0	344.6

Figure 38

Teleseismic Events used for Surface Wave Dispersion Analyses



Reversed coverage from the south was much less frequent, and only one earthquake from South Africa was found to satisfy the requirements. Knopoff, Muller and Pilant (1966) showed that provided the interstation path angle was small, only second order error in the phase velocity arose from disturbances in azimuth, such as refraction at the continental margins. Brune and Dorman (1963) used angles of up to 7^{o} initially, and then restricted the analyses to angles of less than 4^{o} in azimuth in the study of the Canadian Shield.

5.2.2 Instrumentation

Although described (by U.K.A.E.A.) as a wide band instrument, the vertical component (from a set of three) at EKA had a rather limited frequency response. The long period narrow band seismometer at WOL had a similar response to the one at EKA at low frequencies (less than 0.025 Hz) and a slightly lower cut-off at higher frequencies.

The group and phase corrections applied to the filtered records were taken from frequency response curves (U.K.A.E.A.) which were calculated from theoretical 'poles and zeroes' approach using the various instrument and electronic parameters.

5.2.3 Digitising the Records

Long period tapes from EKA and WOL were replayed through demodulators onto a jet pen recorder at a speed of approximately 75 mm/record minute. The traces from the vertical instruments were digitised manually at two second intervals. The Nyquist frequency of 0.25 Hz was considered sufficiently high for the frequencies considered to prevent aliasing. Up to 512 samples were sufficient to span the entire record.

5.3 Calculation of Group Velocities

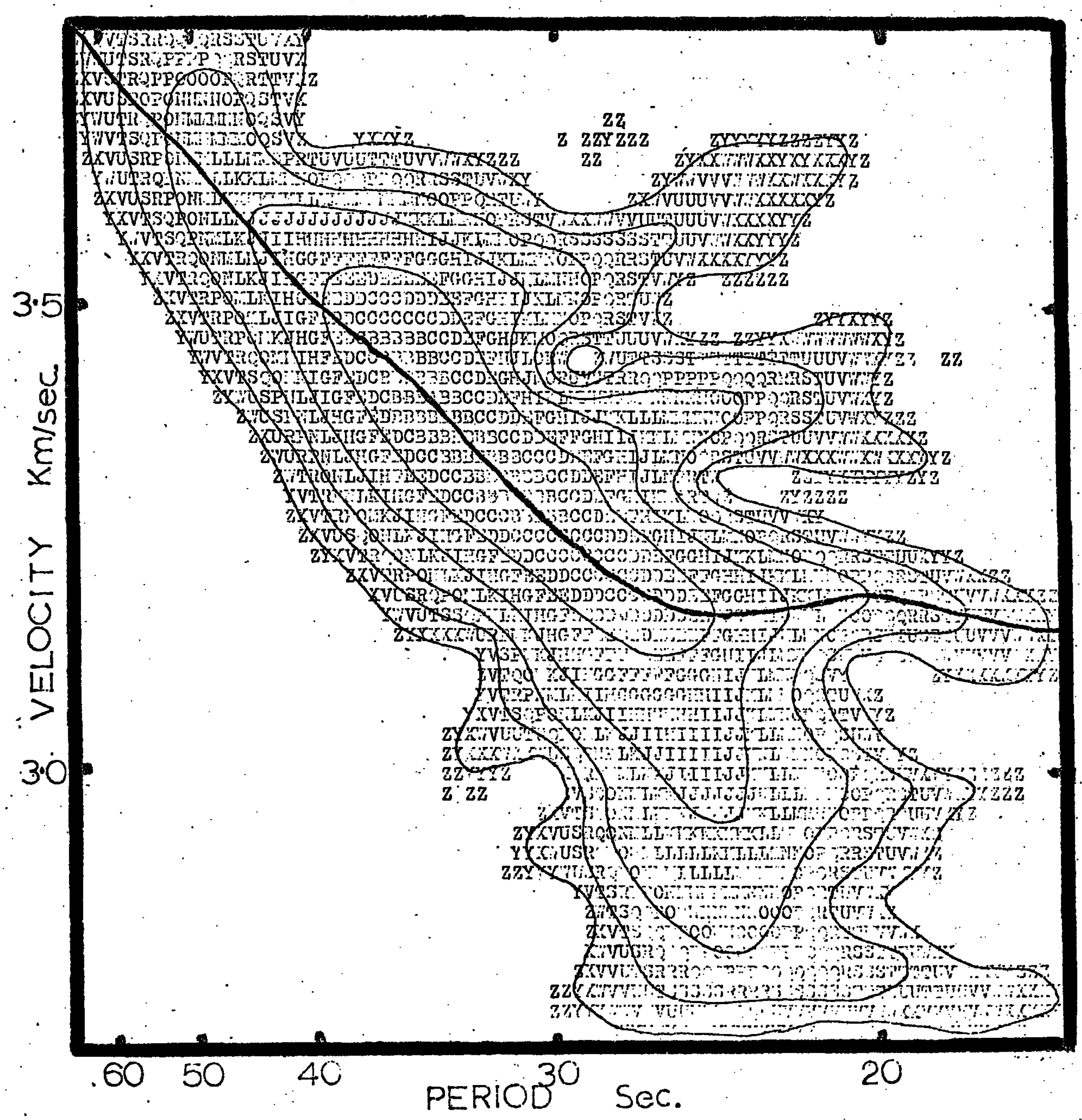
The seismograms were filtered using a series of digital narrow band filters to determine where in the record the maximum energy at a particular frequency occurred (Dziewonski, Bloch and Landisman, 1969). Using the origin time and the distance travelled it was then possible to construct a group velocity-frequency curve for each seismogram (cf. Figure 39). The interstation group velocity curve was calculated from the difference in the arrival of the maximum energy at a particular frequency for the two records.

The programme used to calculate the interstation group velocities was an extensively modified version of the S.W.A.P. programme written by P.W. Burton and C. Blamey (1972).

The Fourier transform of the seismogram was calculated using a procedure based on the Cooley-Tukey algorithm (Cooley and Tukey, 1965). The time series was cosine tapered at both ends and fitted to a mean baseline to reduce the Gibbs phenomenon and 'square wave' effects (Hsu, 1972) caused by a time series superimposed onto a non-zero baseline. The digital time series was expanded by adding zeroes to the end of the seismogram, so that the number of digits was equal to 2^{L+1}, where L was the smallest integer which makes the number of digits greater than the original seismogram. This was an intrinsic requirement of the Cooley-Tukey algorithm. The extra power of two ensured that the

Figure 39

GROUP VELOCITY DISPERSION FOR EVENT ON 24th MARCH 1972 RECORDED AT WOLVERTON



Contours at 5dB intervals

A = 99 dB

convolution formed by the multiplication of two waveforms in the frequency domain, gave accurate values over the time domain in the range of interest.

A narrow band filter was chosen that was a compromise between the resolution of the filtered signal (detectability) and the purity of the frequency component (filter bandwidth). A gaussian shaped filter optimises these conditions (Inston, Marshall and Blamey, 1971). A set of such filters at different central frequencies were constructed such that they correspond to the harmonic frequencies obtained from the fourier analyses. A uniform Q ratio (peak frequency/ bandwidth) was used to ensure a uniform resolution for all frequencies.

Convolution of the time series and the filter was achieved by multiplication in the frequency domain. The re-transformed product gave an oscillating filtered signal. An envelope was constructed in the time domain by setting the negative frequency components of the product to zero. For each envelope at a particular frequency, a correction was applied to allow for the group velocity response of the instrument in question.

The whole set of corrected envelopes were placed into a two dimensional matrix. Amplitudes were converted to decibels and scaled to a 99dB maximum. The matrix was a display of the power of the signal along the length of the record and along the frequency content. The group velocity and arrival time of maximum energy for each frequency can be read directly off the matrix. The difference in arrival time for each frequency was divided into the interstation separation to yield the interstation group velocity curve.

5.4 Calculation of Phase Velocities

The interstation phase velocity is given by Sato (1958):-

$$c(p) = \frac{p\Delta_{12}}{(\phi_2(p) - \phi_1(p) - (\theta_2(p) - \theta_1(p)) + 2n\pi + (t_2 - t_1)}$$

where p is frequency

Δ_{12} is the interstation separation

$\phi_2(p) - \phi_1(p)$ is the difference in phase spectrum

$\theta_2(p) - \theta_1(p)$ is the instrumental phase difference

$t_2 - t_1$ is the time difference between the start of the records.

$2n\pi$ is an integer multiple of pi. This arises because of the multivalued nature of the trigonometric function used to calculate the phase spectrum. The value of n can be set to any integer depending on the whole number of wavelengths shifted. In practise for small separations (461 Km) only one value of n gives velocities comparable with the group velocity values.

The phase spectra for each record was calculated by fourier transforming as in the previous section (5.3). The difference in phase spectra was corrected for instrumental response and the time delay between the start of the records. The value of n was adjusted so that the calculated phase velocity broadly agreed with the group velocities.

A second method of determining the phase velocities was based on the technique described by Bloch and Hales (1968). The programme used (IPV) was written by U.K.A.E.A. and only slightly modified for use at Durham. Basically the programme passed both time series through a narrow bandpass digital filter set at various periods to reduce unwanted noise, and formed the cross product of the filtered seismogram after time shifting. The phase velocity dispersion was determined from a contoured matrix which consisted of amplitudes as a function of phase velocities and period.

The group velocity dispersion was calculated for each record using the procedure as outlined in Section 5.3. A frequency corresponding to one of the harmonic frequencies obtained from the group velocity analyses was selected. From the group velocity dispersion, the arrival time of the particular frequency was calculated and an instrumental phase correction applied. A symmetric window with a length of 4.5 times the period of interest was constructed for each seismogram and cosine tapered at either end. If the window extended beyond the ends of the time series, an asymmetric window was used and a warning printed. This latter problem could be obviated by adding zeros to the beginning of the seismogram. The two windowed time series were fourier transformed and convolved with a narrow band-pass digital filter. This filter was gaussian shaped, with a uniform Q ratio, and was similar to that described previously (5.3).

The two filtered signals were multiplied together for different time shifts. If the two signals were represented by $A \cos wt$ and $B \cos (wt + \phi)$, (the same frequency but phase shifted), then the product was $AB/2[\cos (2\,wt + \phi) + \cos \phi]$. The product had a D.C. shift which was proportional to $\cos \phi$. The D.C. shift was calculated from the maxima and the following minima of the product.

The output consisted of a matrix of D.C. values plotted against period and phase velocity. These values were scaled to a maximum of 99. The phase velocity dispersion was read directly from the contoured matrix. Sets of maximum and minimum D.C. values parallel to the principal curve, correspond to phase shifts of a whole number and half number of wavelengths respectively (c.f. Figure 40).

5.5 Results

The interstation phase and group velocity dispersion curves are shown in Figure 41. It was found that the phase velocity curve calculated using the IPV programme gave the most stable results.

It was found that when calculating the group velocity dispersion of a seismogram (5.3), there appeared low energy values at certain periods of between 20 and 30 seconds, along the record. Brune and Dorman (1963) noted a similar 'beating' effect and explained this in terms of multipath interference of the ray. As this feature was noticeable on all the records from teleseismic events with differing hypocentres, it would be unlikely to be due to a source effect.

5.6 Interpretation

The fundamental problem of the interpretation of surface wave dispersion is the non-uniqueness of the inversion procedure (Knopoff, 1961; Gilbert and Backus, 1968). Inversion is normally achieved by matching the observed dispersion curve with those calculated for a given

Figure 40

Phase Velocity Dispersion
between EKA and WOL
event on 24th March 1972

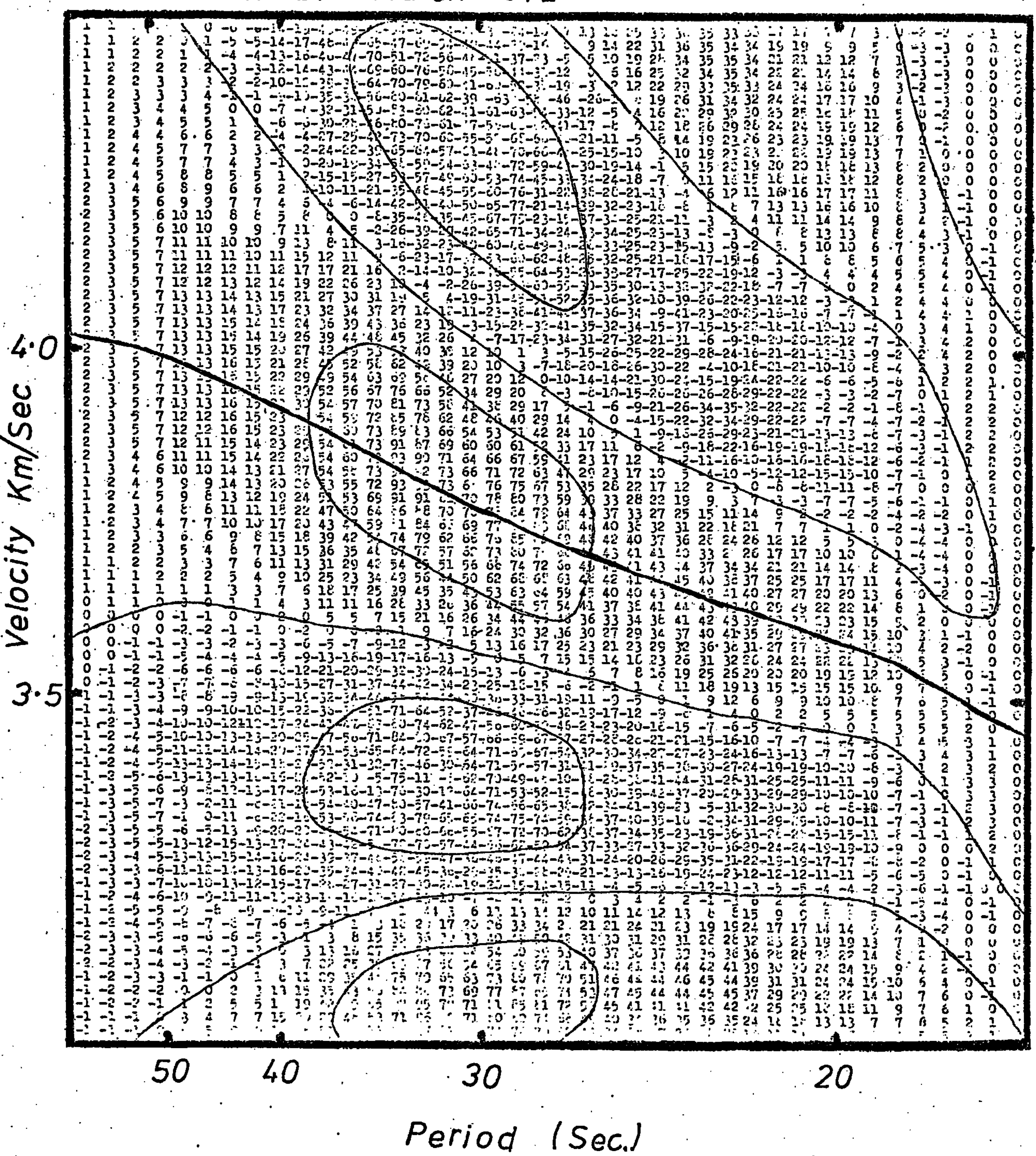
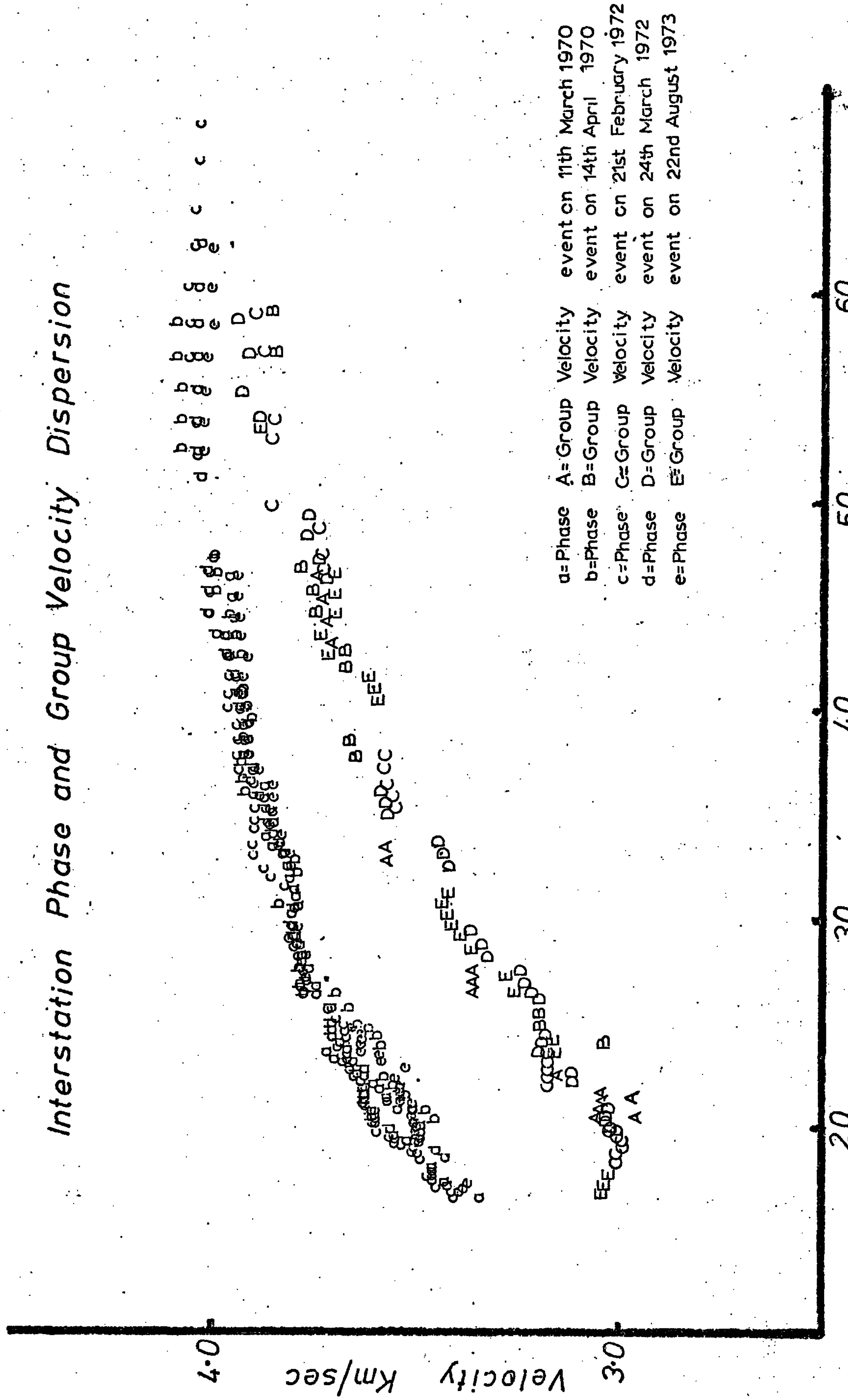


Figure 41


Interstation Phase and Group Velocity Dispersion
a=Phase A=Group Velocity event on 11th March 1970
b=Phase B=Group Velocity event on 14th April 1970
c=Phase C=Group Velocity event on 21st February 1972
d=Phase D=Group Velocity event on 24th March 1972
e=Phase E=Group Velocity event on 22nd August 1973
Velocity Km/sec
4·0
3·0
Period (sec)
20
30
40
50
60

model, the parameters of which are adjusted either manually or automatically to achieve an optimum fit, e.g. Monte Carlo Inversion (Press, 1968) or least squares techniques (Brune and Dorman, 1963). The data has only limited resolving power, and one must strike a balance between the resolution of the model (number of layers) or the accuracy of determination of the parameters for each layer. It is usual to employ as few layers as possible without being geophysically unreasonable.

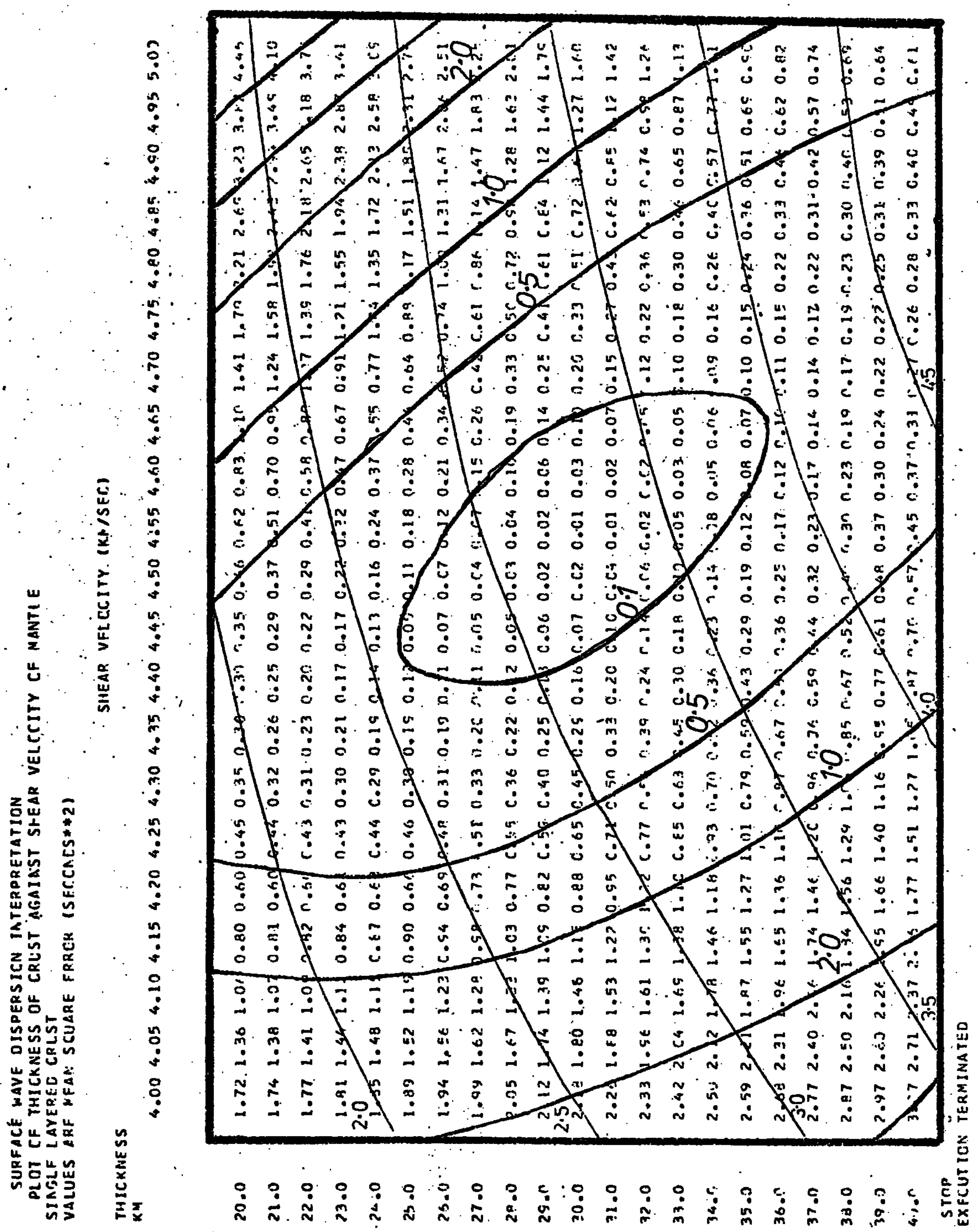
The observed phase velocity dispersion was first interpreted by comparing it with those calculated for layered models derived from the interpretation of refracted arrivals. At long periods (over 50 seconds), the observed dispersion curve flattened and became asymptotic to a value which was found to be related to the shear velocity of the upper mantle. At shorter periods (below 30 seconds), the shape of the phase velocity curve was found to be determined by the thickness and velocity structure of the crust.

A reasonable fit to the observed dispersion curve was made for a single layered crustal model with a thickness of between 25 and 30 Km and a shear velocity of the mantle of 4.6 Km/sec. The fit was poorest between periods of 20 and 30 seconds, and may be explained by velocity layering within the crust.

To explore the variation in the parameters of a single layered crustal model, the thickness of the crust (α = 6.0 Km/sec, β = 3.46 Km/sec) and the shear wave velocity of the mantle were systematically altered. The sum of the residuals squared compared to the observed curve was

Figure 42

Interpretation of Phase Velocity Dispersion



20-Time Term 0·5 Fit of Data

calculated and plotted (Figure 42), to find the optimum fit for a single layered crustal model. The least squares model had a crustal thickness of 30 km and a mantle shear wave velocity of 4.55 Km/sec. The model showed the non-uniqueness of the interpretation in that an interchange between crustal thickness and the shear velocity of the mantle would give a similar fit to the observed data. The fit for a two layered crust showed little improvement over a single layered crust.

Because of the narrow band response of the seismometers there was no indication from the observed dispersion curves of the existence of a low velocity zone within the mantle.

5.7 Conclusions

The interpretation of the observed surface wave dispersion between EKA and WOL stations indicates a crustal thickness of 30 Km and shear velocity of the mantle of 455 Km/sec. Although the method did not have the same resolution as body wave seismology, the data did agree with the deep structure found along the N.E.R.L. profile and provides an independent assessment of the interpretation.

CHAPTER 6

THE CRUSTAL STRUCTURE OF NORTHERN ENGLAND

6.1 Introduction

The upper crustal structure of Northern England has been identified by the interpretation of Pg refracted arrivals, using the time term method, and their apparent velocities across array stations. The lower crustal and upper mantle structure were interpreted from Pn refracted arrivals, wide angle reflections and the surface wave dispersion.

6.2 Character of Phases

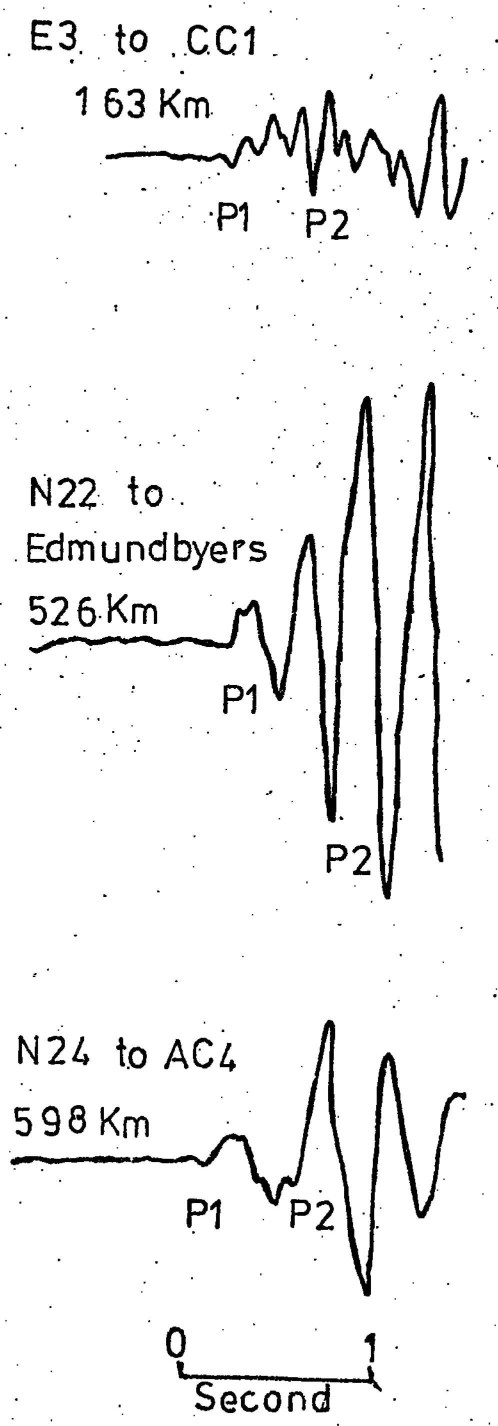
It is useful to examine the common waveform structure of certain phases that had previously been interpreted in separate sections so that a unified crustal model could be derived.

6.2.1 Character of the Pn Phase

Pn arrivals from all the ranges observed (130 to 610 Km) showed a complex waveform indicating multipath arrivals. The most common structure was an emergent low amplitude precursor to be followed about 0.5 seconds later by a high amplitude phase (Figure 43). This was most clearly observed for the large N2 shots recorded on the N.E.R.L. experiment (4.4.6). It would seem unlikely that the cause of the structure was due to reverberations in the upper crust as the phase separation was constant despite lateral cover variation. It would seem more probable that

Figure 43

Character of the Pn Phase



the effect was caused by a sub-moho structure such as an abrupt or continuous increase in velocity with depth.

Because of the constant interphase time separation over large ranges, the two phases had similar apparent velocities. The precursor could be interpreted as a refracted or 'diving ray' from the sub-moho higher velocity layer, or alternatively that the precursor was the true Pn refracted wave and the large amplitude second arrival was a trapped wave within a sub-moho layer.

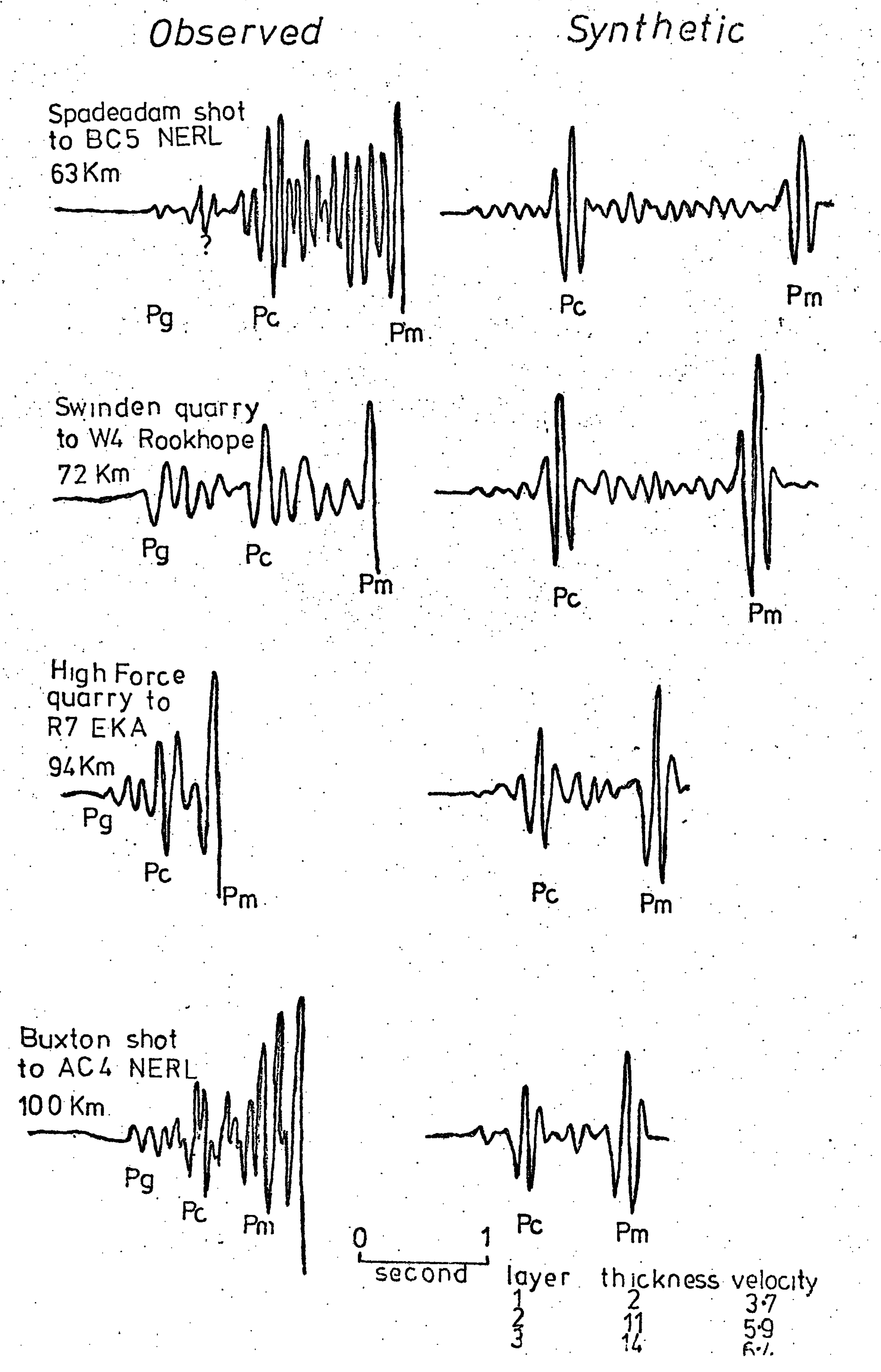
6.2.2 <u>Reverberation of the Pn Refracted Wave</u>

Along the northern end of the N.E.R.L. line, a pronounced arrival about 6.0 seconds after Pn with a similar apparent velocity was observed. This phase was interpreted as a Pn refracted wave that had reverberated within the crust. The delay of this phase was comparable with twice the observed delay times of the Pn refracted arrivals. Because this arrival was most clearly observed at the northern end of the N.E.R.L. profile, from shots to the north and south, it would appear that the reverberation was at the recording site, rather than at the source. Agger and Carpenter (1965) noted multiple reverberations within the crust on records at Eskdalemuir. Because of the large amplitude of this phase compared to Pn, it would be unlikely to be a converted phase e.g. (S.P.S.).

6.2.3 <u>Identification of Wide Angle Reflections</u>

Figure 44 shows some selected records with large amplitude wide angle crustal reflections in the range 60 to 100 km. There was little doubt about the identification

Figure 44
Character of Wide Angle Crustal Reflections



of the Pm phase. It was asymptotic to the Pn phase, had a maximum amplitude just beyond the critical distance, and its apparent velocity decreased with distance (3.5.1). The phase was distinguishable to beyond 200 Km range (4.4.4).

The identification of the Pc phase, a wide angle reflection from an intra-crustal discontinuity was more difficult than Pm, due to its lower amplitude, and it was not persistent on all the records. As a second arrival it can be most easily confused with a P* refracted wave. At supercritical distances, the expected amplitude of the Pc phase would be much greater than the P* phase, the latter being comparable with the amplitude of the Pn phase (Berry and West, 1966a). The high observed amplitude in the range 60 to 90 Km and the manner in which the travel times become asymptotic to the Pg phase, point to the interpretation of this arrival as a wide angle reflection.

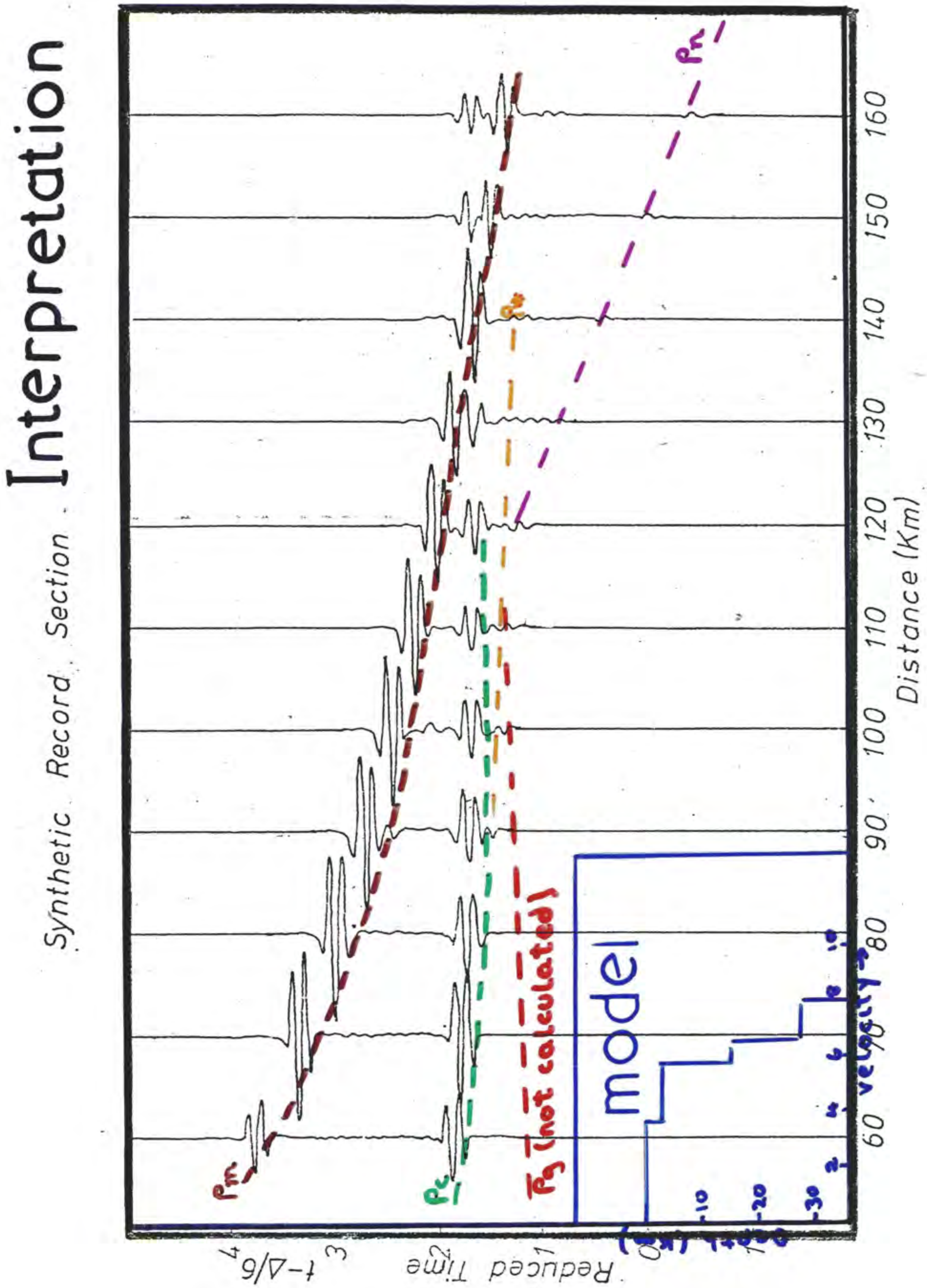
6.3 Synthetic Profile of the Interpreted Structure of Northern England

Because of different recording instrumentation, and the differences in the recording site and shot size, it was not possible to compare amplitudes qualitativity of the various phases between the records directly. One could only make a comparison by examining the ratio of the amplitudes of the different phases. The most satisfactory method to interpret all the information contained on a record section was to compare the observed section with a synthetic one based on the interpreted crustal structure. A programme for the computation of synthetic seismograms was kindly lent by Dr. K. Fuchs. The method involved the computation of displacement potentials by the 'reflectivity' method (Fuchs and Muller, 1971) and used asymptotic expressions to integrate around the critical angle.

The synthetic section shown in Figure 45 is for a two layered crustal model with velocity increasing with depth in the lower crust. The requirement of velocity increasing by about 0.02 Km/sec/Km in the lower crust was indicated from the observed amplitude ratio of Pm/Pn which decreased beyond 160 Km (3.5.2). The very low amplitude of Pn arrivals in the range 140 to 160 Km (3.5.2) was also noted by Fuchs and Muller (1971) and attributed to a sub-moho increase in velocity. This interpretation was entirely consistent with the observed waveform structure of Pn arrivals (6.2.1).

The most obvious difference between the synthetic and the observed sections was the difference in the complexity of the latter. Observed records within the blocks, and particularly the Askrigg block, showed a clarity in the onset of phases not matched with those records from the sedimentary troughs. The conclusion to be drawn was that much of the complexity of the records was due to reverberations within the sedimentary cover. The amplitude and clarity of the wide angle reflections indicated that the main crustal layers may be relatively uniform in their velocity structure.

Figure 45



Synthetic Record Section Interpretation
Pm
Pc
Pg (not calculated)
Pn
model
velocity
Reduced Time t−Δ/6
Distance (Km)
60
70
80
90
100
110
120
130
140
150
160

6.4 Interpretation of the Crustal Structure

6.4.1 Depth to the Moho and Mean Crustal Velocity

Holder and Bott (1971) derived formulae for estimating the mean velocity and crustal thickness, based on the measurement of the critical distance, the Pn velocity and the Pn time intercept. The two way delay time (5.6 ± 0.2 seconds) and the Pn velocity (8.05 ± 0.012 Km/sec) were well known from the N.E.R.L. refraction line (4.5.4). The critical distance may be estimated from the amplitude of Pm reflections, but was estimated at 65 ± 5 Km from the apparent velocity of Pm recorded at Eskdalemuir (3.5.1). The estimated crustal thickness was 27 ± 2 Km and a mean crustal velocity of 6.2 ± 0.2 Km/sec. These estimates were consistent with interpreted velocity structure of the crust.

6.4.2 The Evidence for a Low Velocity Channel in the Crust

Bamford (1972) suggested from an interpretation of records, a low velocity zone immediately above the lower crust beneath Western Britain. The evidence for a low velocity channel is based on the large amplitude and 'ringing' of the Pcp phase (Mueller and Landisman, 1966). The Pg velocity of earthquakes (Gutenberg, 1954) is often less than that from explosion studies, and is attributed to a trapped wave in a low velocity zone at the source depth of the earthquake. Despite the similarity of record sections in North West Europe to those observed in Northern England, there was no conclusive evidence for the existence of such a zone in Northern England.

6.4.3 Composition of the Crust

Beneath the lower Palaeozoic rock exposed in inliers presumably lies pre-Cambrian, high grade crystalline basement, similar to the English Lowlands or the basement of the East Midland Shelf (Kent, 1967). A separate (meta-volcanic ?) composition for the basement beneath the Askrigg block was indicated from the interpretation of magnetic anomalies (1.4). Although the composition of the granite batholiths near the surface was truly granitic, they may well verge into a more basic composition, e.g. granodiorite at depth.

Collette (1970) suggested that the lower crust may be anorthositic in composition, based on the 'low' Pn time terms and 'normal' gravity. It would seem more probable that the composition was more akin to a pyroxene granulite similar to the Scourian of N.W. Scotland, which would have the required velocity and stability of pressure and temperature conditions (Green and Ringwood, 1966).

6.4.4 Isostasy

Bott and Masson Smith showed that the Weardale granite and the Wensleydale granite (Bott, 1967), have a mass deficiency which is approximately equal to the weight of the topography of the blocks, relative to the surrounding levels. The Pn time terms (4.5.6) suggest that the Mohorovicic discontinuity is at the same depth beneath the troughs as under the blocks. This confirms the gravity data in indicating that the relatively uplifted blocks are in isostatic equilibrium by the mechanism of density changes within the crust (Pratt's hypothesis). An intriguing question is the shape of the Moho before the formation of the sedimentary troughs (Silurian-Devonian). Was the crust thinner in the regions of the present sedimentary troughs? The intrusion of the granites may have added crustal material and thickened the crust beneath the blocks. Alternatively there may have been redistribution of lower crustal material in a manner similar to that suggested by Bott (1971) for continental margins.

6.4.5 Basement Control

Bott (1967) attributes the mechanism of basement control as due to the relatively greater strength of the granites and magnetic rocks in relation to shear fracture and to the supplementary stresses set up by the low density granites and topographic features. The upthrust of relatively low density granites and the weight of the excess topography lead to a stress system favourable to normal faulting within the blocks. The granites had an isostatic tendency to be uplifted relative to their surroundings. Continual movement along the hinge lines during the subsidence of sedimentary basins was caused by this isostatic tendency.

6.4.6 The Crustal Structure of Northern England

From the study of the refracted arrivals, it was possible to be most definite about the interpretation of the basement-cover relationships and the depth to the Moho, because of the large velocity contrast at these discontinuities. It was much more difficult to be specific about the nature of the velocity structure within the crust. Although it was possible to interpret the refracted phases in terms of two plane crustal layers; the cover and the main basement layer, there was evidence of a velocity structure within the crust. The interpretation of wide angle reflections and the apparent velocities of crustal phases across Rookhope and Eskdalemuir array suggested the existence of a lower crustal layer and indicated that velocity increased with depth within these layers.

The simplest crustal model which could account for all the observed data was based on a three layer structure. The top layer consisted of the sedimentary cover, with a uniform compressional velocity of about 3.7 Km/sec and considerable lateral variations in thickness. The upper crust contained two main basement rock types; the granites, and the pre-Devonian metamorphic rocks. There was some evidence that the granites had a lower Pg velocity, especially near the surface, and that velocity increased with depth. The lower crust extended from a depth of about 12 Km to the mohorovicic discontinuity at approximately 27 Km deep. The compressional velocity at the top of this layer was about 65 Km/sec and may increase gradually with depth. The upper mantle had a Pn velocity of 8.05 ± 0.012 Km/sec and exhibited evidence of a sub-moho structure.

6.4.7 Comparison with Other Areas

In general the record sections and the interpreted crustal structure bears a strong resemblance to those found over most of N.W. Europe, e.g. Fuchs and Muller, 1971; Smith, 1974; Holder and Bott, 1971. The only major differences in the interpretations were in the existence of a high velocity lower crust. Only rarely does this layer give rise to first arrival refracted waves, and many of the interpretations, including this one, were based on second arrivals such as wide angle reflections. Although varying considerably in layer thicknesses, a three layer model with velocities comparable with those found in this study are commonly interpreted throughout the world (James and Steinhart, 1966).

6.5 Conclusions

The main conclusions of the study were:-

1) The sedimentary cover (velocity about 3.7 Km/sec) varies considerably in thickness, from $2\frac{1}{2}$ to $3\frac{1}{2}$ Km in the troughs to less than 1 Km on the blocks.

2) The blocks are intruded by granites with a slightly lower Pg velocity, especially near the surface, than in the basement beneath the troughs.

3) There is some indication that the velocity of the upper crust increases gradually with depth from about 5.5 Km/sec (5.0 Km/sec for the granites) at the surface to near 6.0 Km/sec at a depth of 8 Km.

4) The interpretation of apparent velocities of crustal phases across Eskdalemuir and Rookhope arrays, and from wide angle reflections suggests a lower crust about 12 Km deep, with a velocity of about 6.5 Km/sec near the top.

5) The Moho appears to be at a uniform depth of

27 ± 2 Km. This means that the relative elevation of the blocks must be supported isostatically by the low density granites.

6) The upper mantle has a velocity of about 8.05 Km/sec and shows some evidence of an increase of velocity with depth.

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COMPUTER PROGRAMMES

The computer programmes listed are written in FORTRAN and are self-explanatory, complete with input-output instructions.

A) Time term programmes

1) The matrix inversion programme calculates errors on the unknowns, and is most suitable for large networks.
2) The householder iterative solution is used for small networks. The input data can be weighted.
3) The two velocity solution calculates the least squares solution to two basement types.
4) The solution to the refractor velocity increasing linearly away from the source.
5) The iterative solution for a dipping refractor.

B) Programme to calculate travel distances from geographical coordinates.

C) Programmes to calculate apparent velocity across an array from the onset times.

1) Known azimuth
2) Unknown azimuth.

D) Wiechert inversion programme.

E) Programmes to calculate the fit of crustal models to the observed wide-angle reflection times

1) Two layered model based on the Pm-Pg times.
2) Single layered model based on the Pc-Pg times.

```
C
C        SWINBURNS TIME TERM PROGRAMME  1
C   MATIX INVERSION PROGRAMME
C
C   CALCULATES ERRORS ON THE UNKNOWNS
C   OUTPUTS     ERROR= REAL VALUE MUST LIE WITHIN THESE ERROR BARS
C               ERG = A GAUSSIAN DISTRIBUTED ERROR ABOUT THE REAL VALUE
C    INPUT DEFAULT =X.4
C
C     MAKES USE OF COMPACT STORAGE OF MATRICES
C    CALLS IBM SSP PACKAGE SUBROUTINE SINV FOR INVERSION OF SYMMETRIC MATRIX
C     USING A CHOLESKY ALGORITHM
C
C   INPUT IS:-
C    CARD 1        N,M,K,((VEL(I),VELERR(I)),I=1,4)
C        FORMAT (3(5X,I5),8F5.2)
C    N= NUMBER OF TIME TERMS,  MUST BE CONSECUTIVE
C    M=NUMBER OF TRAVEL TIMES
C   K=NUMBER OF CONSTRAINT TIME TERMS
C   VEL(I)= UPTO 4 CONSTRAINT VELOCITIES,  IF LEFT BLANK WILL ONLY DO LEAST
C      SQUARES VELOCITY
C   VELERR(I)= ERROR IN CONSTRAINT VELOCITIES
C
C   NEXT K CARDS. (CONSTAINT CARDS)
C      ALPHA(I),NUM(I),TTRM(I),TRERR(I)
C      FORMAT(A8,2X,I5,25X,2F5.2)
C       ALPHA(I)= NAME OF STATION
C    NUM(I)= NUMBER OF STATION
C   TTRM(I)= TIME TERM OF STATION
C    TRERR(I)=  ERROR IN TIME TERM
C
C    NEXT M DATA CARDS (TRAVEL DATA)
C      ALPHA1(I),NUM1(I),EAST1,ANRTH1,ALPHA2(I),NUM2(I),EAST2,ANRTH2,TT(I)
C            TTERR(I),DIST(I),DISTER(I)
C     FORMAT (2(A8,2X,I5,2F5.2),2F5.2,F5.2,F4.2)
C   ALPHA1(I)= NAME OF SHOT STATION
C    NUM1(I)= NUMBER OF SHOT STATION
C   EAST1,ANRTH1= O.S. COORDINATES OF SHOT STATION
C    ALPHA2(I)= NAME OF RECORDING STATION
C    NUM2(I)= NUMBER OF RECORDING STATION
C    EAST2,ANRTH2= O.S. GRID COORDINATES OF RECORDING STATION
C    TT(I)= TRAVEL TIME
C   TTERR(I)= ERROR IN TRAVEL TIME
C   DIST(I)= DISTANCE.  IF EAST1, ETC. ARE SPECIFIED THE CALCULATED DISTANCE
C    FROM THE O.S. COORDINATES ARE USED INSTEAD.
C    DISTERR(I)=  ERROR IN THE DISTANCE
C
C
C   OUTPUT CONSISTS OF  TIME TERM SOLUTION FOR UPTO 4 CONSTRAINED VELOCITIES
C   AND THE LEAST SQUARES VELOCITY.  LIST OF TIME TERMS ARE GIVEN AND
C   THE ORIGINAL CARDS WITH RESIDUALS  ETC. AND THE VARIANCE-COVARIANCE MATRIX
C    TIMES 100.
C   MATRIX E= PART OF THE TIME TERM NOT DEPENDENT ON VELOCITY
C    MATRIX F= PART OF TIME TERM (DISTANCE) VELOCITY DEPENDENT
C    B.W ST.ERROR= STANDARD ERROR ON THE TIME TERM USING THE BERRY AND WEST
C          FORMULAE
C    95 CONF=  95 PER CENT CONFIDENCE LIMIT ON THE TIME TERM ESTIMATED FROM
C     THE MATRIX (ATA)-1
C    NUM DATA=NUMBER OF DATA TO  A STATION
C    MATIX C= PART OF TRAVEL TIME NOT DEPENDENT OF VELOCITY
C    MATRIX D= PART OF TRAVEL DISTANCE VELOCITY DEPENDENT, IE REVERSED
C
C
      DOUBLE PRECISION  ALPHA(25),ALPHA1(500),ALPHA2(500)
      DIMENSION NUM(25),TTRM(25),TRERR(25),LA(1225),
     1NUM1(500),NUM2(500),TT(500),TTERR(500),DIST(500),DISTER(500),Q(505
     20),E(100),F(100),EERR(100),FERR(100),C(500),D(500),DERR(500),TTSE(
     3100),CERR(500),NTTSE(100),RESID(500),RESERR(500),TMTRM(100),TMTERR
     4(100),EERG(100),FERG(100),CERG(500),DERG(500)           ,TMTERG(100
     5),RESERG(500)
C
      DIMENSION TTEST(20)
      DIMENSION VEL(25),VELERR(25),VELERG(25)
      DATA TTEST/12.7,4.3,3.18,2.78,2.57,2.45,2.37,2.31,2.26,2.23,2.2,
     12.18,2.16,2.15,2.13,2.12,2.11,2.10,2.09,2.09/
C
C           READ IN THE NUMBER OF TIME TERMS N, EQUATIONS M, CONSTRAINT
C                 TIME TERMS K, AND UPTO FOUR VELOCITIES WITH ERRORS
C
      READ(5,1) N,M,K,((VEL(I),VELERR(I)),I=1,4)
    1 FORMAT (3(5X,I5),8F5.2)
      DO 96 IJK=1,4
   96 VELERG(IJK)=VELERR(IJK)
C
C
C           READ IN CONSTRAINT CARDS
C
      IF(K) 91,91,90
   90 DO 2 I=1,K
      READ(5,3) ALPHA(I),NUM(I),TTRM(I),TRERR(I)
    3 FORMAT (A8,2X,I5,25X,2F5.2)
    2 LA(I)=NUM(I)
   91 CONTINUE
C
C
C           READ IN THE REMAINING M EQUATIONS
C
      DO 4 I=1,M
      READ(5,5) ALPHA1(I),NUM1(I),EAST1,ANRTH1,ALPHA2(I),NUM2(I),EAST2,
     1ANRTH2,TT(I),TTERR(I),DIST(I),DISTER(I)
    5 FORMAT (2(A8,2X,I5,2F5.2),2F5.2,F5.2,F4.2)
      MN=M
C
C
C           CALCULATE DISTANCES FROM O.S. GRID COORDINATES
```

```
C
      AMN=(EAST1-EAST2)**2+(ANRTH1-ANRTH2)**2
      IF (AMN) 13,13,12
   12 DIST(I)=SQRT(AMN)
   13 CONTINUE
C
C
C         FORMULATE MATRIX LA, CHECK FOR COINCIDENT STATIONS
C
      IF (NUM1(I)-NUM2(I)) 6,7,8
    7 MN=K+I
      WRITE(5,9) MN,ALPHA1(I),ALPHA2(I)
    9 FORMAT(' ERROR CONDITION, SHOT AND RECORDING STATIONS ARE COINCIDE
     1NT ON INPUT CARD ',I5,' READING ',A8,' TO ',A8)
      STOP
C
C         SWOP STATION NUMBERS IF NUM1(I) IS GREATER THAN  NUM2(I)
    8 MN=NUM1(I)
      NUM1(I)=NUM2(I)
      NUM2(I)=MN
C
C         FORMULATE LA
    6 MN2=K+2*I
      MN1=MN2-1
      LA(MN1)=NUM1(I)
      LA(MN2)=NUM2(I)
C
C         SWOP BACK STATION NUMBERS IF ALREADY DONE SO
      IF (MN) 10,10,11
   11 NUM2(I)=NUM1(I)
      NUM1(I)=MN
   10 CONTINUE
    4 CONTINUE
C
C
C         FORMULATION OF (ATA)=Q FROM LOCATIONS IN LA
C
C                        SET Q TO ZERO
      MN=N*(N+1)/2
      DO 50 I=1,MN
   50 Q(I)=0.0
C
C                        SET DIAGONALS
      MN=2*M+K
      DO 51 I=1,MN
      J=LA(I)*(LA(I)+1)/2
   51 Q(J)=Q(J)+1.0
C
C                        SET  OTHER TERMS
      ML=K+2
      DO 52 I=ML,MN,2
      J=LA(I)*(LA(I)-1)/2+LA(I-1)
   52 Q(J)=Q(J)+1.0
C
C
C         CALL MATRIX  INVERSION AND WRITE ERROR PARAMETERS
C
      CALL SINV(Q,N,1.0E-5,IER)
      IF (IER) 40,41,42
   40 WRITE(5,43)
   43 FORMAT('1',' ERROR CONDITION DURING INVERSION, MATRIX Q=ATA IS NOT
     1 POSITIVE DEFINATE, RANK LESS THAN N')
      GO TO 41
   42 WRITE(6,44) IER
   44 FORMAT('1',' WARNING, LOSS OF SIGNIFICANCE DURING INVERSION ',/,'
     1RADICAND FORMED BY FACTORISATION STEP K+1 WAS STILL POSITIVE BUT
     2NO LONGER GREATER THAN ABS(EPS,Q(K+1)(K+1)')
   41 CONTINUE
C
C
C          CALCULATION  OF MATRICES E AND F, ERRORS, DIRECTLY FROM Q-1
C                     E=(Q-1)(A)T(TT)       TT=TRAVEL TIME
C                     F=(Q-1)(A)T(DIST)     DIST=DISTANCE
C                     EERR, FERR ARE ERRORS IN E AND F RESPECTIVELY
C
C
C          CYCLE ON EACH UNKNOWN (N), SET SUMMING TO 0
      DO 72 IN=1,N
      E(IN)=0.0
      F(IN)=0.0
      EERR(IN)=0.0
      FERR(IN)=0.0
      EERG(IN)=0.0
      FERG(IN)=0.0
C
C          CYCLE ON FIRST K ELEMENTS
      IF (K) 93,93,92
   92 DO 71 I=1,K
      CALL LOCQ(LA(I),IN,LQ)
      E(IN)=E(IN)+Q(LQ)*TTRM(I)
      AMN=Q(LQ)*THERR(I)
      EERG(IN)=EERG(IN)+ABS(AMN)*ABS(AMN)
      EERR(IN)=EERR(IN)+ABS(AMN)
   71 CONTINUE
   93 CONTINUE
```

```
C
C           CYCLE ON REMAINING 2M ELEMENTS
      DO 70 I=1,M
      IL2=K+2*I
      IL1=IL2-1
      CALL LOCQ(LA(IL1),IN,LQ1)
      CALL LOCQ(LA(IL2),IN,LQ2)
      R=Q(LQ1)+Q(LQ2)
      E(IN)=E(IN)+R*TT(I)
      F(IN)=F(IN)+R*DIST(I)
      AMN=R*TTERR(I)
      EERR(IN)=EERR(IN)+ABS(AMN)
      EERG(IN)=EERG(IN)+ABS(AMN)*ABS(AMN)
      AMN=R*DISTER(I)
      FERG(IN)=FERG(IN)+ABS(AMN)*ABS(AMN)
   70 FERR(IN)=FERR(IN)+ABS(AMN)
      EERG(IN)=SQRT(EERG(IN))
   72 FERG(IN)=SQRT(FERG(IN))
C
C
C           CALCULATION OF MATRIGES C AND D,LEAST SQUARE VELOCITY
C
      TOTCD=0.0
      TOTDD=0.0
      TCDERR=0.0
      TDDERR=0.0
      TCDERG=0.0
      TDDERG=0.0
      DO 15 I=1,M
      C(I)=TT(I)-E(NUM1(I))-E(NUM2(I))
      D(I)=DIST(I)-F(NUM1(I))-F(NUM2(I))
      TOTCD=TOTCD+C(I)*D(I)
      TOTDD=TOTDD+D(I)*D(I)
      CERR(I)=TTERR(I)+EERR(NUM1(I))+EERR(NUM2(I))
      AMN=TTERR(I)**2+EERG(NUM1(I))**2+EERG(NUM2(I))**2
      CERG(I)=SQRT(AMN)
      DERR(I)=DISTER(I)+FERR(NUM1(I))+FERR(NUM2(I))
      AMN=DISTER(I)**2+EERG(NUM1(I))**2+EERG(NUM2(I))**2
      DERG(I)=SQRT(AMN)
      TCDERR=TCDERR+C(I)*DERR(I)+D(I)*CERR(I)
      TCDERG=TCDERG+(C(I)*DERG(I))**2+(D(I)*CERG(I))**2
      TDDERR=TDDERR+2.0*(D(I)*DERR(I))
   15 TDDERG=TDDERG+2.0*(D(I)*DERG(I))**2
      TCDERG=SQRT(TCDERG)
      TDDERG=SQRT(TDDERG)
      IF (TOTCD) 16,16,17
   16 WRITE(6,18)
   18 FORMAT(' ','UNABLE TO CALCULATE LEAST SQUARES VELOCITY ')
      VEL(5)=0.0
      GO TO 19
   17 VEL(5)=TOTDD/TOTCD
      VELERR(5)=TDDERR/TOTCD+(TOTDD*TDDERR)/(TOTCD*TOTCD)
      AMN=(TDDERG/TOTCD)**2+((TOTDD*TDDERG)/(TOTCD*TOTCD))**2
      VELERG(5)=SQRT(AMN)
      WRITE(6,20) VEL(5),VELERR(5),VELERG(5)
   20 FORMAT('0','LEAST SQUARE VELOCITY IS ',F5.2,' +/- ',F5.2,' +/- ',
     1F5.2)
      WRITE(6,110) TOTDD,TDDERR,TDDERG
  110 FORMAT('0','SUM OF D SQUARED IS ',F8.2,' +/- ',F6.2,' +/- ',F6.2)
   19 CONTINUE
C
C
C           CALCULATE RESIDUALS, STANDARD ERRORS, STATISTICS, OUTPUT
C
      DO 21 J=1,5
      IF (VEL(J)) 22,21,22
   22 DO 23 I=1,N
      TTSE(I)=0.0
   23 NTTSE(I)=0
      TOTRS2=0.0
      DO 24 I=1,M
      RESID(I)=C(I)-D(I)/VEL(J)
      RESERR(I)=CERR(I)+DERR(I)/VEL(J)+(D(I)*VELERR(J))/(VEL(J)**2)
      AMN=CERG(I)**2+(DERG(I)/VEL(J))**2+((D(I)*VELERG(J))/(VEL(J)**2))*
     1*2
      RESERG(I)=SQRT(AMN)
      TOTRS2=TOTRS2+RESID(I)**2
      NTTSE(NUM1(I))=NTTSE(NUM1(I))+1
      NTTSE(NUM2(I))=NTTSE(NUM2(I))+1
      TTSE(NUM1(I))=TTSE(NUM1(I))+RESID(I)**2
   24 TTSE(NUM2(I))=TTSE(NUM2(I))+RESID(I)**2
      DO 25 I=1,N
      AMN=0.0
      IF (NTTSE(I).LE.1) GO TO 25
      AMN=TTSE(I)/(NTTSE(I)*(NTTSE(I)-1))
```

```
 25 TTSE(I)=SQRT(AMN)
    IF (J-5) 26,27,26
 27 MN=M-N+K-1
    GO TO 28
 26 MN=M-N+K
 28 AMN=TOTRS2/MN
    SIGSOL=SQRT(AMN)
    MN=N*(N+1)/2
    DO 29 I=1,MN
 29 Q(I)=AMN*Q(I)
    DO 30 I=1,N
    AMN=(EERG(I))**2+(FERG(I)/VEL(J))**2+((VELERG(J)*F(I))/(VEL(J)*VEL
   1(J)))**2
    TMTERG(I)=SQRT(AMN)
    TMTRM(I)=E(I)-F(I)/VEL(J)
 30 TMTERR(I)=EERR(I)+FERR(I)/VEL(J)+(VELERR(J)*F(I))/(VEL(J)*VEL(J))
    IF (J-5) 100,101,100
101 AMN=(VEL(5)**2*SIGSOL)/SQRT(TOTDD)
    WRITE(6,102) AMN
102 FORMAT('0','STANDARD ERROR OF VELOCITY IS ',F8.4)
100 CONTINUE
    WRITE(6,31) VEL(J),TOTRS2,SIGSOL
 31 FORMAT('1',' SOLUTION USING A VELOCITY OF ',F5.2,/,' SUM OF RESIDU
   1LES SQUARED IS ',F5.2,/,' STANDARD ERROR OF THE SOLUTION IS ',F5.2
   2,///,'STATION      E   ERROR  ERG       F   ERROR  ERG     TTERM ERRO
   3R  ERG  B,W ST.ERR   95 CONF  NUM DATA')
    DO 32 I=1,N
    MN=I*(I+1)/2
    IWORK=NTTSE(I)
    IF (IWORK.GT.20) IWORK=20
    AMN=Q(MN)/NTTSE(I)
    AMN=SQRT(AMN)*TTEST(IWORK)
    WRITE(6,33) I,E(I),EERR(I),EERG(I),F(I),FERR(I),FERG(I),TMTRM(I),
   1TMTERR(I),TMTERG(I),TTSE(I),AMN,NTTSE(I)
 33 FORMAT(' ',I5,3(3X,F6.2,2(1X,F5.2)),2(5X,F5.2),I5)
 32 CONTINUE
C
C          OUTPUT CONSTRAINT CARDS
    IF (K) 94,94,95
 95 CONTINUE
    WRITE(6,34)
 34 FORMAT('0',' CONSTRAINT CARDS ',/,' STATION  NUM   TIME TERM ERROR
   1')
    DO 35 I=1,K
    WRITE(6,36) ALPHA(I),NUM(I),TTRM(I),TRERR(I)
 36 FORMAT(' ',A8,2X,I5,5X,F5.2,1X,F5.2)
 35 CONTINUE
 94 CONTINUE
C          OUTPUT  ORIGINAL DATA CARDS AND RESIDUALS
    WRITE(6,80)
 80 FORMAT('0',' DATA CARDS ',/,'STATION  NUM  TO STATION  NUM    TMTR
   1M ERROR   DIST  ERROR      C   ERROR  ERG       D.  ERROR  ERG     RE
   2SID ERROR  ERG')
    DO 81 I=1,M
    WRITE(6,82) ALPHA1(I),NUM1(I),ALPHA2(I),NUM2(I),TT(I),TTERR(I),
   1DIST(I),DISTER(I),C(I),CERR(I),CERG(I),D(I),DERR(I),DERG(I),RESID(
   2I),RESERR(I),RESERG(I)
 82 FORMAT(' ',A8,I5,' TO ',A8,I5,2(2X,F6.2,1X,F5.2),
   13(2X,F6.2,2(1X,F5.2)))
 81 CONTINUE
C          OUTPUT  VARIANCE-COVARIANCE MATRIX
    WRITE(6,104)
104 FORMAT('0','VARIANCE - COVARIANCE MATRIX  TIMES 100')
    DO  88  I=1,N
    NTTSE(I)=0
 88 TTSE(I)=0.0
    DO 83 IJ=1,5
    MN1=(IJ-1)*20
    MN2=IJ*20
    IF (N.LE.MN1) GO TO 83
    IF (N.LE.MN2) MN2=N
    MN1=MN1+1
    DO 84 JK=MN1,MN2
 84 NTTSE(JK)=JK
    WRITE(6,85) (NTTSE(JK),JK=MN1,MN2)
 85 FORMAT(' ',5X,20I5)
    DO 103 I=1,N
    DO 86 JK=MN1,MN2
    CALL LOCQ(JK,I,LQ)
 86 TTSE(JK)=Q(LQ)*1.0E2
    WRITE(6,87) I,(TTSE(JK),JK=MN1,MN2)
 87 FORMAT(' ',I5,20(1X,F5.3))
103 CONTINUE
 83 CONTINUE
 21 CONTINUE
    STOP
    END
C          SUBROUTINE LOCQ FOR DECIDING LOCATIONS IN MATRIX Q
    SUBROUTINE LOCQ(J,I,LQ)
    IF (J-I) 60,60,61
 60 LQ=(I*(I-1))/2+J
    GO TO 62
 61 LQ=(J*(J-1))/2+I
 62 RETURN
    END
```

```
C
C         SWINBURNS TIME TERM PROGRAMME  2
C      HOUSEHOLDER ITERATIVE SOLUTION
C
C     USES IBM SSP SUBROUTINE LLSQ TO SOLVE MATIX EQUATIONS DIRECTLY
C.     ACCURACY GOOD  BUT COEFFICIENT MATRIX BECOMES VERY LARGE FOR LARGE NETWORKS
C      RECOMMENDED FOR SMALL NETWORKS
C       WEIGHTS INDIVIDUAL DATA CARDS   DEFAULT=1.0
C
C      INPUT IS:-          CARD1
C         N,M,K,(V(I),I=1,4)
C       FORMAT(3(5X,I5)),4(F5.2,5X))
C       N=NUMBER OF TIME TERMS    MUST BE CONSECUTIVE
C      M=NUMBER OF TRAVEL TIMES
C       K=NUMBER OF CONSTAINED TIME TERMS
C      V(I)= UPTO 4 CONSTRAINED VELOCITIES.  IF LEFT BLANK WILL ONLY CALCULATE
C       LEAST SQUARES VELOCITY
C
C      NEXT K CARDS (CONSTAINT CARDS)  :-
C        DA1(I),NUM1(I),DSTIME(I),WT(I)
C       FORMAT(A8,2X,I5,25X,F5.2,30X,F5.2)
C        DA1(I)=  NAME OF STATION
C      NUM1(I)=  NUMBER OF STATION
C      DSTIME(I)= TIME TERM
C       WT(I)= WEIGHT TO TIME TERM
C
C      NEXT M CARDS (DATA CARDS) :-
C         DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
C        DSTIME(I),DIST,WT(I)
C      FORMAT(2(A8,2X,I5,2F5.2),F5.2,5X,F6.2,9X,F5.2)
C     DA1(I)= NAME OF SHOT STATION
C     NUM1(I)= NUMBER OF SHOT STATION
C      EAST1,ANRTH1= O.S. COORDINATES OF SHOT STATION
C     DA2(I)= NAME OF RCORDING STATION
C      NUM2(I)= NUMBER OF RECORDING STATION
C      EAST2,ANRTH2= O.S. COORDINATES OF RECORDING STATION
C     DSTIME(I)= TRAVEL TIME
C     DIST= TRAVEL DISTANCE.  IF O.S. COORDINATES ARE GIVEN THE CALCULATED DISTANCE
C      IS USED
C     WT(I)=  WEIGHT GIVEN TO THE DATA.   DEFAULT=1.0
C
C
C     OUTPUT CONSISTS OF TIME TERM DATA AND ORIGINAL DATA FOR EACH CONSTRAINED
C     VELOCITY AND THE LEAST SQUARES VELOCITY
C     MATRIX E= PART OF THE TIME TERM NOT DEPENDENT ON VELOCITY
C      MATRIX F= PART OF TIME TERM (DISTANCE) VELOCITY DEPENDENT
C     ST.ERROR= STANDARD ERROR OF THE TIME TERM USING  THE BERRY AND WEST
C     FORMULAE
C      NUM DATA=NUMBER OF DATA TO  A STATION
C      MATIX C= PART OF TRAVEL TIME NOT DEPENDENT OF VELOCITY
C      MATRIX D= PART OF TRAVEL DISTANCE VELOCITY DEPENDENT. IE REVERSED
C
C
       DOUBLE PRECISION DA1(450),DA2(450)
       DIMENSION NUM1(410),NUM2(410),A(41000),DSTIME(820),EF(200),IPIV(10
      10),TMTRM(100),RESID(410),C(410),D(820),V(5),DATA(100),TTMES2(100),
      2AUX(400),WT(410)
C
C
C READ IN NUMBER OF TIME TERMS N, EQUATIONS M, AND VELOCITY V
C
       READ(5,1) N,M,K,(V(I),I=1,4)
     1 FORMAT(3(5X,I5),4(F5.2,5X))
C
C
C READ IN DATA CARDS AND FORM MATRICES
C
C SET MATRIX A TO 0
C
       MN=N*(M+K)
       DO 4 I=1,MN
     4 A(I)=0.0
       IF (K) 62,62,63
    63 DO 62 I=1,K
       NUM2(I)=0
       DSTIME(M+K+I)=0.0
C
C        READ IN  CONSTRAINT CARDS
```

```
C
      READ(5,61) DA1(I),NUM1(I),DSTIME(I),WT(I)
   61 FORMAT(A8,2X,I5,25X,F5.2,30X,F5.2)
      IF (WT(I)) 20,20,21
   20 WT(I)=1.0
   21 CONTINUE
      IJ=(NUM1(I)-1)*(M+K)+I
      A(IJ)=WT(I)
      DSTIME(I)=DSTIME(I)*WT(I)
   60 CONTINUE
   52 KI=K+1
      KM=K+M
      DO 2 I=KI,KM
C
C READ DATA
C
      READ(5,3) DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
     1DSTIME(I),DIST,WT(I)
    3 FORMAT(2(A8,2X,I5,2F5.2),F5.2,5X,F6.2,9X,F5.2)
      IF (WT(I)) 22,22,23
   22 WT(I)=1.0
   23 CONTINUE
      DSTIME(I)=DSTIME(I)*WT(I)
C
C FORM MATRIX A
C
      IJ=(NUM1(I)-1)*(M+K)+I
      A(IJ)=WT(I)
      IJ=(NUM2(I)-1)*(M+K)+I
      A(IJ)=WT(I)
      DSTM=((EAST1-EAST2)**2)+((ANRTH1-ANRTH2)**2)
      IF (DSTM.EQ.0.0) GO TO 5
      GO TO 6
    5 DSTIME(M+K+I)=DIST*WT(I)
      GO TO 2
    6 DSTIME(M+K+I)=SQRT(DSTM)*WT(I)
    2 CONTINUE
      MK=M+K
C
      MN=2*(M+K)
      DO 94 I=1,MN
   94 D(I)=DSTIME(I)
C
C CALL SUBROUTINE LLSQ
C
      CALL LLSQ(A,DSTIME,MK,N,2,EF,IPIV,1,0E-5,IER,AUX)
      DO 95 I=1,MN
      DSTIME(I)=D(I)
   95 D(I)=0.0
C
C PRINT OUT ERROR CONDITIONS
C
      IF (IER.EQ.-2) GO TO 10
      GO TO 11
   10 WRITE (6,12)
   12 FORMAT(' ','NUMBER OF EQUATIONS LESS THAN NUMBER OF TIME TERMS')
   11 IF (IER.EQ.-1) GO TO 13
      GO TO 14
   13 WRITE(6,15)
   15 FORMAT(' ','RANK OF MATRIX A IS ZERO')
```

```
14 IF(IER.GT.4) GO TO 16
   GO TO 17
16 WRITE(6,18) IER
18 FORMAT (' ','RANK OF MATRIX A IS LESS THAN N,= ',I5,/,'THE USELESS
  1 COLUMNS ARE' )
   NK=N-K
   WRITE(6,19) (IPIV(J),J=1,NK)
19 FORMAT (' ',5X,I5)
17 CONTINUE
   TOTCD=0.0
   TOTDD=0.0
   K1=K+1
   DO 64 I=K1,MK
   C(I)=DSTIME(I)-EF(NUM1(I))-EF(NUM2(I))
   D(I)=DSTIME(M+K+I)-EF(N+NUM1(I))-EF(N+NUM2(I))
   TOTCD=TOTCD+C(I)*D(I)
64 TOTDD=TOTDD+D(I)*D(I)
   IF (TOTCD) 65,65,66
65 WRITE(6,67)
67 FORMAT('0','UNABLE TO CALCULATE LEAST SQUARES VELOCITY')
   V(5)=0.0
   GO TO 68
66 V(5)=TOTDD/TOTCD
   WRITE(6,69) V(5),TOTDD
69 FORMAT('1','LEAST SQUARE VELOCITY IS ',F5.2,/,'SUM OF D SQUARED IS
  1 ',F10.2)
68 CONTINUE
   DO 70 J=1,5
   IF (V(J)) 71,71,72
72 DO 74 I=1,N
   DATA(I)=0.0
74 TTRES2(I)=0.0
   TOTRS2=0.0
   DO 73 I=K1,MK
   RESID(I)=C(I)-D(I)/V(J)
   TOTRS2=TOTRS2+(RESID(I)**2)*WT(I)
   DATA(NUM1(I))=DATA(NUM1(I))+WT(I)
   DATA(NUM2(I))=DATA(NUM2(I))+WT(I)
   TTRES2(NUM1(I))=TTRES2(NUM1(I))+(RESID(I)**2)*WT(I)
73 TTRES2(NUM2(I))=TTRES2(NUM2(I))+(RESID(I)**2)*WT(I)
   DO 75 I=1,N
   AMN=0.0
   IF (DATA(I).LE.1.0) GO TO 75
   AMN=TTRES2(I)/(DATA(I)*(DATA(I)-1.0))
75 TTRES2(I)=SQRT(AMN)
   SDATAM=0.0
   DO 25 I=K1,KM
25 SDATAM=SDATAM+WT(I)
   IF (J-5) 76,77,76
77 AMN=SDATAM-FLOAT(N)+FLOAT(K)-1.0
   GO TO 78
76 AMN=SDATAM-FLOAT(N)+FLOAT(K)
78 AMN=TOTRS2/AMN
   SIGSOL=SQRT(AMN)
   DO 79 I=1,N
79 TMTRM(I)=EF(I)-EF(N+I)/V(J)
   IF (J-5) 80,81,80
81 AMN=(V(5)**2*SIGSOL)/SQRT(TOTDD)
   WRITE(6,82) AMN
82 FORMAT('0','STANDARD ERROR OF VELOCITY IS ',F8.4)
80 CONTINUE
   WRITE(6,83) V(J),TOTRS2,SIGSOL
83 FORMAT('1',' SOLUTION USING A VELOCITY OF ',F5.2,/,' SUM OF RESIDU
  1ALS SQUARED IS ',F8.2,/,'STANDARD ERROR OF THE SOLUTION IS ',F5.2,
  2///,' STATION  MATRIX E  MATRIX F  TIMETERM  ST.ERROR  NUM DATA')
   DO 84 I=1,N
   WRITE(6,85) I,EF(I),EF(N+I),TMTRM(I),TTRES2(I),DATA(I)
85 FORMAT(' ',2X,I5,5F10.2)
84 CONTINUE
C        OUTPUT CONSTRAINT CARDS
   IF (K) 87,87,86
86 WRITE(6,88)
88 FORMAT('2','CONSTRAINT CARDS',/,' STATION   NUMBER   TIMETERM
  1WEIGHT')
   DO 89 I=1,K
   DSTIME(I)=DSTIME(I)/WT(I)
   WRITE(6,90) DA1(I),NUM1(I),DSTIME(I),WT(I)
90 FORMAT(' ',A8,1X,I5,4X,F6.2,4X,F6.2)
89 CONTINUE
87 CONTINUE
C        OUTPUT ORIGINAL CARDS
   K1=K+1
   WRITE(6,91)
91 FORMAT('2',' DATA CARDS ',/,' STATION    NUM  STATION   NUM  TRAVE
  1L TIME  DISTANCE  MATRIX C  MATRIX D  RESIDUAL  WEIGHT')
   DO 92 I=K1,MK
   DSTIME(I)=DSTIME(I)/WT(I)
   DSTIME(M+K+I)=DSTIME(M+K+I)/WT(I)
   WRITE(6,93) DA1(I),NUM1(I),DA2(I),NUM2(I),DSTIME(I),DSTIME(M+K+I),
  1C(I),D(I),RESID(I),WT(I)
93 FORMAT(' ',A8,I4,3X,A8,I4,2X,6F10.2)
92 CONTINUE
71 CONTINUE
70 CONTINUE
   STOP
   END
```

```
C
C          SWINBURNS TIME TERM PROGRAMME  3
C  TWO VELOCITY SOLUTION
C
C  USED WHEN THE REFRACTOR HAS TWO VELOCITIES AND THE TRAVEL DISTANCES IN
C  EACH REFRACTOR ARE KNOWN  EG NORTHERN ENGLAND,  UPPER CRUSTAL (PG)
C  REFRACTOR CONSISTS OF GRANITES (DISTRIBUTION KNOWN FROM GRAVITY) AND PRE-
C  DEVONIAN METAMORPHIC BASEMENT  SEE BOTT 1967
C  USES IBM SSP SUBROUTINE LLSQ TO SOLVE MATIX EQUATIONS DIRECTLY
C   ACCURACY GOOD  BUT COEFFICIENT MATRIX BECOMES VERY LARGE FOR LARGE NETWORKS
C   RECOMMENDED FOR SMALL NETWORKS
C
C  INPUT:-  CARD 1      N,M,K
C      FORMAT(3(5X,I5))
C    N=NUMBER OF TIME TERMS     MUST BE CONSECUTIVE
C   M=NUMBER OF TRAVEL TIMES
C    K=NUMBER OF CONSTAINED TIME TERMS
C
C    NEXT K CARDS (CONSTAINT CARDS)  :-
C     DA1(I),NUM1(I),DSTIME(I)
C    FORMAT(A5,2X,I5,25X,F6.2)
C     DA1(I)=  NAME OF STATION
C   NUM1(I)=  NUMBER OF STATION
C   DSTIME(I)= TIME TERM
C
C   NEXT M CARDS (DATA CARDS) :-
C      DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
C   DSTIME(I),DIST,DUM(I)
C  FORMAT(2(A5,2X,I5,2F5.2),F5.2,5X,F6.2,4X,F6.2)
C  DA1(I)= NAME OF SHOT STATION
C  NUM1(I)= NUMBER OF SHOT STATION
C   EAST1,ANRTH1= O.S. COORDINATES OF SHOT STATION
C  DA2(I)= NAME OF RCORDING STATION
C   NUM2(I)= NUMBER OF RECORDING STATION
C   EAST2,ANRTH2= O.S. COORDINATES OF RECORDING STATION
C  DSTIME(I)= TRAVEL TIME
C   DIST= TOTAL TRAVEL DISTANCE IN BOTH REFRACTORS  IF O.S. COORDINATES AR
C  GIVEN THE CALCULATED DISTANCE IS USED
C  DUM(I)= TRAVEL DISTANCE IN REFRACTOR 2
C
C
C OUTPUT CONSISTS OF TIME TERM DATA AND ORIGINAL DATA FOR THE TWO LEAST SQUARES
C  VELOCITIES,    MATICES F1,F2,D1,D2 REFER TO EACH REFRACTOR
C  MATRIX E= PART OF THE TIME TERM NOT DEPENDENT ON VELOCITY
C   MATRIX F= PART OF TIME TERM (DISTANCE) VELOCITY DEPENDENT
C  ST.ERROR= STANDARD ERROR OF THE TIME TERM USING  THE BERRY AND WEST
C  FORMULAE
C   NUM DATA=NUMBER OF DATA TO  A STATION
C   MATIX C= PART OF TRAVEL TIME NOT DEPENDENT OF VELOCITY
C   MATRIX D= PART OF TRAVEL DISTANCE VELOCITY DEPENDENT, IE REVERSED
C
C
      DOUBLE PRECISION DA1(450),DA2(450)
      DIMENSION NUM1(410),NUM2(410),A(41000)            ,EF(400),IPIV(10
     10),TMTRM(100),RESID(410),C(410),D1(410),D2(410),NDATA(100),TTRES2(
     2100),AUX(820),           SUM(4),VEL(2),TOT(2),DUM(1230),DSTIME(1230)
C
C
C READ IN NUMBER OF TIME TERMS N, EQUATIONS M, AND VELOCITY V
C
      READ(5,1) N,M,K
    1 FORMAT(3(5X,I5))
C
C
C READ IN DATA CARDS AND FORM MATRICES
C
C SET MATRIX A TO 0
C
      MN=N*(M+K)
      MK2=2*(M+K)
      DO 4 I=1,MN
    4 A(I)=0.0
      IF (K) 62,62,63
   63 DO 60 I=1,K
```

```
      NUM2(I)=0
      DSTIME(M+K+I)=0.0
      DSTIME(MK2+I)=0.0
C
C      READ IN  CONSTRAINT CARDS
C
      READ(5,61) DA1(I),NUM1(I),DSTIME(I)
   61 FORMAT(A8,2X,I5,25X,F5.2)
      IJ=(NUM1(I)-1)*(M+K)+I
   60 A(IJ)=1.0
   62 IJ=K+1
       K1=K+1
      KM=K+M
      DO 2 I=K1,KM
C
C READ DATA .
C
      READ(5,3) DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
     1DSTIME(I),DIST,DUM(I))
    3 FORMAT(2(A8,2X,I5,2F5.2),F5.2,5X,F6.2,4X,F6.2)
C
C FORM MATRIX A
C
      IJ=(NUM1(I)-1)*(M+K)+I
      A(IJ)=1.0
      IJ=(NUM2(I)-1)*(M+K)+I
      A(IJ)=1.0
C
C CALCULATE DISTANCE FROM OS GRID COORDINATES
C
      DSTM=((EAST1-EAST2)**2)+((ANRTH1-ANRTH2)**2)
      IF (DSTM.EQ.0.0) GO TO 5
      GO TO 6
    5 DSTIME(M+K+I)=DIST
      GO TO 2
    6 DSTIME(M+K+I)=SQRT(DSTM)
    2 CONTINUE
      MK=M+K
      MN=3*(M+K)
       DO 100 I=K1,KM
      DSTIME(MK2+I)=DUM(I)
      DSTIME(M+K+I)=DSTIME(M+K+I)-DUM(I)
  100 CONTINUE
      DO 94 I=1,MN
   94 DUM(I)=DSTIME(I)
C
C
C CALL SUBROUTINE LLSQ
C
      CALL LLSQ(A,DSTIME,MK,N,3,EF,NDATA,1.0E-6,IER,AUX)
      DO 95 I=1,MN
   95 DSTIME(I)=DUM(I)
C
C PRINT OUT ERROR CONDITIONS
C
      IF (IER.EQ.-2) GO TO 10
      GO TO 11
   10 WRITE (6,12)
   12 FORMAT(' ','NUMBER OF EQUATIONS LESS THAN NUMBER OF TIME TERMS')
   11 IF (IER.EQ.-1) GO TO 13
      GO TO 14
   13 WRITE(6,15)
   15 FORMAT(' ','RANK OF MATRIX A IS ZERO')
   14 IF(IER.GT.0) GO TO 16
      GO TO 17
   16 WRITE(6,18) IER
   18 FORMAT (' ','RANK OF MATRIX A IS LESS THAN N.= ',I5,/,'THE USELESS
     1 COLUMNS ARE' )
      NK=N-K
      WRITE(6,19) (NDATA(J),J=1,NK)
   19 FORMAT (' ',5X,I5)
   17 CONTINUE
      TOT(1)=0.0
      TOT(2)=0.0
      SUM(1)=0.0
      SUM(2)=0.0
      SUM(4)=0.0
```

```
      DO 64 I=K1,MK
      C(I)=DSTIME(I)-EF(NUM1(I))-EF(NUM2(I))
      D1(I)=DSTIME(M+K+I)-EF(N+NUM1(I))-EF(N+NUM2(I))
      D2(I)=DSTIME(MK2+I)-EF(2*N+NUM1(I))-EF(2*N+NUM2(I))
      TOT(1)=TOT(1)+C(I)*D1(I)
      TOT(2)=TOT(2)+C(I)*D2(I)
      SUM(1)=SUM(1)+D1(I)*D1(I)
      SUM(2)=SUM(2)+D1(I)*D2(I)
   64 SUM(4)=SUM(4)+D2(I)*D2(I)
      SUM(3)=SUM(2)
      CALL LLSQ(SUM,TOT,2,2,1,VEL,NDATA,1.0E-4,IER,AUX)
      IF (IER.EQ.-1) GO TO 102
      GO TO 103
  102 WRITE(6,104)
  104 FORMAT('1','UNABLE TO CALCULATE VELOCITIES')
      STOP
  103 CONTINUE
      IF (VEL(1)) 111,112,111
  111 IF (VEL(2)) 113,112,113
  112 WRITE(5,114)
  114 FORMAT(' ',' UNABLE TO CALCULATE TWO VELOCITIES')
      STOP
  113 CONTINUE
      VEL(1)=1./VEL(1)
      VEL(2)=1./VEL(2)
      WRITE(6,105) VEL(1),VEL(2)
  105 FORMAT('1','VELOCITY OF THE BASEMENT IS ',F5.2,/,'VELOCITY OF THE
     1GRANITE IS ',F5.2)
   72 DO 74 I=1,N
      NDATA(I)=0
   74 TTRES2(I)=0.0
      TOTRS2=0.0
      DO 73 I=K1,MK
      RESID(I)=C(I)-D1(I)/VEL(1)-D2(I)/VEL(2)
      TOTRS2=TOTRS2+RESID(I)**2
      NDATA(NUM1(I))=NDATA(NUM1(I))+1
      NDATA(NUM2(I))=NDATA(NUM2(I))+1
      TTRES2(NUM1(I))=TTRES2(NUM1(I))+RESID(I)**2
   73 TTRES2(NUM2(I))=TTRES2(NUM2(I))+RESID(I)**2
      DO 75 I=1,N
      AMN=0.0
      IF (NDATA(I).LE.1) GO TO 75
      AMN=TTRES2(I)/(NDATA(I)*(NDATA(I)-1))
   75 TTRES2(I)=SQRT(AMN)
      MN=M-N+K-2
      AMN=TOTRS2/MN
      SIGSOL=SQRT(AMN)
      SEBASE=V(1)**2*SIGSOL/SQRT(SUM(1))
      SEGR=V(2)**2*SIGSOL/SQRT(SUM(4))
      WRITE(5,200) SEBASE,SEGR
  200 FORMAT('0',' STANDARD ERROR OF BSAEMENT VELOCITY ',F5.4,' KM/S ',
     1'STANDARD ERROR OF GRANITE VELOCITY ',F8.4,' KM/S ')
      DO 79 I=1,N
   79 TMTRM(I)=EF(I)-EF(N+I)/VEL(1)-EF(2*N+I)/VEL(2)
      WRITE(6,83) TOTRS2,SIGSOL
   83 FORMAT('1','SUM OF RESIDUALS SQUARED IS ',F8.2,/,'STANDARD ERROR
     1OF THE SOLUTION IS ',F6.2,///,' STATION  MATRIX E  MATRIX F1 MATRI
     2X F2 TIMETERM  ST.ERROR  NUM.DATA')
      DO 84 I=1,N
      WRITE(6,85) I,EF(I),EF(N+I),EF(2*N+I),TMTRM(I),TTRES2(I),NDATA(I)
   85 FORMAT(' ',I5,5F10.2,I10)
   84 CONTINUE
C           OUTPUT CONSTRAINT CARDS
      IF (K) 87,87,86
   86 WRITE(6,88)
   88 FORMAT('1','CONSTRAINT CARDS ',/,' STATION   NUMBER    TIMETERM ')
      DO 89 I=1,K
      WRITE(6,90) DA1(I),NUM1(I),DSTIME(I)
   90 FORMAT(' ',A8,1X,I5,4X,F6.2)
   89 CONTINUE
   87 CONTINUE
C           OUTPUT ORIGINAL CARDS
      K1=K+1
      WRITE(6,91)
   91 FORMAT('1','DATA CARDS',/,' STATION  NUM   STATION  NUM  TRAVEL TI
     1ME DISTANCE1 DISTANCE2 MATRIX C  MATRIX D1 MATRIX D2 RESIDUAL')
      DO 92 I=K1,MK
      WRITE(6,93) DA1(I),NUM1(I),DA2(I),NUM2(I),DSTIME(I),DSTIME(M+K+I),
     1DSTIME(MK2+I),C(I),D1(I),D2(I),RESID(I)
   93 FORMAT(2(A8,I3,4X),7F10.2)
   92 CONTINUE
      STOP
      END
```

```
C
C          SWINBURNS TIME TERM PROGRAMME  4
C   VELOCITY INCREASING WITH DISTANCE
C
C   USED WHEN VELOCITY INCREASES LINEARLY AWAY FROM SOURCE  V=V0+K*X
C   USES IBM SSP SUBROUTINE LLSQ TO SOLVE MATIX EQUATIONS DIRECTLY
C    ACCURACY GOOD  BUT COEFFICIENT MATRIX BECOMES VERY LARGE FOR LARGE NETWORKS
C    RECOMMENDED FOR SMALL NETWORKS
C
C    INPUT IS:-          CARD1
C      N,M,K
C      FORMAT(3(5X,I5))
C     N=NUMBER OF TIME TERMS    MUST BE CONSECUTIVE
C    M=NUMBER OF TRAVEL TIMES
C     K=NUMBER OF CONSTAINED TIME TERMS
C
C     NEXT K CARDS (CONSTAINT CARDS)  :-
C      DA1(I),NUM1(I),DSTIME(I)
C     FORMAT(A8,2X,I5,25X,F5.2)
C      DA1(I)=  NAME OF STATION
C    NUM1(I)=  NUMBER OF STATION
C    DSTIME(I)= TIME TERM
C
C    NEXT M CARDS (DATA CARDS) :-
C       DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
C      DSTIME(I),DIST
C    FORMAT(2(A8,2X,I5,2F5.2),F5.2,5X,F6.2)
C   DA1(I)= NAME OF SHOT STATION
C   NUM1(I)= NUMBER OF SHOT STATION
C    EAST1,ANRTH1= O.S. COORDINATES OF SHOT STATION
C   DA2(I)= NAME OF RCORDING STATION
C    NUM2(I)= NUMBER OF RECORDING STATION
C    EAST2,ANRTH2= O.S. COORDINATES OF RECORDING STATION
C   DSTIME(I)= TRAVEL TIME
C   DIST= TRAVEL DISTANCE.  IF O.S. COORDINATES ARE GIVEN THE CALCULATED DISTANCE
C    IS USED
C
C
C   OUTPUT CONSISTS OF TIME TERM DATA AND ORIGINAL DATA CALCULATED FOR THE
C    UNKNOWNS  K AND V0
C   MATRIX E= PART OF THE TIME TERM NOT DEPENDENT ON VELOCITY
C    MATRIX F= PART OF TIME TERM (DISTANCE) VELOCITY DEPENDENT
C   ST.ERROR= STANDARD ERROR OF THE TIME TERM USING  THE BERRY AND WEST
C   FORMULAE
C    MATIX C= PART OF TRAVEL TIME NOT DEPENDENT OF VELOCITY
C    MATRIX D= PART OF TRAVEL DISTANCE VELOCITY DEPENDENT. IE REVERSED
C
C
      DOUBLE PRECISION DA1(450),DA2(450)
      DIMENSION NUM1(410),NUM2(410),A(41000),,          EF(400),IPIV(10
     10),TMTRM(100),RESID(410),C(410),D1(410),D2(410),NDATA(100),TTHES2(
     2100),AUX(800),            SUM(4),VEL(2),TOT(2),DUM(1230),DSTIME(1230)
C
C
C READ IN NUMBER OF TIME TERMS N, EQUATIONS M, AND VELOCITY V
C
      READ(5,1) N,M,K
    1 FORMAT(3(5X,I5))
C
C
C READ IN DATA CARDS AND FORM MATRICES
C
C SET MATRIX A TO 0
C
      MN=N*(M+K)
      MK2=2*(M+K)
      DO 4 I=1,MN
    4 A(I)=0.0
      IF (K) 62,62,63
   63 DO 60 I=1,K
      NUM2(I)=0
      DSTIME(M+K+I)=0.0
```

```
      DSTIME(MK2+I)=0.0
C
C       READ IN  CONSTRAINT CARDS
C
      READ(5,61) DA1(I),NUM1(I),DSTIME(I)
   61 FORMAT(A8,2X,I5,25X,F5.2)
      IJ=(NUM1(I)-1)*(M+K)+I
   60 A(IJ)=1.0
   52 IJ=K+1
       K1=K+1
      KM=K+M
      DO 2 I=K1,KM
C
C READ DATA
C
      READ(5,3) DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
     1DSTIME(I),DIST
    3 FORMAT(2(A8,2X,I5,2F5.2),F5.2,5X,F6.2)
C
C FORM MATRIX A
C
      IJ=(NUM1(I)-1)*(M+K)+I
      A(IJ)=1.0
      IJ=(NUM2(I)-1)*(M+K)+I
      A(IJ)=1.0
C
C CALCULATE DISTANCE FROM OS GRID COORDINATES
C
      DSTM=((EAST1-EAST2)**2)+((ANRTH1-ANRTH2)**2)
      IF (DSTM.EQ.0.0) GO TO 5
      GO TO 6
    5 DSTIME(M+K+I)=DIST
      GO TO 2
    6 DSTIME(M+K+I)=SQRT(DSTM)
    2 CONTINUE
      MK=M+K
      MN=3*(M+K)
       DO 100 I=K1,KM
      DSTIME(MK2+I)=DSTIME(M+K+I)*DSTIME(M+K+I)
  100 CONTINUE
      DO 94 I=1,MN
   94 DUM(I)=DSTIME(I)
C
C
C CALL SUBROUTINE LLSQ
C
      CALL LLSQ(A,DSTIME,MK,N,3,EF,NDATA,1.0E-6,IER,AUX)
      DO 95 I=1,MN
   95 DSTIME(I)=DUM(I)
C
C PRINT OUT ERROR CONDITIONS
C
      IF (IER.EQ.-2) GO TO 10
      GO TO 11
   10 WRITE (6,12)
   12 FORMAT(' ','NUMBER OF EQUATIONS LESS THAN NUMBER OF TIME TERMS')
   11 IF (IER.EQ.-1) GO TO 13
      GO TO 14
   13 WRITE(6,15)
   15 FORMAT(' ','RANK OF MATRIX A IS ZERO')
```

```
14 IF(IER.GT.0) GO TO 16
   GO TO 17
16 WRITE(6,18) IER
18 FORMAT (' ','RANK OF MATRIX A IS LESS THAN N,= ',I5,/,'THE USELESS
  1 COLUMNS ARE' )
   NK=N-K
   WRITE(6,19) (NDATA(J),J=1,NK)
19 FORMAT (' ',5X,I5)
17 CONTINUE
   TOT(1)=0.0
   TOT(2)=0.0
   SUM(1)=0.0
   SUM(2)=0.0
   SUM(4)=0.0
   DO 64 I=K1,KM
   C(I)=DSTIME(I)-EF(NUM1(I))-EF(NUM2(I))
   D1(I)=DSTIME(M+K+I)-EF(N+NUM1(I))-EF(N+NUM2(I))
   D2(I)=DSTIME(MK2+I)-EF(2*N+NUM1(I))-EF(2*N+NUM2(I))
   TOT(1)=TOT(1)+C(I)*D1(I)
   TOT(2)=TOT(2)+C(I)*D2(I)
   SUM(1)=SUM(1)+D1(I)*D1(I)
   SUM(2)=SUM(2)+D1(I)*D2(I)
64 SUM(4)=SUM(4)-D2(I)*D2(I)
   SUM(3)=-SUM(2)
   CALL LLSQ(SUM,TOT,2,2,1,VEL,NDATA,1.0E-6,IER,AUX)
   IF (IER.EQ.-1) GO TO 102
   GO TO 103
102 WRITE(6,104)
104 FORMAT('1','UNABLE TO CALCULATE VELOCITIES')
   STOP
103 CONTINUE
   IF (VEL(1)-1.0E-9) 112,112,111
111 IF (VEL(2)-1.0E-9) 112,112,113
112 WRITE(6,114)
114 FORMAT(' ','UNABLE TO CALCULATE K AND V0')
   STOP
113 CONTINUE
   VELOC=1./VEL(1)
   AK=VEL(2)/(VEL(1)*VEL(1))
   WRITE(6,105) VELOC,AK
105 FORMAT(' ',' LEAST SQUARES VELOCITY ',F5.2,/,' FACTOR K',F8.5)
72 DO 74 I=1,N
   NDATA(I)=0
74 TTRES2(I)=0.0
   TOTRS2=0.0
   DO 73 I=K1,MK
   RESID(I)=C(I)-D1(I)*VEL(1)+D2(I)*VEL(2)
   TOTRS2=TOTRS2+RESID(I)**2
   NDATA(NUM1(I))=NDATA(NUM1(I))+1
   NDATA(NUM2(I))=NDATA(NUM2(I))+1
   TTRES2(NUM1(I))=TTRES2(NUM1(I))+RESID(I)**2
73 TTRES2(NUM2(I))=TTRES2(NUM2(I))+RESID(I)**2
   DO 75 I=1,N
   AMN=0.0
   IF (NDATA(I).LE.1) GO TO 75
   AMN=TTRES2(I)/(NDATA(I)*(NDATA(I)-1))
75 TTRES2(I)=SQRT(AMN)
   MN=M-N+K-2
   AMN=TOTRS2/MN
   SIGSOL=SQRT(AMN)
   DO 79 I=1,N
79 TMTRM(I)=EF(I)-EF(N+I)*VEL(1)+EF(2*N+I)*VEL(2)
   WRITE(6,83) TOTRS2,SIGSOL
83 FORMAT('1','SUM OF RESIDUALS SQUARED IS ',F8.2,/,'STANDARD ERROR.
  1OF THE SOLUTION IS ',F8.2,///,' STATION. MATRIX E  MATRIX F1 MATRI
  2X F2 TIMETERM  ST.ERROR  NUM.DATA')
   DO 84 I=1,N
   WRITE(6,85) I,EF(I),EF(N+I),EF(2*N+I),TMTRM(I),TTRES2(I),NDATA(I)
85 FORMAT(' ',I5,5F10.2,I10)
84 CONTINUE
C        OUTPUT CONSTRAINT CARDS
   IF (K) 87,87,86
86 WRITE(6,88)
88 FORMAT('1','CONSTRAINT CARDS ',/,' STATION   NUMBER    TIMETERM ')
   DO 89 I=1,K
   WRITE(6,90) DA1(I),NUM1(I),DSTIME(I)
90 FORMAT(' ',A8,1X,I5,4X,F6.2)
89 CONTINUE
87 CONTINUE
C        OUTPUT ORIGINAL CARDS
   K1=K+1
   WRITE(6,91)
91 FORMAT('1','DATA CARDS',/,' STATION  NUM   STATION  NUM  TRAVEL TI
  1ME DISTANCE1 DISTANCE2 MATRIX C  MATRIX D1 MATRIX D2 RESIDUAL')
   DO 92 I=K1,MK
   WRITE(6,93) DA1(I),NUM1(I),DA2(I),NUM2(I),DSTIME(I),DSTIME(M+K+I),
  1DSTIME(MK2+I),C(I),D1(I),D2(I),RESID(I)
93 FORMAT(2(A8,I3,4X),7F10.2)
92 CONTINUE
   STOP
   END
```

```
C
C         SKINBURNS TIME TERM PROGRAMME  5
C   ITERATIVE SOLUTION FOR A DIPPING REFRACTOR
C
C  USES IBM SSP SUBROUTINE LLSQ TO SOLVE MATIX EQUATIONS DIRECTLY
C   ACCURACY GOOD  BUT COEFFICIENT MATRIX BECOMES VERY LARGE FOR LARGE NETWORKS
C   RECOMMENDED FOR SMALL NETWORKS
C
C   INPUT IS:-         CARD1
C   N,M,K,V(1)
C    FORMAT(3(5X,I5),F5.2)
C    N=NUMBER OF TIME TERMS    MUST BE CONSECUTIVE
C   M=NUMBER OF TRAVEL TIMES
C    K=NUMBER OF CONSTAINED TIME TERMS
C    V(1)=      ONLY ONE CONSTAINED VELOCITY OR THE LEAST SQUARE VELOCITY CAN
C   BE USED
C
C    NEXT K CARDS (CONSTAINT CARDS)  :-
C     DA1(I),NUM1(I),DSTIME(I)
C    FORMAT(A3,2X,I5,25X,F5.2)
C     DA1(I)=  NAME OF STATION
C  NUM1(I)=  NUMBER OF STATION
C   DSTIME(I)= TIME TERM
C
C   NEXT M CARDS (DATA CARDS) :-
C     DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
C    DSTIME(I),DIST
C   FORMAT(2(A6,2X,I5,2F5.2),F5.2,5X,F6.2)
C  DA1(I)= NAME OF SHOT STATION
C  NUM1(I)= NUMBER OF SHOT STATION
C   EAST1,ANRTH1= O.S. COORDINATES OF SHOT STATION
C  DA2(I)= NAME OF RCORDING STATION
C   NUM2(I)= NUMBER OF RECORDING STATION
C   EAST2,ANRTH2= O.S. COORDINATES OF RECORDING STATION
C  DSTIME(I)= TRAVEL TIME
C  DIST= TRAVEL DISTANCE.  IF O.S. COORDINATES ARE GIVEN THE CALCULATED DISTANCE
C   IS USED
C
C    OUTPUT CONSISTS OF TIME TERM DATA AND ORIGINAL DATA AND DEPTHS TO THE
C    REFRACTOR
C   N.B.    SET FOR A COVER VELOCITY OF 4.0KM/SEC
C  MATRIX E= PART OF THE TIME TERM NOT DEPENDENT ON VELOCITY
C   MATRIX F= PART OF TIME TERM (DISTANCE) VELOCITY DEPENDENT
C   NUM DATA=NUMBER OF DATA TO  A STATION
C   MATIX C= PART OF TRAVEL TIME NOT DEPENDENT OF VELOCITY
C
C
      DOUBLE PRECISION DA1(350),DA2(350)
      DIMENSION NUM1(310),NUM2(310),A(31000),DSTIME(620),EF(200),IPIV(10
     10),TMTRM(170),RESID(310),C(310),D(620),V(5),NDATA(100),TTRES2(100)
     2,AUX(400)
      DIMENSION X(310),Z(100),COS(310)
      DIMENSION DS1(620)
      DIMENSION LA(620)
C
C
C READ IN NUMBER OF TIME TERMS N, EQUATIONS M, AND VELOCITY V
C
      READ(5,1) N,M,K,V(1)
    1 FORMAT(3(5X,I5),F5.2)
      DO 124 I=2,4
  124 V(I)=0.0
C
C
C READ IN DATA CARDS AND FORM MATRICES
C
      IF (K) 62,62,63
   63 DO 63 I=1,K
      NUM2(I)=0
      DSTIME(M+K+I)=0.0
      LA(2*I)=0
C
C      READ IN  CONSTRAINT CARDS
C
      READ(5,61) DA1(I),NUM1(I),DSTIME(I)
   61 FORMAT(A3,2X,I5,25X,F5.2)
   64 LA(2*I-1)=NUM1(I)
   62 KI=K+1
      KM=K+M
      DO 2 I=KI,KM
C
C READ DATA
C
      READ(5,3) DA1(I),NUM1(I),EAST1,ANRTH1,DA2(I),NUM2(I),EAST2,ANRTH2,
     1DSTIME(I),DIST
    3 FORMAT(2(A6,2X,I5,2F5.2),F5.2,5X,F6.2)
C
C FORM MATRIX A
C
```

```
      LA(2*I-1)=NUM1(I)
      LA(2*I)=NUM2(I)
      DSTM=((EAST1-EAST2)**2)+((ANRTH1-ANRTH2)**2)
      IF (DSTM.EQ.0.0) GO TO 5
      GO TO 6
    5 DSTIME(M+K+I)=DIST
      GO TO 2
    6 DSTIME(M+K+I)=SQRT(DSTM)
    2 CONTINUE
      MK=M+K
      MN=2*(M+K)
      DO 112 I=1,MK
  112 X(I)=DSTIME(MK+I)
      DO 201 I=1,MN
  201 DST(I)=DSTIME(I)
      DO 70 J=1,5
      IF (J.EQ.5) GO TO 72
      IF (V(J)) 71,71,72
   72 CONTINUE
      DO 102 I=1,MK
      COS(I)=1.0
  102 CONTINUE
      DO 202 I=1,MN
  202 DSTIME(I)=DST(I)
      NIT=0
  108 CONTINUE
      NIT=NIT+1
      DO 94 I=1,MN
   94 D(I)=DSTIME(I)
      NMK=N*(M+K)
      DO 4 I=1,NMK
    4 A(I)=0.0
      DO 7 I=1,MK
      IK=2*I
      IK=(LA(IK)-1)*MK+I
      IF (IK) 9,9,8
    8 A(IK)=1.0
    9 IK=2*I-1
      IK=(LA(IK)-1) *MK+I
    7 A(IK)=1.0
C
C CALL SUBROUTINE LLSQ
C
      CALL LLSQ (A,DSTIME,MK,N,2,EF,NDATA,1.0E-5,IER,AUX)
      DO 95 I=1,MN
      DSTIME(I)=D(I)
   95 D(I)=0.0
C
C PRINT OUT ERROR CONDITIONS
C
      IF (IER.EQ.-2) GO TO 10
      GO TO 11
   10 WRITE (6,12)
   12 FORMAT(' ','NUMBER OF EQUATIONS LESS THAN NUMBER OF TIME TERMS')
   11 IF (IER.EQ.-1) GO TO 13
      GO TO 14
   13 WRITE(6,15)
   15 FORMAT(' ','RANK OF MATRIX A IS ZERO')
   14 IF(IER.GT.0) GO TO 16
      GO TO 17
   16 WRITE(6,18) IER
   18 FORMAT ('  ','RANK OF MATRIX A IS LESS THAN N,= ',I5,/,'THE USELESS
     1 COLUMNS ARE' )
      NK=N-K
      WRITE(6,19) (NDATA(J),J=1,NK)
   19 FORMAT (' ',5X,I5)
   17 CONTINUE
      TOTCD=0.0
      TOTDD=0.0
      K1=K+1
      DO 64 I=K1,MK
      C(I)=DSTIME(I)-EF(NUM1(I))-EF(NUM2(I))
      D(I)=DSTIME(M+K+I)-EF(N+NUM1(I))-EF(N+NUM2(I))
      TOTCD=TOTCD+C(I)*D(I)
   64 TOTDD=TOTDD+D(I)*D(I)
      IF (TOTCD) 65,65,66
   65 WRITE(6,67)
   67 FORMAT('0','UNABLE TO CALCULATE LEAST SQUARES VELOCITY')
      V(5)=0.0
      GO TO 68
   66 V(5)=TOTDD/TOTCD
   68 CONTINUE
      WRITE(6,200) V(5)
  200 FORMAT(' ',F8.3)
      DO 79 I=1,N
      TMTRM(I)=EF(I)-EF(N+I)/V(J)
      AMN=V(J)*V(J)-16.0
      IF (AMN) 101,101,102
  101 WRITE(6,103)
  103 FORMAT('1','VELOCITY LESS THAN 4.0KM/S')
      STOP
  102 Z(I)=TMTRM(I)*V(J)*4.0/SQRT(AMN)
   79 CONTINUE
      MIT=0
      DO 124 I=K1,MK
      AMN=COS(I)
      Z1=Z(NUM1(I))/COS(I)
      Z2=Z(NUM2(I))/COS(I)
      COS(I)=(X(I)*X(I)+(Z1-Z2)**2)
      COS(I)=X(I)/SQRT(COS(I))
      DSTIME(MK+I)=X(I)*COS(I)
```

```
      AMN=AMN-COS(I)
      AMN=ABS(AMN)-1.0E-3
      IF (AMN) 125,124,104
  105 MIT=MIT+1
  104 CONTINUE
      IF (NIT-150) 120,123,121
  121 WRITE(5,122)
  122 FORMAT(' ','MORE THAN 20 ITERATIONS REQUIRED')
      GO TO 123
  120 CONTINUE
      IF (MIT-M ) 106,107,106
  106 GO TO 108
  107 CONTINUE
  123 CONTINUE
      DO 74  I=1,N
      NDATA(I)=0
   74 TTRES2(I)=0.0
      TOTRS2=0.0
      DO 73 I=K1,MK
      RESID(I)=C(I)-D(I)/V(J)
      TOTRS2=TOTRS2+RESID(I)**2
      NDATA(NUM1(I))=NDATA(NUM1(I))+1
      NDATA(NUM2(I))=NDATA(NUM2(I))+1
      TTRES2(NUM1(I))=TTRES2(NUM1(I))+RESID(I)**2
   73 TTRES2(NUM2(I))=TTRES2(NUM2(I))+RESID(I)**2
      DO 75 I=1,N
      AMN=0.0
      IF (NDATA(I).LE.1) GO TO 75
      AMN=TTRES2(I)/(NDATA(I)*(NDATA(I)-1))
   75 TTRES2(I)=SQRT(AMN)
      IF (J-5) 76,77,76
   77 MN=M-N+K-1
      GO TO 78
   76 MN=M-N+K
   78 AMN=TOTRS2/MN
      SIGSOL=SQRT(AMN)
      DO 109 I=1,N
  109 AUX(I)=0.0
      DO 110 I=K1,MK
      AUX(NUM1(I))=AUX(NUM1(I))+COS(I)
  110 AUX(NUM2(I))=AUX(NUM2(I))+COS(I)
      DO 111 I=1,N
      AMN=AUX(I)/FLOAT(NDATA(I))
  111 Z(I)=Z(I)/AMN
      IF (J-5) 80,81,80
   81 AMN=(V(5)**2*SIGSOL)/SQRT(TOTDD)
      WRITE(6,82) AMN
   82 FORMAT('0','STANDARD ERROR OF VELOCITY IS ',F8.4)
   80 CONTINUE
      WRITE(6,93) V(J),TOTRS2,SIGSOL,NIT
   83 FORMAT('1','SOLUTION FOR A VELOCITY OF ',F8.2,/,'SUM OF RESIDUALS
     1',F8.2,/,'STANDARD ERROR OF SOLUTION ',F8.2,/,'NUMBER OF ITERATION
     2S ',I5,///,' STATION  MATRIX E  MATRIX F  TIMETERM  DEPTH     ST.E
     3RROR  NUM.DATA')
      DO 84 I=1,N
      WRITE(6,85) I,EF(I),EF(N+I),TMTRM(I),Z(I),TTRES2(I),NDATA(I)
   85 FORMAT(' ',2X,I5,5F10.2,I10)
   84 CONTINUE
C          OUTPUT CONSTRAINT CARDS
      IF (K) 87,87,86
   86 WRITE(6,88)
   88 FORMAT('1','CONSTRAINT CARDS ',/,' STATION   NUMBER    TIMETERM ')
      DO 89 I=1,K
      WRITE(6,90) DA1(I),NUM1(I),DSTIME(I)
   90 FORMAT(' ',A8,1X,I5,4X,F6.2)
   89 CONTINUE
   87 CONTINUE
C          OUTPUT ORIGINAL CARDS
      K1=K+1
      WRITE(6,91)
   91 FORMAT('1',' DATA CARDS ',/,' STATION    NUM  STATION   NUM  TRAVE
     1L TIME  DISTANCE  MATRIX C  MATRIX D  RESIDUAL')
      DO 92 I=K1,MK
      WRITE(6,93) DA1(I),NUM1(I),DA2(I),NUM2(I),DSTIME(I),DSTIME(M+K+I),
     1C(I),D(I),RESID(I)
   93 FORMAT(' ',2(A8,I5),3X,5F12.2)
   92 CONTINUE
   71 CONTINUE
      IF (V(1)) 70,70,125
   70 CONTINUE
  125 STOP
      END
```

```
C     PROGRAMME FOR CALCULATING TRAVEL DISTANCES FROM GEOGRAPHICAL COORDINATES
C
C   INPUT IS:-    CARD 1-        N
C        FORMAT(I2)
C     N= NUMBER OF SHOTS (OR RECORDING STATIONS) UPTO A MAXIMUM OF 15
C    THEN N CARDS:-    LATD,SLATM,LONGD,SLONGM
C          FORMAT(2(1X,I2,1X,F6.3))
C       LATD= LATITUDE (DEGREES)
C     SLATM= LATITUDE (MINUTES)
C       LONGD= LONGITUDE (DEGREES)
C       SLONGM= LONGITUDE (MINUTES)
C
C    THEN  NEXT CARD:-       M
C           FORMAT(I2)
C    M= NUMBER OF RECORDING STATIONS (OR SHOTS) UPTO A MAXIMUM OF 99
C   THEN M CARDS :-  LATD,SLATM,LONGD,SLONGM
C          FORMAT(2(1X,I2,1X,F6.3))
C       LATD= LATITUDE (DEGREES)
C     SLATM= LATITUDE (MINUTES)
C       LONGD= LONGITUDE (DEGREES)
C       SLONGM= LONGITUDE (MINUTES)
C
C
C   OUTPUT CONSISTS OF AN M*N MATRIX OF DISTANCES  AND MATICES OF DISTANCES
C       DEVIDED BY 6.0 AND 8.0
C    DISTANCES ARE STRAIGHT LINE DISTANCES
C
C
      DOUBLE PRECISION A,F,FACT,SLAT(15),SLONG(15),SLAT2,SR(15)
     1,ALAT,ALONG,R,DLONG,DLAT,THETA,DIST(15,99)
      DIMENSION IDUM(15)
      A=6378.160
      F=1./298.247
      READ(5,1) N
    1 FORMAT(I2)
      FACT=3.14159265/180.
      DO 2 I=1,N
      READ(5,7) LATD,SLATM,LONGD,SLONGM
    7 FORMAT(2(1X,I2,1X,F6.3))
      SLAT(I)=FLOAT(LATD)+SLATM/60.
      SLONG(I)=FLOAT(LONGD)+SLONGM/60.
      SLAT(I)=SLAT(I)*FACT
      SLONG(I)=SLONG(I)*FACT
      SLAT(I)=DATAN(0.99330544*DTAN(SLAT(I)))
      SLAT2=SLAT(I)*2.
      SR(I)=A*(1.-F*DSIN(SLAT(I))**2)
    2 IDUM(I)=I
      WRITE(6,4) (IDUM(I),I=1,N)
    4 FORMAT('1','SHOT DISTANCES CALCULATED FROM LATITUDE AND LONGITUDE'
     1,/,'RECORDING',/,'STATION                            SHOT NUMBERS',/,5X
     2,15I7)
      READ(5,5) M
    5 FORMAT(I2)
      DO 6 I=1,M
      READ(5,7) LATD,SLATM,LONGD,SLONGM
      ALAT=FLOAT(LATD)+SLATM/60.0
      ALONG=FLOAT(LONGD)+SLONGM/60.0
      ALAT=ALAT*FACT
      ALONG=ALONG*FACT
      ALAT=DATAN(0.99330544*DTAN(ALAT))
      SLAT2=ALAT*2
      R=A*(1.-F*DSIN(ALAT)**2)
      DO 8 J=1,N
      DLONG=ALONG-SLONG(J)
      DLAT=ALAT-SLAT(J)
      THETA=DSIN(SLAT(J))*DSIN(ALAT)+DCOS(SLAT(J))*DCOS(ALAT)*DCOS(DLONG
     1)
      DIST(J,I)=SR(J)*SR(J)+R*R-2.*SR(J)*R*THETA
    8 DIST(J,I)=DSQRT(DIST(J,I))
      WRITE(6,9) I,(DIST(J,I),J=1,N)
    9 FORMAT(' ',I5,15(1X,F6.2))
    6 CONTINUE
      WRITE(6,12) (IDUM(I),I=1,N)
   12 FORMAT('1','SHOT DISTANCES/6.0',/,'RECORDING',/,'STATION
     1                  SHOT  NUMBER',/,5X,15I7)
      DO 10 I=1,M
      DO 11 J=1,N
   11 DIST(J,I)=DIST(J,I)/6.
      WRITE(6,13) I,(DIST(J,I),J=1,N)
   13 FORMAT(' ',I5,15(1X,F6.2))
   10 CONTINUE
      WRITE(6,14) (IDUM(I),I=1,N)
   14 FORMAT('1','SHOT DISTANCES/8.0',/,'RECORDING',/,'STATION
     1                  SHOT  NUMBER',/,5X,15I7)
      DO 15 I=1,M
      DO 16 J=1,N
   16 DIST(J,I)=DIST(J,I)*0.75
      WRITE(6,17) I,(DIST(J,I),J=1,N)
   17 FORMAT(' ',I5,15(1X,F6.2))
   15 CONTINUE
      STOP
      END
```

```
C  SWINBURNS VELOCITY PROGRAMME
C      PROGRAMME TO CALCULATE APPARENT VELOCITY ACROSS AN ARRAY WHEN THE
C   SHOT POSITION IS KNOWN  (KNOWN AZIMUTH)  FOR A CURVED WAVEFRONT.
C
C  INPUT IS:-
C   CARD1        N
C    FORMAT(I2)
C    N= NUMBER OF EVENTS TO BE CALCULATED
C
C   FOR EACH EVENT
C    EAST,ANORTH,NSHOT,NDATA
C   FORMAT(2F5.2,/,12X,I6,/,4X,I2)
C    EAST,ANORTH=  O.S. COORDINATES OF THE SOURCE
C     NSHOT= NUMBER CODING OF THE EVENT
C    NDATA=  NUMBER OF ONSET TIMES
C
C   THEN NDATA ONSET TIME CARDS
C     APIT(I),ONTIME
C       FORMAT(5X,A2,6X,F10.5)
C    APIT(I)=   NAME OF PIT
C      ONTIME=  ONSET TIME
C
C
C  OUTPUTS APPARENT VELOCITY WITH 95 PER CENT CONFIDENCE LIMIT, CONSTANT T0,
C     STANDARD ERROR OF THE SOLUTION, AND RESIDUALS TO EACH PIT,
C  ALSO OUTPUTS A GRAPH OF QUALITY OF FIT OF THE DATA TO REFACTOR VELOCITY
C
C
      DIMENSION PIT(20),PN(20),PE(20),HI(20),F(20),X(20),Y(20),AMAP(41,1
     101),DUMV(11),RESD(20),APIT(20),ERR(20)
      DATA HI/0.032,0.020,0.018,0.0,0.022,0.006,-0.011,-0.013,-0.013,
     1-0.013,0.021/
      DATA     F/12.7,4.3,3.18,2.78,2.57,2.45,2.37,2.31,2.26,2.23,2.2,2.
     118,2.16,2.15,2.13,2.12,2.11,2.10,2.09,2.09/
      DATA BLANK/' '/,STAR/'*'/,CROSS/'+'/,STROKE/'I'/,DASH/'-'/
      DATA ERR/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,
     10.0,0.0,0.0,0.0,0.0,0.0/
      DATA CEAST,CANRTH/393.93,543.69/
      DATA CON,VCOVER/14.0,3.8/
      DATA PIT/2HW1,2HW2,2HW3,2HW4,2HW5,2HS1,2HS2,2HS3,2HH1,2HH2,2HN1/
      DATA X/-3.274,-2.344,-1.14,0.0,0.892,-0.38,0.032,-0.169,-0.169,
     1-0.169,-0.264/
      DATA Y/0.153,0.079,0.158,0.0,0.021,-3.152,-1.811,-0.956,-0.956,
     1-0.956,0.761/
      DO 900 IJ=1,20
      PE(IJ)=CEAST+X(IJ)
  900 PN(IJ)=CANRTH+Y(IJ)
C       READ IN INITIAL STATEMENTS
      READ (5,32) N
   32 FORMAT(I2)
      DO 33 III=1,N
      READ(5,1) EAST,ANORTH,NSHOT,NDATA
    1 FORMAT(2F5.2,/,12X,I6,/,4X,I2)
      DATA=FLOAT(NDATA)
C         WORK OUT DISTANCE AND SET UP LEAST SQUARE SUMMATION
      TOTX=0.0
      TOTY=0.0
      TOTXX=0.0
      TOTYY=0.0
      TOTXY=0.0
      DO 2 I=1,NDATA
      READ (5,3) APIT(I),ONTIME
    3 FORMAT(5X,A2,6X,F10.5)
      DO 4 J=1,20
      IF (APIT(I)-PIT(J)) 4,5,4
    4 CONTINUE
    5 Y(I)=ONTIME-HI(J)-ERR(J)
      X(I)=(EAST-PE(J))**2+(ANORTH-PN(J))**2
      TOTY=TOTY+Y(I)
      TOTXX=TOTXX+X(I)
      TOTYY=TOTYY+Y(I)*Y(I)
```

```
      X(I)=SQRT(X(I))
      TOTX=TOTX+X(I)
    2 TOTXY=TOTXY+X(I)*Y(I)
C      WORK OUT VARIANCES AND 95 PER CENT CONFIDENCE LIMITS
      SXX=TOTXX/(DATA-1.0)-(TOTX*TOTX)/(DATA*(DATA-1.0))
      SYY=TOTYY/(DATA-1.0)-(TOTY*TOTY)/(DATA*(DATA-1.0))
      SXY=TOTXY/(DATA-1.0)-(TOTX*TOTY)/(DATA*(DATA-1.0))
      VEL=SXX/SXY
      CONST=TOTY/DATA-TOTX/(DATA*VEL)
      IWORK=NDATA-2
      IF (IWORK.GT.20) IWORK=20
      C=F(IWORK)
      DV=(DATA-1.0)*(SYY-SXX/(VEL*VEL))
      CONF=DV/((DATA-2.0)*(DATA-1.0)*SXX)
      CONF=ABS(CONF)
      CONF=SQRT(CONF)
      CONF=C*CONF
      CONF=CONF*VEL*VEL
      TOTRES=0.0
      DO 7 I=1,NDATA
      RESD(I)=Y(I)-CONST-X(I)/VEL
    7 TOTRES=TOTRES+RESD(I)*RESD(I)
      SIGSOL=TOTRES/(DATA-2.0)
      SIGSOL=SQRT(SIGSOL)
C          OUTPUT DATA
      WRITE(6,6) NSHOT,VEL,CONF,CONST,SIGSOL
    6 FORMAT('1','SHOT NUMBER ',I6,10X,'BEST FIT VELOCITY ',F8.3,' + OR
     1- ',F5.3,/,'CONSTANT ',F5.3,10X,'STANDARD ERROR OF SOLUTION ',F5.3
     2,/,'RESIDUALS')
      DO 34 I=1,NDATA
      WRITE (6,35) APIT(I),RESD(I)
   35 FORMAT(' ',10X,A2,4X,F5.3)
   34 CONTINUE
C          SET UP GRID FOR GRAPH
      DO 20 I=1,41
      DO 20 J=1,101
   20 AMAP(I,J)=BLANK
      DO 21 I=1,41
      DO 22 K=1,5
      IF ((I+9)-10*K) 22,23,22
   22 CONTINUE
      GO TO 21
   23 DO 24 J=1,101
   24 AMAP(I,J)=DASH
   21 CONTINUE
      DO 25 J=1,101
      DO 26 K=1,11
      IF ((J+9)-10*K) 26,27,26
   26 CONTINUE
      GO TO 25
   27 DO 28 I=1,41
      IF (AMAP(I,J).EQ.DASH) GO TO 29
      GO TO 30
   29 AMAP(I,J)=CROSS
      GO TO 28
   30 AMAP(I,J)=STROKE
   28 CONTINUE
   25 CONTINUE
C          SET UP PLOTTING
      IVEL=IFIX(VEL)
      DUMV(1)=FLOAT(IVEL)-2.0
      IVEL=IVEL*100-205
      DO 10 J=1,101
      IVEL=IVEL+5
      B=FLOAT(IVEL)
      B=100.0/B
      TOTRES=0.0
      DO 11 K=1,NDATA
      RES=TOTY/DATA-B*TOTX/DATA+B*X(K)-Y(K)
   11 TOTRES=TOTRES+RES*RES
      TOTRES=TOTRES/(DATA-1.0)
      TOTRES=-ALOG10(TOTRES)*10.0-8.5
      IF (TOTRES.LT.1.0) TOTRES=1.0
      IF (TOTRES.GT.41.0) TOTRES=41.0
      I=IFIX(TOTRES)
   10 AMAP(I,J)=STAR
C          PRINT  OUT PLOT
      WRITE(6,17)
   17 FORMAT('0','PLOT OF STANDARD ERROR AGAINST VELOCITY',///,' STANDAR
     1D ERROR',/,' LOG SCALE')
      DUM=-0.25
      DO 12 I=1,41
      DO 50 K=1,5
      IF ((I+9)-10*K) 50,13,50
   50 CONTINUE
      GO TO 14
   13 DUM=DUM-0.25
      WRITE(6,15) DUM,(AMAP(I,J),J=1,101)
   15 FORMAT(' ',5X,F5.2,101A1)
      GO TO 12
   14 WRITE(6,16)(AMAP(I,J),J=1,101)
   16 FORMAT(' ',10X,101A1)
   12 CONTINUE
      DO 18 I=2,11
      DUM=FLOAT(I)
   18 DUMV(I)=DUMV(1)+(DUM-1.0)*0.5
   19 WRITE(6,31)(DUMV(I),I=1,11)
   31 FORMAT(' ',2X,11(6X,F4.1),/,'                              VELOCITY')
   33 CONTINUE
      STOP
      END
```

```
C     PROGRAMME TO CALCULATE APPARENT VELOCITY AND AZIMUTH ACROSS AN ARRAY FOR
C      A CURVED WAVEFRONT
C
C
C
C     INPUT IS:-
C      CARD 1    MN
C         FORMAT(I2)
C     MN=  NUMBER OF EVENTS TO BE CALCULATED
C
C     THEN FOR EACH EVENT
C     EAST,ANRTH,NEVENT,NPIT,SPST
C       FORMAT(2F5.2,/,12X,I6,/,4X,I2,16X,F8.3)
C       EAST,ANRTH= O.S. COORDINATES OF THE SOURCE (IF KNOWN) ELSE BLANK
C     NEVENT= NUMBER CODING OF THE EVENT
C     NPIT= NUMBER OF ONSET TIMES
C      SPST= P-S TIME  ONLY NEED BE GIVEN IF THE O.S. COORDINATES OF THE SOURCE
C      ARE NOT SPECIFIED
C
C     THEN  NPIT ONSET TIME CARDS
C       APIT,T
C        FORMAT(8X,A2,6X,F10.5)
C     APIT= NAME OF PIT
C      T= ONSET TIME
C
C
C     OUTPUTS  APPARENT VELOCITY, AZIMUTH AND CROSS OVER TIME WITH 95 PER CENT
C     CONFIDENCE LIMITS AND ORIGINAL DATA WITH THE RESIDUALS CALCULATED.   ALSO
C      OUTPUTS NUMBER OF ITERATIONS FOR A SOLUTION, SUM OF RESIDUALS SQUARED,
C      DISTANCE OF EVENT TO THE CROSS.OVER POINT, AZIMUTHAL ANOMALY, AND THE
C      RECALCULATED SHOT POSITION.
C       CALLS  IBM  SSP SUBROUTINE  SINV FOR MATRIX INVERSION
C
C
       DIMENSION PIT(20),X(20),Y(20),AT(20),ATT(20),RES(20),L(20),HI(20),
      1TIME(50),F(20,3),B(3,20),A(6),S(3),SI(3)
       DATA X/-3.274,-2.344,-1.14,0.0,0.892,-0.38,2.032,-0.169,-0.169,
      1-0.169,-0.264/
       DATA Y/0.153,0.079,2.158,0.0,0.021,-3.152,-1.811,-0.956,-0.956,
      1-0.956,0.781/
       DATA HI/0.118,2.074,0.068,0.0,0.062,0.422,-0.042,-0.048,-0.048,
      1-0.048,0.077/
       DATA PIT/2HW1,2HW2,2HW3,2HW4,2HW5,2HS1,2HS2,2HS3,2HH1,2HH2,2HN1/
       DATA CEAST,CANRTH/393.93,543.69/
       DATA CON,VCOVER/10.0,3.8/
       DATA TIME/1.9,3.2,4.4,5.7,7.0,8.2,9.5,10.8,11.8,13.0,14.1,15.3,16.
      14,17.5,18.5,19.9,21.0,22.0,23.1,24.2,25.3,26.4,27.5,28.6,29.7,30.8
      2,31.9,33.0,34.1,35.2/
       DIMENSION TTEST(20)
       DATA TTEST/12.7,4.3,3.18,2.78,2.57,2.45,2.37,2.31,2.26,2.23,2.2,2.
      118,2.16,2.15,2.13,2.12,2.11,2.10,2.09,2.09/
       READ(5,1) MN
     1 FORMAT(I2)
       DO 10 JJJ=1,MN
       READ(5,2) EAST,ANRTH,NEVENT,NPIT,SPST
     2 FORMAT(2F5.2,/,12X,I6,/,4X,I2,16X,F8.3)
       WRITE(6,3) NEVENT
     3 FORMAT('1','EVENT NUMBER ',I6)
       DO 4 K=1,NPIT
       READ(5,5) APIT,T
     5 FORMAT(8X,A2,6X,F10.5)
       DO 6 I=1,20
       IF (APIT-PIT(I)) 6,7,6
     6 CONTINUE
     7 L(K)=I
       ATT(K)=T
       AT(K)=T
       F(K,1)=-Y(I)
       F(K,2)=-X(I)
     4 F(K,3)=1.0
       IF (NPIT-3) 33,34,34
    33 WRITE(6,35)
    35 FORMAT('0','SOLUTION NEEDS AT LEAST THREE ONSET TIMES')
       GO TO 10
    34 CONTINUE
       DIST=(CEAST-EAST)**2+(CANRTH-ANRTH)**2
       DIST=SQRT(DIST)
       IF (EAST-ANRTH)  9,8,9
     8 CALL LIFIND(TIME,30,SPST,CON,DIST)
     9 CONTINUE
       DO 11 I=1,3
       DO 11 J=I,3
       WORK=0.0
       DO 12 K=1,NPIT
    12 WORK=WORK+F(K,I)*F(K,J)
       K=(J*(J-1))/2+I
    11 A(K)=WORK
       CALL SINV(A,3,1.0E-5,IER)
       DO 32  I=1,NPIT
       DO 31 J=1,3
       B(J,I)=0.0
       DO 13 K=1,3
       IK=((K-1)*K)/2+J
       IF (K.LT.J) IK=((J-1)*J)/2+K
    13 B(J,I)=B(J,I)+F(I,K)*A(IK)
    31 CONTINUE
    32 CONTINUE
       NIT=0
    23 CONTINUE
       NIT=NIT+1
       DO 14 I=1,3
       S(I)=0.0
       DO 14 J=1,NPIT
```

```
14 S(I)=S(I)+A(I,J)*AT(J)
   VEL=S(1)*S(1)+S(2)*S(2)
   VEL=1/SQRT(VEL)
   AZ=ATAN2(S(2),S(1))
   IF (DIST) 15,15,16
16 IF (MIT-20) 26,26,15
26 MIT=0.0
   DO 17 K=1,NPIT
   I=L(K)
   WORK=X(I)*SIN(AZ)+Y(I)*COS(AZ)
   WORK=DIST*DIST+X(I)*X(I)+Y(I)*Y(I)-2.0*DIST*WORK
   WORK=SQRT(WORK)
   WORK1=X(I)*COS(AZ)-Y(I)*SIN(AZ)
   WORK1=WORK*WORK-WORK1*WORK1
   WORK1=SQRT(WORK1)
   WORK1=(WORK-WORK1)/VEL
   WORK=VEL*VEL-VCOVER*VCOVER
   IF (WORK) 19,18,18
19 WRITE(6,20)
20 FORMAT(' ','VELOCITY LESS THAN COVER')
   GO TO 10
18 WORK=SQRT(WORK)
   WORK=HI(I)*WORK/(VEL*VCOVER)
   WORK1=WORK+WORK1
   WORK=AT(K)
   AT(K)=ATT(K)-WORK1
   WORK=WORK-AT(K)
   WORK=ABS(WORK)-1.0E-3
   IF (WORK.LE.0.0) MIT=MIT+1
17 CONTINUE
   IF (MIT-NPIT) 23,15,15
15 WORK=0.0
   DO 24 K=1,NPIT
   I=L(K)
   RES(I)=AT(K)+S(1)*Y(I)+S(2)*X(I)-S(3)
24 WORK=WORK+RES(I)*RES(I)
   IF (NPIT-3) 36,36,37
36 WRITE(6,38)
38 FORMAT('0','ONLY THREE ONSET TIMES GIVEN  UNABLE TO CALCULATE STAN
  1DARD ERRORS')
   DO 39 I=1,3
   WORK=1.0E9
39 SI(I)=1.0E9
   GO TO 40
37 CONTINUE
   WORK1=FLOAT(NPIT)-3.0
   WORK1=WORK/WORK1
   DO 25 I=1,3
   IK=((I+1)*I)/2
25 SI(I)=A(IK)*WORK1
   FACT=45.0/ATAN(1.0)
   AZ=AZ*FACT
   IF (AZ.LT.0.0) AZ=AZ+360.
   IWORK=NPIT-3
   IF (IWORK.GT.20) IWORK=20
   WORK1=(S(1)*S(1)*SI(1)+S(2)*S(2)*SI(2))*(VEL**6)
   SI(2)=(S(1)*S(1)*SI(2)+S(2)*S(2)*SI(1))*(VEL**4)
   SI(1)=SQRT(WORK1)*TTEST(IWORK)
   SI(2)=SQRT(SI(2))*TTEST(IWORK)*FACT
   SI(3)=SQRT(SI(3))*TTEST(IWORK)
40 CONTINUE
   WRITE(6,21) MIT,VEL,SI(1),AZ,SI(2),S(3),SI(3),WORK,DIST
C  CONFIDENCE LIMITS ARE 95 PERCENT
21 FORMAT('2',' FROM LEAST SQUARES ',/,'NUMBER OF ITERATIONS ',I2,/,
  1'  ALL CONFIDENCE LIMITS ARE 95 PERCENT  ',/,' VELOCITY  ',F8.3,
  2' +OR- ',F8.3,/,'AZIMUTH ',F8.3,' +OR- ',F8.3,/,'CROSS OVER TIME '
  3,F8.3,' +OR- ',F8.3,/,'SUM OF RESIDUALS SQUARED ',F8.5,/,'DISTANCE
  4 ',F8.3,/,'   PIT  ARRIVAL TIME  RESIDUAL')
   DO 28 K=1,NPIT
   I=L(K)
   WRITE(6,29) PIT(I),AT(K),RES(I)
29 FORMAT(' ',8X,A2,2(2X,F8.3))
28 CONTINUE
   IF (DIST.EQ.0.0) GO TO 10
   WORK=EAST-CEAST
   WORK1=ANRTH-CANRTH
   TAZ=ATAN2(WORK,WORK1)
   TAZ=TAZ*FACT
   IF (TAZ.LT.0.0) TAZ=TAZ+360.0
   TAZ=TAZ-AZ
   AZ=AZ/FACT
   EAST=DIST*SIN(AZ)+CEAST
   ANRTH=DIST*COS(AZ)+CANRTH
   WRITE(6,27) TAZ,EAST,ANRTH
27 FORMAT(' ','AZIMUTHAL ANOMALY ',F8.3,/,'OS GRID COORDINATES OF SOU
  1RCE ',2(2X,F6.2))
10 CONTINUE
   STOP
   END
   SUBROUTINE DIFIND(TIME,LTIME,SPST,CON,DIST)
   DIMENSION TIME(1)
   IF (SPST.GE.TIME(LTIME)) GO TO 2
   DO 1 II=1,LTIME
   DIST=FLOAT(II)*CON
   IF (SPST.GE.TIME(II).AND.SPST.LT.TIME(II+1)) GO TO 3
 1 CONTINUE
 3 DIST=DIST+((SPST-TIME(II))/(TIME(II+1)-TIME(II)))*CON
   GO TO 4
 2 DIST=0.0
 5 FORMAT(' ','DISTANCE OUT OF CURVE RANGE')
 4 RETURN
   END
```

```
C      WHH   INVERSION
C
C  PROGRAMME FOR CONVERTING VELOCITY-DISTANCE FUNCTION INTO A VELOCITY DEPTH
C   FUNCTION  USING TRAPEZOIDAL INTEGRATION. ALSO CALCULATES THE DELAY TERM
C  TO THE HIGHEST VELOCITY LAYER AND TO ONE OTHER SPECIFIED REFRACTOR
C
C  INPUT IS:-     CARD 1-      N,VEL
C         FORMAT(I5,F10.0)
C          N=NUMBER OF VELOCITY DISTANCE CARDS
C     VEL=  SPECIFIED REFRACTOR VELOCITY FOR CALCULATING DELAY TERM ,   ELSE
C    BLANK
C
C    THE N CARDS
C       X(I),V(I)
C        FORMAT(F10.0,10X,F10.0)
C       X(I)=  DISTANCE
C     V(I)=  VELOCITY
C
C  N.B.  X(1) MUST BE 0.0
C   X(I) MUST BE IN ASCENDING ORDER
C    V(I) MUST BE IN ASCENDING ORDER
C
C
C  OUTPUT IS THE ORIGINAL DATA AND DEPTHS WITH DELAY TERMS
C
C
      DIMENSION V(99),X(99),Z(99),DT(99)
      READ(5,1) N,VEL
    1 FORMAT(I5,F10.0)
      READ(5,2) (X(I),V(I),I=1,N)
    2 FORMAT(F10.0,10X,F10.0)
      IF (X(1)) 3,4,3
    3 WRITE(6,5)
    5 FORMAT(' ',' X(1) MUST BE 0.0  IMPOSSIBLE TO INTEGRATE ')
      STOP
    4 DO 9 I=2,N
      IF (X(I)-X(I-1)) 10,9,9
   10 WRITE(6,12)
   12 FORMAT(' ',' DISTANCES NOT IN ASCENDING ORDER')
      STOP
    9 CONTINUE
      DO 11 I=2,N
      IF (V(I)-V(I-1)) 15,11,11
   15 WRITE(6,13)
   13 FORMAT(' ',' VELOCITIES NOT IN ASCENDING ORDER')
      STOP
   11 CONTINUE
      DO 6 I=2,N
      J=N-I+2
    6 X(J)=X(J)-X(J-1)
      PINV=0.125/ATAN(1.0)
      DO 8 JJ=2,N
      SUM=0.0
      JK=JJ-1
      DO 7 I=1,JK
      WORK=V(JJ)/V(I)
      CALL ACOSH(WORK)
    7 SUM=SUM+WORK*(X(I)+X(I+1))
    8 Z(JJ)=SUM*PINV
      Z(1)=0.0
      DO 16 I=2,N
   16 X(I)=X(I)+X(I-1)
      WRITE(6,14) (Z(I),V(I),X(I),I=1,N)
   14 FORMAT(' ','  DEPTH  VELOCITY DISTANCE',50(/,3F8.3))
      J=N-1
   22 DO 17 I=1,J
      WORK=V(N)*V(N)-V(I)*V(I)
      WORK=SQRT(WORK)
   17 DT(I)=WORK/(V(N)*V(I))
      DT(N)=0.0
      SUM=0.0
      DO 18 I=1,J
   18 SUM=SUM+0.5*(DT(I)+DT(I+1))*(Z(I+1)-Z(I))
      WRITE(6,19) SUM,V(N)
   19 FORMAT(' ','DELAY TERM IS',F6.4,' SECONDS TO THE',F6.4,' KM/SEC RE
     1FRACTOR')
      IF (VEL) 20,21,20
   20 V(N)=VEL
      VEL=0.0
      GO TO 22
   21 STOP
      END
      END
      SUBROUTINE ACOSH(WORK)
      A=WORK*WORK-1.0
      A=SQRT(A)
      A=A+WORK
      WORK=ALOG(A)
      RETURN
      END
```

```
C    PROGRAMME FOR CALCULATING THE BEST FITTING TWO LAYERED MODEL TO FIT THE
C    OBSERVED PN-PG TIMES.    MAPS OUT THE VELOCITY OF THE TOP OF LAYER 2
C    AGAINST THE THICKNESS OF LAYER 2
C
C   CALLS SUBROUTINES INPUT AND RESID2
C     V(I)=  VELOCITY OF I TH LAYER
C    K(I)=  RATE OF INCREASE OF VELOCITY (LINEAR) WITHIN THE I TH LAYER
C      D(I)=  THICKNESS OF THE I TH LAYER
C
C    INPUT IS :-  CARD 1:-  M        FORMAT(I2)
C    M= NUMBER OF OBSERVATIONS TO FOLLOW
C   THEN M CARDS  T(JJ),X(JJ),DT(JJ)
C         FORMAT(3F10.0)
C     T(JJ)= OBSERVED PN-PG TIME
C    X(JJ)= DISTANCE
C     DT(JJ)=   ESTIMATE OF THE SUM OF THE DELAY TERMS FOR THE SHOT AND
C     RECEIVER
C
C    PARAMETERS FOR LAYER 1 AND LAYER 3 ARE WRITTEN IN THE PROGRAMME AND MAY
C    NEED CHANGING.
C
C    OUTPUT CONSISTS OF AN ALPHANUMERIC MAP OF THE FIT OF THE MODEL TO THE
C      OBSERVED DATA
C
      REAL*8 V(10),D(10),K(10),X(100),T(100),DT(100)
      DIMENSION ALPHA(26),AMAP(101)
      DATA ALPHA/'A','B','C','D','E','F','G','H','I','J','K','L','M','N'
     1,'O','P','Q','R','S','T','U','V','W','X','Y','Z'/
      DATA BLANK/' '/,STAR/'*'/
      CALL INPUT(M,T,X,DT)
      D(1)=12.0
      V(1)=5.7
      K(1)=0.02
      K(2)=0.02
      K(3)=0.045
      V(3)=8.0
      WRITE(6,9)
    9 FORMAT('1','SWINBURNS RESIDUAL CONTOUR MAP FOR A TWO LAYERED CRUST
     1 BASED ON PN-PG TIMES',/,' THICKNESS LAYER 2
     2     VELOCITY OF LAYER2',/,' 6.0          6.1          6.2          6.3
     3 6.4          6.5          6.6          6.7          6.8          6.9          7.0'
     4)
      DO 1 I=1,45
      D(2)=FLOAT(I)*0.5+4.5
      DO 2 J=1,101
      V(2)=5.99+FLOAT(J)*0.01
      CALL RESID2(2,M,V,K,D,T,X,DT,RES2)
      RES2=RES2/FLOAT(M)
      WORK=ALOG10(RES2)
      IF (WORK) 3,4,4
    4 AMAP(J)=STAR
      GO TO 2
    3 IF (WORK+2.6) 6,6,7
    6 AMAP(J)=BLANK
      GO TO 2
    7 WORK=-WORK*10.0
      IWORK=IFIX(WORK)+1
      AMAP(J)=ALPHA(IWORK)
    2 CONTINUE
      WRITE(6,8) D(2),(AMAP(J),J=1,101)
    8 FORMAT(' ',F4.1,1X,101A1)
    1 CONTINUE
      STOP
      END
```

```
C    PROGRAMME FOR CALCULATING THE BEST FITTING ONE LAYERED MODEL TO OBSERVED
C     PC-PG  TIMES
C
C   CALLS SUBROUTINES INPUT AND RESID2
C     V(I)=  VELOCITY OF I TH LAYER
C    K(I)=  RATE OF INCREASE OF VELOCITY (LINEAR) WITHIN THE I TH LAYER
C      D(I)=  THICKNESS OF THE I TH LAYER
C
C     INPUT IS 1-  CARD 1:-  M        FORMAT(I2)
C    M= NUMBER OF OBSERVATIONS TO FOLLOW
C   THEN M CARDS   T(JJ),X(JJ),DT(JJ)
C          FORMAT(3F10.0)
C      T(JJ)= OBSERVED PM-PG TIME
C     X(JJ)= DISTANCE
C      DT(JJ)=   ESTIMATE OF THE SUM OF THE DELAY TERMS FOR THE SHOT AND
C      RECEIVER
C
C   OUTPUT PRINTS A GRAPH OF THE FIT OF THE DATA TO THE THICKNESS OF THE LAYER
C    PARAMETERS FOR V(1), AND K(1) ARE SPECIFIED IN THE PROGRAMME AND MAY
C    NEED CHANGING
C
      REAL*8 V(10),K(10),D(10),DT(100),X(100),T(100)
      DIMENSION AMAP(51,101)
      DATA BLANK/' '/,STAR/'*'/,CROSS/'+'/,STROKE/'!'/,DASH/'-'/
      DO 20 I=1,51
      DO 20 J=1,101
   20 AMAP(I,J)=BLANK
      DO 21 I=1,51
      DO 22 L=1,6
      IF ((I+9)-10*L)  22,23,22
   22 CONTINUE
      GO TO 21
   23 DO 24 J=1,101
   24 AMAP(I,J)=DASH
   21 CONTINUE
      DO 25 J=1,101
      DO 26 L=1,11
      IF ((J+9)-10*L)  26,27,26
   26 CONTINUE
      GO TO 25
   27 DO 28 I=1,51
      IF (AMAP(I,J).EQ.DASH) GO TO 29
      GO TO 30
   29 AMAP(I,J)=CROSS
      GO TO 28
   30 AMAP(I,J)=STROKE
   28 CONTINUE
   25 CONTINUE
      V(1)=5.7
      K(1)=0.02
      V(2)=6.5
      K(2)=0.02
      CALL INPUT(M,T,X,DT)
      DO 10 J=1,101
      D(1)=FLOAT(J)*0.1+4.9
      CALL RESID2(1,M,V,K,D,T,X,DT,TOTRES)
      TOTRES=TOTRES/FLOAT(M)
      TOTRES=-ALOG10(TOTRES)*10.0+0.5
      IF (TOTRES.LT.1.0) TOTRES=1.0
      IF (TOTRES.GT.51.0) TOTRES=51.0
      I=IFIX(TOTRES)
   10 AMAP(I,J)=STAR
      WRITE(6,17)
   17 FORMAT('1','      SWINBURNS INTERMEDIATE REFLECTION GRAPH',/,'
     1MEAN SQUARE ERROR',/,'  LOG SCALE')
      DUM=1.0
      DO 12 I=1,51
      IF (AMAP(I,1).EQ.CROSS) GO TO 13
      GO TO 14
   13 DUM=DUM-1.0
      WRITE(6,15) DUM,(AMAP(I,J),J=1,101)
   15 FORMAT(' ',5X,F5.2,101A1)
      GO TO 12
   14 WRITE(6,16) (AMAP(I,J),J=1,101)
   16 FORMAT(' ',10X,101A1)
   12 CONTINUE
      WRITE(6,18)
   18 FORMAT(' ','           5.0         6.0         7.0         8.0         9.0
     1   10.0        11.0        12.0        13.0        14.0        15.0',/,'
     2                          DEPTH  (KM)    ')
      STOP
      END
```

```
C     SUBROUTINES CALLED FOR THE WIDE ANGLE REFLECTION PROGRAMMES
C     SUBROUTINE INPUT READS IN THE TIMES AND DISTANCES
C     SUBROUTINE RESID2 CALCULATES THE SUM OF RESIDUALS SQUARED
C     SUBROUTINE RESID CALCULATES THE RESIDUAL TO THE FIT OF THE MODEL WITH THE
C     OBSERVED TRAVEL TIME
C     SUBROUTINE CORR CORRECTS FOR THE DIFFERENTIAL DELAY OF THE LOW VELOCITY
C     COVER
C     SUBROUTINE REFR  CALCULATES THE REFRACTED ARRIVAL WITH THE LEAST TRAVEL TIME
C     SUBROUTINE REF CALCULATES THE TRAVEL TIME OF THE REFRACTED WAVE
C     SUBROUTINES ASINH AND ACOSH CALCULATE INVERSE HYPERBOLIC FUNCTIONS
C     SUBROUTINE PEST CALCULATES THE P PARAMETER OF THE REFLECTED WAVE
C     SUBROUTINE XMAX1 CALCULATES THE MAXIMUM DISTANCE THAT THE REFLECTED WAVE
C     EXISTS
C
C
      SUBROUTINE INPUT(M,T,X,DT)
      REAL*8 T(1),X(1),DT(1)
      READ(5,1) M
    1 FORMAT(I5)
      DO 2 JJ=1,M
      READ(5,3) T(JJ),X(JJ),DT(JJ)
    3 FORMAT(3F10.0)
    2 CONTINUE
      RETURN
      END



      SUBROUTINE RESID2(N,M,V,K,D,T,X,DT,RES2)
      REAL*8 V(1),K(1),D(1),T(1),X(1),DT(1),RES2,TIME,DIST,P1,P,RES,
     1DELAY
      RES2=0.0
      CALL XMAX1(N,V,K,D,XMAX,P1)
      DO 1 JJ=1,M
      TIME=T(JJ)
      DIST=X(JJ)
      DELAY=DT(JJ)
      P=P1
      IF (DIST-XMAX) 3,4,4
    4 RES2=1E9
      GO TO 1
    3 CONTINUE
      CALL PEST(N,V,K,D,DIST,P)
      CALL RESID(N,V,K,D,P,DIST,TIME,RES,DELAY)
      RES2=RES2+RES*RES
    1 CONTINUE
      RETURN
      END



      SUBROUTINE RESID(N,V,K,D,P,X,TIME,RES,DELAY)
      REAL*8 V(1),K(1),D(1),P,P2,X,TIME,RES,WORK,WORK1,TMIN,DELAY
      RES=0.0
      DO 1 I=1,N
      IF (K(I)) 2,3,2
    3 WORK=1.0-V(I)*V(I)*P*P
      IF (WORK.LT.0.0) WORK=-WORK
      WORK=DSQRT(WORK)
      RES=RES+D(I)/(V(I)*WORK)
      GO TO 1
    2 WORK=V(I)+K(I)*D(I)
      WORK=1.0/(P*WORK)
      WORK1=1.0/(P*V(I))
      CALL ACOSH(WORK)
      CALL ACOSH(WORK1)
      RES=RES+(WORK1-WORK)/K(I)
    1 CONTINUE
      CALL REFR(N,V,K,D,X,TMIN,P2)
      CALL CORR(DELAY,P,P2)
      RES=TIME-2.0*RES+TMIN-DELAY
      RETURN
      END



      SUBROUTINE CORR(DELAY,P,P2)
      REAL*8 DELAY,P,P2,V0,V1,V2,V3,WORK1,WORK2,WORK3
      V0=4.0
      V1=5.8
      V2=1.0/P2
      V3=1.0/P
      WORK1=V1*V1-V0*V0
      WORK1=DSQRT(WORK1)/V1
      WORK2=V2*V2-V0*V0
      WORK2=DSQRT(WORK2)/V2
      WORK3=V3*V3-V0*V0
      WORK3=DSQRT(WORK3)/V3
      DELAY=DELAY*(WORK3-WORK2)/WORK1
      RETURN
      END
```

```
      SUBROUTINE REFMIN(N,V,K,D,X,TMIN,P2)
      REAL*8 V(1),K(1),D(1),X,TMIN,TIME,P2,P
      TMIN=1.0E50
      JJ=N+1
      DO 1 I=1,JJ
      CALL REF(I,V,K,D,X,TIME,P)
      IF (TIME-TMIN) 2,2,1
    2 TMIN=TIME
      P2=P
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE REF(N,V,K,D,X,TIME,P)
      REAL*8 V(1),K(1),D(1),X,TIME,P,DIST,WORK,WORK1,WORK2
      M=N-1
       TIME=0.0
      DIST=X
      IF (M) 15,15,10
   15 P=K(1)*K(1)*DIST*DIST+4.0*V(1)*V(1)
      P=2.0/DSQRT(P)
      GO TO 9
   10 TIME=V(N)
    4 P=1.0/TIME
      DIST=0.0
      DO 1 I=1,M
      WORK1=1.0-V(I)*V(I)*P*P
      IF (WORK1.LT.0.0) WORK1=-WORK1
      WORK1=DSQRT(WORK1)
      IF (K(I)) 2,3,2
    3 DIST=DIST+D(I)*V(I)*P/WORK1
      GO TO 1
    2 WORK2=V(I)+K(I)*D(I)
      WORK2=1.0-WORK2*WORK2*P*P
      IF (WORK2.LT.0.0) WORK2=-WORK2
      WORK2=DSQRT(WORK2)
      WORK=1.0/(K(I)*P)
      DIST=DIST+WORK*(WORK1-WORK2)
    1 CONTINUE
      DIST=X-2.0*DIST
      WORK=(K(N)*K(N)*DIST*DIST)/4.0+V(N)*V(N)
      WORK=DSQRT(WORK)
      WORK1=WORK-TIME
      TIME=WORK
      WORK1=DABS(WORK1)
      IF (WORK1-1.0E-5) 5,5,4
    5 TIME=0.0
      DO 6 I=1,M
      IF (K(I)) 7,8,7
    8 WORK=1.0-V(I)*V(I)*P*P
      IF (WORK.LT.0.0) WORK=-WORK
      WORK=DSQRT(WORK)
      TIME=TIME+D(I)/(V(I)*WORK)
      GO TO 6
    7 WORK=V(I)+K(I)*D(I)
      WORK=1.0/(WORK*P)
      WORK1=1.0/(V(I)*P)
      CALL ACOSH(WORK)
      CALL ACOSH(WORK1)
      TIME=TIME+(WORK1-WORK)/K(I)
    6 CONTINUE
    9 IF (K(N)) 12,13,14
   12 TMIN=1.0E50
      RETURN
   13 TIME=2.0*TIME+DIST/V(N)
      RETURN
   14 WORK=(K(N)*DIST)/(2.0*V(N))
      CALL ASINH(WORK)
      TIME=2.0*(TIME+WORK/K(N))
      RETURN
      END
```

```
      SUBROUTINE ASINH(X)
      REAL*8  A,X
      A=X*X+1.0
      A=DSQRT(A)
      A=A+X
      X=DLOG(A)
      RETURN
      END
```

```
      SUBROUTINE ACOSH(X)
      REAL*8 A,X
      A=X*X-1.0
      IF (A) 1,2,2
    1 WRITE(6,3)
    3 FORMAT(' ',' X LESS THAN 1.0  NO REAL ACOSH')
      STOP
    2 A=DSQRT(A)
      A=A+X
      X=DLOG(A)
      RETURN
      END



      SUBROUTINE PEST(N,V,K,D,X,P)
      REAL*8 V(1),K(1),D(1),X,P,WORK,WORK1,WORK2,FUNCT,DERIV,PMAX
      WORK=0.0
      WORK1=0.0
      PMAX=P
      DO 1 I=1,N
      IF (K(I))  8,9,8
    9 WORK1=WORK1+D(I)/V(I)
      GO TO 1
    8 WORK2=V(I)+K(I)*D(I)
      WORK2=WORK2/V(I)
      WORK1=WORK1+DLOG(WORK2)/K(I)
    1 WORK=WORK+D(I)
      WORK2=X*X+WORK*WORK*4.0
      WORK=X*WORK1/(WORK*DSQRT(WORK2))
      IF (WORK.LT.P) P=WORK
      NCOUNT=0
    2 FUNCT=0.0
      DERIV=0.0
      IF (NCOUNT-100) 3,4,4
    3 NCOUNT=NCOUNT+1
      DO 5 I=1,N
      IF (P.GT.PMAX) P=PMAX
      WORK=1.0-V(I)*V(I)*P*P
      WORK1=DSQRT(WORK)
      IF (K(I)) 5,7,6
    7 WORK=WORK1*WORK
      FUNCT=FUNCT+D(I)*V(I)*P/WORK1
      DERIV=DERIV+D(I)*V(I)/WORK
      GO TO 5
    6 WORK2=V(I)+K(I)*D(I)
      WORK=1.0/(K(I)*P)
      WORK2=1.0-WORK2*WORK2*P*P
      WORK2=DSQRT(WORK2)
      FUNCT=FUNCT+WORK*(WORK1-WORK2)
      DERIV=DERIV+WORK*(1.0/WORK2-1.0/WORK1)/P
    5 CONTINUE
      WORK=X/2.0-FUNCT
      WORK=WORK/DERIV
      P=P+WORK
      WORK=DABS(WORK)
      IF (WORK.GT.1.0E-9) GO TO 2
    4 RETURN
      END



      SUBROUTINE XMAX1(N,V,K,D,XMAX,P)
      REAL*8 V(1),K(1),D(1),WORK,WORK1,WORK2,FUNCT,XMAX,P
      WORK=V(1)+K(1)*D(1)
      IVMAX=1
      DO 1 I=1,N
      WORK1=V(I)+K(I)*D(I)
      IF (K(I).LT.0.0) WORK1=V(I)
      IF (WORK1-WORK) 1,1,2
    2 WORK=WORK1
      IVMAX=I
    1 CONTINUE
      P=1.0/WORK
      P=P*0.999
      IF (K(IVMAX)) 9,9,10
    9 XMAX=1.0E50
      GO TO 11
   10 CONTINUE
      FUNCT=0.0
      DO 5 I=1,IVMAX
      WORK=1.0-V(I)*V(I)*P*P
      IF (WORK.LT.0.0) WORK=-WORK
      WORK1=DSQRT(WORK)
      IF (K(I)) 6,7,6
    7 FUNC1=FUNCT+D(I)*V(I)*P/WORK1
      GO TO 5
    6 WORK2=V(I)+K(I)*D(I)
      WORK=1.0/(K(I)*P)
      WORK2=1.0-WORK2*WORK2*P*P
      IF (WORK2.LT.0.0) WORK2=-WORK2
      WORK2=DSQRT(WORK2)
      FUNCT=FUNCT+WORK*(WORK1-WORK2)
    5 CONTINUE
      XMAX=2.0*FUNCT
   11 CONTINUE
      RETURN
      END
```