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# A Lithospheric Seismic Profile in Britain—I Preliminary Results*

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## *Summary*

The planning, execution and preliminary results of a major Anglo-German explosion seismic project are presented in this, paper I of a series. This Lithospheric Seismic Profile in Britain (LISPB) was planned as a reversed 1000 km line between two major sea-shot points off Cape Wrath in Scotland and one in the English Channel; additional sea-shots and intermediate land-shots were fired to give reversed and overlapping crustal coverage (to 180–400 km distance) along the line. In all, 29 shots were fired and 60 mobile magnetic tape stations recorded three-components of ground motion. The resulting 14 crustal and three long-range profiles have observations at intervals of typically 2–4 km. Recordings have been digitized and four examples of filtered, computer-plotted record sections are presented to illustrate data quality. In a preliminary analysis, phase correlations are discussed and some models presented; the latter especially are more relevant to future interpretations than to geological or tectonic problems. However, significant variations in crustal thickness and in the nature of the crust–mantle transition do seem to occur beneath the British Isles.

## 1. Introduction

During the Geodynamics Project, explosion seismologists face the exciting challenge of assisting tests and developments of the plate tectonics hypothesis by carrying out detailed studies of the whole lithosphere in interesting areas such as orogenic belts, rift systems, epeirogenic basins, continental margins and so on. In the beginning, explosion seismology investigations—often based only on first-arrival data—yielded relatively poor returns, for example simple two- or three-layered crust-mantle models that bear little relation to surface geology and hence are of little relevance to tectonic problems. Russian explosion seismologists on the other hand, by using very dense observation schemes and attempting to explain as many aspects of the observed seismograms as possible, have consistently produced crust–mantle models of considerable detail; these models play a central role in Russian tectonic studies. Whilst not so detailed as the Russian measurements, recent experi-

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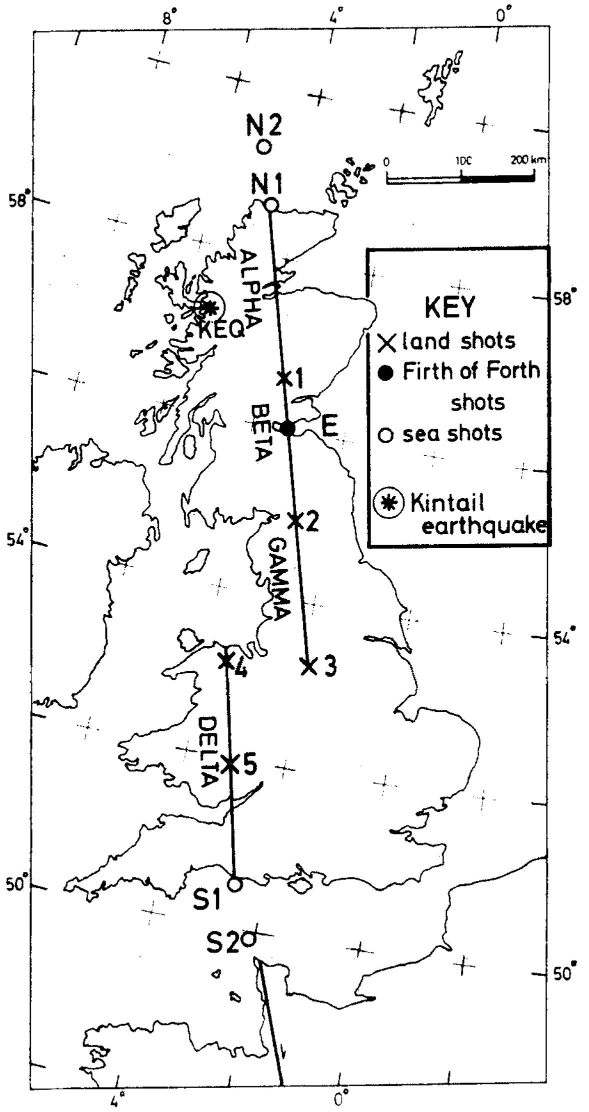

FIG. 1 (b)

FIG. 1(a) Simplified tectonic map of the British Isles. After Dunning & Stubblefield (1966). (b) Location of shots and profiles.

ments in western Europe have also demonstrated that—coupled with new and powerful interpretation techniques—explosion studies are capable of producing results of tectonic significance; examples include work in the Ivrea zone of the Alps (Berckhemer 1968), the Rhône Valley (Sapin & Hirn 1974) and the Rhinegraben (Edel *et al.* 1975).

Furthermore, the advent of densely observed long-range profiles offers the opportunity for detailed studies of the lower lithosphere. The published results of the 900 km long-range profile in France indicate that the lower lithosphere may possess a previously unexpected fine structure (Hirn *et al.* 1973; Kind 1974). Also, as the scope of attempted interpretations is widened to include dynamic and kinematic aspects of more and more phases, so our knowledge of the physical properties of the whole lithosphere will be improved.

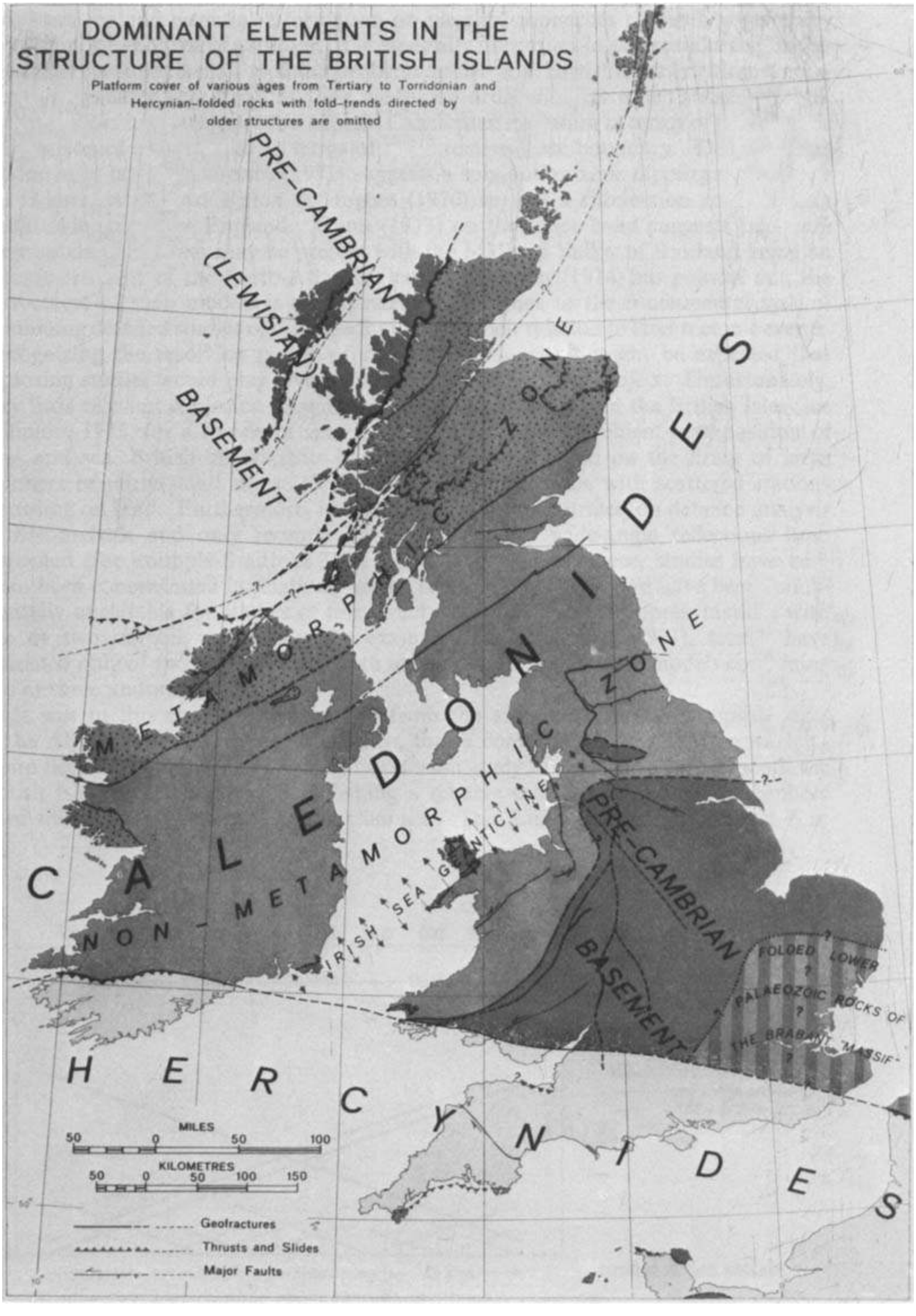
DOMINANT ELEMENTS IN THE STRUCTURE OF THE BRITISH ISLANDS
Platform cover of various ages from Tertiary to Torridonian and Hercynian-folded rocks with fold-trends directed by older structures are omitted
PRE-CAMBRIAN (LEWISIAN) BASEMENT
METAMORPHIC ZONE
CALEDONIDES
NON-METAMORPHIC ZONE
IRISH SEA GEANTICLINE
PRE-CAMBRIAN BASEMENT
FOLDED LOWER PALAEOZOIC ROCKS OF THE BRABANT 'MASSIF'
HERCYNIDES
MILES
50 0 50 100
KILOMETRES
50 0 50 100 150
Geofractures
Thrusts and Slides
Major Faults

FIG. 1 (a).

The ability of controlled source seismology to provide both detailed structural cross-sections and essential information on physical properties at depth is generally important for geodynamic studies. It is especially important in an area like the British Isles where a fundamental tectonic problem exists. The British Isles are almost completely dominated (*Fig.* 1(*a*)) by the Caledonian orogenic belts which strike SW–NE. Many authors have attempted to explain Caledonian evolution in terms of lithospheric plate tectonics in particular in terms of a destructive plate boundary. Details of the models vary however; Dewey (1971) suggests a subduction zone dipping *north* under the Highlands whereas Fitton & Hughes (1970) suggest a subduction zone dipping *south* under northern England. Gunn (1973) on the other hand suggests that *both* these subduction zones may be present with the Midland Valley of Scotland being an oceanic remnant of the Proto-Atlantic Ocean. As Dewey (1974) has pointed out, the correctness of such models is of secondary importance to the fundamental task of continuing detailed studies of the Caledonides and their relation to later tectonic events. Recognizing the resolving power of current techniques, it might be expected that explosion studies would play a very important part in such a project. Unfortunately, very little relevant explosion seismology has been carried out in the British Isles (see Willmore 1973, for a review of activity); because of the convenient juxtaposition of land and sea British experiments have typically been based on the firing of large numbers of fairly small shots (136 kg depth charges) at sea with scattered stations recording on land. Furthermore, interpretation has concentrated on detailed analysis of first-arrivals and only recently have good quality wide-angle reflections been presented (for example Smith & Bott 1975). As a consequence, studies have very often been concentrated in relatively young sedimentary basins and have been fundamentally unsuitable for studies of fine structure in the crust and upper mantle; with one or two notable exceptions (for example Holder & Bott 1971), results have consisted only of spot estimates of depth to Moho or at best simple models containing two or three uniform layers.

It was in this context following on from the aforementioned accomplishments in the Alps, France and the Rhinegraben, that a combined Anglo-German working group decided to undertake a detailed explosion study of the lithosphere beneath the British Isles with the aim of establishing a reliable cross-section of the lithosphere from the north of Scotland to the Channel. This Lithospheric Seismic Profile in

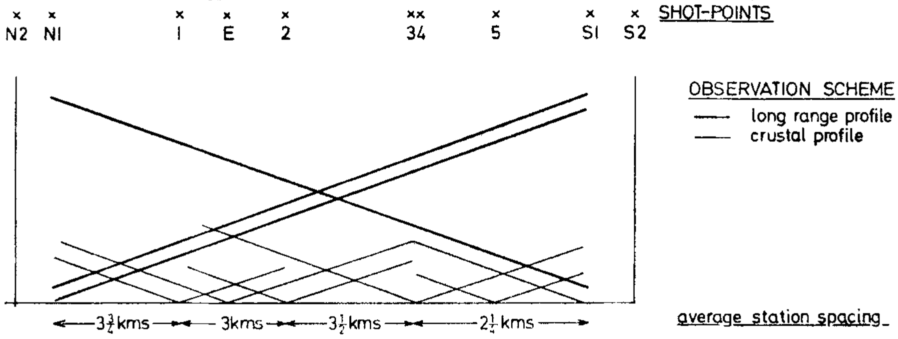

FIG. 2. Observation scheme: arrangement of shot-points and profiles.

**Table 1**

*Data for the* 1973 *LISPB trial profile*

| Shot | Date | Time (BST)<br>h m | s | Co-ordinates (NG) | | Elevation (m) | Wt in lbs. | Observed range (km) |
|---|---|---|---|---|---|---|---|---|
| T1 | 27·8 | 19·01 | 04·39 | 359·60 | 576·00 | 365 | 1000 | 10–95 |
| T2 | 28·8 | 19·01 | 00·75 | 359·60 | 576·00 | 365 | 2000 | 100–140 |
| T3 | 29·8 | 19·00 | 58·47 | 359·60 | 576·00 | 365 | 3000 | 145–200 |

Britain (henceforth, LISPB) was completed during summer 1974 and some of the data and some preliminary results are now available for publication as Paper I in a series which will describe the results of this project.

## 2. The LISPB experiment

Figs. 1(b) and 2 summarize the LISPB measurements, the majority of which were completed in a four-week period during July and August 1974. A single test profile was completed in late August 1973 using land shot-point 2 and recording slightly to the east of segment GAMMA (Fig. 1(b)): some details of this profile are presented in Table 1—otherwise the operation was conducted in exactly the same way as the main phase.

Shots on land ranged in size from 1 to 4 tons depending upon the required observation distance: the shooting system consisted of specially drilled boreholes 150 ft deep and 100 ft apart, each hole containing 500 lb of explosive. Hole patterns were compact and any elongation of the pattern was always normal to the observation direction rather than parallel to it. All planning for land-shots was based on previous experience —tested for LISPB purposes during the 1973 test profile; there were no special features.

The mode of firing for the smaller sea-shots (E and S1) depended on the shot-point conditions, especially the depth of water available: the main aim was to ensure that adequate energy propagated to the full range of observation for the crustal profiles.

The largest sea-shots had to produce a strong enough signal to give good observations up to a range of about 1000 km. Previous experience had shown that an optimum depth shot of about 5 tons would be more than adequate; however such a shot requires a water depth of at least 180 m and this was not available sufficiently close to the ends of the LISPB line. A further difficulty is that the main energy from such

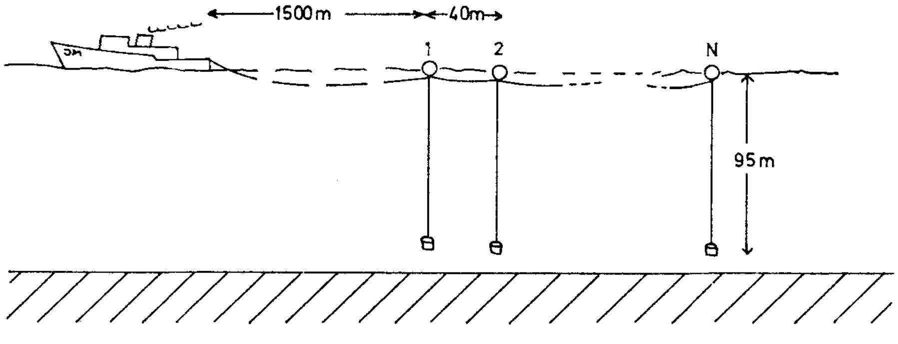

FIG. 3. Dispersed shot lay-out with approximate dimensions (schematic). The shots were fired electrically with the detonation in series and the line preferably perpendicular to the observation direction.

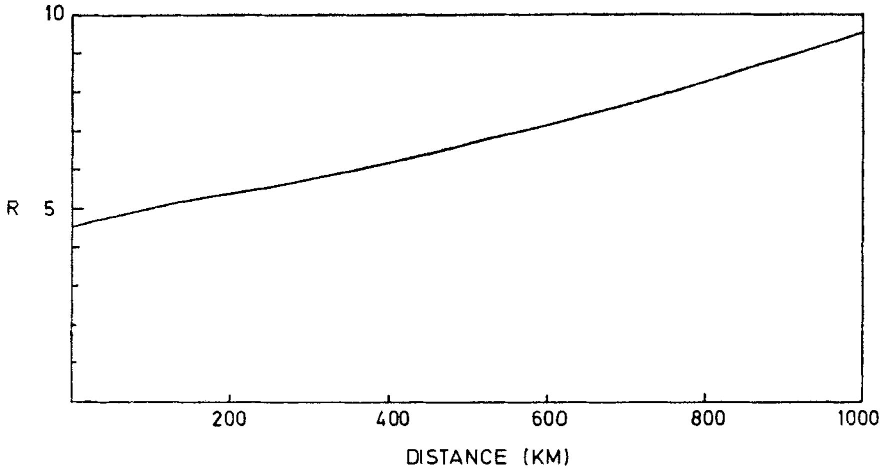

FIG. 4. Dominant period trace amplitude ratio (*R*) between 5 tons and 0·2 tons TNT charges (assumed $Q = 1000$) as a function of distance.

a shot is at about 2 Hz and this lies on one edge of the flat velocity response band of most of the equipment used in the experiment. In addition, if single charges were used whose size depended on the range of observation, the complete long-range sections would be generated by different source functions at different ranges.

To overcome these problems, Jacob (1975) devised a simple but effective system using multiples of much smaller charges (' dispersed shots '). The system and its consequences have already been discussed by Jacob but here we show (Fig. 3) a schematic drawing of the method actually used for LISPB; also shown (Fig. 4) is the graph of the ratio of the dominant period trace amplitudes between 5 tons and 0·2 tons TNT charges, the latter being the basic unit used for LISPB. A $Q$ value of 1000 was assumed in the pre-experiment planning and the change in the amplitude ratio for distances up to 1000 km is due to absorption. Fig. 4 shows why a maximum shot string of 9 was used for the larger distances (Table 2).

In addition to the planned shots, an earthquake occurred in the Kintail area of north-west Scotland during recording. This gave excellent arrivals in the distance range 80–300 km on the stations spread out along segments ALPHA and BETA (Fig. 1(b)); this data will be shown and discussed in Paper II of this series. Details of all main phase shots and the earthquake are presented in Table 2.

Sixty mobile stations, 50 of the German MARS type (Berckhemer 1970) and 10 of the British GEOSTORE type, each recording three-components of ground motion and time signals (MSF, DCF or HBG) on analogue magnetic tape, took part in the measurements: they acted as a mobile array occupying various segments (ALPHA, BETA, GAMMA, DELTA—Fig. 1(b)) of the profile for a certain period and recording shots from various shot-points. In this way the observation scheme shown in Fig. 2 was built up. In this figure, the thin lines show the system of reversed and overlapping crustal profiles—with observations out to at least 180 km and sometimes 300 or 400 km distance—intended for the evaluation of the lateral variations in crustal structure that might occur as the profiles cross the Caledonides (Fig. 1(a)). The thicker lines show the observed long-range profiles—one from the south and two from the north—with observation distances up to slightly less than 1000 km in each case.

## Table 2

*LISPB shot data* 1974

1. Land shots

| Shot | Date | Time (BST) h m | s | Co-ordinates (NG) | | Elevation (m) | Wt in lb | Observed on segments | Observed range (km) |
|---|---|---|---|---|---|---|---|---|---|
| 51 | 23·7 | 0704 | 37·06 | 324·49 | 227·90 | 535 | 2000 | DELTA | 0–150 (north and south) |
| 41 | 24·7 | 0701 | 17·91 | 296·75 | 355·85 | 366 | 5000 | DELTA | 0–20 (north)<br>0–280 (south) |
| 42 | 24·7 | 1901 | 07·06 | 296·80 | 355·90 | 366 | 5000 | DELTA | 0–20 (north)<br>0–280 (south) |
| 31 | 26·7 | 2101 | 10·43 | 403·09 | 370·35 | 535 | 3000 | GAMMA | 0–210 |
| 32 | 29·7 | 1905 | 02·54 | 403·08 | 370·43 | 540 | 8000 | BETA | 210–390 |
| 21 | 26·7 | 1901 | 10·92 | 359·60 | 576·00 | 366 | 3000 | GAMMA | 0–210 |
| 22 | 29·7 | 2101 | 10·35 | 359·60 | 576·10 | 366 | 3000 | BETA | 0–180 |
| 11 | 30·7 | 1901 | 11·37 | 296·75 | 747·05 | 425 | 3000 | BETA | 0–180 |
| 12 | 1·8 | 1901 | 14·83 | 296·85 | 747·05 | 425 | 3000 | ALPHA | 0–225 |

2. Firth of Forth shots

| Shot | Date | Time (BST) h m | s | Lat. | Long. | Depth | Wt in tons | Observed on segments | Observed range (km) |
|---|---|---|---|---|---|---|---|---|---|
| E1 | 26·7 | 1503 | 11·69 | 56° 01·63′ N | 03° 19·73′ W | All E shots were fired at a depth of 80 feet in water of depth 110 feet | 0·6 | GAMMA | 115–325 |
| E2 | 30·7 | 1501 | 02·14 | 56 01·63 N | 03 19·73 W | | 0·6 | BETA | 0–70 (north), 0–115 (south) |
| E3 | 1·8 | 1505 | 59·39 | 56 01·63 N | 03 19·73 W | | 0·6 | ALPHA | 70–290 |

**Table 2** (*continued*)

3. Sea-shots

| (a) North | | Time (BST) | | | | Water depth | No of 0·2 ton | Observed on | Observed range |
|---|---|---|---|---|---|---|---|---|---|
| Shot | Date | h m | s | Lat. | Long. | (m)* | charges* | segments | (km) |
| N11 | 4·8 | 2058 | 49·75 | 58° 34·66′ N | 04° 38·38′ W | 115 | 3 | ALPHA+BETA | 0–400 |
| N12 | 5·8 | 2112 | 02·56 | 58 34·60 N | 04 38·19 W | 94 | 3 | ALPHA+BETA | 0–405 |
| N13 | 10·8 | 1859 | 21·22 | 58 34·57 N | 04 38·47 W | 108 | 3 | GAMMA | 410–620 |
| N14 | 16·8 | 1355 | 56·30 | 58 34·58 N | 04 38·34 W | 102 | 6 | DELTA | 600–890 |
| N21 | 6·8 | 1850 | 51·13 | 59 14·44 N | 05 02·50 W | 115 | 6 | ALPHA+BETA | 80–485 |
| N22 | 8·8 | 1850 | 33·12 | 59 14·48 N | 05 02·71 W | 116 | 6 | ALPHA+BETA | 80–480 |
| N23 | 11·8 | 1950 | 15·50 | 59 14·57 N | 05 02·85 W | 115 | 6 | GAMMA | 485–695 |
| N24 | 13·8 | 2052 | 25·10 | 59 14·78 N | 05 02·95 W | 120 | 8 | DELTA | 675–975 |
| N25 | 14·8 | 1905 | 54·59 | 59 15·33 N | 05 03·19 W | 125 | 9 | DELTA | 675–975 |

| (b) South | | Time (BST) | | | | Water depth | No. of 0·2 ton | Observed on | Observed range |
|---|---|---|---|---|---|---|---|---|---|
| Shot | Date | h m | s | Lat. | Long. | (m) | charges* | segments | (km) |
| S21 | 7·8 | 1510 | 54·11 | 49° 54·08′ N | 02° 07·38′ W | 121* | 6 | ALPHA+BETA | 580–975 |
| S23 | 11·8 | 1806 | 37·12 | 49 54·1 N | 02 10·5 W | 122* | 4† | GAMMA | 370–575 |
| S24 | 13·8 | 1852 | 56·02 | 49 53·5 N | 02 11·9 W | 137* | 4 | DELTA | 85–390 |
| S25 | 14·8 | 2059 | 06·11 | 49 53·6 N | 02 10·5 W | 132* | 4 | DELTA | 85–390 |
| | | | | | | | Wt in tons | | |
| S11 | 14·8 | 0701 | 59·03 | 50 31·95 N | 02 35·8 W | 37‡ | 0·4 | DELTA | 0–310 |
| S12 | 15·8 | 0656 | 19·96 | 50 31·95 N | 02 35·8 W | 37‡ | 0·4 | DELTA | 0–310 |
| S26 | 15·8 | 1457 | 49·06 | 49 53·8 N | 02 11·1 W | 135§ | 0·4 | observed only in France | |
| S27 | 15·8 | 2059 | 59·37 | 49 53·6 N | 02 11·0 W | 137§ | 0·4 | DELTA | a few observations from 0–310 |

* Each charge was at optimum depth.
† Some uncertainty regarding efficiency of this shot.
‡ Charge on sea-bed.
§ Charge at optimum depth.

4. The Kintail earthquake (KEQ)

| | Time (BST) | | | | | | Observed on | Observed range |
|---|---|---|---|---|---|---|---|---|
| Date | h m s | | Lat. | Long. | Depth | Magnitude | segments | (km) |
| 6·8 | 1917 | 36·90 | 57·23° N | 05·35° W | 14 km | 3·0 | ALPHA+BETA | 80–300 |

French and Swiss groups also recorded LISPB shots at S1, S2, N1 and N2 in France along a 700 km line running from the region of Cherbourg (Fig. 1(b)) to the Pyrenees; 40 MARS stations took part.

In the year prior to the experiment, a considerable effort had been put into finding, along the line of the profile, suitable sites for recording. Over 300 of these site investigations were completed as a result of which every observer was effectively given a choice of good sites (i.e. low noise, bed-rock nearby etc.) within a small area (about 1 km square) which defined an 'ideal' station position, together with ancillary information such as the name of the landowner, location of telephones, hotels and so on. This effort contributed very much to the smooth running of the operation.

In the area of the Grampian Highlands (south end of segment ALPHA), the site investigations showed that access for temporary stations was very difficult; as a result a telemetered array with three vertical out-stations and one three-component set was installed for the period of the experiment (the Atholl array).

During the experiment, a central headquarters controlled the operation, provided the necessary communication with the shot-points and stations (and other interested groups) and checked continuously throughout the experiment the quality of recordings and performance of instruments by regular data collection and playback. As a result the operation, though complex, was flexible and amenable to rapid changes and improvement—for example a decision to fire extra shots at position N1 (shots N13 and N14)—thereby extending observations from N1 into GAMMA and DELTA—was taken during the experiment on the basis of results available in the headquarters. During recording on segments ALPHA and BETA, the headquarters were in Edinburgh, for the remainder of the time, in Birmingham.

## 3. The data

Initial data analysis was carried out in the headquarters; analogue replay (with band pass filtering) provided the check on data quality and preliminary record sections were constructed from the analogue data. Thus at the end of the experiment, the quality of the data, location of events on tape and so on were well known; this greatly facilitated subsequent processing.

All of the data were digitized in the Geophysikalisches Institut, Universität Karlsruhe, the MARS data at a rate of 400 samples per second, the GEOSTORE at 200 samples per second; the digitization rate was controlled in the case of the MARS by the 6·4 kHz 'pilot' signal recorded on the analogue tapes and for the GEOSTORE by an external frequency source. The three seismic channels and the time channel were digitized concurrently, typically from half to one minute before the first-arrivals to half to one minute after the last source-related energy. As a first step in data processing, the digitized time channel was analysed to establish to high accuracy both the digitization rate and the starting time of the digitization ($\tau_0$); by using correlation techniques accurate results are possible even with time signals that are so badly recorded as to be indiscernable in analogue form. With both sampling rate and $\tau_0$ well known, the seismic information can then be reduced to time series beginning perhaps 10 s before the first-arrivals and containing all useful information. Preliminary plots are then made to permit checks on data quality and to make sure that the data contains no errors such as integer minute or second shifts, polarity changes etc. The data are then filtered with an anti-aliasing filter and resampled at 10-ms intervals; at this stage, the useful seismic data has been compressed from over 1500 analogue tapes onto a few digital tapes.

Filtered record sections with reduced travel time are the best means of presenting explosion seismic data: with digitized data available, the plotting of any such section—with any required filtering—takes at most 1 or 2 hr. Initial efforts with LISPB data

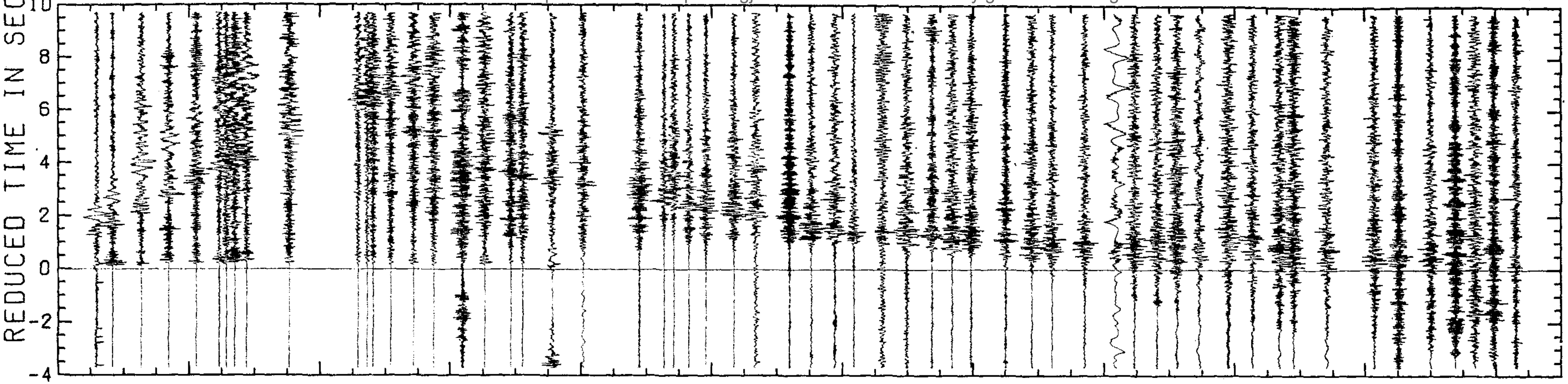

FIG. 5(a)

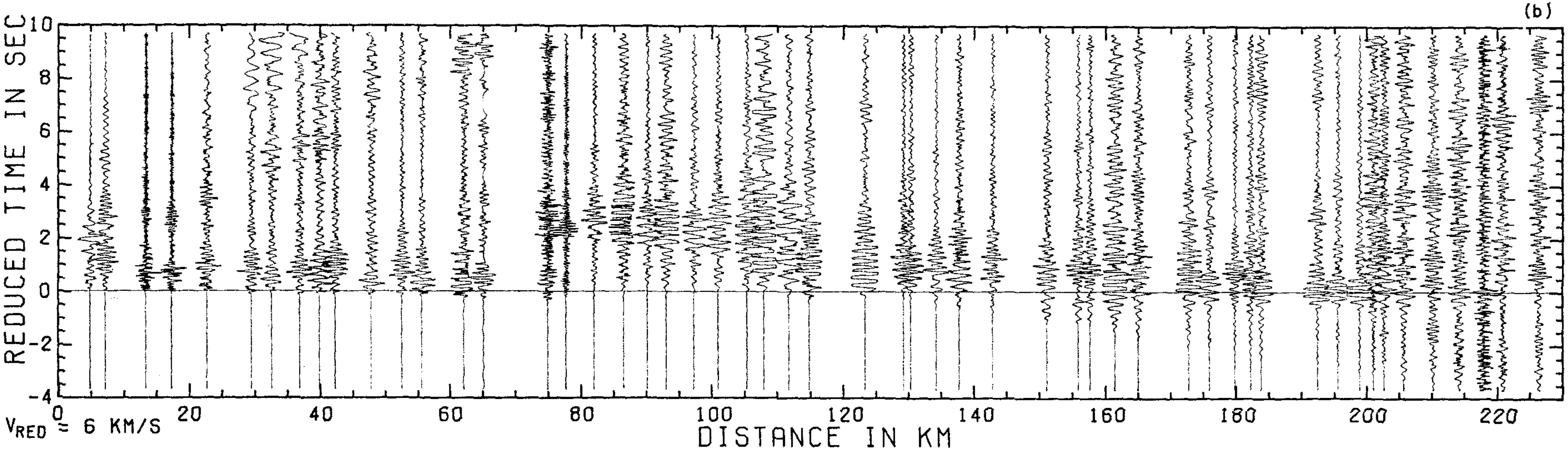

FIG. 5. Crustal record sections: (a) Shot-point 1 into ALPHA. (b) Shot-point N1 into ALPHA. Reduction velocity 6 km s$^{-1}$, seismograms plotted normalized and filtered 1–30 Hz.

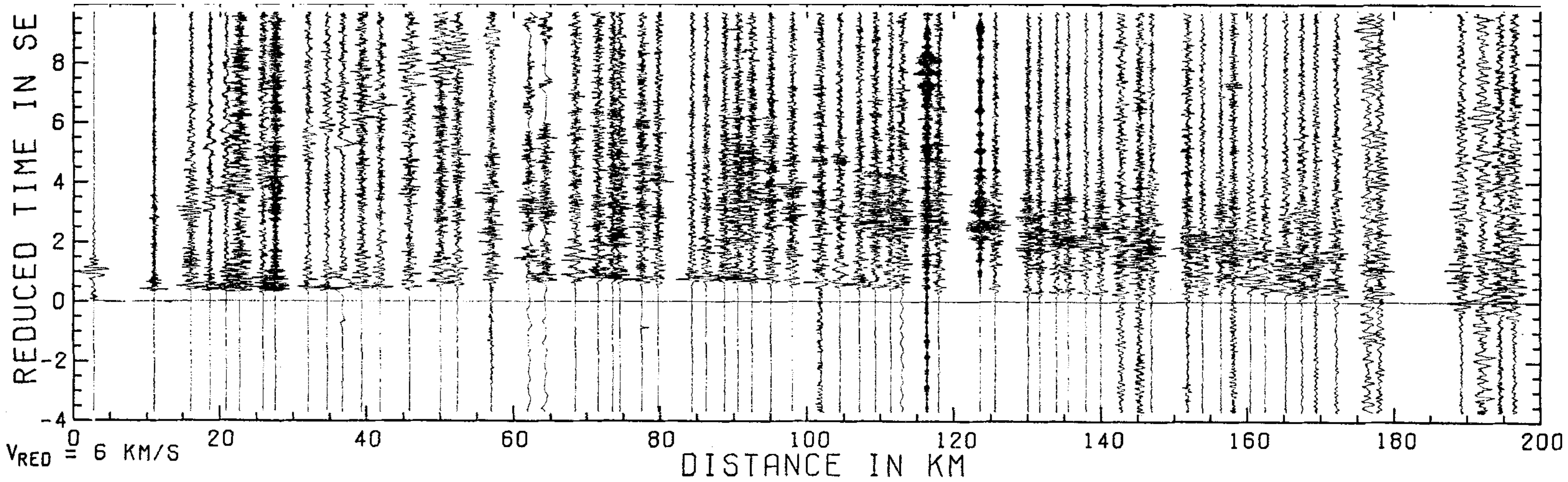

FIG. 6. Crustal record section for shot-point 4 into DELTA (not to complete range). Reduction velocity 6 km s$^{-1}$, seismograms plotted normalized and filtered 1–30 Hz.

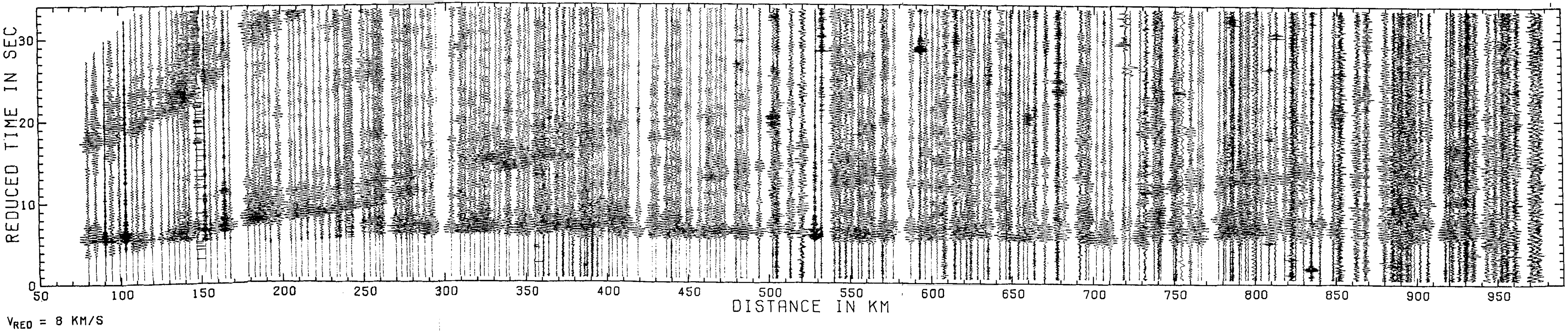

FIG. 10. The long-range profile observed from shot-point N2. Reduction velocity 8 km s$^{-1}$, seismograms plotted normalized and filtered 1–30 Hz.

have concentrated upon producing record sections of vertical seismometers for all profiles in our observation scheme (Fig. 2); examples of crustal data (reduced with a velocity of 6 km $s^{-1}$) are shown in Figs 5 and 6, and a long-range profile (reduction velocity 8 km $s^{-1}$) in Fig. 10. These sections do not always contain all the available seismograms; in distance ranges where observations are very closely spaced, some seismograms have been omitted so that the plots are not too confused.

## 4. Crustal profiles

The system of reversed and overlapping crustal profiles (Fig. 2) essentially serve two purposes. Primarily they are intended to establish, after a thorough interpretation, a crustal velocity cross-section of considerable detail which will be crucial to discussions of tectonic problems in the British Isles. Secondly, the data which bears on the structure of the lower lithosphere cannot be considered as a separate problem from that for the upper lithosphere and hence the crustal profiles also provide essential control for the long-range data.

Fairly obviously the presentation of a detailed velocity cross-section for the crust is a matter for considerable effort which will involve data processing, sophisticated interpretation methods and so on. However, a preliminary interpretation of the crustal profiles is desirable at this stage, especially to demonstrate just what degree of variation is to be expected in the crust. Such a description will necessarily be approximate and smoothed but will at least provide guide-lines for future interpretation of crustal data and for preliminary studies of long-range data.

### *Correlations and travel-time branches*

The crustal record sections which form the basis for this discussion, examples of which are shown in Figs 5 and 6, are plotted normalized (i.e. true amplitude information is not portrayed) with only broadband filtering (1–30 Hz). Furthermore, the dominant frequency varies according to the type of source, and processing which might be expected to improve the reliability of certain correlations (e.g. polarization filters) has not yet been attempted. For these reasons, correlations made at this stage should be regarded as at best preliminary—in some cases very tentative.

Bearing in mind the variations in geologic /tectonic structure crossed by the profiles, it is unlikely that a single system of travel-time curves could be recognized which, with only small fluctuations, would apply more or less to all observations; however, the following generalizations can be made:

The charge sizes were always adequate—the data are of good quality with generally clear first arrivals. Between zero and 120 to 140 km, first arrivals—with a character that varies from very impulsive to emergent—have apparent velocities ranging from 5·5 to 6·5 km $s^{-1}$: it is unlikely that the same horizon(s) are everywhere responsible for these arrivals and certainly it would be inappropriate to refer to them with any notation which presupposes their origin (e.g. $P_g$, $P^*$). Sometimes these arrivals continue quite strongly to 120–140 km but more often have become quite weak, eventually to be replaced as a first-arrival by a typically weak but clear $P_n$ phase with an apparent velocity in the range 8·0 to 8·3 km $s.^{-1}$.

Amongst later arrivals, the Moho reflected phase $P_M P$ may be seen on most sections; on sections within segment ALPHA, $P_M P$ is quite well developed (Fig. 5) but on others—especially on the southern half of BETA and on GAMMA—$P_M P$ can scarcely be detected. The data quality is much the same everywhere and thus such variations in $P_M P$ presumably imply real variations in the nature of the transition from lower crust to upper mantle. On many profiles there appears to be coherent energy lying in the record sections between the first arrivals and the $P_M P$

branch; presumably this energy is related to fine structure in the middle and lower crust.

One other second arrival should be noted. Beginning at about 140–160 km distance and moving with an apparent velocity close to 6 km $s^{-1}$ is a very strong phase; on Fig. 10, for example, this phase is seen very clearly to ranges in excess of 300 km. Although at shorter distances this phase arrives close in time to $P_M P$ it does not in fact appear to be related to a simple reflection from the crust–mantle transition: a possible interpretation of this phase is discussed towards the end of this section in connection with examples of velocity–depth functions.

In Fig. 7, preliminary first-arrival and $P_M P$ travel-time correlations on the crustal profiles are presented: in this figure, some variations in structure can be clearly seen. From this data, some preliminary models have been calculated.

## *Preliminary models*

The following two approximate methods have been used to give some preliminary ideas on crustal structure:

(i) $T^2 - X^2$ fits to $P_M P$—where observed—to give mean crustal velocities and crustal thicknesses; these results were then checked with a theoretical travel-time computer program in comparison with observed $P_M P$ and $P_n$ travel times.

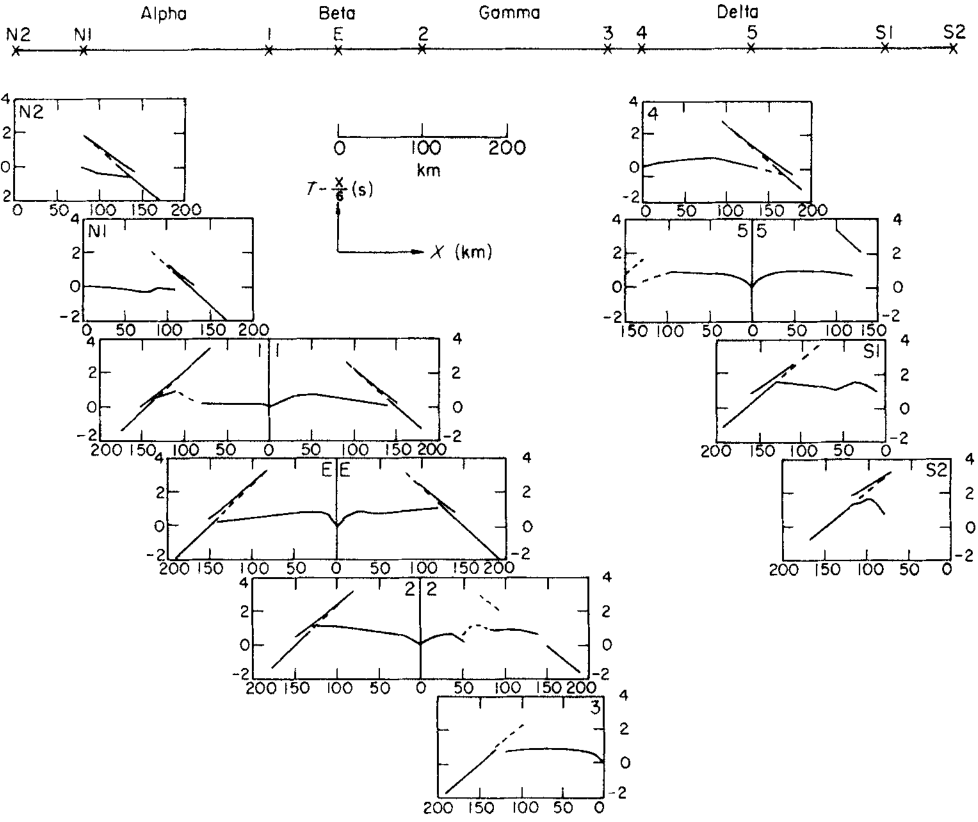

FIG. 7. Montage of reduced travel-time versus distance plots for crustal profiles. Only first-arrivals and $P_M P$ are plotted and the distance is restricted to 200 km.

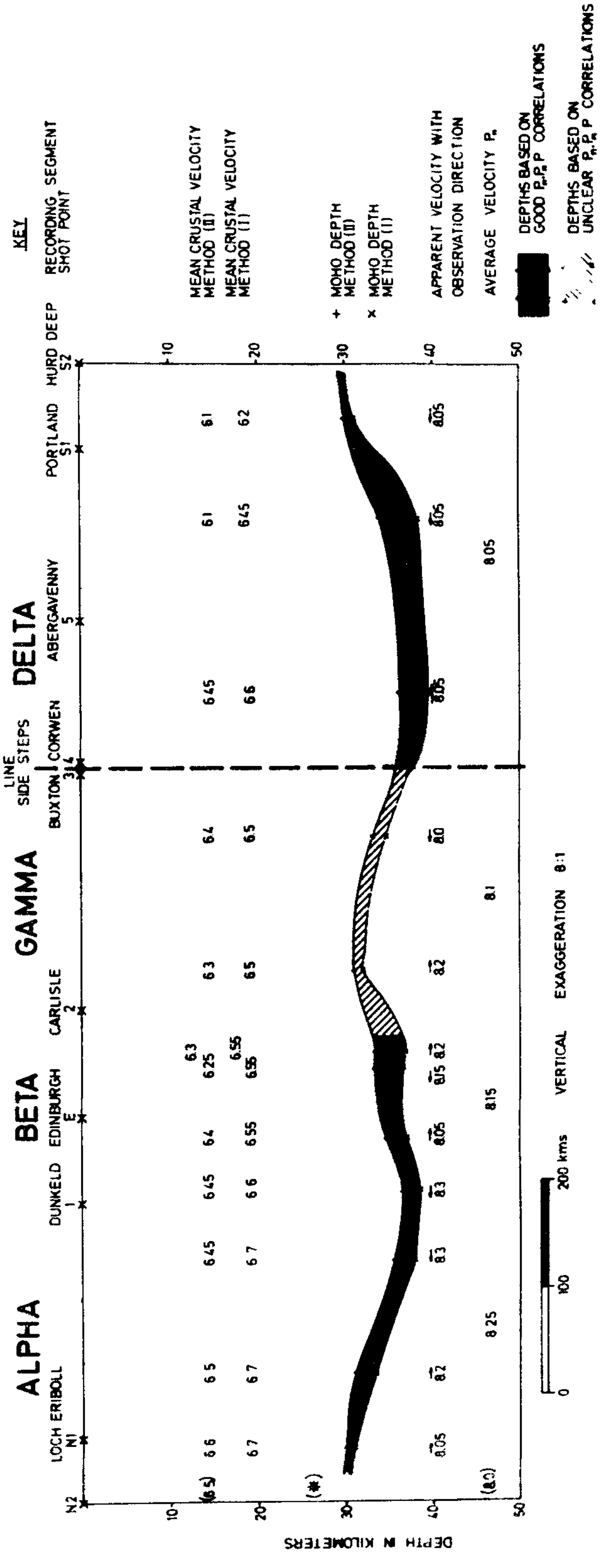

FIG. 8. Generalized crustal cross-section through the British Isles based on methods (i) ($T^2-X^2$) and (ii) (due to Holder & Bott (1971)): see text for discussion of methods. At the extreme left, the values of Smith & Bott (1975) are plotted (in brackets).

(ii) Use of formulas due to Holder & Bott (1971) which give mean crustal thickness ($H$) and mean crustal velocity ($\overline{V}$) from the following $P_n$ information:

critical range $x_c$,

velocity $v_n$,

intercept time $t_i$

thus

$$H = \tfrac{1}{2}(x_c \cdot t_i \cdot v_n)^{\frac{1}{2}}$$

$$\overline{V} = v_n(v_n \cdot t_i / x_c + 1)^{-\frac{1}{2}}$$

All the information based on these two methods together with $P_n$ velocities has been combined to give Fig. 8. As might be expected the values obtained using $T^2 - X^2$ are relatively high; taken together the results of (i) and (ii) above can be regarded as indicating a range of uncertainty, typically 3 km. In Fig. 8 the results of Smith & Bott (1975) for the Caledonian foreland to the north of Scotland have been included between N1 and N2; first impressions are of reasonable consistency.

Within Fig. 8, the main results of significance appear to be the relatively thin crust at the extreme north and south ends of the profile—presumably the thicker crust beneath the main Caledonian belt is the remnant root of the mountain belt—and the change in mean crustal velocity, possibly indicative of a change in crustal type from north to south. Furthermore, the crust–mantle boundary seems to be a clear boundary in the north and in the south but appears to be confused in the middle of the profile (Fig. 1).

We have attempted to establish preliminary velocity–depth functions for segment ALPHA and for the northern part of DELTA. Examples are shown in Fig. 9 for those profiles presented in record section form in Figs 5 and 6; theoretical travel-time curves and observed first-arrival and $P_M P$ travel times are compared. It might be expected that those aspects of these models which depend on clear features such as first-arrival or $P_M P$ travel-time branches might not change too dramatically in future interpretations whereas the fine structure might change in detail. However, fine structure in the middle and lower crust does appear to be necessary to explain the very energetic slow phase (velocity slightly greater than 6 km s$^{-1}$) so clearly observed from 150 km to beyond 300 km in many of our sections. Preliminary synthetic seismograms computed for models containing such fine structure (for example, the 1-ALPHA model in Fig. 9) do show substantial energy at the right time and distance; in the travel-time plot for this model we have included observed travel times for this phase in addition to first-arrivals and $P_M P$. Quantitative interpretation awaits true amplitude record sections. It is interesting to note a similar effect in the true amplitude section of Smith & Bott (1975, Fig. 2).

## 5. Long-range profiles

One of the three long-range profiles—reduced to 8 km s$^{-1}$ is presented in Fig. 10; immediately striking is the fact that clear arrivals are observed out to the full distance of observation (nearly 1000 km) thus vindicating the special shooting system (Jacob 1975) devised for the LISPB project.

Because of the evident variations within the upper lithosphere, which may either delay in time or change the amplitude of energy penetrating the lower lithosphere, we are reluctant to enter at this stage into explicit correlations which would imply details of the velocity–depth structure within the lower lithosphere. However, independently of whatever structure there is in the lithosphere, it is clear from the

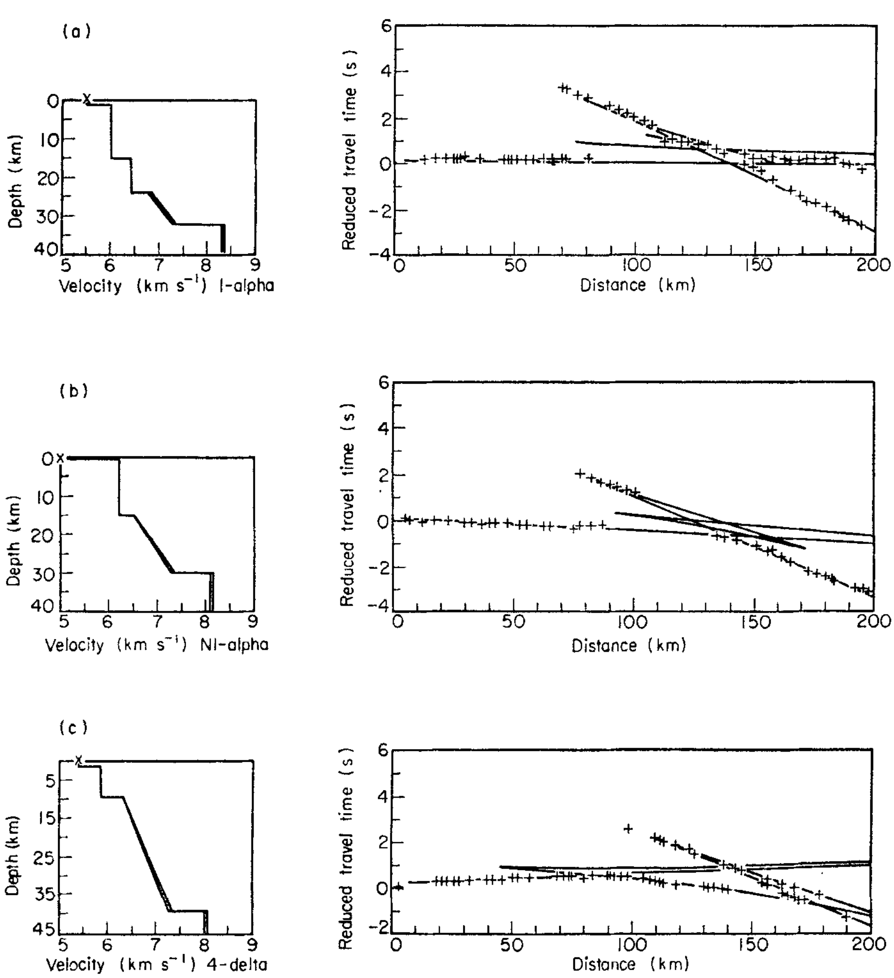

FIG. 9. Velocity–depth functions, theoretical and observed travel times for crustal profiles: (a) Shot-point 1 into ALPHA. (b) Shot-point N1 into ALPHA. (c) Shot-point 4 into DELTA. The reduction velocity is 6 km s$^{-1}$ in each case.

long-range profiles that the $P_n$ phase eventually dies away at 250–300 km; much stronger and slightly faster phases which have clearly penetrated the lower lithosphere are observed, typically from 200 to 250 km distance onwards.

The data on the other two long-range profiles (from shot-points N1 and S1) is also of good quality and the energy pattern seems to resemble that on N2. In addition, some of the energy observed on the longer crustal profiles (e.g. from shot-points E, 3 and 4—Fig. 2) has also penetrated the lower lithosphere. Hence this project offers a real opportunity to consider lateral variations in the structure of the lower lithosphere and, following a complete interpretation, will allow a meaningful comparison with other results describing the structure of the lower lithosphere, for example from the 1971 French profile (Hirn *et al.* 1973; Kind 1974).

## 6. Concluding remarks

In this preliminary paper, we have attempted to describe the LISPB project and to show that our efforts were successful. We believe that the LISPB data is of excellent quality and that there is sufficient information to permit an eventual detailed cross-section of lithospheric structure beneath the British Isles.

The preliminary interpretation presented here clearly shows that crustal structure does vary considerably throughout the British Isles; this result has the important implication that interpretation of the long-range profiles must take into account the variations in upper lithospheric structure.

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