Mechie, J., Brooks, M. (1984): A seismic study of deep geological structure in the Bristol Channel area, SW Britain. - *Geophysical Journal International*, *78*, 3, pp. 661—689.

DOI: http://doi.org/10.1111/j.1365-246X.1984.tb05064.x

Geophys. J. R. astr. Soc. (1984) **78**, 661–689

A seismic study of deep geological structure in the Bristol Channel area, SW Britain

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Received 1983 November 14; in original form 1983 July 11

Summary. Results from eight seismic refraction lines, 35–90 km long, in the Bristol Channel area are presented. The data, mostly land recordings of marine shots, have been interpreted mainly by ray-tracing and time-term modelling. Upper layer velocities through Palaeozoic rocks usually fall within the range 4.8–5.2 km s^{-1}. Below the Carboniferous Limestone with a normal velocity of 5.1–5.2 km s^{-1}, the Old Red Sandstone with a velocity of 4.7–4.8 km s^{-1} acts as a low velocity layer, as do parts of the underlying Lower Palaeozoic succession. In the central South Wales/Bristol Channel area and the Mendips, a 5.4–5.5 km s^{-1} refractor is correlated with a horizon at or near the top of the Lower Palaeozoic succession. Under the whole area, except for north Devon, a 6.0–6.2 km s^{-1} basal refractor has been located and is correlated with Precambrian crystalline basement rocks. In general, this refractor deepens southwards from a series of basement highs, which existed before the major movements of the Variscan orogeny in South Wales, resulting in a southerly thickening of the pre Upper Carboniferous supra-basement sequence. In north Devon, a 6.2 km s^{-1} refractor at shallow depth, interpreted as a horizon in the Devonian or Lower Palaeozoic succession, overlies a deep reflector that may represent the Precambrian crystalline basement.

1 Introduction and geology

In the period 1973–78, a series of seismic refraction experiments was completed in the Bristol Channel and surrounding land areas to obtain information on the geological structure of the top 5–10 km of the crust (Fig. 1). Brooks, Bayerly & Llewellyn (1977), Bayerly & Brooks (1980) and Llewellyn (1981) have provided interpretations of refraction lines completed before 1976 (thin lines, Fig. 1). Interpretation of subsequent lines (thick lines, Fig. 1) and a regional time-term analysis of a 6.0–6.2 km s^{-1} basal refractor, using all available data, was the purpose of a PhD project (Mechie 1980) and is summarized in this paper.

A geological map of the region is shown in Fig. 2. The land areas around the Bristol Channel are dominated by Variscan structures including the South Wales and Pembrokeshire Coalfields, the Mendip Hills, and the North Devon anticline. However, over large parts of the

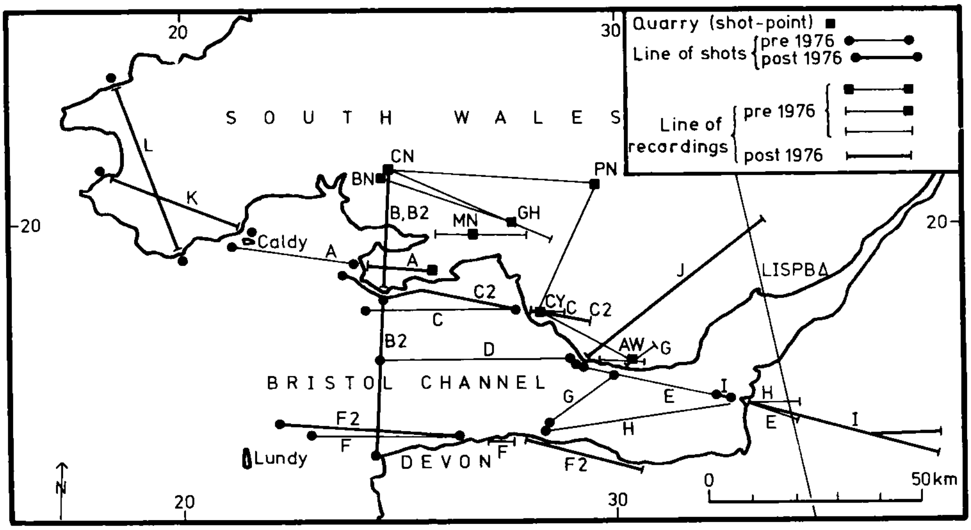

Figure 1. Large-scale seismic refraction lines in the Bristol Channel area.

region, including the Bristol Channel, the Vale of Glamorgan, SE Wales, and Somerset the Variscan terrains are concealed beneath a variable cover of Mesozoic rocks.

The South Wales and Pembrokeshire Coalfields represent a synclinal zone containing a thick sequence of Upper Carboniferous rocks. In the South Wales Coalfield, about 10 km east of refraction line B2, a maximum thickness of about 3 km of Upper Carboniferous rocks is preserved. North of the coalfield progressively older rocks occur, including Old Red Sandstone (ORS) and the thick Lower Palaeozoic sequence of the Welsh basin. In south-east Carmarthenshire (Cope 1977) and the St David's district of Pembrokeshire, Precambrian igneous and sedimentary rocks are preserved in local inliers. Line L crossed one such inlier, the Hayscastle anticline, and thus provided the opportunity to test for correlation between the 6.0–6.2 $km\,s^{-1}$ basal refractor and Precambrian rocks. In Pembrokeshire, the southern edge of the coalfield is partly defined by the Johnson thrust. Along this fault, Precambrian and Silurian rocks of the Johnston-Benton fault block (Brooks, Mechie & Llewellyn 1983), which lines K and L crossed, have been thrust northwards over Upper Carboniferous rocks. In southern Pembrokeshire, several E–W trending Variscan structures give rise to outcrops of Lower Ordovician to Upper Carboniferous rocks (see Fig. 2).

South of the South Wales Coalfield, in Gower and the Vale of Glamorgan, the dominant Palaeozoic rock-type exposed is Carboniferous Limestone. However, a series of en echelon WNW–ESE trending Variscan anticlines bring ORS and Silurian rocks to the surface. In south Gower, in the vicinity of lines B2 and C2, the Carboniferous Limestone is about 1 km thick but on the north and east crops of the coalfield, which lines B2 and J respectively crossed, the Carboniferous Limestone is very thin (30–200 m). Between the east crop and the Silurian rocks exposed in the core of the Usk anticline, a wide outcrop of ORS occurs which line J traversed.

In the Mendip Hills, where line I was located, Carboniferous Limestone, ORS, and Silurian rocks including volcanics emerge from beneath the Mesozoic cover in a series of en echelon, E–W trending Variscan periclines (Fig. 2). In north Devon and west Somerset, where line F2 was situated, a thick Devonian succession crops out in the major North Devon anticline (Fig. 2).

Beneath the Bristol Channel thick Mesozoic sequences are preserved in major E–W trending synclines. The most important of these is the Bristol Channel syncline which con-

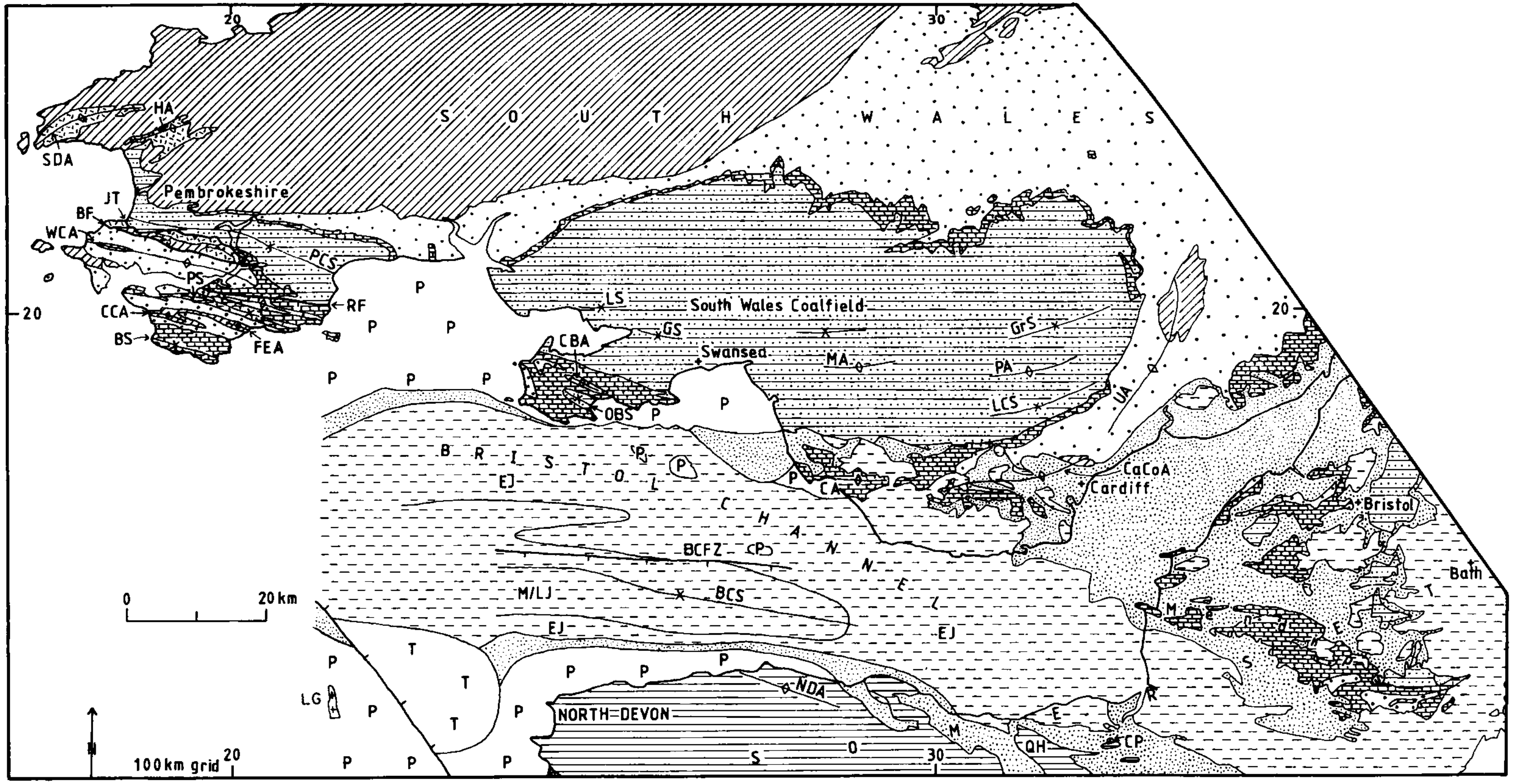

Figure 2. Geology of the Bristol Channel area.

Key:

Onshore

- Cretaceous
- Jurassic
- Permo–Trias
- Upper Carboniferous
- Lower Carboniferous
- Old Red Sandstone
- Marine Devonian
- Lower Palaeozoic
- Precambrian

Offshore

- Tertiary
- Middle–late Jurassic
- Early Jurassic
- Permo–Trias
- Palaeozoic
- syncline
- anticline
- fault (tick on down thrown side)
- thrust

JT Johnston thrust; BF Benton fault; BCFZ Bristol Channel fault zone; HA Hayscastle anticlines; PCS Pembrokeshire Coalfield syncline; CBA Cefn Bryn anticline; CaCoA Cardiff–Cowbridge anticline; UA Usk anticline; BCS Bristol Channel syncline; NDA North Devon anticline; LG Lundy granite (Tertiary); other unreferenced structures – see Mechie (1980).

tains about 2 km of Mesozoic rocks (Brooks & James 1975) of which the youngest are of late Jurassic age (Lloyd *et al.* 1973; Evans & Thompson 1979). The northern limb of the syncline is complicated by the major E–W trending Bristol Channel fault zone (Fig. 2). In the outer part of Barnstaple Bay, where the western shots of line F2 were located, a Tertiary basin (Fletcher 1975) containing about 350 m of sediments (Brooks & James 1975) is located immediately east of the Sticklepath fault.

In the study area, the prediction of the deep geological structure using seismic refraction data is complicated by the severity of the Variscan structures and the likely presence of major unconformities at depth. Direct information on the deep geology is limited to two boreholes drilled by Cambrian Exploration Ltd in the southern part of the South Wales Coalfield. These reveal the presence of 1–1.6 km of ORS and 350 km (base not reached) of Lower Palaeozoic rocks.

Previous seismic studies (Bayerly & Brooks 1980) suggested that the pre-Carboniferous supra-basement sequence thickens from under the central part of the South Wales Coalfield to beneath Gower and the Vale of Glamorgan. In the Bristol Channel, the success of the short marine refraction lines in delineating the structure of the Palaeozoic rocks beneath the thick Mesozoic cover has been limited 'due to the problem of overlapping velocity ranges for the main Upper Palaeozoic rock-types' (Brooks & Al-Saadi 1977).

2 Collection, processing, and methods of interpretation of data

Lines B2, C2, F2, I, J, K and L (Fig. 1) were established during a research cruise of RRS *John Murray* in 1976. Forty-one shots were fired using Superflex 200 explosive cord (Nobels). The shot instant was recorded by hydrophones towed in the vicinity of the explosive charges. Each marine shot was recorded on land at 10 three-component stations, using MARS 66 (Berckhemer 1976) and Racal Geostore analogue tape recording systems with HS-10 or Willmore Mk III seismometers and HBG or MSF time signal receivers. A total of 410 recordings was made during the experiment.

During 1977–78, 42 additional recordings were obtained from four marine shots, fired from MV *Edward Forbes*, and 10 quarry blasts, in order to improve the regional time-term analysis of the basal refractor.

Shot position fixing at sea was achieved by radar and Decca fixes and the maximum positional error is estimated to be ± 200 m. On land, the positions of recording stations and quarry blast locations were located with an accuracy of ± 25 m or better.

Lines B2, C2 and F2 each comprise a long line of eight or nine shots fired into an in-line recording array of ten stations, while lines I and J have essentially one shot-point fired into an in-line recording array of around 25 stations (Fig. 1). In Pembrokeshire, two conventional reversed lines, K and L, were established.

Data were digitized at 100 samples s^{-1}. Figs 3, 6, 7, 9, 10, 12, 15 and 16 show, for 2.25 s of the vertical components, normalized and filtered *P*-wave record sections, plotted with a reduction velocity of 6 km s^{-1}. In these record sections the seismograms have been relatively shifted to correct first arrival times for water depth, elevation, Mesozoic rocks and, on line B2, Upper Carboniferous rocks. Of the corrections which were made, only those for Mesozoic and Upper Carboniferous rocks on line B2 were significant. In the ray-tracing analysis, the observed travel-times were only corrected for water depth and elevation. The Mesozoic and Upper Carboniferous rocks were included in the ray-tracing models. The direct and refracted phases P_0, P_0', P_1 and P_2, drawn in on the record sections, have been fitted to the arrivals as T–X straight lines by least-squares. Thus, apparent velocities and intercept times, together with standard error estimates, have been obtained for the phases. The P_0 and P_0' phases represent direct or refracted waves through the upper layers. The P_1 phase represents a refracted wave from an intermediate layer with a true velocity of about 5.5 km s^{-1}. The P_2 phase represents the wave from the 6.0–6.2 km s^{-1} basal refractor.

As a first step in interpreting the data, a planar-layer interpretation was derived for each line (Johnson 1976). In the case of lines B2, C2 and F2, the interstation and intershot velocities were used as the forward and reverse apparent velocities respectively. In most cases, the planar-layer interpretations were taken as starting models for two-dimensional modelling using the ray-tracing method for laterally inhomogeneous media with curved interfaces (Červený, Langer & Pšenčík 1974). The starting models were adjusted by manual iteration until the observed travel times closely matched the calculated (ray-tracing) travel-times. The average absolute differences between the observed and calculated travel-times are given in Table 1. In addition, the time-term method (Willmore & Bancroft 1960; Berry & West 1966) was used to obtain a three-dimensional picture of the 6.0–6.2 km s^{-1} basal refractor using arrivals from this refractor obtained from the 1976–78 experiments together with those from previous experiments (Bayerly & Brooks 1980; Llewellyn 1981).

Table 1. Average absolute differences between observed travel times and those calculated by ray-tracing for phases P_1 and P_2 from the various seismic refraction lines.

Phase	P_1		P_2	
Line	Difference (s)	No. of observations	Difference (s)	No. of observations
L	–	–	0.03	16
K	–	–	0.05	16
B2	0.03	12	0.05	19
C2	0.05	13	0.07	26
J	0.04	6	0.04	5
I	0.03	9	0.02	6

3 Lines in Pembrokeshire – K, L

Two lines, K and L (Fig. 1), both reversed with effectively one shot-point at each end and 18–20 recording stations about 2 km apart, were completed in Pembrokeshire. Both lines, for which the record sections are shown in Fig. 3, were approximately 40 km long and crossed at a common recording station, K12–L8.

Line L trends NNW–SSE, almost perpendicular to the local geological strike, and crosses a variety of Caledonian and Variscan structures. The northern part of the line (recording stations L11–L20) mainly crosses ENE–WSW trending Caledonian structures, the chief of which is the Hayscastle anticline exposing Precambrian igneous rocks in its core (Figs 2 and 4). The southern part of the line (recording stations L1–L10) crosses E–W trending Variscan structures, including the synclinal structure of the Pembrokeshire Coalfield and, at the southern edge of the coalfield, the Johnston thrust defining the northern margin of the Johnson–Benton fault block. The southern boundary of the block is defined by the Benton fault, which brings ORS against ORS, Silurian, or Precambrian rocks along a southerly dipping fault plane (Figs 2 and 4) (Hancock, Dunne & Tringham 1983). Line K runs almost parallel to the trend of local Variscan structures. West of station K9, it follows the line of the Johnston–Benton fault block while east of station K9, it follows approximately the Carboniferous Limestone outcrop on the southern limb of the Pembrokeshire coalfield (Figs 2 and 5).

On record section L(S) (Fig. 3a), the direct phase P_0 has a velocity of 5.01 ± 0.06 km s^{-1} which represents an average velocity through a varied sequence of Precambrian to Upper Carboniferous rocks. However, along the southern part of line L there is a 13 km section of

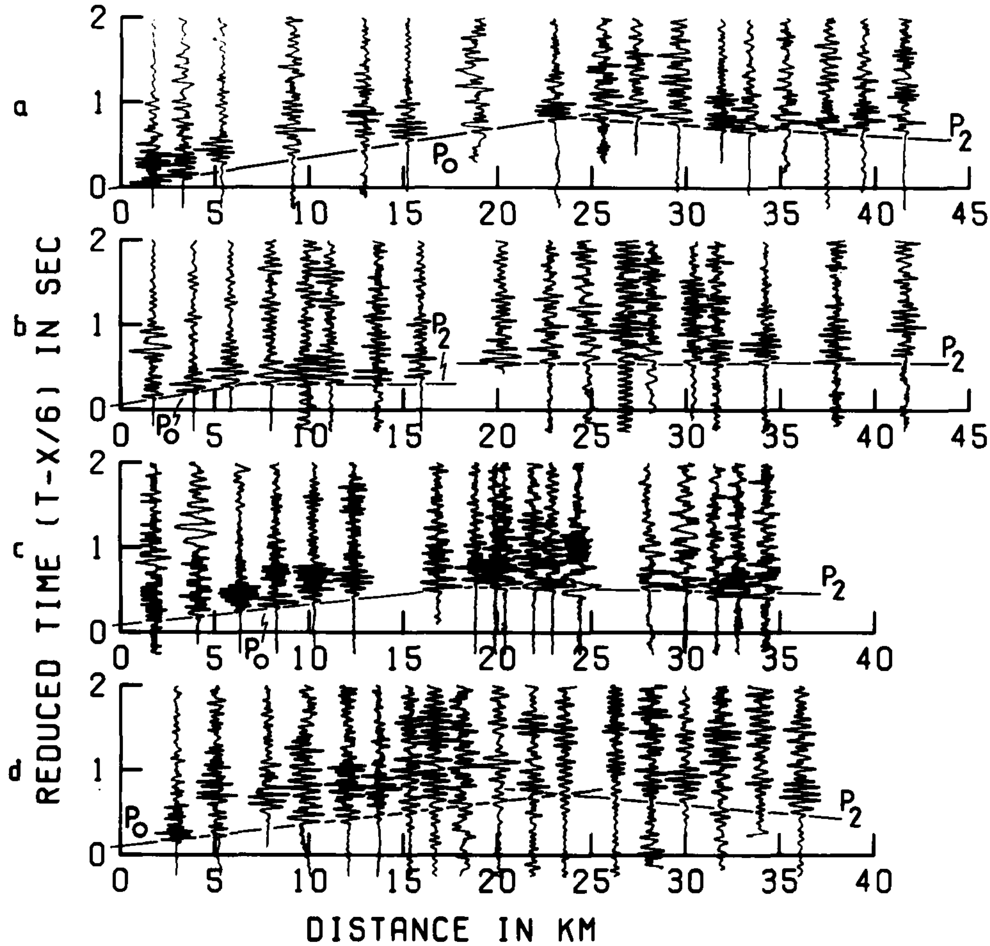

Figure 3. Normalized, band-pass filtered record sections for (a) L(S), (b) L(N), (c) K(W) and (d) K(E), plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the P-wave arrivals.

which 9.2 km are represented by ORS and the velocity of 4.85 ± 0.13 km s^{-1} across this 13 km section must be close to the local ORS velocity. The onsets on the first two traces from record section L(N) (Fig. 3b) poorly define the direct phase P_0 with a velocity of 4.86 km s^{-1}. This is the only case in the study area where a direct phase through the varied Upper Cambrian–Lower Ordovician sequence has been observed and thus the local velocity represents the only direct evidence of the velocity of this major rock interval. On record section K(W) (Fig. 3c), the direct phase P_0 has a velocity of 5.22 ± 0.06 km s^{-1} representing, again, an average velocity through a varied sequence of Precambrian to Upper Carboniferous rocks. Finally, the direct phase P_0, on record section K(E) (Fig. 3d), has a velocity of 5.20 ± 0.19 km s^{-1} representing Carboniferous rocks.

The remainder of the onsets define arrivals of the phase P_2 from the basal refractor, with apparent velocities of 6.46 ± 0.12, 5.96 ± 0.07, 6.19 ± 0.09, and 6.82 ± 0.11 km s^{-1} on record sections L(S), L(N), K(W) and K(E) respectively (Fig. 3a–d).

Two-layer dipping models for lines L and K gave true velocities for phase P_2 of 6.19 ± 0.10 and 6.48 ± 0.18 km s^{-1} respectively, while time-term solutions for the data of lines L and K resulted in refractor velocities of 6.05–6.22 km s^{-1}. In addition to these results, true velocity values of 6.0–6.2 km s^{-1} for the basal refractor are almost everywhere encountered throughout the South Wales/Bristol Channel region (see Bayerly & Brooks 1980; Brooks *et al.* 1983; sections 4 and 5), and thus the value of 6.48 km s^{-1} obtained from the planar-layer interpretation of line K appears anomalous. As the two apparent velocities observed along line K are determined from different sections of the refractor, however, it is possible that both are up-dip apparent velocities (see p. 669). Thus, in the ray-tracing interpretation, in which a vertical velocity gradient is necessary in a layer in order to make the ray curve, true velocities of 6.1 and 6.3 km s^{-1} were used at the top and bottom, respectively, of the basal layer (Figs 4 and 5).

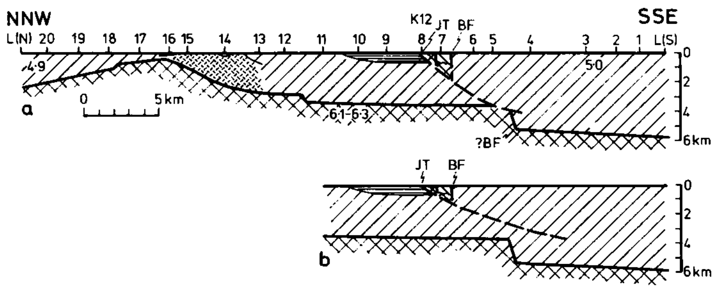

Figure 4. Combined ray-tracing and geological model for line L. Key: ray-tracing interfaces ——; ray-tracing velocities in km s^{-1}; faults — —; other geological boundaries ——; Upper Carboniferous; pre-Upper Carboniferous supra-basement rocks; Silurian; Precambrian volcanics; Precambrian crystalline basement rocks; JT Johnston thrust; BF Benton fault.

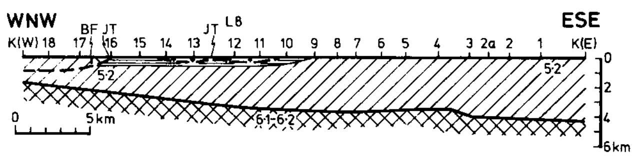

Figure 5. Combined ray-tracing and geological model for line K. Key as for Fig. 4.

Anomalies in the arrival times of refracted rays, such as early arrival times at stations in the vicinity of the Hayscastle anticline, seemed to be better correlated with the structure of the basal refractor than with variations in top layer velocity. Thus, in attempting to interpret the anomalies in terms of refractor structure, the rock-types above the basal refractor on both lines were modelled with the constant velocities (Figs 4 and 5) derived for the direct phase P_0 (Fig. 3a–d). For the models shown in Figs 4 and 5, ignoring variations in velocity of surface rock-types may lead to maximum errors of 0.03 s for rays travelling through the Precambrian rocks of the Johnston–Benton fault block.

Time-term solutions for the data of lines L and K showed the shallowest depths to the basal refractor, of 0–0.7 km, beneath station L16, immediately north of the outcropping Precambrian in the Hayscastle anticline. Thus, the refractor depth beneath station L16 was set equal to 0.3–0.4 km in the ray-tracing interpretation (Figs 4 and 5), for which the average absolute differences between calculated and observed travel-times are 0.03 and 0.05 s for lines L and K respectively (Table 1).

The ray-tracing interpretation shows that, where the Precambrian volcanics crop out in the Hayscastle anticline, the basal refractor is encountered at depths of 1–2 km and that, at least locally, it must represent Precambrian rocks. This 6.0–6.2 km s^{-1} refractor, encountered throughout the South Wales/Bristol Channel region, is thought to represent a Precambrian crystalline basement, partly intrusive igneous and partly metamorphic in character. In considering the possibility of a 1–2 km thickness of volcanics in the Hayscastle anticline, it may be noted that 13 km to the west, in the St David's area, a thickness of 1.5 km (base unseen) of Precambrian volcanics has been recorded (George 1970). North of the Hayscastle anticline, the ray-tracing interpretation suggests that the basal refractor shallows and that, consequently, the Precambrian volcanics decrease by about 1.7 km in thickness towards station L16 (Fig. 4).

North and south of station 16, the depths to the refractor increase to 1.5–2 km under the northern end of the line and to about 3.5 km under the Pembrokeshire Coalfield. On record section L(N) (Fig. 3b), there is a time-shift of 0.23 s in the refracted phase P_2 between stations L11 and L13. In the ray-tracing interpretation (Fig. 4) this time-shift results in a step of 600 m in the refractor, downthrowing to the south, just north of station L11. To account for the delay in arrival times of refracted rays at the southern shot-point and station L1, another step feature is introduced in the ray-tracing model between stations L4 and L5 with a downthrow to the south of 1–2 km. Thus, at the southern end of line L, the depth to the refractor is around 5.5 km.

The ray-tracing model for line K (Fig. 5) shows that the shallowest refractor depths of about 2 km occur beneath the western end of the Johnston–Benton fault block. Depths to the

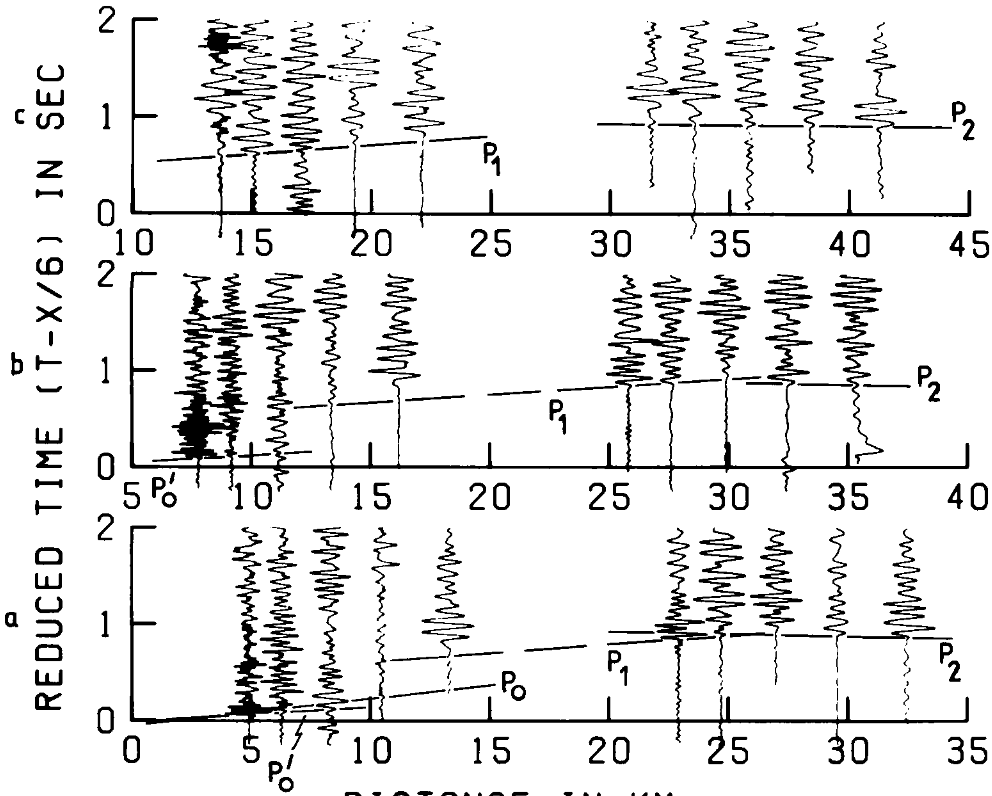

Figure 6. Normalized, band-pass filtered record sections for line B2 for shots (a) 2, (b) 3, (c) 5, (d) 7, (e) 8 and (f) 9 to all stations, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the *P*-wave arrivals.

refractor increase to about 3.5 km beneath the eastern end of the Johnston–Benton fault block. Further east, depths remain at 3.5–3.8 km before increasing to 4–4.5 km near the eastern end of the line. The structure of the refractor beneath line K, as shown in the ray-tracing model (Fig. 5), is such that an updip apparent velocity would be observed beneath the western part of the line from the eastern shot-point while approximately the true velocity would be observed beneath the eastern part of the line from the western shot-point. This is in agreement with the apparent velocities of 6.19 and 6.82 km s^{-1} determined for phase P_2 on record sections K(W) and K(E) respectively (Fig. 3c, d).

Where both lines cross the Johnston–Benton fault block at its eastern end, the depth to the refractor, which is correlated with the Precambrian crystalline basement (see above), is about 3.5 km. Thus it seems that the Precambrian rocks of the Johnston–Benton fault block are contained within an isolated thrust slice with a source at depth to the south.

At the western end of the Johnston–Benton fault block the Johnston thrust dips south to SW at 25–45°. Thus, in one model (Fig. 4a) the Johnston thrust is shown to dip 45° S at the surface. On this view it is possible that the southernmost step of 1–2 km in the basal refractor represents the downward continuation, displaced along the Johnston thrust, of the Benton fault. In this connection, while little or no movement took place along the Benton fault at the end of the Carboniferous, substantial movement occurred of post lower ORS–pre-Carboniferous age (Strahan *et al.* 1914). A downthrow to the south exceeding 1.5 km

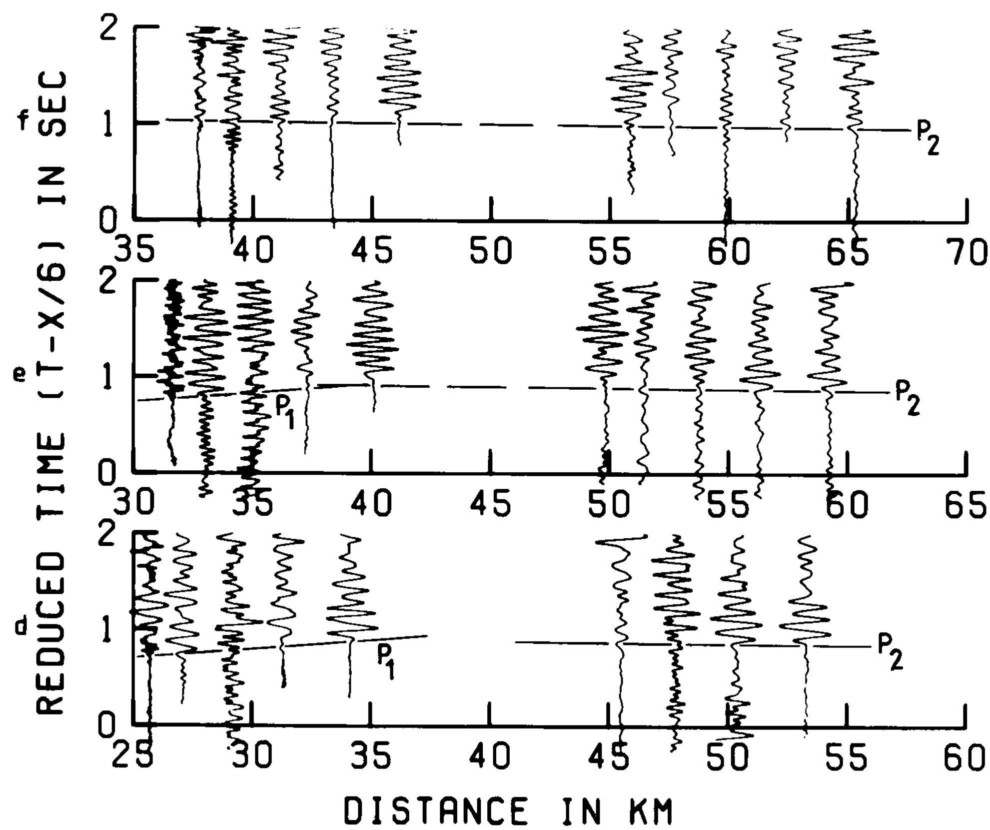

Figure 6 – *continued*

(Hancock *et al.* 1983) is indicated where the fault is exposed about 5 km east of station L7. This model requires about 3–4 km of vertical movement and 4–5 km of horizontal movement along the Johnston thrust. An unknown but possibly substantial amount of movement took place along the Johnston thrust at the end of the Carboniferous (Strahan *et al.* 1914; George 1970).

In the other model (Fig. 4b) the Johnston thrust is shown to dip 30° S at the surface. In this case, no correlation between the southernmost step feature in the basal refractor and the Benton fault is possible. Moreover, greater horizontal and vertical movements than those shown in Fig. 4(a) are required along the Johnston thrust. One possible major difficulty with both models is, however, that at the eastern end of the Johnston–Benton fault block, about 5 km east of line L, the geological evidence for the eastward continuation of a major thrust is debatable. Hancock *et al.* (1983) stated that at the eastern end of the block the Johnston thrust 'is represented by a swarm of subordinate splay faults' and that 'the total displacement is reduced to 500 m'. On this basis they refute the views of Sanzen-Baker (1972) and Owen (1974) that the Johnston thrust continues east of the block as a major structure with significant displacement along it. Nevertheless, the present seismic interpretation suggests that the structural setting for the Precambrian rocks of the block does involve major thrust faulting.

4 Lines in the Central South Wales/Bristol Channel area and the Mendips – B2, CY-A, C2, J, I

In this area, five profiles were completed: four, B2, C2, I and J, using marine shots and one, CY-A, using quarry blasts (Fig. 1).

4.1 LINE B2

Line B2 was a N–S line, planned as an extension of earlier line B (Fig. 1). The line was 65 km long, with nine marine shots fired across the Bristol Channel and 10 recording stations set up across Gower and the northern limb of the South Wales Coalfield (Fig. 8). The line crossed several major E–W trending structures. In the Bristol Channel, the profile first crossed, at its southern end, Devonian rocks (Lloyd *et al.* 1973). It then crossed the Mesozoic rocks of the Bristol Channel syncline (BCS) (Figs 2 and 8) and, further north, the Helwick syncline. Estimates of the maximum thickness of Mesozoic strata preserved in the centre of the Bristol Channel syncline include 1.85 km (Lloyd *et al.* 1973), 2.1 ± 0.3 km (Brooks & James 1975), and 2.47 ± 0.18 km (Evans & Thompson 1979). Brooks & James (1975) and Evans & Thompson (1979) postulated a southerly downthrow of about 1 km on the Bristol Channel fault zone (BCFZ). The Helwick syncline contains about 300 m of Mesozoic strata beneath line B2 (C. R. Price, private communication).

The five recording stations on Gower were sited on Carboniferous Limestone, although the line also crossed the Cefn Bryn anticline (CBA) exposing ORS in its core. Immediately north of Gower, the line crossed on to the steeply dipping southern limb of the South Wales Coalfield. Where the line crossed the main synclinal axis of the coalfield, geological data (Archer 1968) suggest a thickness of around 2.6 km of Upper Carboniferous rocks. After crossing the gently dipping northern limb of the coalfield, the line ended on the north crop of Carboniferous Limestone flanking the coalfield (Fig. 8).

Between shot 3 and station 3 phase P_0', with a velocity of $5.52 \pm 0.03\ \mathrm{km\,s^{-1}}$, is observed (Figs 6a, b and 7a). A similar phase was observed by Bayerly & Brooks (1980) and Llewellyn (1981) at short range in the Carboniferous Limestone in the South Wales area. Bayerly & Brooks (1980) attributed the phase to dolomitized sections of Carboniferous Limestone and

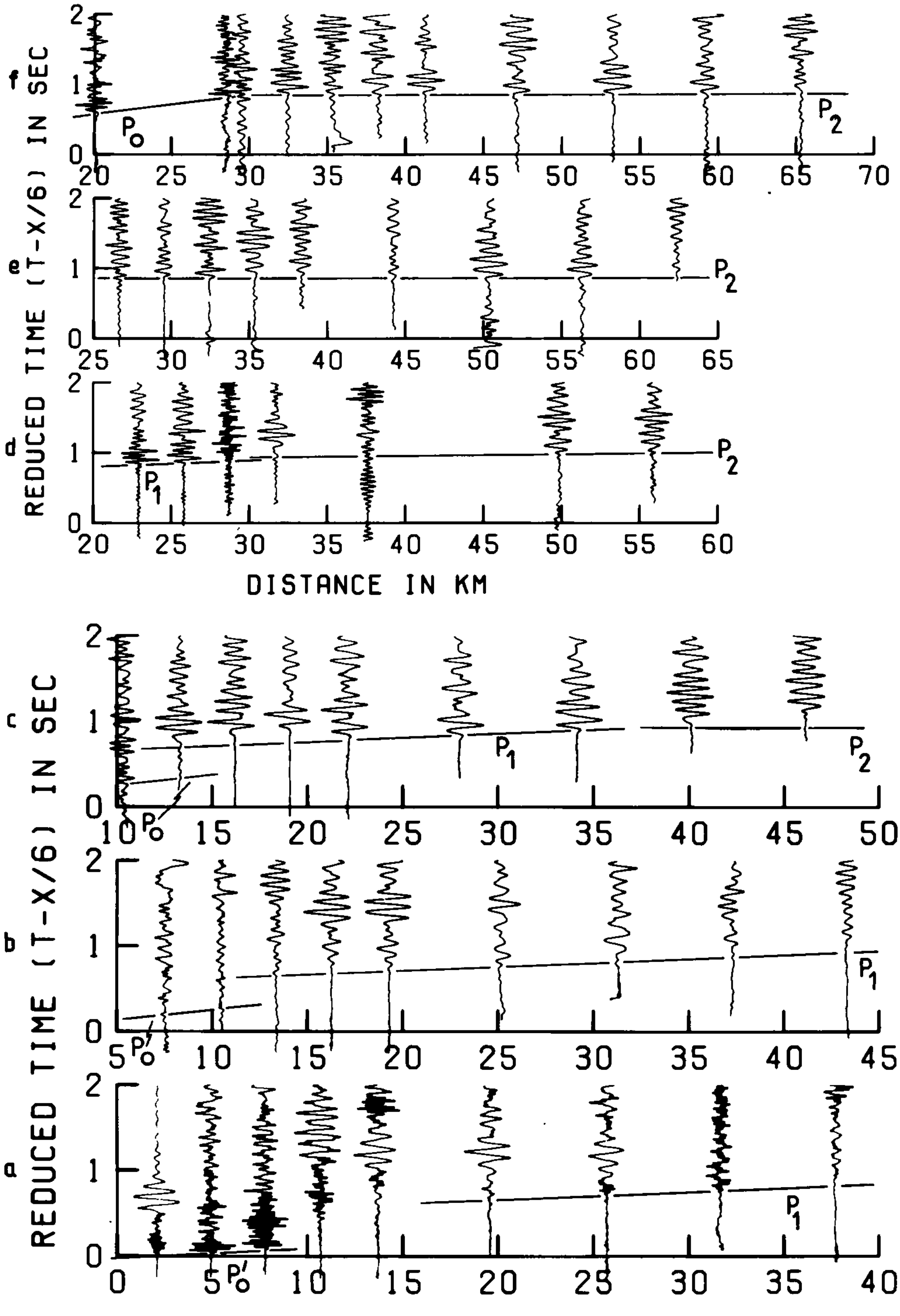

Figure 7. Normalized, band-pass filtered record sections for line B2 for stations (a) 1, (b) 4, (c) 5, (d) 6, (e) 9 and (f) 10 to all shots, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the *P*-wave arrivals.

suggested that wedging out or faulting out of the dolomitized zone might account for the disappearance of the phase at greater ranges. North of shot 3, phase P_0, with a velocity of $5.11 \pm 0.06\,\mathrm{km\,s^{-1}}$, is observed (Figs 6a and 7b, c, f). If the P_0 (and P_0') phases represent arrivals from Carboniferous Limestone, it follows that the limestone exists beneath the coalfield and extends south of Gower, under the Mesozoic rocks, at least as far south as shot 3. The amplitudes of the P_0 and P_0' phases often decay quite rapidly to the point where the phase is no longer observable as a first arrival (Figs 6a, b and 7a–c). Hence, between shots 3 and 9 no phase through the upper layers was observed. Thus, in the various interpretations (see, e.g. Fig. 8), the velocity in these layers between shots 3 and 9 is only assumed.

Phase P_1 is observed with an interstation apparent velocity of $5.39 \pm 0.08\,\mathrm{km\,s^{-1}}$ (Fig. 6a–f) and an intershot apparent velocity of $5.68 \pm 0.04\,\mathrm{km\,s^{-1}}$ (Fig. 7a–d). Phase P_2 has an interstation apparent velocity of $6.09 \pm 0.03\,\mathrm{km\,s^{-1}}$ (Fig. 6a, c–f) and an intershot apparent velocity of $5.97 \pm 0.04\,\mathrm{km\,s^{-1}}$ (Fig. 7c–f). True velocities of $5.52 \pm 0.09\,\mathrm{km\,s^{-1}}$ and $6.01 \pm 0.15\,\mathrm{km\,s^{-1}}$ were derived for phases P_1 and P_2 from a planar-layer interpretation and these velocities are approximately equal to the average velocities of the layers propagating the P_1 and P_2 phases in the ray-tracing analysis discussed below (Fig. 8). The planar-layer interpretation showed that the refractors propagating the P_1 and P_2 phases dip north and south, respectively, and that the former wedges out north of station 7. Thus, these features were included in the ray-tracing analysis.

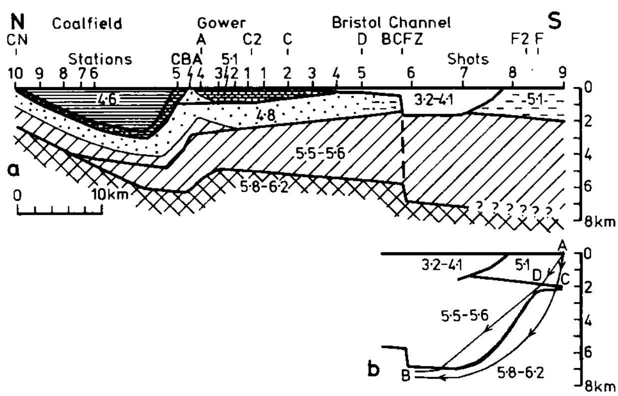

Figure 8. **Combined ray-tracing and geological model for line B2. Key: ray tracing interfaces —; ray-tracing velocities in km s⁻¹; faults – –; other geological boundaries —; ☐ Mesozoic rocks; ▤ Upper Carboniferous; ▦ Carboniferous Limestone; ▩ Old Red Sandstone; ▧ marine Devonian rocks; ▨ Lower Palaeozoic/?Precambrian supra-basement rocks; ▩ Precambrian crystalline basement rocks; cross-over points with other lines are indicated (*cf.* Fig. 1). (b) Shows alternative interpretation at south end of line (see Section 5).**

For the final ray-tracing model (Fig. 8), the averave absolute differences between calculated and observed travel-times for the P_1 and P_2 phases are 0.03 and 0.05 s respectively (Table 1). Results from marine seismic surveys were used to delineate the base of the Mesozoic sequence in the Bristol Channel syncline (Brooks & James 1975; C. R. Price, private communication) and Geological Survey maps and borehole data (Archer 1968) were used to delineate the base of the Upper Carboniferous succession in the South Wales Coalfield (see above).

The thickness of the Carboniferous Limestone is 900 m in south Gower and decreases to 200 m north of the coalfield (George 1970) and to nil between shots 3 and 8. These thicknesses are too small to account for the delay times to the refractor propagating the P_1 phase.

Thus the material above this refractor must include the ORS. Thickness estimates of the ORS near the northern end of the line range from 1 km (Cope 1979) to 1.5 km (George 1970). Thus it seems likely that under the coalfield low velocity Lower Palaeozoic and, possibly, Precambrian rocks are present to account for the large delay times to the refractors propagating the P_1 and P_2 phases (Fig. 8). In South Wales, velocities of 4.69–4.85 km s^{-1} have been obtained for the ORS from refraction profile measurements (see Section 3; James 1971; Bayerly 1978). In north Pembrokeshire a velocity of 4.86 km s^{-1} for low velocity Lower Palaeozoic rocks was also encountered (see Section 3). Thus in the ray-tracing analysis the low velocity layer consisting of ORS, Lower Palaeozoic and, possibly, Precambrian rocks was assigned a velocity of 4.8 km s^{-1}. Across the Bristol Channel there is a lateral transition of ORS into marine Devonian rocks which have a higher velocity (Brooks *et al.* 1977) and the low velocity layer, mainly representing ORS, is thus truncated under the Bristol Channel (Fig. 8).

Under the southern Bristol Channel, from thickness estimates of the Devonian in nearby north Devon (Edmonds, McKeown & Williams 1975), it is thought that the 5.5 km s^{-1} refractor, occurring at a depth of about 2 km, represents approximately the top of the Lower Palaeozoic. Between shots 6 and 7 the 5.5 km s^{-1} refractor is interpreted to lie directly beneath the Mesozoic rocks of the Bristol Channel syncline, suggesting that the syncline is located over a pre-existing anticlinal structure from which the Upper Palaeozoic section has been eroded. Under Gower and the northern Bristol Channel, it is uncertain whether the low velocity layer includes a few hundred metres of Lower Palaeozoic rocks or whether the 5.5 km s^{-1} refractor, at 1.5–3 km depth, represents the top of the Lower Palaeozoic succession. Beneath the coalfield, the 5.5 km s^{-1} refractor falls to a depth of 4–5 km and eventually wedges out north of station 7 (Fig. 8).

By virtue of its velocity and depth, the refractor propagating the P_2 phase is thought to represent Precambrian crystalline basement rocks (*cf.* Section 3). Except for a local deepening beneath the coalfield, this refractor dips southwards from about 2.5 km in the north to around 7.5 km in the south (Fig. 8). Hence, although the 5.5 km s^{-1} refractor may not represent a constant geological horizon along line B2, it is safe to conclude from the above discussion that there is a southwards thickening of the Lower Palaeozoic/?Precambrian supra-basement sequence under Gower and the Bristol Channel (Fig. 8). To account for the delay in arrivals times at shot 9, the basal refractor exhibits a step feature which may be the continuation at depth of the Bristol Channel fault zone (Fig. 8). The only reason why the model does not show the step feature in the 5.5 km s^{-1} refractor is that the model does not test its existence.

Line B2 crossed several E–W trending refraction lines (Figs 1 and 8) and except for the case of lines F2 and F (see Section 5), depths to the refractors propagating the P_1 and P_2 phases at crossover points with other lines are in agreement to within 1.5 km (Table 2).

4.2 LINE C2

Line C2, 60 km long, was planned to complement earlier line C (Fig. 1). Nine marine shots were fired in an E–W line across the northern Bristol Channel sited, as often as possible, on Carboniferous rocks to avoid the thick Mesozoic sequences further south (Figs 2 and 11). On land, 10 recording stations were set up across the western Vale of Glamorgan sited either on Carboniferous Limestone or on a thin veneer of Mesozoic rocks (Fig. 11).

As on line B2 phase P_0', with a velocity of 6.00 ± 0.15 km s^{-1}, is observed at short range (Fig. 9a, b). On line C2 it occurs between stations 1 and 5, near Cornelly Quarry, in the same area that Bayerly & Brooks (1980) and Llewellyn (1981) found a similar phase associated with the local Carboniferous Limestone. Between shot 2 and station 3 phase P_0 is observed

Table 2. Comparison of depths (in km) to the refractors propagating the P_1 and P_2 phases at crossover points between the various seismic refraction lines.

Phase	P_1		P_2	
Line	Cross-profile	Profile B2	Cross-profile	Profile B2
B[a]	2.8[5]	2.2–3	–	–
CN	–	–	2.9–3.7[3]	2.2
A	1.6–2.5[2]	2.7	5.9[3]	5.5
C2	2.4[4]	2.4	5.4[4]	5.0
C	2.2[5]	2.2	–	–
D	2.2[1]	1.7	5.2[1]	5.5
F2	–	–	2.3[4]	?7.5
F	0.9[1]	1.9	2.2[1]	?7.5
		Profile C2		Profile C2
C	2.2[5]	2–2.5	–	–
CY (– PN)	–	–	3.9[5]	4.2
CY (– AW)	1.8[3]	2.3	4.7–5.3[3]	4.2
B2	2.4[4]	2.4	5.0[4]	5.4
		Profile J		Profile J
D	2.2[1]	2.5	5.2[1]	5.8
CY–AW	0.9–1.7[2,3]	2.4	4.1–5.4[2,3]	5.5
LISPB	–	–	6[6]	–
		Profile I		Profile I
E	1.2[5]	1.6	6.7[5]	5.6
H	–	–	6.5–10.2[5]	5.6
LISPB	–	–	6[6]	5.6

[1] Brooks *et al.* (1977).
[2] Bayerly (1978).
[3] Bayerly & Brooks (1980).
[4] This study.
[5] Llewellyn (1981).
[6] K. R. Nunn (private communication).
[a] Depths do not include Upper Carboniferous.

with a velocity of $5.12 \pm 0.09\,\mathrm{km\,s^{-1}}$ (Fig. 10a, b). If, as on line B2, the P_0 (and P_0') phases are assumed to propagate through Carboniferous Limestone, the limestone must exist under the Mesozoic cover between shot 2 and station 3. Between shots 2 and 9 and stations 5 and 10 no phase through the upper layers was observed due to the rapid decay in amplitude of the P_0 and P_0' phases. However, as these shots and stations were sited on either Carboniferous Limestone or a thin veneer of Mesozoic rocks, and as a velocity for phase P_0 of $5.1\,\mathrm{km\,s^{-1}}$ through the local Carboniferous Limestone was observed on line B2 where it crossed line C2, a velocity of $5.1\,\mathrm{km\,s^{-1}}$ was used for the upper layers in the various interpretations (see, e.g. Fig. 11).

Phases P_1 and P_2 are also represented along line C2. Phase P_1 has an interstation apparent velocity of $5.44 \pm 0.15\,\mathrm{km\,s^{-1}}$ (Fig. 9a–c) and an intershot apparent velocity of $5.49 \pm 0.15\,\mathrm{km\,s^{-1}}$ (Fig. 10a, c–f), and phase P_2 has an interstation apparent velocity of $6.05 \pm 0.07\,\mathrm{km\,s^{-1}}$ (Fig. 9d–f) and an intershot apparent velocity of $5.88 \pm 0.06\,\mathrm{km\,s^{-1}}$ (Fig. 10a–f). Planar-layer interpretation yielded true velocities for these phases of $5.46 \pm 0.15\,\mathrm{km\,s^{-1}}$ and $5.96 \pm 0.25\,\mathrm{km\,s^{-1}}$, which were subsequently used in the ray-tracing analysis (Fig. 11). As the planar-layer interpretation indicated that the refractors propagating

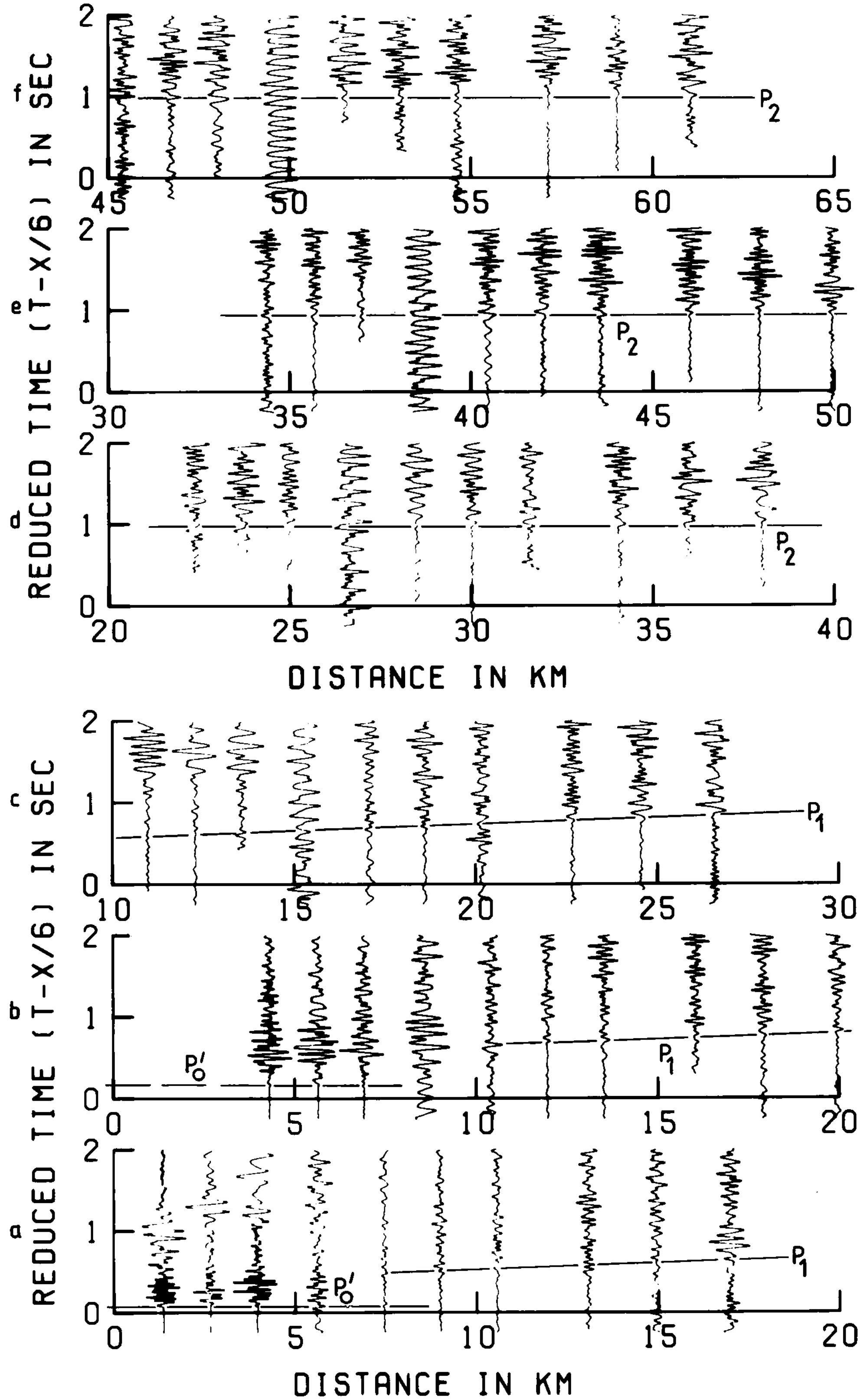

Figure 9. Normalized, band-pass filtered record sections for line C2 for shots (a) 1, (b) 2, (c) 3, (d) 5, (e) 7 and (f) 9 to all stations, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the *P*-wave arrivals.

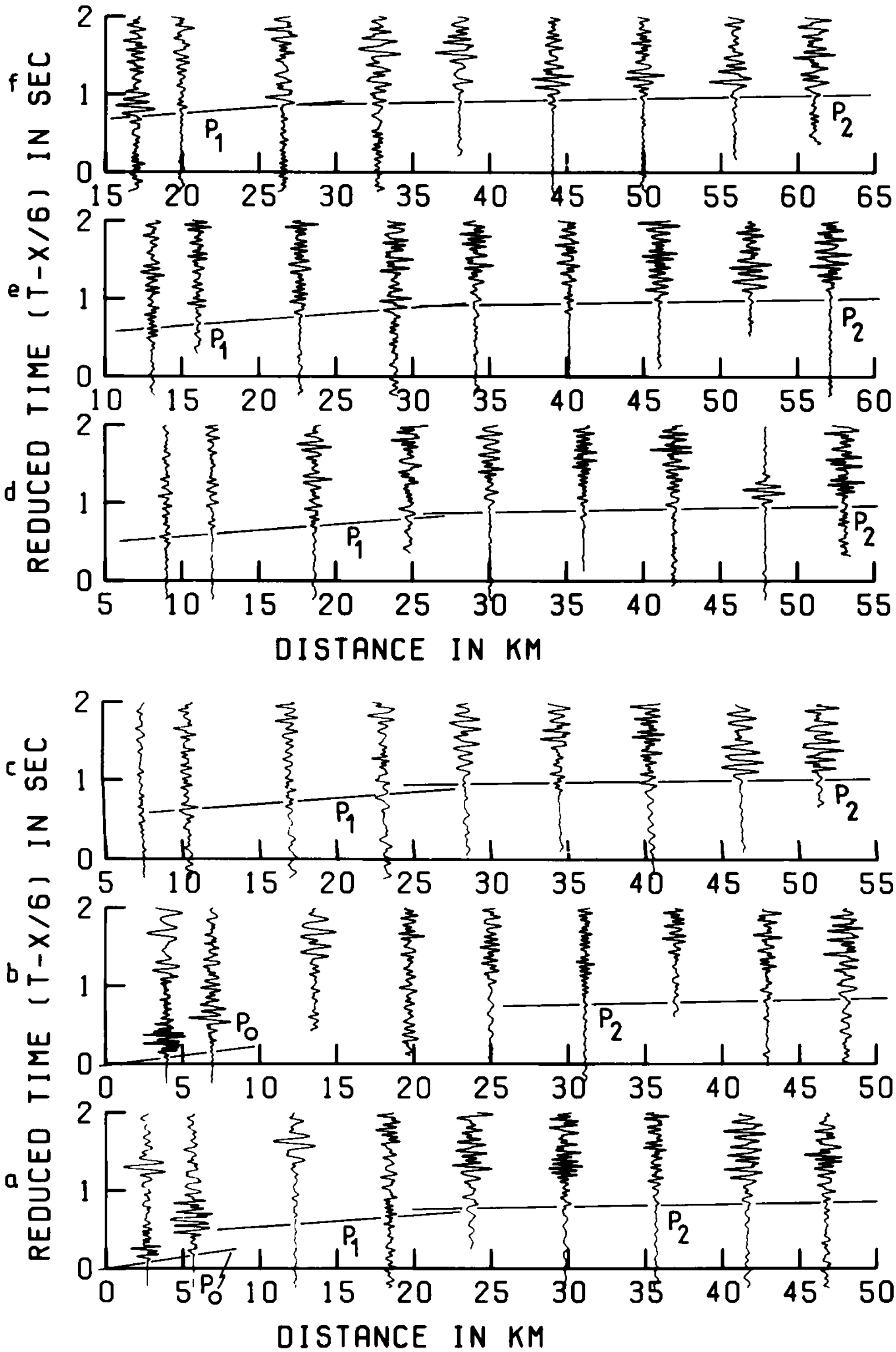

Figure 10. Normalized, band-pass filtered record sections for line C2 for stations (a) 2, (b) 3, (c) 5, (d) 6, (e) 8 and (f) 10 to all shots, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the *P*-wave arrivals.

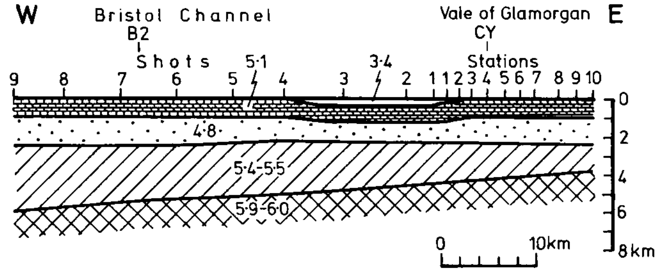

Figure 11. Combined ray-tracing and geological model for line C2. Key as for Fig. 8.

the P_1 and P_2 phases dipped respectively east and west, these dips were incorporated in the ray-tracing analysis.

The average absolute differences between calculated and observed travel-times for the final ray-tracing model (Fig. 11) are 0.05 and 0.07 s for the P_1 and P_2 phases respectively (Table 1). Thickness estimates of Mesozoic rocks beneath line C2, incorporated in the model, were obtained from Bluck (1965), George (1970), Brooks & James (1975), and C. R. Price (private communication).

Beneath line C2 the thickness of the Carboniferous Limestone, which decreases from 900 m in SW Gower to 800 m in the Vale of Glamorgan (George 1970), is too small to account for the delay times to the refractor propagating the P_1 phase. Thus, as for line B2 and the quarry blast line CY–AW in the Vale of Glamorgan (Bayerly & Brooks 1980), ORS with a velocity of 4.8 km s^{-1} was included in the sequence above this refractor. The thickness of the low velocity layer from the ray-tracing analysis is 1.0–1.5 km and this thickness is in agreement with local estimates of ORS thickness (George 1970) and measured thicknesses in boreholes about 10 km north of line C2. Thus it is thought that beneath line C2 the 5.5 km s^{-1} refractor at a depth of 2–2.5 km (Fig. 11) represents the top of the Lower Palaeozoic sequence.

The refractor propagating the P_2 phase dips west from 3.7 to 6 km (Fig. 11), and because of these depths and its velocity, it is taken to represent Precambrian crystalline basement rocks (*cf.* Section 3). Thus the Lower Palaeozoic/?Precambrian supra-basement sequence is interpreted to thicken from 1.4 km in the east to 3.5 km in the west.

Depth estimates to the refractors propagating the P_1 and P_2 phases at crossover points with other seismic lines agree to within 1.1 km (Table 2).

4.3 LINE CY–A

In 1977, three shots from Cornelly Quarry in the Vale of Glamorgan were recorded on Gower along E–W trending line A at ranges of 30–44 km (Fig. 1). Cornelly Quarry is sited on Carboniferous Limestone and the stations were sited on Carboniferous Limestone and ORS (Fig. 2). On the record section (Fig. 12a), phase P_2 can be recognized with an apparent velocity of 6.47 ± 0.22 km s^{-1}. Thus the arrivals could be used in the regional time-term analysis of the 6.0–6.2 km s^{-1} refractor discussed below (Section 6).

4.4 LINE J

This SW–NE trending, 57 km long line (Fig. 1) was unreversed with one marine shot-point and 24 recording stations on land. The south-western end of the line, including the shot-point in the Bristol Channel, crossed Mesozoic rocks up to 300 m thick (Brooks & Al-Saadi

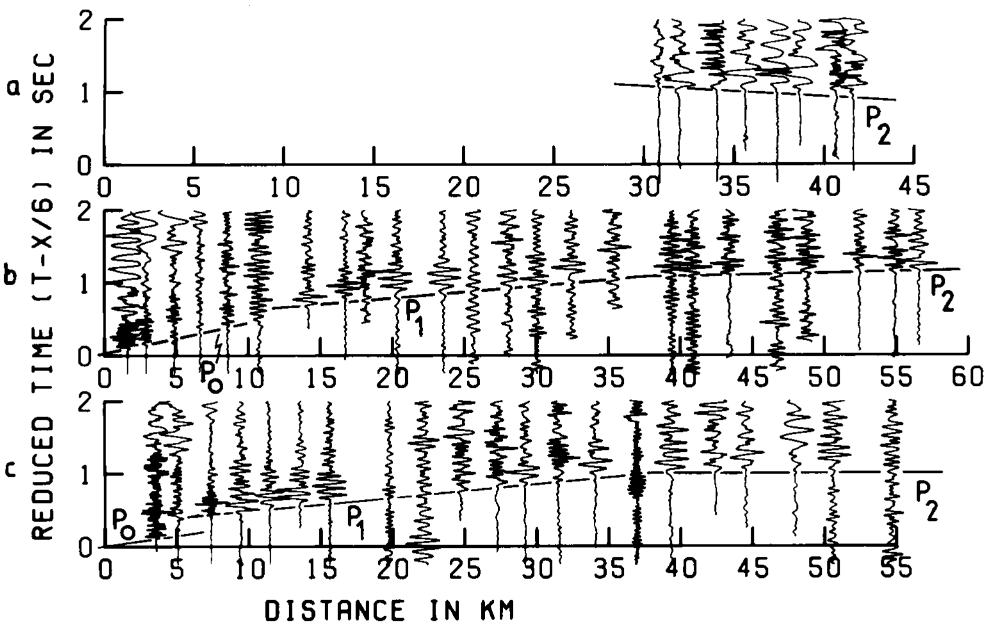

Figure 12. Normalized, band-pass filtered record sections for lines (a) CY-A, (b) J and (c) I, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the P-wave arrivals.

1977; C. R. Price, private communication) resting unconformably on the Palaeozoic sequence (Fig. 13). The line then crossed the Carboniferous Limestone and ORS outcrops immediately SE of the South Wales Coalfield before crossing the western limb of the N–S Usk anticline exposing Silurian rocks in its core (Figs 2 and 13).

Phase P_0, with a velocity of 5.19 ± 0.11 km s^{-1}, is observed between the shot-point and station 5 after which its amplitude decays rapidly (Fig. 12b). As on lines B2 and C2, this phase is thought to represent arrivals through Carboniferous Limestone which emerges from beneath a Mesozoic cover NE of station 6 (Fig. 13). Phases P_1 and P_2 are observed with apparent velocities of 5.42 ± 0.08 and 5.83 ± 0.11 km s^{-1} respectively (Fig. 12b), and horizontal interpretation yields depths of 3.9 and 5.5 km to the relevant refractors.

Although line J had only one shot-point, a ray-tracing model (Fig. 13) which took into account the varied surface geology, was computed, resulting in average absolute differences between calculated and observed travel-times of 0.04 s for both phases P_1 and P_2 (Table 1).

The thickness of the Carboniferous Limestone beneath line J decreases from 700 m under the shot-point (George 1970) to zero (or almost zero) north of station 7. Hence, as on lines

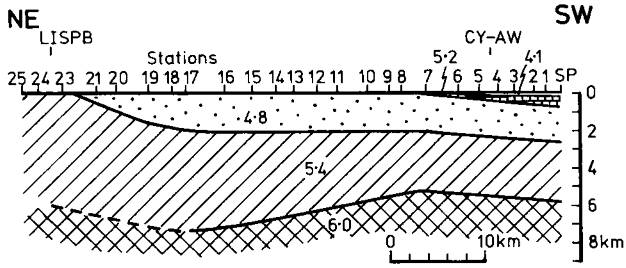

Figure 13. Combined ray-tracing and geological model for line J. Key as for Fig. 8.

B2 and C2, much of the delay time to the refractor propagating the P_1 phase must be accounted for by ORS. From beneath the shot-point to beneath station 17 the 4.8 km s^{-1} layer has an almost constant thickness of 2 km (Fig. 13). Local estimates of ORS thickness (George 1970) and thicknesses encountered in nearby boreholes range from 1–1.6 km. Thus it is possible that the refractor propagating the P_1 phase represents the top of the underlying Lower Palaeozoic sequence (Fig. 13), although the possibility that the 4.8 km s^{-1} layer includes a few hundred metres of Lower Palaeozoic rocks cannot be ruled out. North-east of station 17, the ORS wedges out until, between stations 21 and 23, Silurian rocks crop out. Thus in the ray-tracing model the 4.8 km s^{-1} layer was thinned out and the 5.4 km s^{-1} refractor brought to the surface where Silurian rocks crop out (Fig. 13). The low velocity of 5.83 km s^{-1} for the P_2 phase was assumed to be a downdip apparent velocity and a true velocity of 6 km s^{-1} was selected (Fig. 13), in accord with velocities on lines B2 and C2. Assuming a local southerly dip of the refractor at the southern end of line J in agreement with the surface geology (Figs 2 and 13), the refractor is interpreted to lie at depths of 5–7.5 km, the overall refractor geometry being shown in Fig. 13. As on lines B2 and C2, the 6 km s^{-1} refractor is thought to represent Precambrian crystalline basement rocks and on this basis the Lower Palaeozoic/?Precambrian supra-basement succession is interpreted to thicken north-eastwards from 3 to 5.5 km.

At crossover points with other seismic lines, depth estimates to the refractors propagating the P_1 and P_2 phases agree to within 1.5 km (Table 2). It should be noted that the LISPB line (Bamford *et al.* 1976) crossed line J near its north-eastern end where there is no information from line J about the structure of the 6.0 km s^{-1} refractor. Results from the LISPB line (K. R. Nunn, private communication) indicate that the 6 km s^{-1} refractor shallows north-eastwards from about 7.3 km depth beneath station 17 to around 6 km depth beneath the crossover point (Fig. 13).

4.5 LINE I

Line I, 60 km long, extended WNW–ESE along the Mendip Hills and split into two branches at its eastern end (Fig. 1). From one marine shot-point a single-ended seismic line was established on land with 30 recording stations, of which 23 (1–18 and 26–30) form the main line and seven (19–25) occupy a subsidiary branch following the curve of the Mendip structural axis (Fig. 1). In addition, an off-end shot was fired along the trend of line I about 4 km WNW of the other shot-point. This shot was observed by the five most easterly recording stations on the two branches of the line (Fig. 1).

The shots in the Bristol Channel were sited on Keuper Marl (Lloyd *et al.* 1973) with a local thickness of 100–200 m (Brooks & Al-Saadi 1977). On land, line I ran along the Mendip Hills which comprise a series of periclinal Variscan structures emerging from beneath a Mesozoic cover (Figs 2 and 14). Although the main Palaeozoic rock-type exposed is Carboniferous Limestone, ORS crops out in the cores of the four individual periclinal folds. Silurian rocks, including volcanics, are also exposed in the core of the easternmost fold – the Beacon Hill pericline. At its eastern end, line I crossed back on to Mesozoic rocks.

Interpretation was based mainly on observations from the inner shot-point along the main line (including the southern branch) for which the record station is shown (Fig. 12c). Phase P_0 with a velocity of 5.1 km s^{-1} is observed between the inner shot-point and station 2, after which its amplitude decays rapidly (Fig. 12c). As stations 1 and 2 were sited on Carboniferous Limestone, the phase is considered to represent this geological unit, as on lines B2, C2 and J. Phases P_1 and P_2 are observed with apparent velocities of 5.43 ± 0.06 and 6.01 ± 0.10 km s^{-1} respectively (Fig. 12c). Horizontal interpretation yields a depth of 2.3 km to

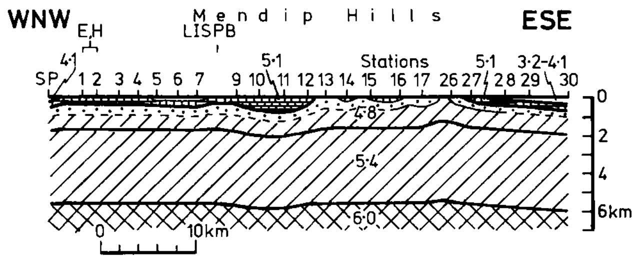

Figure 14. Combined ray-tracing and geological model for line I. Key as for Fig. 8.

the refractor propagating the P_1 phase and a depth of 5.7 km, beneath both the northern and southern branches of the lines, to the refractor propagating the P_2 phase. For arrivals from the 6 km s^{-1} refractor at the outer shot-point there is a time delay of about 0.1 s with respect to arrivals at the inner shot-point. This time delay can be explained by an increase of 1–1.5 km in the depth to the 6 km s^{-1} refractor between the inner and outer shot-points.

Again, a ray-tracing model (Fig. 14) which took into account the varied surface geology was computed, resulting in average absolute differences between calculated and observed travel-times of 0.03 and 0.02 s for phases P_1 and P_2 respectively (Table 1).

Along Line I, a maximum thickness of 650 m of Carboniferous Limestone occurs beneath station 11. In contrast, where line I crosses the periclinal folds of North Hill, Pen Hill and Beacon Hill, the Carboniferous Limestone is absent and ORS and Silurian rocks crop out. Thus, as on lines B2, C2 and J, in addition to Carboniferous Limestone, an ORS layer must contribute to the delay times associated with the P_1 phase. The 4.8 km s^{-1} layer has an average thickness of 1.3 km and the 5.4 km s^{-1} refractor occurs at about 1.6 km depth (Fig. 14). Thickness estimates of about 500 m are given for the ORS in the area including the Beacon Hill pericline, between stations 16 and 27 (Fig. 14), where the top and base of the local ORS succession can be seen (Green & Welch 1965; Kellaway & Welch 1948). Thus, unless significant variations of ORS thickness occur locally, the 5.4 km s^{-1} refractor must lie 0.5–1 km below the top of the Lower Palaeozoic sequence (Fig. 14). Between stations 17 and 26, Silurian rocks crop out. However, as the most easterly sampled point giving rise to a first arrival from the 5.4 km s^{-1} refractor occurs beneath station 14, it cannot be tested whether or not the 5.4 km s^{-1} refractor comes to the surface between stations 17 and 26.

The refractor propagating the P_2 phase, interpreted as Precambrian crystalline basement rocks as on profiles B2, C2 and J, occurs at a depth of 5.6 km (Fig. 14). The 5.4 km s^{-1} layer is about 4 km thick and thus the total thickness of the Lower Palaeozoic/?Precambrian suprabasement sequence is about 4.5–5 km.

Except for line H (Llewellyn 1981) depth estimates to the refractors propagating the P_1 and P_2 phases at the crossover point with other seismic lines agree to within 1.1 km (Table 2).

5 The line in SW England – F2

This 88 km long, E–W trending line was planned as an extension of earlier line F (Fig. 1). Eight marine shots were fired across the southern Bristol Channel from off the north Devon coast towards Lundy while 10 recording stations were set up on land in west Somerset. At its western end, line F2 crossed Tertiary rocks about 200 m thick underlain by Mesozoic rocks about 300 m thick (Brooks & James 1975). Eastwards the Tertiary and Mesozoic sequences thin out and the eastern four shots were located on Devonian rocks (Fig. 17). Between shot 1 and recording station 1, which were located 18 km apart, line F2 crossed the

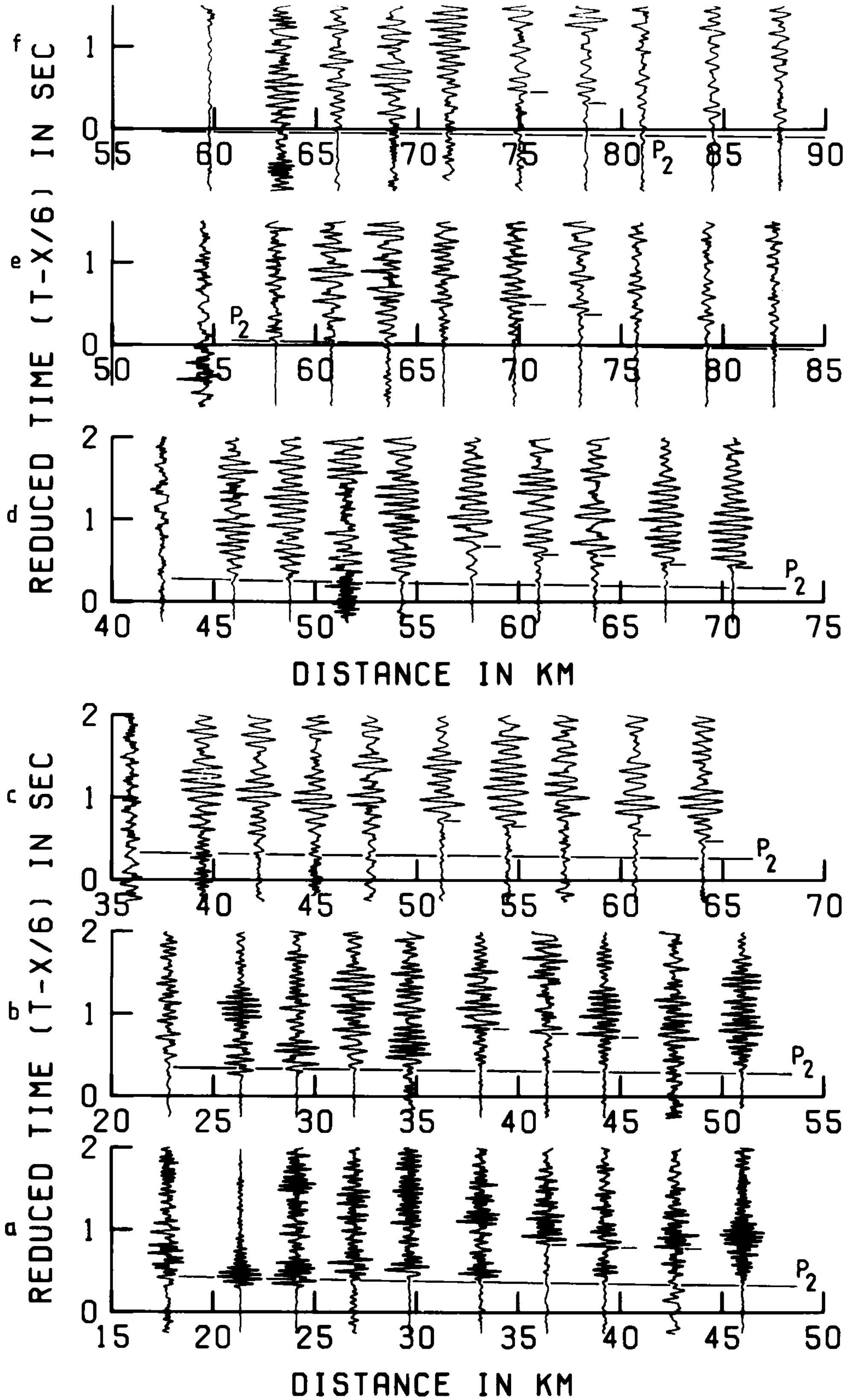

Figure 15. Normalized, band-pass filtered record sections for line F2 for shots (a) 1, (b) 2, (c) 4, (d) 5, (e) 7 and (f) 8 to all stations, plotted with a reduction velocity of 6 km s^{-1}, and showing least-squares fits of the *P*-wave arrivals. Phase *PP* arrivals are marked by –.

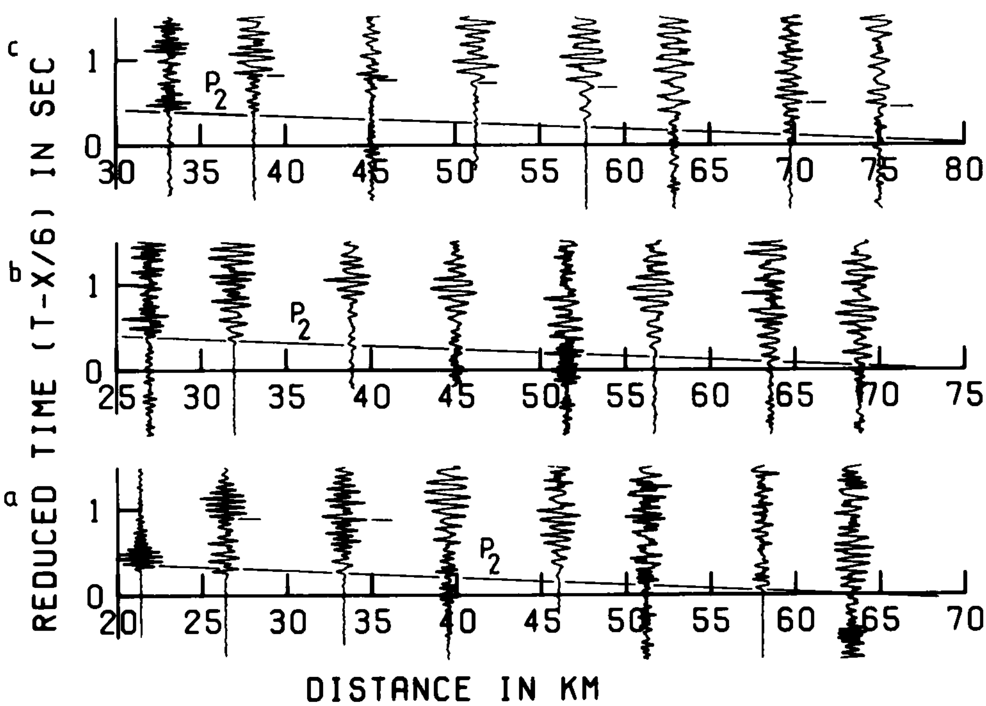

Figure 16. Normalized, band-pass filtered record sections for line F2 for stations (a) 2, (b) 4, (c) 6, (d) 7, (e) 8, (f) 10 to all shots and (g) a selection of seismograms showing the reflected phase *PP*. Sections are plotted with a reduction velocity of 6 km s^{-1} and (a–f) show least-squares fits of the *P*-wave arrivals. In (a–f), phase *PP* arrivals are marked by –.

fold axis of the north Devon anticline. The recording stations were located on the northern limb of this anticline on Devonian rocks or on overlying Triassic rocks up to 250 m thick (Thomas 1940).

The only refracted phase that can be observed in the record sections is phase P_2 with an interstation apparent velocity of 6.10 ± 0.02 km s^{-1} (Fig. 15a–f) and an intershot apparent velocity of 6.33 ± 0.03 km s^{-1} (Fig. 16a–f). Using a top layer velocity of 5.54 km s^{-1}, which is an average of the two velocities, 5.43 and 5.65 km s^{-1}, for the layers above the 6.2 km s^{-1} refractor on line F (Brooks *et al.* 1977, fig. 1), a planar-layer interpretation yielded a true velocity of 6.21 ± 0.04 km s^{-1} for phase P_2. The refractor is interpreted to dip east from a depth of 800 m in the west to 4.7 km in the east (Fig. 17). Where lines F2 and F approximately coincide, depth estimates to the 6.2 km s^{-1} refractor of 2.3–2.8 km were obtained for line F2, while for line F an average depth of 2.1–2.2 km was obtained (Brooks *et al.* 1977).

Where line B2 crosses lines F2 and F, it appears that there may be a strong disagreement between the interpretations (Table 2). A particular problem is whether or not the 6 km s^{-1} refractor occurring at 7–8 km depth under the southern part of line B2 represents the same geological interface as the 6.2 km s^{-1} refractor occurring at 2–3 km depth beneath the shot-points of lines F2 and F. If the two refractors represent the same geological interface and that interface is the top surface of the Precambrian crystalline basement (*cf.* Section 4.1, line B2), the latter must occur at shallow depths under lines F2 and F (Fig. 8b). There must be a rapid southward reduction in the thickness of the Lower Palaeozoic/?Precambrian supra-basement sequence from about 5 km beneath the central Bristol Channel to only a few hundred metres under the north Devon coast. Even if Fig. 8(b) shows the true model,

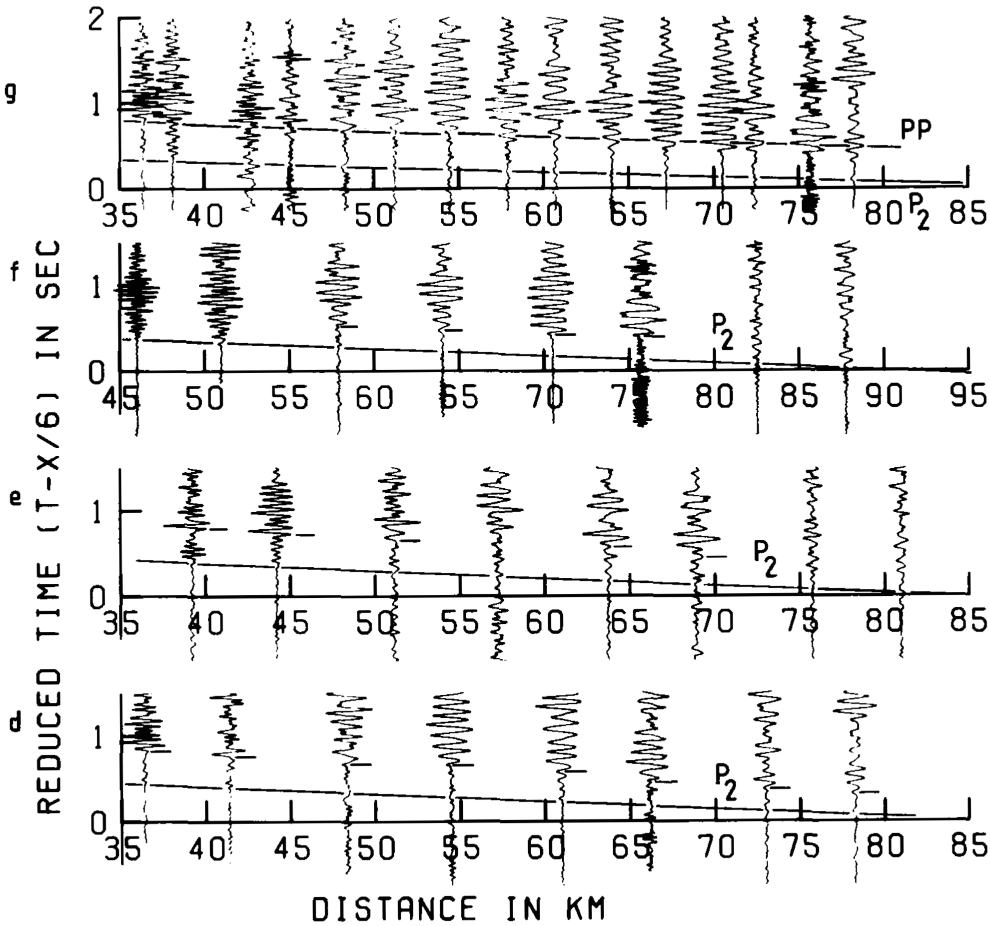

Figure 16 – *continued*

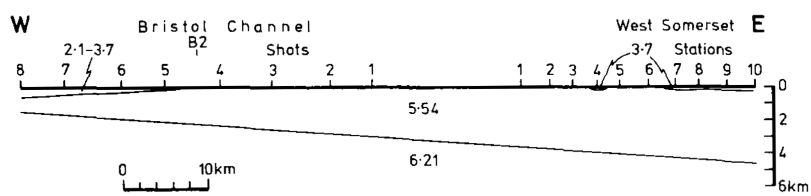

Figure 17. Planar-layer model, including the Mesozoic and Tertiary rocks, the line F2. Velocities are in km s^{-1}.

however, line B2 does not continue far enough south to detect the shallow 6.0–6.2 km s^{-1} refractor beneath lines F2 and F. The ray-path ADB, which does not intersect the 6.0–6.2 km s^{-1} refractor at shallow depths, has approximately the same travel-time as the ray-path ACB (Fig. 8b).

If the two refractors do not represent the same geological interface and if the 5.5–5.6 km s^{-1} refractor detected under lines F and B2 represents the top of the Lower Palaeozoic sequence (*cf.* Section 4.1, line B2), the shallow 6.2 km s^{-1} refractor beneath lines F2 and F probably represents a rock-type occurring a few hundred metres below the top of the Lower Palaeozoic sequence and terminating a short distance north of line F2, possibly along a major fault or thrust (see below). Alternatively, if the 5.5–5.6 km s^{-1} refractor represents a horizon in the Lower Devonian sequence, then the shallow 6.2 km s^{-1} refractor may represent a high velocity rock-type also occurring in the Lower Devonian sequence (Matthews 1981).

In addition to the first arrival phase P_2 a reflected phase *PP* was recognized along line F2 (Fig. 16g). The interpretation of this reflected phase is made uncertain as no associated refracted phase can be observed, possibly because of the 'screening' effect of the shallow high velocity refractor or because line F2 was not long enough for the associated refracted phase to occur as a first arrival. Nevertheless, assuming that velocity varies only with depth, an average one dimensional interpretation of the reflected phase *PP* was attempted. Synthetic seismograms (Fig. 19) using the ray theoretical method (Červený, Molotkov & Pšenčík 1977) and travel-time curves (Fig. 16g) for the velocity–depth (*V–Z*) function (Fig. 18) are presented. Differences between observed and theoretical travel-times are less than 0.17 s (Fig. 16g), while the synthetic seismograms show, in agreement with the observed data, that the amplitudes of phase *PP* are much greater than those of phase P_2 out to a distance of about 75 km (Fig. 19).

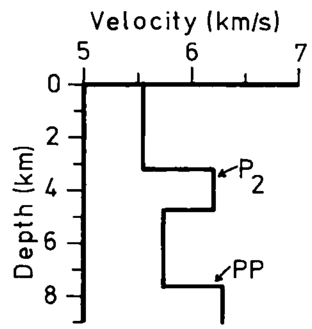

Figure 18. Average velocity–depth function for line F2.

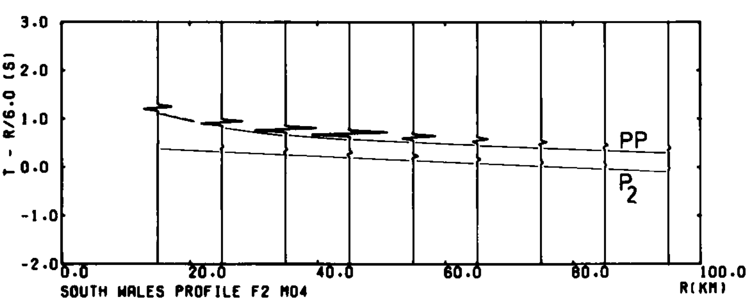

Figure 19. Synthetic seismograms for line F2, calculated for phases P_2 and *PP* using the ray theoretical method.

In the *V–Z* function (Fig. 18) the 6.2 km s^{-1} layer has, at 1.5 km, a thickness which is considered to be great enough to propagate the P_2 phase, with a frequency of at least 8–10 Hz, over a distance of about 100 km. Taking the critical distance for the reflected phase *PP* to be about 45 km and assuming a thickness of 1.5 km for the 6.2 km s^{-1} layer, a low velocity layer must occur between the 6.2 and 6.3 km s^{-1} layers. The average velocity of the low velocity layer is calculated to be 5.74 km s^{-1}, which is considerably less than the true velocities of 5.96–6.21 km s^{-1} derived in this region for Precambrian crystalline basement rocks. Thus, in this model (Fig. 18), the 6.2 and 5.74 km s^{-1} layers are taken to represent part of the Lower Palaeozoic sequence. The 6.3 km s^{-1} basal layer at a depth of 7.6 km is taken to represent Precambrian crystalline basement rocks.

The postulated velocity structure below a depth of about 5 km along line F2 is in approximate agreement with the velocity structure determined beneath the southern part of line B2 and thus represents one possible way of resolving the apparent differences of structure beneath line B2 and lines F2 and F.

In considering the possible geological significance of the *V–Z* function (Fig. 18), it is interesting to recall earlier attempts to explain the northward fall of Bouguer gravity values across Exmoor, north Devon (Bott, Day & Masson-Smith 1958). It was suggested by Bott *et al.* (1958) and by later workers (Bott & Scott 1964; Brooks & Thompson 1973) that the gravity gradient may be caused by the overthrusting of the Devonian sequence of north Devon over a concealed sedimentary sequence of lower density. The proposed *V–Z* function under line F2 is entirely compatible with such a structural model and the base of the shallow high velocity layer might represent the basal unit of the overthrust sheet. The underlying low velocity layer would then represent autochthonous Palaeozoic strata and the basal high velocity layer Precambrian crystalline basement, equivalent to the basal refractor encountered in other parts of the region. Northward wedging out of a thrust sheet would account conveniently for the absence of the shallow high velocity layer under lines B2 and D.

6 Regional time-term analysis

A time-term analysis was attempted to determine the depths to and average velocity of the Precambrian crystalline basement across the region. In this analysis, data from quarry blasts including those from lines CN/BN-GH, PN-CN, and CY-A (Bayerly & Brooks 1980), the 1975 cruise lines A and D (Brooks *et al.* 1977; Bayerly & Brooks 1980), the 1976 cruise lines B2, K and L, and the 1978 cruise were included. Mechie (1980) provided details of the analysis, from which a contoured version of the map of Precambrian crystalline basement depths (Brooks *et al.* 1983, fig. 10.4) is presented (Fig. 20). The average velocity for the

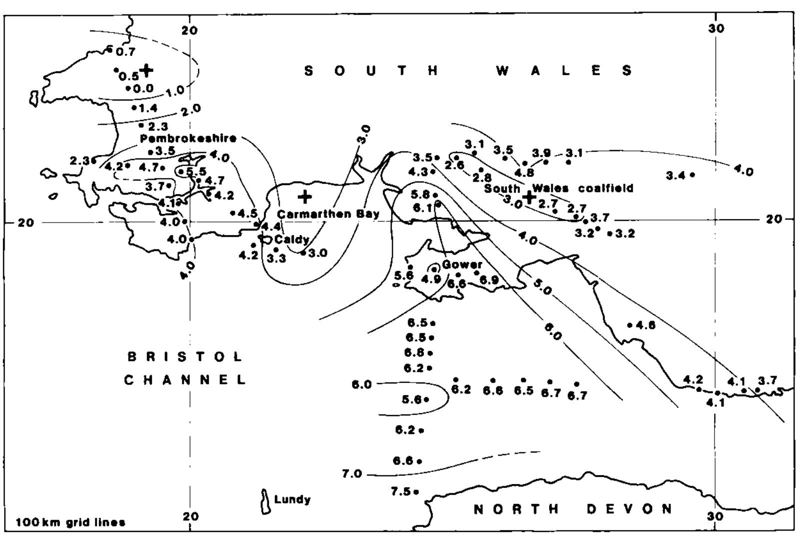

Figure 20. Contoured map showing Precambrian crystalline basement depths (in km), derived from time-term analysis, under the South Wales/Bristol Channel area. Main basement highs are marked by +.

Precambrian basement obtained from the analysis was 6.06 km s^{-1}, which is within the range of 5.96–6.21 km s^{-1} for true velocities determined by other methods for Precambrian crystalline basement in this region. In converting time-terms to depths an average top layer velocity of 5.28 km s^{-1} was used (*cf.* Bayerly & Brooks 1980).

The pattern of basement depths obtained from the time-term analysis is similar to that obtained from the planar-layer and ray-tracing interpretations. The shallowest depths to the basement occur in north Pembrokeshire, in the vicinity of the Hayscastle anticline where Precambrian rocks crop out (Fig. 20), and the basement deepens to 4–4.5 km beneath south Pembrokeshire. Under the Johnston–Benton fault block, where Precambrian intrusive igneous rocks crop out, the time-term analysis yields depths of 2–5 km to the basement (*cf.* Section 3). In Carmarthen Bay, the basement shallows eastwards from 4–4.5 km depth near Caldy to about 3 km in central Carmarthen Bay.

Shallow basement depths of about 3 km occur beneath the central and north-western parts of the South Wales Coalfield. From this area, the basement deepens southwards to around 6 km beneath the south-western part of the coalfield, 5–7 km beneath Gower, and 4–4.5 km beneath the Vale of Glamorgan. Under the Bristol Channel basement depths are generally in excess of 6 km, while a depth of 7.5 km is encountered off the north Devon coast. Beneath the central part of the coalfield where the basement occurs at a depth of about 3 km, thicknesses of about 2 km of Upper Carboniferous rocks are preserved. Thus the pre-Upper Carboniferous supra-basement sequence must thicken southwards from about 1 km beneath this area to more than 4 km in Gower and the Bristol Channel area.

7 Discussion

The seismic refraction results show that beneath lines B2, C2 and J in the central South Wales/Bristol Channel area and line I in the Mendip Hills the structure is similar. Below the Carboniferous Limestone with a normal velocity of 5.1–5.2 km s^{-1}, the ORS, with a velocity of 4.7–4.85 km s^{-1}, and sometimes parts of the Lower Palaeozoic succession act as a low velocity layer. Below this low velocity layer, a refractor propagating phase P_1 with a velocity of 5.4–5.5 km s^{-1} is commonly detected. This refractor is considered to represent a horizon at or near the top of the Lower Palaeozoic sequence and it could possibly come to the surface at the northern end of line J (Fig. 13) where Silurian rocks crop out in the Usk anticline. Beneath the northern end of line B2, the 5.4–5.5 km s^{-1} layer wedges out which is in agreement with the absence of a 5.4–5.7 km s^{-1} refractor under the South Wales Coalfield lines CN/BN-GH and CN-PN (Bayerly & Brooks 1980). Thus, the refractor seems to be absent below the central and northern parts of the coalfield and it was also undetected along lines K and L in Pembrokeshire, where top layer velocities of 4.9–5.2 km s^{-1}, representing very varied sequences of Palaeozoic and Precambrian rock-types, were obtained.

Beneath most lines in the region a basal refractor, propagating phase P_2 with a velocity of 6.0–6.2 km s^{-1}, has been detected (Table 2). Except under lines F2 and F in SW England, it is considered safe to correlate this refractor with the top surface of Precambrian crystalline rocks, forming a seismic/geological basement beneath the region. Broadly speaking, the refractor deepens southwards (Fig. 20). Under lines F2 and F, the shallow 6.2 km s^{-1} refractor could possibly represent Precambrian rocks (Fig. 8) but, taking account of the results from line B2 and interpretation of the reflected phase *PP* observed on line F2, it is considered more likely that the refractor represents a horizon within the Palaeozoic sequence.

In north Pembrokshire, Precambrian igneous rocks crop out in the Hayscastle anticline (Fig. 2). The seismic experiment has shown that in the vicinity of the Hayscastle anticline the Precambrian crystalline basement occurs at a depth of about 1 km (Figs 4 and 20). As

Upper Carboniferous rocks crop out next to the Precambrian rocks of the Hayscastle anticline without a major fault boundary being involved (Hancock *et al.* 1983, fig. 3.3) this basement high must have existed during the late Carboniferous. In the central part of the South Wales Coalfield, the Precambrian crystalline basement occurs at about 3 km depth (Fig. 20; Bayerly & Brooks 1980). As the Upper Carboniferous sequence is about 2 km thick in this area, the pre-Upper Carboniferous supra-basement sequence must be only about 1 km thick. Thus in the central part of the main coalfield, a basement high must similarly have existed in the late Carboniferous.

Combining geological, seismological and aeromagnetic evidence, Brooks *et al.* (1983) proposed the existence in South Wales of a series of basement highs in an E–W zone, of which the Hayscastle anticline and the central part of the South Wales Coalfield can be shown to have existed before the main movements of the Variscan orogeny. As shown by the seismic experiments, the basement deepens beneath south Pembrokeshire, Gower, the Vale of Glamorgan, and the Bristol Channel and, consequently, the pre-Upper Carboniferous supra-basement sequence thickens (Figs 20, 4 and 8). This zone of shallow basement was perhaps responsible for controlling the position of the Variscan orogenic 'front' which runs through South Wales to the south of the basement highs (Rast 1983, fig. 1.3; Hancock *et al.* 1983) and which is used to delineate the northern boundary of the Variscan orogenic belt.

From thickness estimates of the Upper Palaeozoic sequence in the central South Wales area (see Sections 1 and 4), it can be deduced that the pre-Upper Palaeozoic sequence, possibly including Precambrian strata, also thickens southwards from almost zero where the basement high exists in the central part of the coalfield (Bayerly & Brooks 1980; Brooks *et al.* 1983) to 1–3 km beneath the Vale of Glamorgan (Figs 11 and 13; Bayerly & Brooks 1980), 2–5 km beneath Gower and the northern Bristol Channel (Figs 8 and 11; Brooks *et al.* 1983), and 3–5 km beneath the middle and southern Bristol Channel (Fig. 8; Brooks *et al.* (1983). In Pembrokeshire, the pre-Upper Palaeozoic supra-basement sequence, including Precambrian volcanic rocks, thickens southwards from a few hundred metres where the basement high exists in the vicinity of the Hayscastle anticline to around 3.5 km at the northern edge of the Pembrokeshire Coalfield (Fig. 4). In south Pembrokeshire, because of the complicated geological structure and the absence of a refractor at or near the top of the Lower Palaeozoic succession (*cf.* central South Wales), it is difficult to separate, on the basis of the seismic results, the Upper Palaeozoic sequence from the pre-Upper Palaeozoic sequence. However, to explain the position of the Precambrian crystalline rocks in the Johnston–Benton block, the seismic interpretation requires at least 3 km of vertical movement and 4–5 km of horizontal movement along the Johnston thrust during the Variscan orogeny (Brooks *et al.* 1983, Fig. 10.6).

Acknowledgments

This research was carried out while JM was at University College, Swansea, supported by a NERC Research Studentship. Research grants to MB from the NERC and the Royal Society were awarded for the purchase of explosives. The Captain, officers and crew of RRS *John Murray* and MV *Edward Forbes*, the managers of Crwbin and Cornelly quarries, and many land owners are thanked for their help and cooperation. The Universities of Cardiff and East Anglia, the NERC geophysical pool, and the IGS Global Seismology Unit are thanked for loaning seismic equipment. For their useful discussions and help, we would like to mention Drs M. Bayerly, D. J. Llewellyn, P. Styles, A. M. Sykes, J. Cope, the late Mr P. Corles, Mr D. Lancy and Mr M. Punter. The calculations were carried out at the Computer Centres of the University College, Swansea and the Universities of Manchester and Karlsruhe. M. Bigott typed the manuscript.

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