A relative $P$-wave delay study between Eskdalemuir and Charnwood Forest

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Summary. The relative $P$-wave delay between CWF, a permanent seismic station on the Precambrian rocks of Charnwood Forest in the English Midlands and EKA, the Eskdalemuir Seismological Array, shows a large azimuthal variation of 1.3 s. This is examined and is consistent with a thinning of the crust from EKA to CWF, together with a considerable thickness of high velocity (most probably greater than 7.0 km/s$^{-1}$) lower crust beneath CWF. The Southern Uplands Fault, approximately 42 km to the north-west at its closest approach to EKA, seems to be associated with a large anomaly in the relative $P$-wave delay. Raypaths from events originating between azimuths 260 to 350° from EKA apparently pass through anomalously high velocity material entering the crust just to the south of the fault.

Introduction

First arrival times of teleseismic events with epicentral distances up to 100° have been used to determine the relative $P$-wave delay (Long & Mitchell 1970) between two short period, seismic stations, EKA, the Eskdalemuir seismological array (Truscott 1964) and CWF, a station on the Precambrian rocks of Charnwood Forest (Fig. 1). The method presumes that a non-zero relative delay time is due to a difference in crustal and upper mantle structure beneath the two recording stations. Simple inversion of the relative delay in terms of velocity–depth models can only be undertaken if there exist other controls on the structure and even then will only provide a coarse picture of the crust and upper mantle of interest.

In the case of EKA, the structure in the vicinity of the station is most probably complex, geologically, due to its proximity to the Southern Uplands Fault and the suture of the vanished Iapetus ocean (Dewey 1971). However, geophysically the crustal and immediate sub-Moho structure are relatively well defined (Agger & Carpenter 1964; Jacob 1969; Bamford et al. 1978; Faber & Bamford 1979). The crust and upper mantle is poorly defined beneath CWF.

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The data

The final data set was limited by the following restrictions:

1. An event had to be recorded at both site B4 on the EKA array and on the vertical component instrument at CWF.
2. On playback on to paper, the estimated observational error, $e_\theta$, on the first arrival time at both CWF and EKA had to be less than ±0.2 s.
3. The epicentral distance had to be less than 100°, ensuring the ray paths did not enter the core.
4. For the major data set, the epicentral distance had to be greater than 30° from one of the stations (the distance between EKA and CWF is 2.81°). Relative delays for events with smaller epicentral distances would be more likely to be contaminated by gross lateral variations along the raypath. Seven events with epicentral distances less than 30° were also considered, once the variations from the major set had been examined.

Of more than 200 examined events, only 38 satisfied the above restrictions and together with the seven events mentioned in item 4 above, are plotted in Fig. 2. All are of shallow focal depth (less than 70 km), other than one intermediate (less than 300 km) and one deep focus event (greater than 300 km). It can be seen that there is good coverage over a small azimuth range from about 350 to 120°. The remaining regions are limited to one event from Zambia, four from western South America and nine from the Nevada test site. Twenty-nine events originated between epicentral distances of approximately 70 to 90°. Fig. 3 is a plot of the relative delay versus azimuth from CWF of events originating between epicentral distances 30 and 100°, averaged over one degree of latitude and longitude. A positive value indicates a ‘delay’ beneath CWF, or alternatively an ‘advance’ beneath EKA.

In order to estimate the effect of inaccuracies in the USGS epicentral parameters on the relative delay, the calculated delay was computed for 27 different event foci 'rocked' about the published focus by ±0.5° latitude and longitude (at the equator) and ±30 km focal depth. As expected the error, $e_\theta$, about the mean of the 27 delays decreased with increasing epicentral distance and varied with azimuth. In the latter case the largest errors occurred at
Figure 2. Location of epicentres of events used in the analysis. Map centred on CWF.

Figure 3. Relative P-wave delay versus azimuth of EKA versus CWF for events with epicentral distances between 30 and 100º, averaged over one degree.

azimuths of 68 and 248º, normal to the line joining CWF to EKA (bearing 338º). The error bars on Fig. 3 are all maximum errors (observed, \( e_0 \) plus calculated, \( e_c \)) except for the following three event groups:

1. Nevada. The nine events were amalgamated to give a mean and standard error.
2. Kamchatka. Five events were amalgamated to give a mean and standard error.
3. E. Kazakh. Blamey & Gibbs (1968) showed that USGS locations for twenty events from the E. Kazakh test site agreed within 0.15 degrees of latitude and 0.22 degrees of longitude with locations using the joint epicentre method (Douglas 1967). The calculated error in the present analysis was determined by ‘rocking’ the focus through ±0.25 degrees of latitude and longitude with zero focal depth.
The relative delay values show enormous variation with azimuth, from $-0.61 \pm 0.43$ s for events from Novaya Zemlya, a Russian nuclear test site, to $+0.69 \pm 0.13$ s for events from Nevada, an American nuclear test site. Although not precisely defined due to the sparse data between azimuths 120 and 350°, there appears to be a rapid increase at about 260°, with a corresponding decrease between 310 and 350°.

Known structure

The LISPB crustal model of northern Britain (Bamford et al. 1978) shows considerable structure in the vicinity of EKA, including a change in the intermediate crustal layer, suggested to be Precaledonian basement, 'at or just south of the Southern Uplands Fault'. The change itself is of 'uncertain structure'. Since the dimensions of this model reach vertically to the upper mantle and laterally to within 66 km of CWF, the structural model beneath EKA used in the present analysis has been derived principally from the LISPB results. The superficial layer is presumed absent as suggested by the results of Agger & Carpenter (1964) and Jacob (1969).

From an analysis of the regional gravity field over the southern British Isles, Maroof (1973) estimated the crustal thickness beneath CWF at about 29.5 km. Whitcombe (1979) derived compressional wave velocities for the Precambrian Charnian basement in and around Chamwood Forest. These average to $5.7 \pm 0.1$ km s$^{-1}$. This is similar to that of the 'Lower Palaeozoic' sequence of northern England defined by LISPB. A southward extrapolation of the LISPB model to CWF is not inconsistent with the controls of surface velocity and crustal thickness mentioned above. However, the lower crust at the southern end of the LISPB model is poorly defined. There is a suggestion that the Moho may be a gradational boundary.

Bamford et al. (1978) find that a uniform sub-Moho velocity close to 8 km s$^{-1}$ is acceptable beneath northern Britain. Examining deeper structure, Faber & Bamford (1979) find evidence for layering within the sub-crustal lithosphere. However, the relevant region beneath the LISPB profile, immediately to the east of EKA was not sampled by observations. Here, the evidence for lateral uniformity of structure is solely from the observation of reflections from similar depths and with similar underlying velocities on either side of the unsampled region. There is no information on the subcrustal lithosphere as far south as CWF. For want of a definite model, and in the light of the above comments, the subcrustal lithospheric structure is considered to be the same beneath CWF and EKA in the following discussion.

Discussion

The azimuthal limits of the positive relative delay values (Fig. 3), and the azimuth of the Nevada events in particular, coincide with the closest approach to EKA of the surface expression of the Southern Uplands fault.

It was considered likely that these delays were directly related to structure associated with this fault. Some effect may be being introduced by structure to the north-west of CWF. However, the regional gravity field (Maroof 1973) gives no indication of lateral variations in structure which would be necessary to explain these anomalous delays. In order to further examine this problem, the relative delay between CWF and WHF (see Fig. 1) was calculated for another 22 events which covered similar azimuth ranges to the previous data set. Although not strictly conclusive due to the proximity of WHF to CWF (a distance of only 3 km), a lateral change in structure between the ray paths to the two stations, should produce an azimuthal variation in the relative P-wave delay. No significant anomaly was
apparent at any azimuth, suggesting that the positive anomaly between CWF and EKA is due principally to structure beneath EKA.

It was assumed that the small negative relative delay between EKA and CWF between azimuths 350 and 150° was due to a shallower Moho and different crustal layer thicknesses beneath CWF as suggested by previous geophysical work.

AZIMUTHS 350 TO 150°

Using the EKA crustal model of Fig. 4(a) it is possible to determine the distance from EKA at which the ray from a particular event enters the crust. Ray paths from those events with epicentral distances greater than 70 and less than 90° enter the crust in the narrow annulus between approximately 9 and 12 km from EKA. In order to compare crustal structures at the two stations, initially only those events originating within the above epicentral range were considered.

The mean relative delay for these events is \(-0.32 \pm 0.08\) s. By presuming:

1. the crustal thickness at CWF is 29.5 km;
2. the depth to the top of the 'Pre-Caledonian basement' is 8 km, being extrapolated to CWF from the LISPB model;
3. the velocities of the crustal layers CWF are as in Fig. 4(b); and
4. the subcrustal lithosphere at CWF is the same as at EKA. This relative delay necessitates the layer thicknesses as defined by CWF (1) (Fig. 4b). (The difference in height between CWF and EKA gives a maximum relative delay of \(-0.02\) s and has been neglected.) Obviously many other combinations of layer thickness and velocity are possible, but this reasonable model suggests that there is likely to be a substantial thickness of high velocity material in the lower crust. A deeper Moho would require even higher velocity material within the lower crust. A Moho as shallow as 26 km still requires 11 km of 7.1 km s\(^{-1}\) material in the lower crust (Fig. 4c) to provide the relative delay of \(-0.32\) s. A gradational Moho as suggested by Bamford et al. (1978) is more difficult to consider. If modelled as a simple linear gradient centred on a depth of 29.5 km (similar to that defined in fig. 4h of their paper) the constraints on the intermediate boundaries will be the same as in Fig. 4(b), provided the gradational Moho exists completely below the 6.25/7.1 km s\(^{-1}\) interface and that assumptions (2), (3) and (4) above are still valid.

Figure 4. Crustal models. (a) EKA; (b) CWF (1); (c) CWF (2).
In order to check the model, the variation in relative delay with epicentral distance was determined using all the events occurring between azimuths 30 and 150° (Fig. 5). This was compared with the theoretical relative delay between the models for CWF (1), CWF (2) and EKA. As the models for the two stations are substantially different, the theoretical relative delay has to allow for the different distances travelled along the raypaths before entering the two structures. It was found that the difference in relative delay between CWF (1) and CWF (2) versus EKA was insignificant. Accepting that the near events may be contaminated by lateral variation along the ray path, the data although scattered are not inconsistent with the theoretical prediction.

AZIMUTHS 260 TO 350°

The positive relative delay between azimuths 260 and 350° is difficult to model. By ray tracing through the crustal structure for EKA in Fig. 4(a), it is found that ray paths for the events from this range of azimuths enter the crust just to the south of the fault. However, beneath and to the south of the fault itself, Bamford et al. (1978) model ‘uncertain structure’ at mid-crustal levels. If this were to contain high velocity material, it would account for part of the positive relative delay between CWF and EKA. However, the large value of the anomaly suggests that its source probably lies within the upper mantle to the north-west of EKA. Further studies are necessary to outline the location of the anomalous zone, and to see whether it affects the possible continuity of subcrustal structure across the region beneath the Southern Uplands Fault, and not sampled by LISP (Faber & Bamford 1979).

Conclusions

Analysis of the relative P-wave delay between EKA and CWF suggests that (1) there is a considerable thickness of high velocity lower crust beneath CWF in the English Midlands, and (2) the crustal and upper mantle structure associated with the Southern Uplands Fault includes some high velocity material which is ‘speeding up’ arrivals into the EKA array from the north-west, causing a large azimuthal variation of 1.3 s in the relative P-wave delay between CWF and EKA.

Figure 5. Relative P-wave delay versus epicentral distance, of EKA versus CWF for events with azimuths between 30 and 150°. Dashed line gives theoretical relative delay using EKA and CWF models mentioned in text.
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References
