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Velocity structure of the UK continental shelf from a compilation of wide-angle and refraction data

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Abstract – Maps showing depth to the Moho, the 6 km/s and 7 km/s isovelocity surfaces and the thickness of the crust with a velocity greater than 7.0 km/s for the UK and surrounding continental crust have been generated from a compilation of wide-angle/refraction data. The data show that the crust beneath northwestern Scotland is thinner and of higher velocity than that beneath southern Britain. The lower crust beneath the East Irish Sea and parts of the southern North Sea is formed from thick layers of high velocity rock. The lateral extent of these layers cross-cuts the downward projection of major structures mapped at the surface. This suggests that the major structures do not bound regions of lower crust with contrasting properties at depth. Instead these structures may be overprinted by modification of the lower crust, for example, by magmatic underplating, which is not observed directly at the surface. Mapped variations in crustal thickness do not mirror the variations in surface topography, which appears to contradict the view that the crust is in Airy isostatic equilibrium.

Keywords: crustal structure, seismic velocity, Britain, Ireland, deep seismic sounding.

1. Introduction

The determination of the physical properties of the continental crust is essential in understanding its response to stresses, applied internally through topographic loading and irregular sub-surface mass distributions, or externally through relative plate motions. If the three-dimensional structure of the crust can be better constrained, it will be possible to quantify fully its state of isostatic equilibrium, its ability to support loads and its response to stress. Potential field studies and two-dimensional deep seismic profiling have demonstrated the heterogeneous nature of the crust in cross-section, but to date little effort has been made to constrain 3-D heterogeneity throughout the whole thickness of the crust. This is largely due to the limited availability of 3-D seismic data from which physical properties can be recovered.

Interpretations of crust and mantle structure around the UK, Ireland and adjacent shelves using deep seismic reflection profiles have been made by several workers (Matthews, 1986; Meissner, Matthews & Wever, 1986; McGeary *et al*. 1987; Chadwick & Pharaoh, 1998; England, 2000). These datasets exploit the densest coverage of publicly available 2-D deep reflection profiles to extend interpretations of structure into the third dimension. While each profile itself has been extensively studied and used to provide detailed interpretations of particular crustal cross-sections, the combination of data is a powerful tool for investigating aspects of crustal evolution that are not elucidated by a single profile alone since it potentially enables study of the crust in three dimensions.

Similarly, combining deep wide-angle/refraction profiles can result in a greater understanding of the nature and evolution of a particular region of crust (e.g. Braille *et al*. 1989; Christensen & Mooney, 1995). These data, while of lower resolution than the normal incidence data, provide the best estimates of crustal velocity and depth to major interfaces, which cannot be determined accurately using deep reflection data. While the study by Christensen & Mooney (1995) used a variety of data from northwestern Europe in a global compilation, such a compilation has not been produced specifically to examine the velocity structure of the UK and surrounding regions and its relationship to major structural features of the crust.

2. The deep seismic wide-angle/refraction database

Details of 66 deep wide-angle/refraction profiles from published and unpublished sources have been compiled. These data are of varying age and quality, and the distribution of data is neither as even nor as comprehensive as the deep reflection data (Fig. 1). The quality of these data was assessed, and the list reduced to a database containing 19 profiles (Table 1). This database and the maps derived from it are continually being updated as more data become available. Profiles which fall into the group of 19 have all been modelled using ray tracing techniques (Cerveny & Firbas, 1984),

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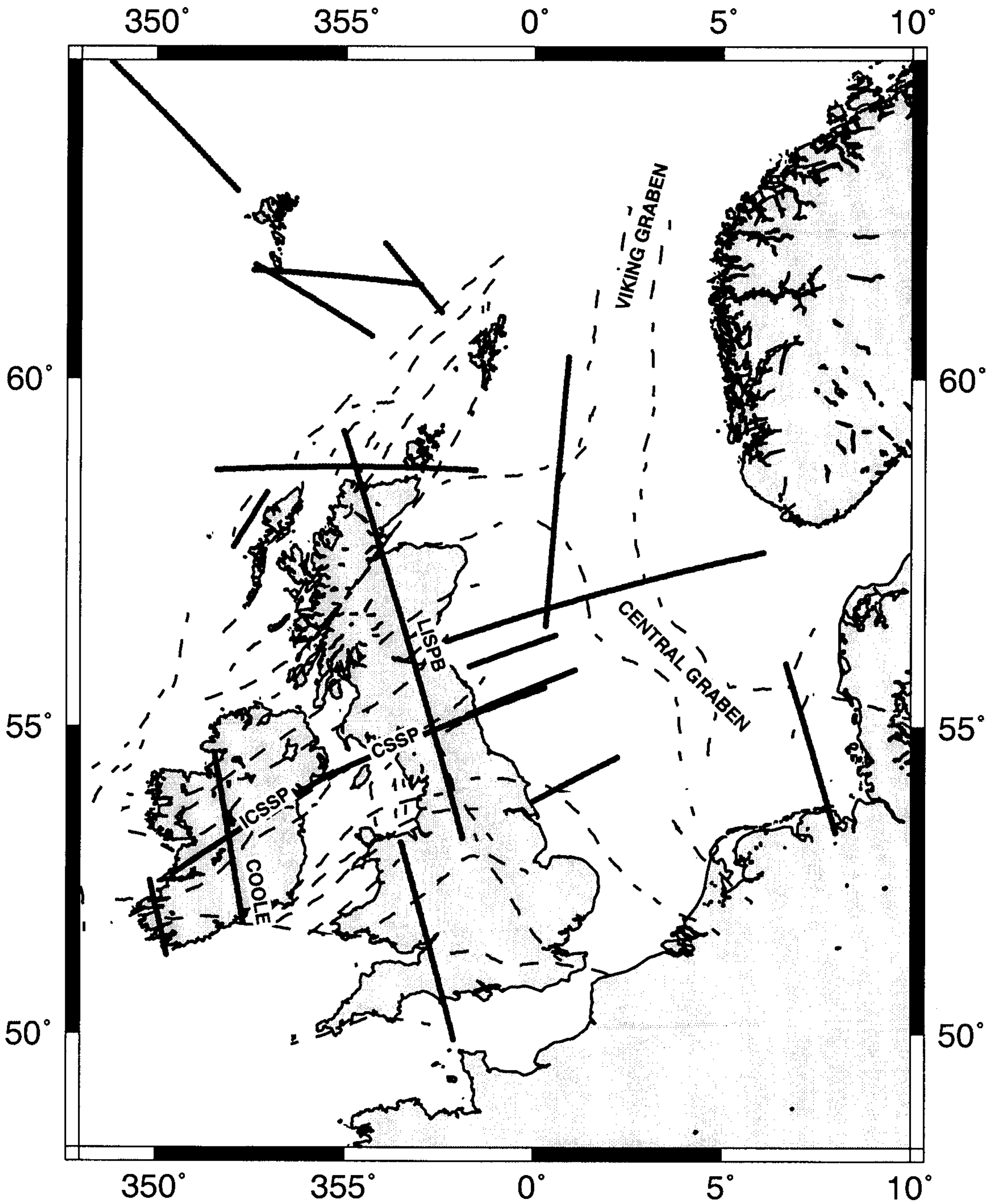

Figure 1. Map showing the location of deep seismic wide-angle and refraction profiles selected for use in this study (thick black lines) and location of major structural trends (broken lines).

ray tracing and inversion (Zelt & Smith, 1992), or full waveform tomographic inversion (McCaughey & Singh, 1997). In some of these interpretations, amplitudes have been modelled to constrain velocity gradients and fine-scale crustal structure. In addition, note was taken of data which were coincident with deep reflection profiles and which had used other data (e.g. potential field modelling) in order to constrain the models or modify them to produce consistent interpretations at profile intersections. A vertical velocity–depth profile at 5 km intervals along each of the 19 profiles was entered into a database (Table 2). In attempting to retain as much information from the primary data source as possible, this database departs from the approach of Christensen & Mooney (1995) which took the average velocity at 5 km depth intervals. However, the approach taken here results in a number of problems. Primarily, the dataset is four-dimensional, in that it contains location in latitude and longitude, depth to interface *and* velocity at

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Table 1. Nineteen profiles used in this study

Profile	Reference
CSSP	Lewis (unpub. Ph.D. thesis, Univ. Durham, 1986)
Faroes	Hughes, Barton & Hamson (1997)
FIRE 1	Richardson *et al*. (1999)
FAST	England *et al*. (unpub. data)
FLARE	Richardson *et al*. (1999)
COOLE	Lowe & Jacob (1989)
ICSSP	Jacob *et al*. (1985)
VARNET	Masson *et al*. (1998)
LISPB (North)	Barton (1992)
LISPB (South)	Bamford *et al*. (1976)
MOBIL 1	West (unpub. Ph.D. thesis, Univ. Durham, 1992)
MOBIL 5	Matthews (unpub. M.Sc. thesis, Univ. Durham, 1989)
W – Reflector	Morgan (unpub. Ph.D. thesis, Univ. Cambridge, 1995)
MONA LISA 1	Abramovitz, Thybo & MONA LISA Working Group (1998)
Central North Sea	Barton & Wood (1984)
Northern North Sea	Christie (1982)
SWABS	Singh, Hague & McCaughey (1998)
PUMA	Powell & Sinha (1987)
Rockall Bank	Bunch (1979)

N.B. This list is not exhaustive and the database is being enhanced through work in progress, particularly to the west of the UK and Ireland.

the interface. Consequently, there are no common depth horizons in the database, which makes direct comparisons between profiles impossible, except where they tie at intersections, because choices of gradients and interfaces vary between datasets. An advantage is that in this form the data can be used to determine better estimates of average crustal velocities and plot average crustal velocity on a map. After some manipulation, which involves gridding, minimization of misfits and recontouring the data, it is possible to produce 5 km (distance) by 2 km (depth) matrices from which depth (to within 2 km) to particular velocities can be determined and mapped. Inevitably, this recontouring results in some smoothing of the data (see Appendix 1), but this is felt justifiable since it enables a common dataset to be derived from the 19 profiles, which retains as much of the characteristics of the original data as possible.

The major limitation of this database is the lack of coverage for some areas of the UK, such as western Scotland, southeast England and the Central and Viking graben regions of the North Sea (Fig. 1). To a certain extent this is being remedied by work in progress (England and others, unpub. data) but the coverage of wide-angle profiling will never reach that of the normal incidence data. Also, there are relatively few coincident deep reflection and deep wide-angle refraction profiles. When producing and interpreting maps from the data it is essential that this limitation is borne in mind. It underlines the importance of acquiring coincident normal incidence and wide-angle profiles if crustal structure is to be fully characterized. Here the data are used to examine lateral variations in velocity structure across the UK, and the distribution of high velocity lower crust.

3. The maps

The data contained in the database have been used to construct contoured maps with which different aspects of crustal velocity structure may be studied. Four basic types of maps are presented: maps showing the depth in kilometres to a particular interface (in this case the Moho); a map of average seismic P-wave velocity for the whole crust; maps showing depth to a particular velocity; and a map showing the thickness of the lower crust where a particular velocity is exceeded. These maps reveal different features of the seismic velocity structure of the crust.

As noted above, one limitation of these maps is the sparse data coverage. A further limitation is the smoothing effect of the contouring process. While wide-angle refraction surveys are good at imaging horizontal gradients and discontinuities in velocity structure they are relatively poor at defining steep contacts, which tend to be smoothed into lateral velocity changes. These changes are further smoothed by the mapping process, so it is very unlikely that these maps would show steep discontinuities such as faults. Contours on the maps run perpendicular to gradients which reveal the location of lateral changes in crustal structure in the 2-D profiles. The locations of the contours beyond 30 km from any of the profiles are entirely a function of the contouring algorithm, but it should be noted that the contouring algorithm was parameterized to suppress rapid changes in gradients which could be interpreted as major changes in velocity. Hence, the displayed contours are the simplest required to link points of common velocity on adjacent profiles. There are no closed loops in the contour maps which are not crossed by profiles. If such features were present it would indicate that the contouring algorithm was producing artefacts in the maps. A more detailed explanation of the selection and application of the gridding and mapping procedure is contained in the appendix to this paper.

Long regional profiles, particularly LISPB, COOLE, ICSSP and CSSP, tend to dominate the features of the maps (see Fig. 1 for line locations). This is inevitable with such a sparse and irregularly distributed dataset but it is also an indication of the objective nature of the mapping achieved by contouring the data using a computer without regard for the orientations of major crustal structures known from deep near-normal incidence profiling and surface mapping. If the dominant features of the maps were distant from the actual data it would indicate that the mapping of the data into the third dimension was generating artefacts. However, because of the sparse

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Table 2. Extract from the initial database for the LISPB profile

Lon	Lat	Dist	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel	Depth	Vel
– 5.02	59.29	0	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.99353	59.2471	5	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.96712	59.2042	10	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.94078	59.1613	15	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.91451	59.1184	20	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.8883	59.0755	25	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.86215	59.0326	30	0	6.2	0.001	6.2	0.002	6.2	19.99	6.4	20	6.5	20.001	6.5	20.002	6.5	26.99	7	27	8.1	45	8.2
– 4.83608	58.9897	35	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.81006	58.9468	40	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.78411	58.9039	45	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.75823	58.8609	50	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.73241	58.818	55	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.70665	58.7751	60	0	6.2	0.001	6.2	0.002	6.2	20.09	6.4	20.1	6.5	20.101	6.5	20.102	6.5	26.99	7	27	8.1	45	8.2
– 4.68096	58.7321	65	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	27.19	7.1	27.2	8.1	45	8.2
– 4.65533	58.6892	70	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	27.39	7.1	27.4	8.1	45	8.2
– 4.62977	58.6462	75	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	27.59	7.1	27.6	8.1	45	8.2
– 4.60426	58.6032	80	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	27.79	7.1	27.8	8.1	45	8.2
– 4.57882	58.5603	85	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	27.99	7.1	28	8.1	45	8.2
– 4.55344	58.5173	90	0	6.2	0.001	6.2	0.002	6.2	20.19	6.4	20.2	6.5	20.201	6.5	20.202	6.5	28.19	7.1	28.2	8.1	45	8.2
– 4.52813	58.4743	95	0	6.2	0.001	6.2	0.002	6.2	20.29	6.4	20.3	6.5	20.301	6.5	20.302	6.5	28.39	7.1	28.4	8.1	45	8.2

Lon – Longitude; Lat – Latitude; Dist – Distance along profile; Depth – Depth to velocity pick in km; Vel – Seismic P-wave velocity in km/s.

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data distribution it is not possible to indicate whether the contouring approach would produce maps of major structures. For example, if there were more wide-angle profiles crossing the North Sea rift system it would be possible to test whether the contouring would accurately map the rift structure. England (2000) successfully applied this same mapping technique to the normal incidence reflection profiles crossing the rift system. This computerized approach offers the advantage of revealing deep structure which cross-cuts boundaries at the surface that could be overlooked by contouring the maps by hand, based on a knowledge of near-surface structure. The dominance of the long regional profiles illustrates the value of such data to study large-scale crustal structure. Each map will be described briefly and some of its uses and limitations outlined.

3.a. Depth to Moho

This map (Fig. 2) shows the variation in depth from sea level to the Moho, defined as the depth at which seismic P-wave velocity exceeds 7.8 km/s. A number of broad trends are discernable. Across northwestern Scotland, the Faroe-Shetland Trough and northwestern Ireland, the contours have a general NE–SW trend, and at 24 to 30 km, the crust is relatively thin in this region. In contrast, a region of thicker crust lies beneath the Midland Valley of Scotland. A distinct discontinuity, separating thin crust to the north from thicker crust to the south, runs in a NE–SW trend across northeastern England, which is close to the position of the Iapetus suture as inferred from mapping and interpretation of deep seismic reflection profiles. A region of thick crust can also be identified beneath the Mid-North Sea and Ringkøbing-Fyn Highs. Across southern England the contours run NNW–SSE, but this is parallel to the two LISPB profiles and should be treated with caution. The North Sea rift system does not have a strong signature in the data. This is due to a relative paucity of data shot orthogonal to the rift, rather than an absence of Moho topography, as is demonstrated by the one profile currently included in the database which crosses the Central Graben. There is no correlation between depth to Moho and topography. In general, the crust is thicker beneath England and Wales and thinner beneath the Highlands of Scotland.

3.b. Depth to 6 km/s and 7 km/s

These maps were generated to map lateral changes in velocity at intermediate and deep levels within the crust and hence locate major boundaries within the crust. In the 2-D models of wide-angle/refraction data, lower crustal layers are crossed by fewer ray paths and so these layers are less well constrained than upper crustal structure, and structures are generally smoothed. While this limitation is recognized as a potential source of error in the locations of gradients in the maps, it is inherent in the data acquisition and will vary from profile to profile as shot spacing and receiver spacing/data recovery vary along and between profiles.

The depth to 6 km/s isovelocity surface map (Fig. 3) shows some prominent features. Firstly, the rocks at the surface in northwestern Scotland appear to have velocities of 6 km/s close to or at the surface. The second feature is the depression of the 6 km/s contour to the northeast of the Firth of Forth. In broad terms the contours have a NE–SW trend, mirroring the major structural trends in the north and west of the UK, but there is no strong correlation with any individual major structure.

In contrast to the broad NE–SW trend shown in the depth to 6 km/s map the majority of the contours in the depth to 7 km/s map (Fig. 4) show an irregular pattern. The contour is shallower beneath the triple junction between the Central and Viking graben and the Moray Firth and in a region immediately to the north of the Isle of Man and beneath the North Channel. Very high velocities are reached at less than 20 km in the vicinity of the Faroe Islands. The deepest point at which high velocity rocks are reached is beneath Wales and the Welsh Borders.

3.c. Average crustal velocity

This map (Fig. 5) was produced by calculating the average crustal velocity at each data point in the database of ungridded data (Table 2). Those regions with extensive deeply buried sediment should show lower average velocities than regions where the majority of the crust is, for example, composed of gneiss. The map confirms this. The lowest average velocities are found along the profile crossing the Central Graben and some of the highest are found over northwestern Scotland. For studying the degree of isostatic compensation of the crust or depth conversion of deep reflection profiles this map is useful. However, the effects of the lower velocity sediments will mask any regional variations in crystalline basement velocity which might indicate terrane boundaries in the crust. Hence the depth to 6 km/s and 7 km/s maps are a more objective measure of lateral changes in crustal velocity. In general the map shows that northwestern Scotland is underlain by higher velocity crust than much of England, Wales and southern Ireland, which is covered by thicker sedimentary rocks. However, there are notable exceptions, such as the regions centred on the East Irish Sea and Mid-North Sea High, which have higher average velocities. This is consistent with the shallow 7 km/s contour observed in the depth to 7 km/s map.

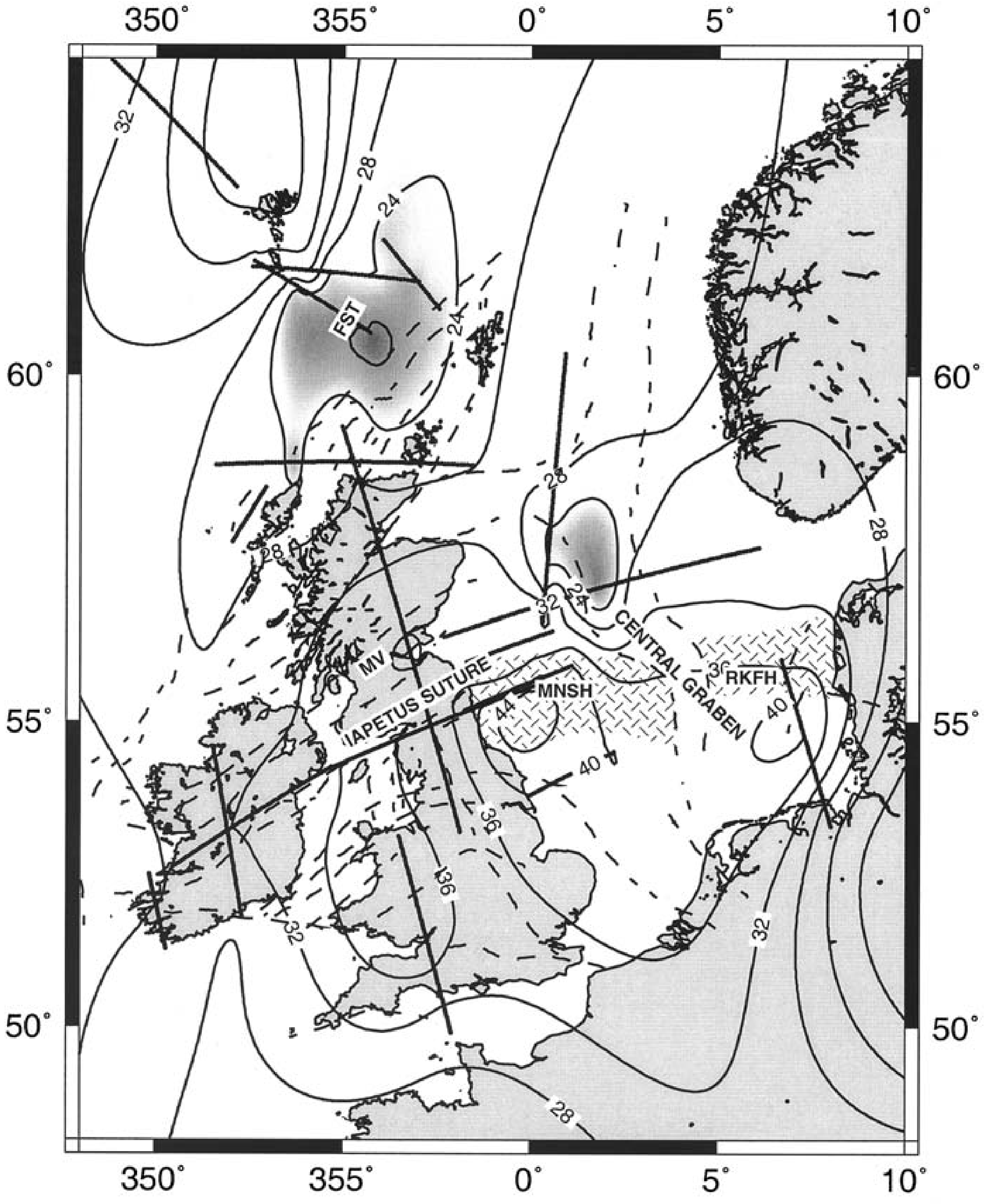

Figure 2. Contour map showing depth to Moho in kilometres. Contours are plotted at an interval of 4 km (vertical resolution of the data is 2 km) Areas where the Moho is shallow are shaded. Line locations are shown as thick black lines. FST – Faroe-Shetland Trough, MV – Midland Valley, MNSH – Mid-North Sea High, RKFH – Ringkøbing-Fyn High. Major structural trends are shown as broken lines.

4. Interpretation

4.a. Origin of velocity surfaces

The Moho is defined as the depth at which seismic P-wave velocities exceed 7.8 km/s. The common occurrence of refracted arrivals (Pn) with velocities of 7.8 km/s or greater indicates that this interface is a sharp (on the scale of a seismic wavelength) step or gradient, rather than a gradational interface. This is generally accepted as corresponding to the depth at which the mineralogical composition of rock becomes dominated by olivine. This is probably one of the few velocity depth interfaces which can be uniquely defined. As Christensen & Mooney (1995)

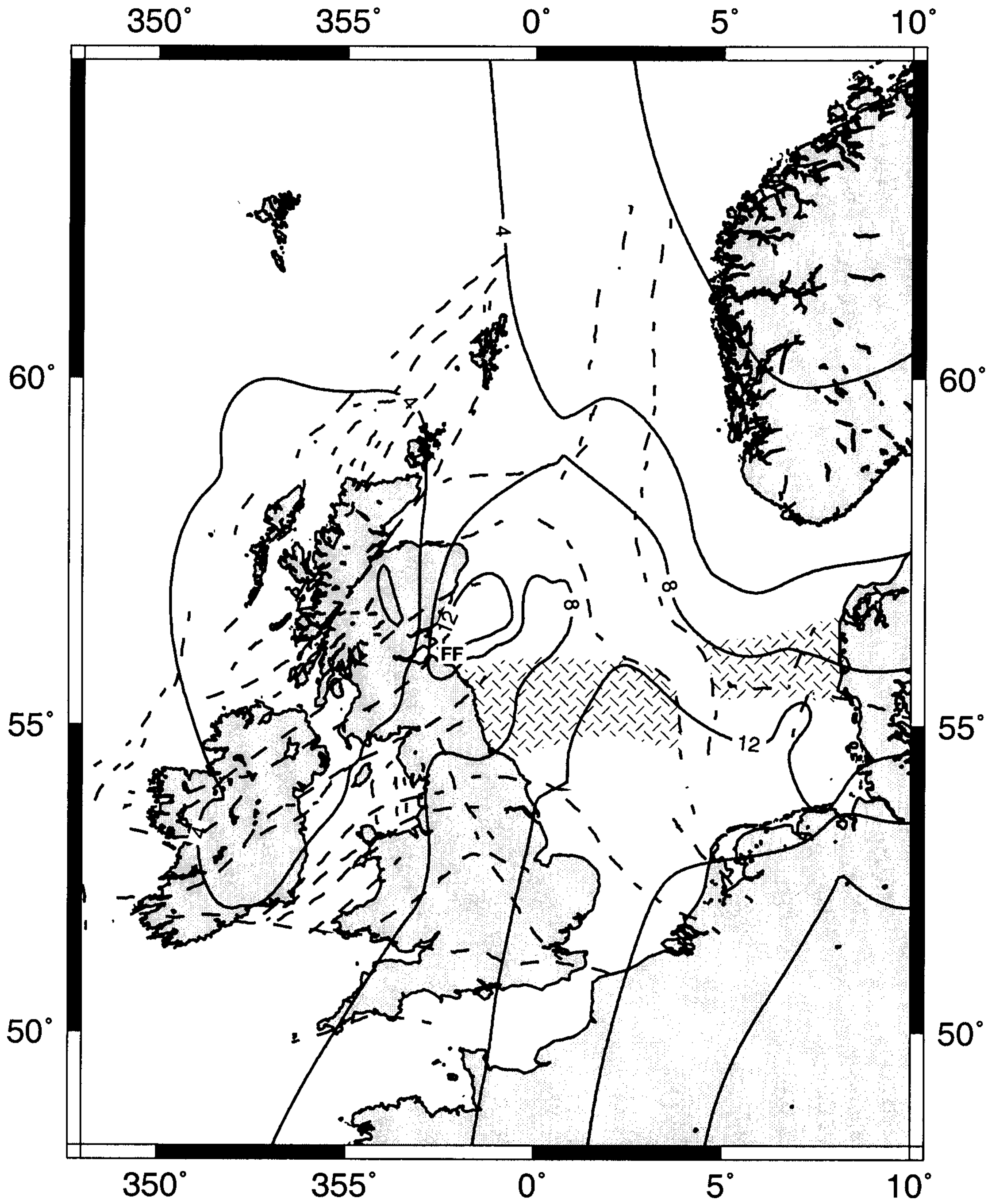

Figure 3. Contour map showing depth to 6 km/s velocity contour. Contours are plotted at an interval of 4 km (vertical resolution of the data is 2 km). Major structural trends are shown as broken lines and the Mid-North Sea–Ringkøbing-Fyn High is stippled. FF – Firth of Forth.

and others before them have demonstrated, there is a broad similarity in seismic P-wave velocities for many crustal rocks at a given pressure and temperature. Therefore, without other information, it is difficult to determine the mineralogical composition of continental crust with a particular velocity at a particular depth without a significant degree of uncertainty.

In the velocity models forming the database, a number of discrete interfaces were often defined by the presence of refracted arrivals in the seismograms from which they were constructed. However, these interfaces can rarely be correlated between profiles. This may be attributable to a number of causes: anisotropy, different acquisition configurations/resolution, different modelling packages and different individuals modelling the data. Given the large amount of reliable data in the database it is, at present, impractical for one person to attempt to remodel all the data using the same modelling package to produce an internally

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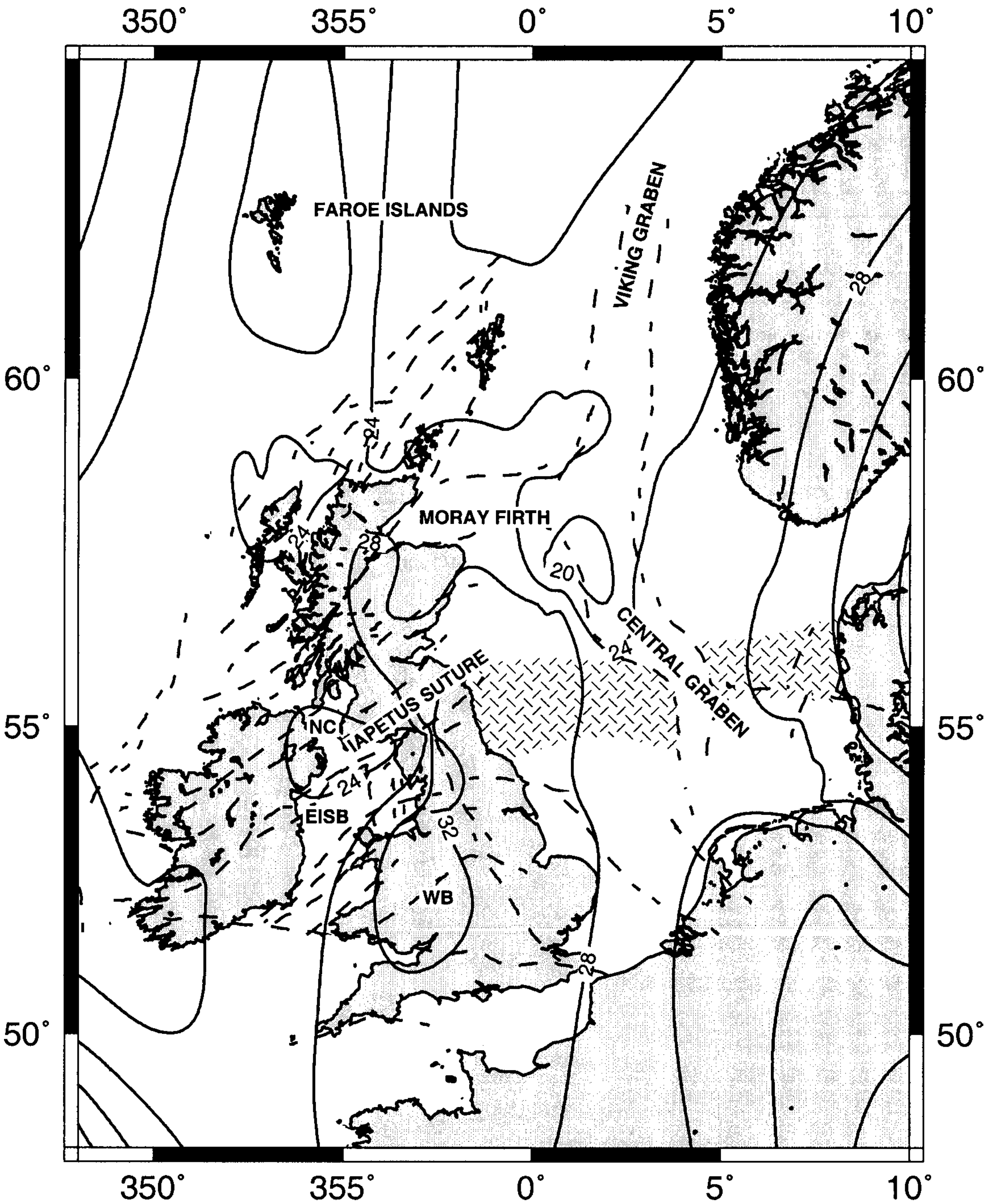

Figure 4. Contour map showing depth to 7 km/s velocity contour. Contours are plotted at an interval of 4 km (vertical resolution of the data is 2 km). Major structural trends are shown as broken lines and the Mid-North Sea–Ringkøbing-Fyn High is stippled. EISB – East Irish Sea Basin, NC – North Channel, WB – Welsh Borders.

consistent dataset, although this would eliminate some of the limitations described. In producing the maps illustrating the depth to a particular seismic velocity these differences have been smoothed by the process of resampling and gridding all the models to a common sampling interval. As a result, some of the differences between profiles have been masked, and steep gradients and interfaces have been removed from the data. However, local pinching or angularity in the contours reveals that this smoothing effect is not ubiquitous.

Consequently, given the limitations of assigning a particular rock type to a particular velocity, and that the maps represent a smoothed imitation of the original models, no attempt is made to relate particular velocities to particular rock types. In general, low velocities indicate silicic rocks, and higher velocities are taken to be indicative of increasing amounts of

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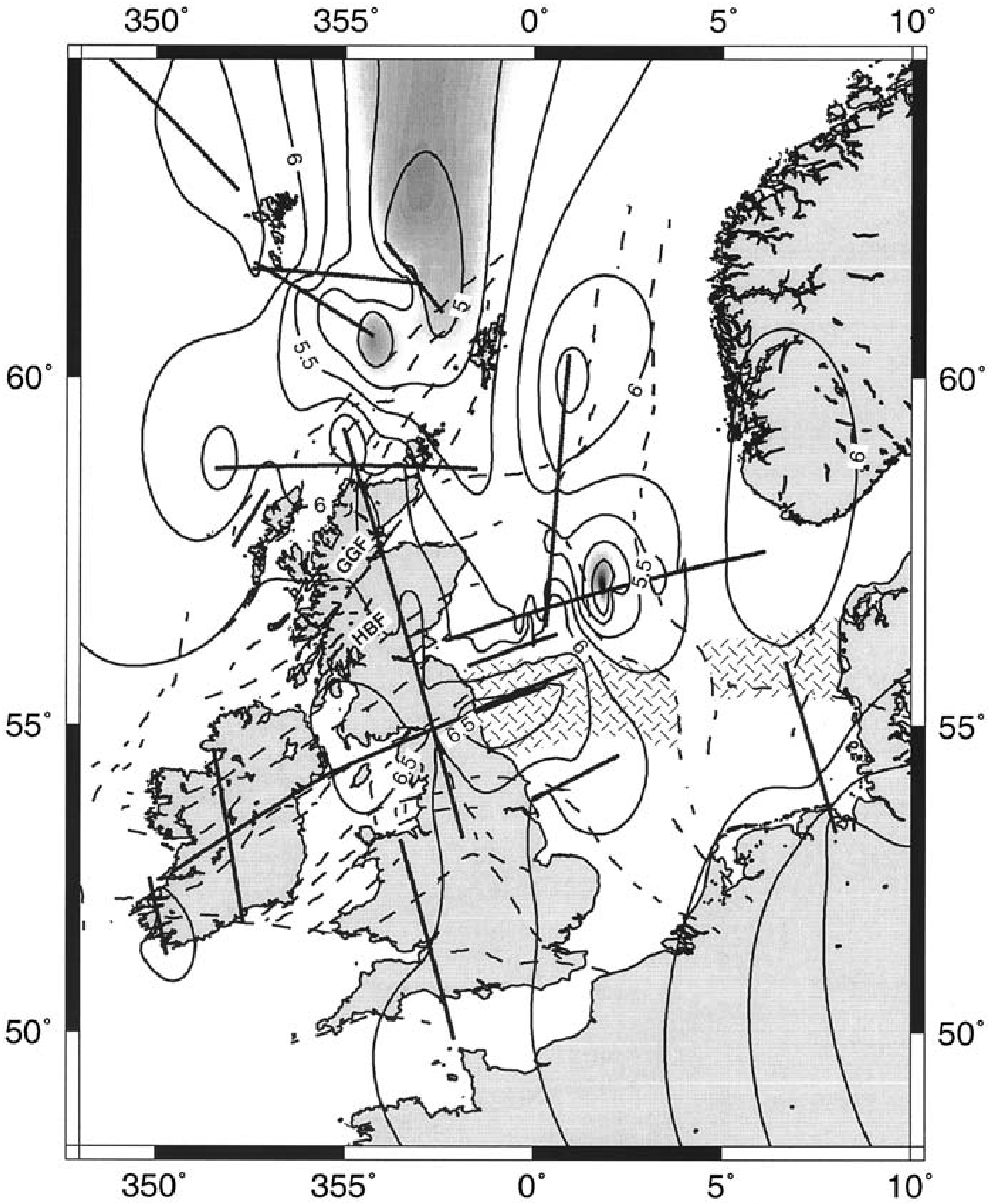

Figure 5. Contour map of average crustal velocity. Contours are plotted at an interval of 0.25 km/s. Areas with low average velocities are shaded. Line locations are shown as thick black lines. Major structural trends are shown as broken lines. GGF – Great Glen Fault, HBF – Highland Boundary Fault. Mid-North Sea–Ringkøbing-Fyn High is stippled.

mafic rocks in the crust. Only the most significant changes in velocity structure are preserved in the contoured maps.

4.b. Lateral changes in velocity structure

The 2-D wide-angle/refraction profiles incorporated into the database illustrate the location of horizontal interfaces and vertical changes in seismic velocity. When mapped and contoured these changes in velocity are imaged as lateral changes in the velocity structure of the crust. The depth to Moho map shows a significant southward increase in thickness of the crust across the Iapetus Suture (Fig. 2), and the general NE–SW trend of the contours in the depth to 6 km/s map (Fig. 3) are also sub-parallel to this structure. This suture was formed during the closure of the Iapetus Ocean at *c*. 380 Ma, during which a number of continental

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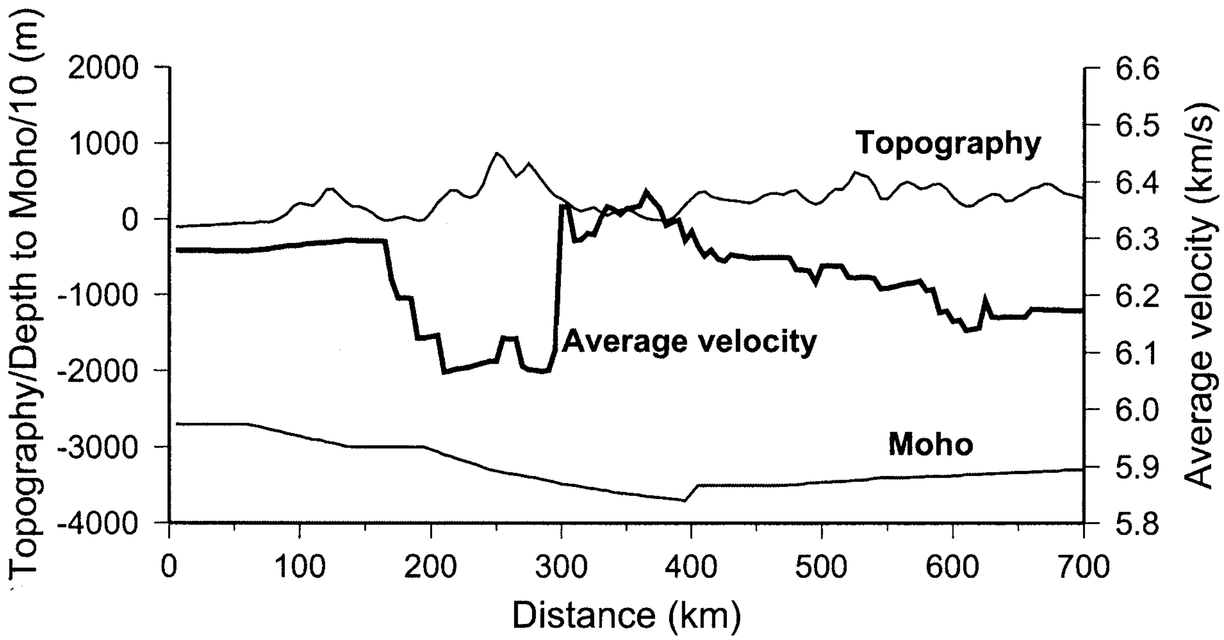

Figure 6. Combined plot of average crustal velocity, topography and depth to Moho along the LISPB profile. (Note: depth to Moho is divided by 10 to display data on plot.)

fragments, or terranes, were trapped between the Laurentian continent to the north and the Gondwanan continent to the south (Soper *et al*. 1992; Hutton, 1987; Woodcock & Strachan, 2000). The gradient is shallow on the 6 km/s map but steeper and more distinct in the Moho map. As a consequence of the smoothing inherent in the way that the data are processed it is not possible to assign the change in gradient or the direction of the contours exactly to the suture. However, it is apparent that terranes to the north and south of the suture have different velocity structures, with the 6 and 7 km/s isovelocity surfaces occurring at shallower levels to the north of the suture. This is also apparent from the map of average seismic velocity (Fig. 5), which shows that northwestern Scotland is underlain by higher velocity crust than much of England, Wales and southern Ireland, although as noted above, this variation in average crustal velocity may be assigned to the difference in the thickness of sedimentary cover.

It has been argued that the terranes to the north of the suture are derived either from oceanic/back-arc crust or from Laurentian crust (Hutton, 1987). The oceanic crust is only preserved as relatively thin slivers along major fault zones and hence present crustal velocities should be, and are, dominated by those typical of continental crust (5.5 to 6.5 km/s average velocity). It is not possible to distinguish major terranes on the basis of differing seismic velocities (cf. Figs 3, 4, 5).

Major fault zones do not have any expression in the data. The Highland Boundary Fault, which is considered to be the edge of the Laurentian continent after rifting formed the Iapetus ocean (Ryan *et al*. 1995), does not show up in the maps, although there is a discontinuity in shallow crustal velocity structure observed in the LISPB data 15 km to the north of the surface trace of the fault (Barton, 1992; Leslie & England, unpub. data). Similarly, the Great Glen fault, which cuts deep mantle reflectors (Snyder & Flack, 1990) and separates mantle with different petrological characteristics (Canning *et al*. 1998) does not have a crustal expression. This may be because wide-angle data will not image vertical structures, but it should still indicate significant lateral changes in seismic velocity if any were present.

As noted above, the map of average crustal velocity indicates that the basement of the Laurentian craton and associated terranes is characterized by a higher velocity crust than the Gondwanan terranes beneath southern Britain and Ireland. Stratigraphic studies have demonstrated that a substantial thickness of the sedimentary rocks covering the Gondwanan terranes were deposited after closure of the Iapetus Ocean. It would appear from these observations that the crust beneath southern Britain and Ireland has gradually thickened by accumulation of sediments, resulting in a lower velocity thick crust. In contrast, the higher velocity crust beneath Scotland and northern Ireland has probably thinned gradually over time after it was thickened in the Grampian orogeny (*c*. 470 Ma). This thinning may be attributed to orogenic collapse or later rifting.

Studies of the average wavelength of gravity anomalies over the UK continental shelf (Barton & Wood, 1984) have shown that the crust has an elastic thickness of less than 5 km, and that for most purposes it can be assumed to be in isostatic equilibrium. If density is equated with velocity, the low velocity crust beneath southern Britain should have a low density and the

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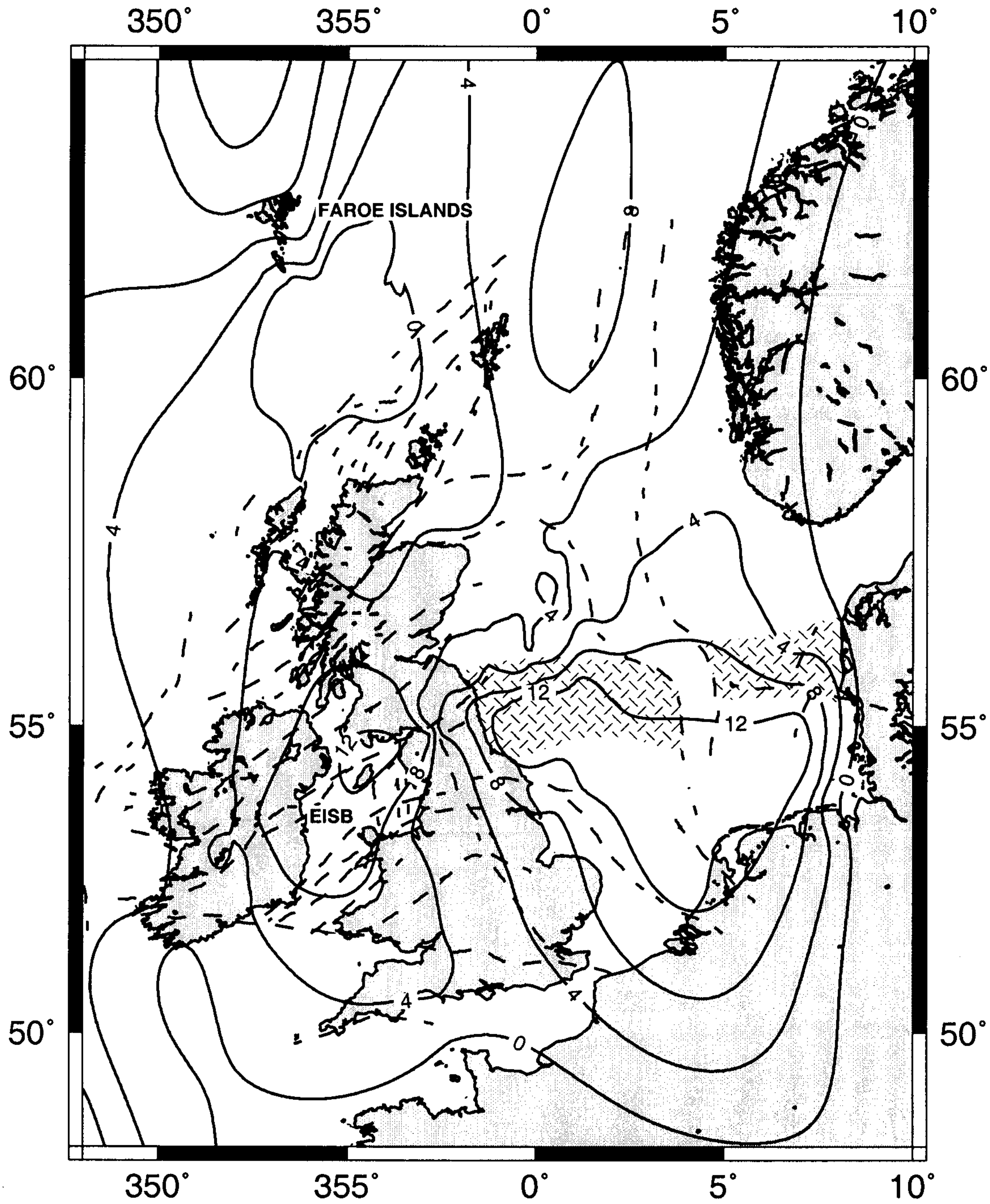

Figure 7. Contour map showing the thickness of the lower crustal layer where the velocity exceeds 7 km/s. Contours are plotted at an interval of 4 km. Major structural trends are shown as broken lines. Mid-North Sea–Ringkøbing-Fyn High is stippled. EISB – East Irish Sea Basin.

high velocity thin crust beneath Scotland and northern Ireland should have a high density. Consequently, the state of isostatic equilibrium across the UK and Irish continental shelf must in part be maintained by lateral variations in density (Pratt isostasy) as opposed to changes in thickness of constant density crust (Airy isostasy). Of further interest is the observation that there is no distinct correlation between topography and crustal thickness apparent on the Moho map. This is particularly apparent in the region of the Grampian Highlands of Scotland, which, while forming one of the highest topographic regions of the UK, is underlain by crust which thins gradually northward (Fig. 6). This may be a function of the distribution of the profiles used in the maps, but the LISPB profile, which dominates the contours along the axis of the UK, crosses the central and northern Highlands of Scotland. Regional gravity maps show a large negative Bouguer anomaly over the Scottish Highlands, implying that the load of the Grampian mountains is

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compensated by a root of low density crust, but the LISPB seismic data show the Moho shallowing beneath the Grampian mountains. The alternative is that the Bouguer correction overcompensates for the load of the mountains and the lower crust is considerably denser than the upper crust, which is consistent with the observations made from wide-angle/refraction data (Figs 3, 4). This provides further evidence that the commonly applied concept of Airy isostasy may not be appropriate when attempting to understand variations in crustal thickness.

4.c. High velocity lower crust

The maps show that parts of the UK and Irish continental shelf are underlain by high velocity lower crust. In particular the depth to 6 km/s and 7 km/s contour maps (Figs 3, 4) show high velocity rocks at shallow depths beneath the Faroe Islands, northern Scotland, the East Irish Sea and the Mid-North Sea High, indicating that significant volumes of high velocity rocks lie beneath these areas. A limitation of the 7 km/s map, in particular, is that in some regions the 7 km/s contour also marks the base of the crust. In order to overcome this problem a map is presented showing the thickness of crust with velocities in excess of 7.0 km/s (Fig. 7). Studies of the North Atlantic margins, where a good case can be made for the presence of underplated material in the crust, have identified bodies of rock with seismic P-wave velocities of greater than 7.2 km/s, which are interpreted as underplated material (White, 1988). The map of thickness of crust with velocities in excess of 7.0 km/s (Fig. 7) can be used to determine the thickness of crust with high velocity rocks which might include a mixture of high velocity underplated material intruded into lower velocity crustal rocks.

The map of crustal thickness with velocities greater than 7 km/s shows areas of thick high velocity lower crust beneath the Faroe Islands, the East Irish Sea, the Mid-North Sea–Ringkøbing-Fyn High and a large area of the southern North Sea. Figure 7 shows a substantial thickness of high velocity rock beneath the East Irish Sea. A comparison with the depth to 7.0 km/s contour map (Fig. 4) shows that this high partially overprints the trend of the Iapetus Suture suggesting that it may be a feature which is younger than the suture. To prove this would require a profile crossing the East Irish Sea orthogonal to the suture showing that the region of high velocity straddles the suture zone.

As inferred above, a probable explanation for the presence of high velocity lower crust occurring in regions of otherwise low average velocity is that mantle derived basaltic magmas have been intruded into the crust. An important consequence of this ‘magmatic underplating’ is that it reduces the density of the lithospheric column in which it is emplaced. This results in uplift at the surface (McKenzie, 1984) which causes erosion of the surface rocks, producing an unconformity, and exhumation of basement. The stratigraphy of the Mid-North Sea–Ringkøbing-Fyn High is poorly constrained but Late Palaeozoic and younger sediments become substantially thinner where they cross the High. However, early Tertiary uplift and exhumation is well documented for the East Irish Sea (Rowley & White, 1998). The coincidence of regions of uplift and exhumation and high lower crustal velocities provides compelling evidence for interpreting the high seismic velocities in the lower crust beneath the East Irish Sea in terms of magmatic underplating (Al-Kindi *et al*. 2003). Early Tertiary underplating has been inferred beneath northwest Scotland from exhumation and petrological studies (Brodie & White, 1995; White & Lovell, 1997) but the maps of lower crustal velocities do not provide strong supporting evidence (Fig. 7). It is possible that the underplating is sparsely distributed, which might explain the higher average velocities for the crust beneath Scotland, but it is difficult to hide the 5 km of underplated material required to produce the observed (3 km) of exhumation within the crust by distributing it in sills. This is because there is no evidence for the increase in crustal thickness that would result. The crust beneath northwestern Scotland is relatively thin, as noted in Section 3.a.

5. Conclusions

A database containing details of the lateral and vertical variation in seismic P-wave velocity across the UK, Ireland and the North Sea has been compiled from wide-angle/refraction profiles. This database has been used to derive depth to particular velocities and the average velocity of the crust which have been used to produce a series of contour maps. The resolution of these maps, obtained by minimizing misfits between contours and observed data, is 7.5′ by 7.5′ by 2 km, but their accuracy is limited by the irregular and relatively sparse distribution of the data.

The maps presented enable the seismic P-wave velocity structure of the UK to be viewed in a number of ways. The map of depth to Moho defines the variations in the thickness of the continental crust, revealing that the southern UK is underlain by thicker crust than that beneath northern and western Scotland. There is no direct correlation between crustal thickness and topography, as might be expected if topographic loads were compensated by crustal roots. The map of average P-wave velocity reveals that the crust beneath northern and western Scotland has a higher average velocity than most of England and Wales, but the crust beneath the East Irish Sea and the Mid-North Sea High also shows higher than average velocity. These variations partly reflect the increased thickness of sedimentary cover across southern Britain, which lowers average velocities. These variations in velocity structure are consistent with maps of depth of the

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6 km/s and 7 km/s isovelocity contours which show that high velocities are reached at shallower depths beneath northwest Scotland, and the East Irish Sea and at deeper levels beneath southern Britain. A map of the thickness of the crust with velocities greater than 7.0 km/s shows that the lower crust beneath the East Irish Sea is formed from rocks with particularly high velocities, comparable to those associated with magmatic underplating. While the distribution of the wide-angle data is limited, the available coverage suggests that these high velocity regions cross the downward extrapolation of major structures identified at the surface and hence may represent younger modifications of the crust.

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References

ABRAMOVITZ, T., THYBO, H. & MONA LISA WORKING GROUP. 1998. Seismic structure across the Caledonian front along MONA LISA profile 1 in the southeastern North Sea. *Tectonophysics* **288**, 153–76.

AL-KINDI, S., WHITE, N., SINHA, M., ENGLAND, R. & TILEY, R. 2003. Crustal trace of a hot convective sheet. *Geology* **31**, 207–10.

BAMFORD, D., FABER, S., JACOB, B., KAMINSKI, W., NUNN, K., PRODEHL, C., FUCHS, K., KING, R. & WILLMORE, P. 1976. A lithospheric seismic profile in Britain – 1. Preliminary results. *Geophysical Journal of the Royal Astronomical Society* **44**, 145–60.

BARTON, P. J. 1992. LISPB Revisited: A new look under the Caledonides of northern Britain. *Geophysical Journal International* **110**, 371–91.

BARTON, P. J. & WOOD, R. 1984. Tectonic evolution of the North Sea basin: crustal stretching and subsidence. *Geophysical Journal of the Royal Astronomical Society* **79**, 987–1022.

BRAILLE, L. W., HINZE, W. J., VON FRESE, R. R. B. & KELLER, G. R. 1989. Seismic properties of the crust and uppermost mantle of the conterminous United States and adjacent Canada. In *Geophysical framework of the continental United States* (eds L. C. Pakiser and W. D. Mooney), pp. 655–75. Geological Society of America, Memoir no. 172.

BRODIE, J. & WHITE, N. 1995. The link between sedimentary basin inversion and igneous underplating. In *Basin Inversion* (eds J. G. Buchanan and P. G. Buchanan), pp. 21–38. Geological Society of London, Special Publication no. 88.

BUNCH, A. W. H. 1979. A detailed structure of Rockall Bank (55 N 15 W) – A synthetic seismogram analysis. *Earth and Planetary Science Letters* **45**, 453–63.

CANNING, J. C., HENNEY, P. J., MORRISON, M. A., VAN CALSTEREN, P. W. C., GASKARTH, J. W. & SWARBRICK, A. 1998. The Great Glen Fault; a major vertical lithospheric boundary. *Journal of the Geological Society, London* **155**, 425–8.

CERVENY, V. & FIRBAS, P. 1984. Numerical modelling and inversion of travel times of seismic body waves in inhomogeneous anisotropic media. *Geophysical Journal of the Royal Astronomical Society* **76**, 41–51.

CHADWICK, R. A. & PHARAOH, T. C. 1998. The seismic reflection Moho beneath the United Kingdom and adjacent areas. *Tectonophysics* **299**, 255–79.

CHRISTENSEN, N. I. & MOONEY, W. D. 1995. Seismic velocity structure and composition of the continental crust. *Journal of Geophysical Research* **100**, 9761–88.

CHRISTIE, P. A. F. 1982. The interpretation of refraction experiments in the North Sea. *Philosophical Transactions of the Royal Society* **A305**, 101–11.

ENGLAND, R. W. 2000. Deep structure of North West Europe from Deep Seismic Profiling: The link between basement tectonics and Basin development. In *Atlantic rifts and continental margins* (eds W. Mohriak and M. Talwani), pp. 57–83. American Geophysical Union, Geophysical Monograph no. 115.

HUGHES, S., BARTON, P. J. & HAMSON, D. J. 1997. Characterising the Mid-Faroe Ridge using seismic velocity measurements. *Journal of Geophysical Research* **102**, 7837–47.

HUTTON, D. H. W. 1987. Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine* **124**, 405–25.

JACOB, A. W. B., KAMINSKI, W., MURPHY, T., PHILLIPS, W. E. A. & PRODEHL, C. 1985. A Crustal model for a northeast–southwest profile through Ireland. *Tectonophysics* **113**, 75–105.

LOWE, C. & JACOB, A. W. J. 1989. A north–south profile across the Caledonian suture zone in Ireland. *Tectonophysics* **168**, 297–318.

MASSON, F., JACOB, A. W. B., PRODEHL, C., READMAN, P. W., SHANNON, P. M., SCHULZE, A. & ENDERLE, U. 1998. A wide-angle seismic traverse through the Variscan of southwest Ireland. *Geophysical Journal International* **134**, 689–705.

MATTHEWS, D. 1986. Seismic reflections from the lower crust around Britain. In *The nature of the lower continental crust* (eds J. B. Dawson, D. A. Carswell, J. Hall, and K. H. Wedepohl), pp. 11–22. Geological Society of London, Special Publication no. 24.

MCCAUGHEY, M. & SINGH, S. C. 1997. Simultaneous velocity and interface tomography of normal-incidence and wide-aperture seismic traveltime data. *Geophysical Journal International* **131**, 87–99.

MCGEARY, S., CHEADLE, M. J., WARNER, M. R. & BLUNDELL, D. J. 1987. Crustal structure of the continental shelf around Britain derived from BIRPS deep seismic profiling. In *Petroleum geology of North West Europe* (eds J. Brooks and K. Glennie), pp. 33–41. London, Institute of Petroleum.

MCKENZIE, D. 1984. A possible mechanism for epeirogenic uplift. *Nature* **307**, 616–18.

MEISSNER, R., MATTHEWS, D. & WEVER, T. 1986. The "Moho" in and around Great Britain. *Annales Geophysicae* **4B**, 659–64.

POWELL, C. M. R. & SINHA, M. C. 1987. The PUMA experiment west of Lewis, UK. *Geophysical Journal of the Royal Astronomical Society* **89**, 259–64.

RICHARDSON, K. R., WHITE, R. S., ENGLAND, R. W. & FRUEHN, J. 1999. Crustal structure east of the Faroe islands: mapping sub-basalt sediments using wide-angle seismic data. *Petroleum Geoscience* **5**, 161–72.

ROWLEY, E. & WHITE, N. 1998. Inverse modelling of extension and denudation in the East Irish Sea and surrounding areas. *Earth and Planetary Science Letters* **161**, 57–71.

RYAN, P. D., SOPER, N. J., SNYDER, D. B., ENGLAND, R. W. & HUTTON, D. H. W. 1995. The Antrim-Galway line: A resolution of the Highland Border Fault enigma of the British Caledonides. *Geological Magazine* **132**, 171–84.

SINGH, S. C., HAGUE, P. J. & MCCAUGHEY, M. 1998. Study of the crystalline crust from two-ship normal incidence and wide-angle experiment. *Tectonophysics* **286**, 79–92.

SMITH, W. H. F. & WESSEL, P. 1990. Gridding with continuous curvature splines in tension. *Geophysics* **55**, 293–305.

SNYDER, D. B. & FLACK, C. A. 1990. A Caledonian age for reflectors within the mantle lithosphere north and west of Scotland. *Tectonics* **9**, 903–22.

SOPER, N. J., STRACHAN, R. A., HOLDSWORTH, R. E., GAYER, R. A. & GREILING, R. O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society, London* **149**, 871–80.

WESSEL, P. & SMITH, W. H. F. 1991. Free software helps map and display data. *Eos, Transactions, American Geophysical Union* **72**, 441, 445–6.

WHITE, N. & LOVELL, B. 1997. Measuring the pulse of a plume with the sedimentary record. *Nature* **387**, 888–91.

WHITE, R. S. 1988. A hot spot model for early Tertiary volcanism in the N Atlantic. In *Early Tertiary volcanism and the opening of the N E Atlantic* (eds A. C. Morton and L. M. Parson), pp. 3–13. Geological Society London, Special Publication no. 39.

WOODCOCK, N. & STRACHAN, R. 2000. The Caledonian Orogeny: a multiple plate collision. In *Geological History of Britain and Ireland* (eds N. Woodcock and R. Strachan), pp. 187–206. Oxford: Blackwell Science.

ZELT, C. A. & SMITH, R. B. 1992. Seismic traveltime inversion for 2-D crustal velocity structure. *Geophysical Journal International* **108**, 16–34.

Appendix 1

Data were taken from published and unpublished sources (Table 1) and velocity depth values at major interfaces were entered into a database (see example record in Table 2). These data were used to calculate average crustal velocity at each datapoint. A Fortran77 program was then written to convert the database data into a form readable by Generic Mapping Tools (GMT) (Wessel & Smith, 1991). Once in GMT format the data were first gridded and then contoured to produce the depth to Moho map (Fig. 2) using the BLOCKMEAN and SURFACE routines in GMT. The BLOCKMEAN routine takes the irregularly spaced data (velocity and depth along seismic profiles) and populates a regular grid with a single value posted at the centre of each grid square based on the mean of the observed values falling within a square, with sides equal to the grid spacing, around the point. Any grid squares not containing data are left empty. This process has two important roles. Firstly, it creates a regularly spaced grid of data for the contouring algorithm to operate on. Secondly, it constrains the minimum spatial wavelength of the data to twice that of the grid spacing. Wavelengths below that of twice the grid spacing are spatially aliased. In simple terms any wavelength below 15 minutes of latitude and longitude in the maps should be regarded as spurious or undersampled and inaccurate. The choice of grid spacing was selected using the method described below.

Table A1. Estimation of misfit between observed and contoured data

Map	Typical value (km or km/s)	Mean error	RMS error
Depth to Moho	30	0.00015	0.0173
Depth to 6 km/s	7	0.00179	0.0467
Depth to 7 km/s	28	0.00361	0.0643
Average crustal velocity (km/s)	6	0.00087	0.0780

After gridding, the data were contoured using the SURFACE algorithm of Wessel & Smith (1991). This is a modification of a minimum curvature algorithm. Minimum curvature algorithms generally produce the best fit to observed data and in general produce fewer artefacts than other contouring methods. However, they do not work well with data which contain steep gradients. As noted above, steep gradients in velocity, such as those produced at faults, tend to be smoothed out in wide-angle data, so this is not a particular problem in this case. A more serious problem is that minimum curvature algorithms can generate spurious maxima and minima between data points. This is avoided in the SURFACE algorithm through the use of a tension operator which suppresses local maxima and minima.

In order to offset the effects of the sparse dataset the grid size was optimized, by trial and error, to minimize misfit between observed and contoured data using the output from SURFACE as a guide. If the grid size is too large only the largest wavlengths of the data will be sampled and the contoured data will have a poor match with the observed data. If the grid size is too small the contoured data will fit all the detail in the data but the contours will contain spurious features in unpopulated parts of the grid in order that the contoured data fit the observed data exactly. In addition to minimizing the misfit between the observed and contoured data the curvature of the contoured surface was also minimized to reduce the appearance of artefacts in the contours. Again this was achieved by trial and error. The parameters which resulted in the best fit between the observed and contoured data and the minimum curvature of the contours was a grid size of 7.5 minutes and a tension factor of 0.25. In practical terms this means that the contours are reliable to within *c*. 30 km of the actual profiles. Beyond this point the contours map the minimum gradient necessary to fit with the velocity structure on adjacent profiles. A fuller explanation of gridding and contouring using minimum curvature algorithms is given by Smith & Wessel (1990). Mean and rms errors for each map are given in Table A1. It should be noted that there is no direct means of measuring the accuracy of the contours in unpopulated regions of the grid, since there are no other independently determined more densely sampled datasets for the velocity structure of the UK and its surroundings. A comparison, by England (unpub. data), between contoured bathymetry data picked from the seabed reflections from a sparse grid of seismic reflection data and more densely sampled ship data showed that the SURFACE algorithm generated a bathymetry map closely comparable with the ship data.

To produce the maps of depth to 6 and 7 km/s contour and thickness of crust with velocities greater than

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7 km/s, the data for each profile were gridded, using BLOCKMEAN and contoured in velocity using SURFACE, at a grid node spacing of 2 km vertical interval (depth) and 5 km horizontal interval (distance). This process recontours the wide-angle/refraction data at a common contour interval. Visual checks and errors were calculated to reduce the difference between the contouring pattern on the original data, which may also have contained discontinuities (refracting interfaces or reflecting surfaces) which are replaced with very steep gradients during this contouring process, and the observed data. The resulting files of depths to particular velocities along the track of the profiles were then processed to produce maps by the method described above.

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