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Interpretation of Refraction Experiments in the North Sea [and Discussion]

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Interpretation of refraction experiments in the North Sea

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Before 1977, only three long-range seismic refraction profiles had been shot in the North Sea Basin, with somewhat inconsistent results in terms of a description of the Mohorovičic discontinuity (Moho). In the summer of 1977, the Marine Group of Cambridge University fired three refraction lines with the use of pull-up, shallow-water seismometers, the longest reversed profile extending for 400 km along the 0.5° E meridian from east of the Shetland Islands to the latitude of Dundee.

Although records varied in quality, a time term interpretation of the results was made with the use of detailed velocity–depth information supplied by the oil industry. This interpretation indicates that there is an anticlinal form to the Moho beneath the deepest sediments of the Moray Firth Basin, as demanded by gravity data from the area. It is further suggested that the seismic evidence supports an extensional model to explain the origin of the North Sea Basin.

Introduction

The Cambridge North Sea Experiment was conceived against a background of intense activity in the field of long-range seismic refraction seismology. Much work had already been performed by the Groupe Grands Profils Sismiques and the Lithospheric Seismic Profile of Britain (LISPB) working party in an effort to study the deep crustal and uppermost mantle velocity structures beneath continental Europe (Sapin & Prodehl 1973) and mainland Britain (Bamford *et al.* 1978).

At the Bloomsbury meeting, of industrial and academic geologists and geophysicists, where so much proprietary data was released for the first time, Matthews (in Woodland (ed.) 1974, p. 453) announced that the Cambridge Marine Group intended to fire a long-range refracton profile in the North Sea during the summer of 1977. The intention of the experiment was to compare the compressional wave velocity structure beneath the subsiding North Sea Basin with the velocity structures beneath the stable areas of western Europe. Between the conception and execution of the experiment a great deal of interest arose in explaining the origins of sedimentary basins in general and the North Sea Basin in particular, with important contributions being made by Bott (1976), Collette (1968), Sleep & Snell (1976), Illies (1970), Artemjev & Artyushkov (1971), Ziegler (1975) and McKenzie (1978), to name but a few. The Cambridge experiment, in conjunction with the newly released data, should clearly provide important constraints in determining the types of model applicable to the North Sea.

The refraction data available in 1977 provided inconclusive information concerning the crustal structure of the North Sea. Although Collette's (1960) early studies of the North Sea

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gravity field eventually led him to propose an Airy type of compensation for the basin, his seismic investigations (Collette *et al.* 1970) found the Mohorovičic discontinuity (Moho) at a depth of about 31 km on his Dogger Bank Profile, which was shot by using the expanding spread technique from a fixed midpoint. Two lines by Sørnes (1971) and Solli (1976) were fired from the Shetlands across the northern North Sea Basin to Norway with conflicting results. Sørnes's profile was originally published as a time term interpretation but an inversion of the delay times to depths was published by Ziegler (1975) showing a deep crustal root below the Viking Graben with a Moho depth of some 38 km. Solli's profile, however, published in Ziegler (1977), shows a dramatic thinning of the crystalline crust to about 10 km beneath the Viking Graben with the shallowest Moho depth at about 18 km. There is thus a discrepancy of about 20 km in the estimated Moho depths from two effectively coincident refraction profiles, although the later profile had the benefit of a greater knowledge of the velocity structure of the sedimentary cover.

Experimental procedure

The recording equipment used in the North Sea experiment consisted of pull-up, shallow-water seismometers (Puss) designed and built at Cambridge (Smith & Christie 1976). Each instrument contained a three-component set of geophones mounted in 'sticky' gimbals and a pressure-sensitive hydrophone. The seismic signals were amplified by preset gain amplifiers and recorded in frequency modulated form on a standard cassette tape unit fitted with a four-track head. A clock and programmer allowed the preselection of shooting windows to avoid the requirement for continuous operation and also provided timing signals recorded with the shots.

The charges used were of 'Geophex' (I.C.I. registered trade mark) and were fired either as free-sinking single units varying in mass from 45 to 182 kg, or as dispersed charges comprising three simultaneously detonated charges of 204 kg per unit. Dispersed charges were chosen for their efficiency in long-range propagation (Jacob 1975) and because of the difficulty in firing a large single charge at its optimum depth (Burkhardt & Vees 1975) in the shallow waters of the North Sea.

The observation scheme in relation to the Tertiary isopach map from Ziegler (1978) is shown in figure 1. Three profiles in all were fired, the Firth of Forth profile, the Main Line and the Crustal Control Line. The first of these was fired by using seven free-sinking charges from the Firth of Forth towards an array of four Pusses placed near to the southern end of the Main Line. These receivers were then recovered and 13 were laid at about 30 km spacing on the 0.5° E meridian from a point east of the Shetlands to Devils Hole, a local deep at the latitude of Dundee. Reversed coverage was achieved by firing two dispersed charges at each end of the Main Line offset by about 15 km, being half the receiver spacing. Finally, six Pusses were laid in an extended array towards the northern end of the Main Line, and the Crustal Control profile was obtained by firing eight free-sinking charges to the south of this array. This procedure gave reversed coverage over the crystal refractors at the northern end of the Main Line.

Shot and receiver positions were obtained by using the standard Decca Navigator system. Shot times were computed by using a hull geophone to record the water arrival at the shooting ship simultaneously with the timing signals broadcast by M.S.F. Radio Rugby. A correction was made to allow for the travel time of the water wave arrival from the charge to the ship, which was typically 0.2 s for the free-sinking charges and 0.8 s for the dispersed charges. Upon return to Cambridge all records were digitized, allowing filtered, computer-drawn record sections to be prepared.

The quality of the data varied widely, with the hydrophone traces being more reliable on the whole than the geophone signals, owing to the uncertain ground coupling of the geophones. However, few recording points were totally lost since four channels of information

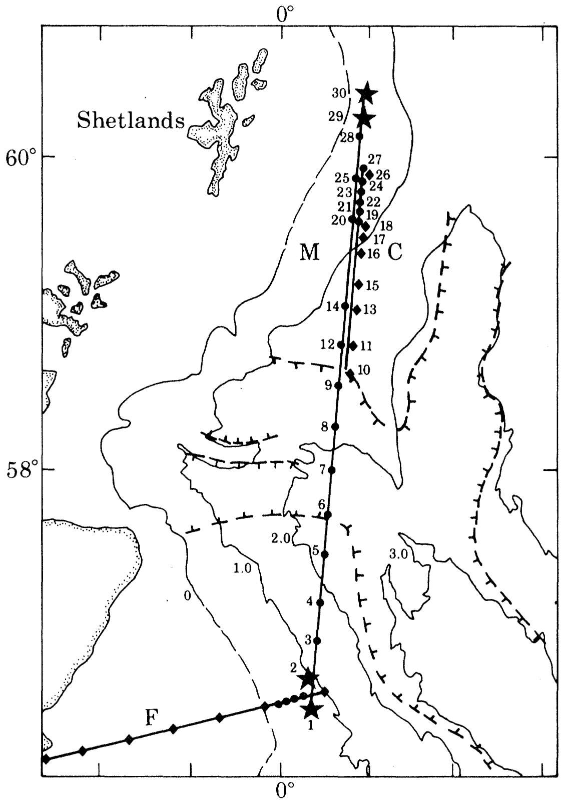

FIGURE 1. Seismic observation scheme in relation to the North Sea Tertiary isopach map from Ziegler (1978). The isopachs are marked in kilometres. Three refraction profiles were recorded as indicated by the letters C (Crustal Control Line), M (Main Line) and F (Firth of Forth Line). Free sinking shot points are denoted by diamonds, dispersed shot points by large stars and recording points by solid circles.

were recorded from each shot. Positioning errors were estimated by Decca to be ± 50 m at a 68% confidence level. Timing precision was estimated at a few hundredths of a second while the probable error in picking arrival times was about one tenth of a second, a figure that was shot-dependent.

Arrival time analysis

(a) *Crustal Control Line*

The travel time – distance curve for Crustal Control Line shots fired to the south of the Puss array is shown in figure 2. The arrival times have been computed by using a reduction velocity of 6.7 km s^{-1} and the observations have been linked together for each shot. There

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is evidence for an upper crustal refractor out to about 25 km range, where there is a cross-over to a travel time branch from a higher velocity refractor. However, the linked observations have an *en échelon* pattern and are offset to increasing travel times with increasing range. Although the apparent velocity across the Puss array between 25 km and 115 km is 6.7 km s^{-1}, the apparent velocity across the shot array as observed at a single receiver is rather less than 6 km s^{-1}. The *en échelon* pattern is an indicator of refractor dip with a southerly direction consistent with the basinwards direction of shooting (figure 1).

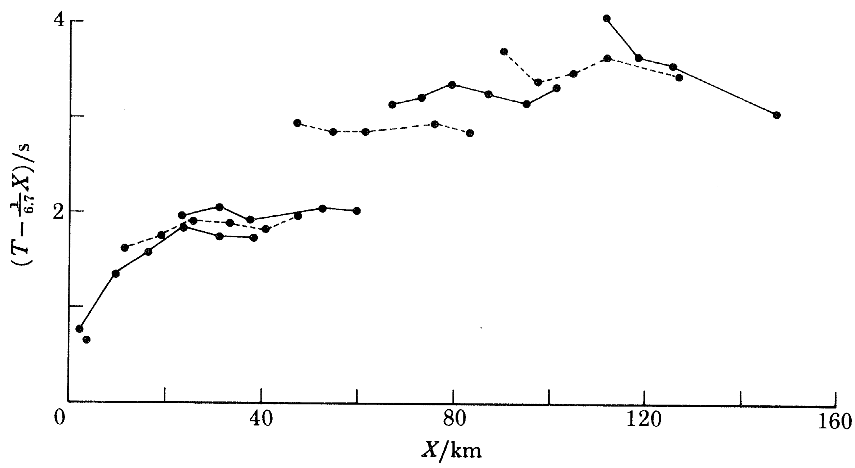

FIGURE 2. Crustal Control Line arrivals reduced at 6.7 km s^{-1}. Arrivals from each shot are linked revealing an *en echelon* pattern, which suggests a southward-dipping refractor.

Since the Crustal Control Line overlaps the northern end of the Main Line and there is a coincidence of observation points between the two profiles, it is possible to carry out a time term analysis by using the reversed coverage thus afforded. The time term method (Scheidegger & Willmore 1957; Berry & West 1966) is usually applied to shot and receiver networks of random geometry, but the method works well in the case of reversed linear profiles where there are points in common between the forward and reverse directions.

In fact, time term analysis is necessary when, as in this case, the refractors are not dipping planes, as can be seen from the jump in reduced time from the linked arrivals terminating at 60 km to the group starting at 47 km (figure 2). From an examination of the curves of travel times, there is a sharp break from an upper crustal refractor of relatively low velocity to a deeper refractor of significantly higher velocity. The assignment of travel time – distance observations to a given refractor for the time term analysis was made by using the travel time curves, phase correlation and iterative examination of the distribution of residuals with range from successive solutions of the time term equations. The final solution indicated the presence of two crustal refractors, over which there was reversed control, with true velocities of 5.66 km s^{-1} and 6.18 km s^{-1}. The corresponding delay times are displayed in table 1.

By using the first arrival times out to 3.5 km and after correcting for the thin Tertiary cover by using the Tertiary isopach data published by Ziegler (1978), it was possible to arrive at an unreversed estimated of 4.1 km s^{-1} as being the velocity of the Devonian Old Red Sandstone of this part of the East Shetland Platform. This compares with a velocity of 4.0 km s^{-1} as found from borehole measurements in a nearby well.

Table 1. Time terms for the two crustal refractors covered by the northern part of the Main Line and the Crustal Control Line

site	term time (s)	s.d. (s)	number of observations	term time (s)	s.d. (s)	number of observations
27	0.26	—	1	0.41	0.03	5
26	0.21	0.01	4	—	—	0
24	—	—	0	0.50	0.02	7
23	0.50	0.01	3	0.64	0.05	3
22	0.44	0.01	4	0.65	0.03	3
21	0.42	0.01	3	0.80	0.05	4
19	0.51	0.00	2	0.87	0.02	4
18	0.71	0.01	3	0.88	0.03	2
17	0.79	0.01	3	0.88	0.04	3
16	0.82	—	1	0.84	0.02	4
15	—	—	0	1.44	0.02	5
13	—	—	0	1.51	0.03	5
11	—	—	0	1.50	0.05	3
refractor velocity/(km s^{-1})	5.66	0.06	13	6.18	0.06	24

(*b*) *Firth of Forth profile*

The reduced-time record section of the observations made in the Firth of Forth refraction line is shown in figure 3. Many data were also recorded by the Lownet and Eskdalemuir arrays, and by temporary stations installed in the Southern Uplands by Cambridge personnel. However, the recording geometry of the lands stations was such that split profile observations, incorporating both land and sea data, could not be made over any one refractor. Consequently, the analysis of the land data set is not treated in this contribution, and the data from the Puss recording positions must be interpreted essentially as a single-ended profile, although, as figure 3 demonstrates, there is a reversed coverage out to 25 km provided by shots at each end of the Puss array. From the absence of an *en échelon* pattern as seen in the Crustal Control Line, there is apparently little structural dip below the profile. This is further supported by the reversed coverage on the upper crustal refractor, which is the first arrival out to 25 km and has apparent velocities of 5.63 km s^{-1} shooting west–east and 5.69 km s^{-1} shooting east–west. The least-square time term solution gives 5.66 km s^{-1}, which agrees very well with the value from the Crustal Control Line.

From 25 km range out to about 100 km, the first arrival is that due to the main crustal refractor with an apparent velocity greater than 6 km s^{-1}. Since little dip is apparent from these arrivals a linear least-squares fit can be applied, yielding a velocity of 6.2 km s^{-1} with an intercept time of 1.54 s. At ranges greater than 70 km, the dominant phase is a large-amplitude ringing arrival, which is interpreted as being the post-critical reflexion from the Moho. This phase persists out to 200 km, even though the charge mass decreases with increasing range since the profile was fired principally for land-based recorders.

By using the asymptote of the post-critical Moho reflexion as a guide, and by making a phase correlation of second arrivals in the interval 60–90 km and at about 2.7 s reduced time, it is possible to fit a straight line indicating the presence of a lower crustal refractor of velocity 7.2 km s^{-1} with an intercept time of 4.55 s. Although the existence of a fast crustal refractor is somewhat tentatively postulated, it is consistent with the position of the Moho critical point at about 70 km and is also suggested by an analysis of the Moho reflexion arrival times, which results in an average crustal velocity of 6.4 km s^{-1}. With such a strong wide-angle Moho reflexion, suggesting a sharp transition between crust and upper mantle, the Moho refraction is weak and is not observed as a first arrival. The best indication of where the travel time curve should lie is given by assuming the value of 8.16 km s^{-1} for the Moho velocity (from the Main Line analysis) and fitting the line through the critical point, which is at about 70 km in range and 3.2 s reduced time. This gives an estimate of 6.6 s for the Moho intercept time, which is in agreement with the time term for shot point 2 (figure 1) of the Main Line determined from Puss observations augmented with Eskdalemuir and Lownet data.

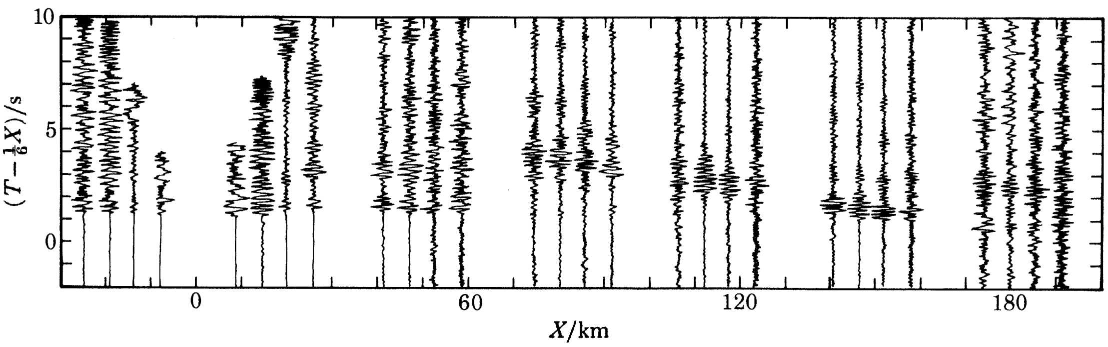

Figure 3. Firth of Forth hydrophone record section reduced at 6 km s^{-1}. The arrivals have been low pass filtered at 15 Hz. Both directions of cover are displayed.

Using data from a nearby borehole and an interpreted seismic reflexion profile, the intercept times can be inverted to a velocity–depth profile beneath the Puss array. A comparison of this structure with that obtained by the Lispb profile beneath the Southern Uplands of Scotland is shown in figure 4, where there is a broad agreement. Apart from the superficial sedimentary cover at the seaward end of the section, the main difference between the two structures lies in the velocity–depth function of the upper 20 km of crust. The Southern Uplands structure displays a velocity gradient from 5.8 to 6.0 km s^{-1} at a depth of about 14 km, where there is a step to a velocity of 6.3 km s^{-1}. Over approximately the same interval, the plane refractor interpretation at Devil's Hole results in a two-layer upper crust with velocities of 5.7 and 6.2 km s^{-1}. On both interpretations, there is a lower crustal refractor of slightly differing velocities, apparently thinning towards the basin. There is a significant difference in Moho velocities, although the depth to the Moho is similar on both structures, shallowing from about 32 km beneath the Southern Uplands to 30 km near Devil's Hole. It should be borne in mind that the Lispb profile has a much greater density of observations and has been tested by ray tracing, whereas the Puss profile has only had an arrival-time analysis made upon it.

(c) *Main Line*

The first arrival time – distance curves for the Main Line observations are shown in figure 5, where the first arrival points are plotted by using a reduction velocity of 8 km s^{-1} and are linked by shot. The break to the upper mantle refractor is clearly seen in both forward and reverse directions, but the apparent velocity of the crustal arrivals in both directions is about 5.8 km s^{-1} over ranges from 25 to 120 km. From the reversed cover at the northern end of the Main Line, the main crustal refractor has a velocity of 6.2 km s^{-1} (figure 6), which agrees with the unreversed estimate from the Firth of Forth profile. By adopting this value it appears that the refractor is also dipping into the basin at the southern end of the Main Line. The intercepts of the travel time curves give an indication of the relative thicknesses of sediments beneath the northern and southern shot points, with a considerably greater delay at the southern end being consistent with its position in relation to the Tertiary isopachs (figure 1).

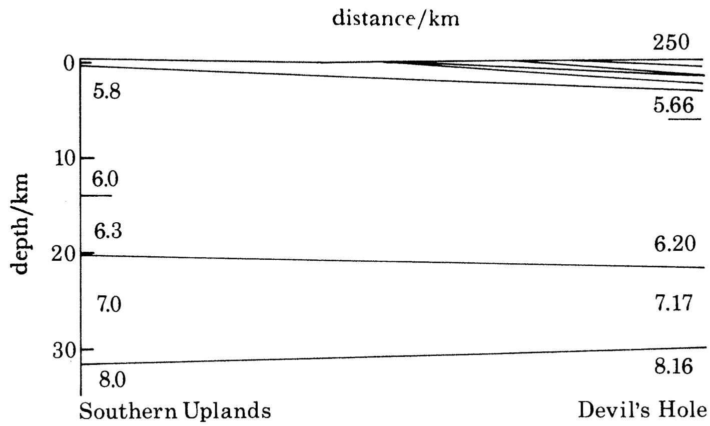

Figure 4. Velocity–depth structures beneath the Southern Uplands as revealed by the Lispb experiment and beneath Devil's Hole as determined by the Pusses in the Firth of Forth Profile. Vertical exaggeration × 4. Refractor velocities are shown in kilometres per second.

A time term analysis of the upper mantle arrivals gives a well constrained value for the Moho velocity of 8.16 km s^{-1}, which is significantly higher than the value obtained beneath mainland Britain (8.0 km s^{-1}). However, the velocity is in good agreement with the estimate from Collette's Dogger Bank profile (8.15 km s^{-1}) and Sørnes's Norway Shetlands profile (8.12 km s^{-1}), although somewhat less than Solli's value of 8.3 km s^{-1}. The Moho velocity beneath France as reported by Sapin & Prodehl (1973) is 8.1 km s^{-1}. There is thus consistent evidence that the Moho velocity beneath the North Sea Basin is higher than that beneath the stable areas of western Europe.

An attempt was made to solve for a horizontal velocity gradient beneath the Moho by modifying the travel time equations to allow for the possibility of a velocity function varying linearly with range. With this model, an apparent horizontal velocity gradient can provide an estimate of the change of velocity with depth by inverting the function with the Weichert–Herglotz relation. However, a least-square solution of the time–distance data predicted a decrease in velocity with increasing range with a standard deviation greater than the absolute value of the horizontal gradient. The standard deviation of the solution as a whole was greater than that for the uniform refractor model and since the physical implications of a negative velocity gradient were inconsistent with the observed strong Moho arrivals, it was concluded that the data set could resolve neither the magnitude nor the sign of a horizontal velocity gradient. The uniform refractor solution was adopted, and the values of the Moho time terms are listed in table 2.

There is a discrepancy between the time terms of the two southern shot points. An investigation was made into possible sources of shot timing errors, since the magnitude of the dispersed charge time-of-flight correction was about 0.8 s, without finding any correlation between errors and wind or sea conditions. Since the discrepancy is visible on both crustal and Moho branches of the travel time curves for shots 1 and 2 in figure 5 and is also observed on LOWNET and Eskdalemuir records, the source of the discrepancy probably lies in near-surface structure since there are abrupt changes in the thickness of the high-velocity Zechstein salt in the vicinity of Devil's Hole, but because of the uncertainty it was decided to adopt the time terms for the PUSS array from the Firth of Forth profile.

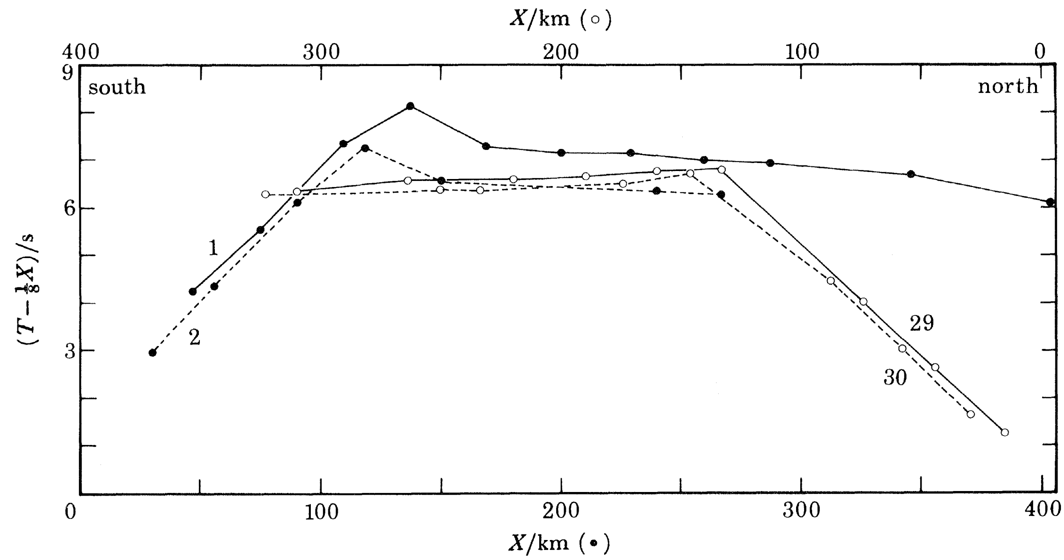

FIGURE 5. Reduced time – distance curves for all shots fired in the Main Line. Solid circles are observations from southern shots, open circles from northern shots.

Because of the good agreement between the Firth of Forth profile and the reversed crustal control line in the estimate of 6.2 km s^{-1} for the main crustal refractor, crustal time terms at the southern end of the Main Line were obtained by constraining the refractor velocity to 6.2 km s^{-1}, and are displayed in table 2.

TIME TERM INVERSION

In order to strip off the effects of the sediments from the time terms, recourse was made to seismic, borehole and velocity survey data kindly provided by many oil companies, which allowed the delay due to the upper 4 km of sediment to be removed. This had the effect of reversing the trend of increasing Moho time terms towards the centre of the basin. The inversion was continued by using the refraction information from all three profiles, and by making certain assumptions in regions of missing coverage the velocity–depth profile in figure 6 was obtained. Control points are indicated by a solid circle. The assumptions made in the course of the inversion were as follows:

(i) missing time terms on the Moho and 6.2 km s^{-1} refractor were obtained by interpolation;

(ii) the lower crustal refractor was assumed to exist over all the profile and was constrained to be half the thickness of the 6.2 km s^{-1} refractor, as observed on the Firth of Forth profile;

(iii) material below the depth of well control was assumed to have a velocity of 4.8 km s^{-1};

Table 2. Time terms to the main crustal refractor and to the Moho for the area covered by the Main Line

site	time term (s)	s.d. (s)	number of observations	time term (s)	s.d. (s)	number of observations
30	0.39	0.01	3	3.21	0.04	5
29	0.45	0.01	3	3.30	0.03	6
28	0.18	0.01	2	3.26	—	1
25	0.50	0.02	7	—	—	0
20	0.87	0.02	4	3.63	—	1
14	—	—	0	3.78	0.02	4
12	—	—	0	3.77	0.04	4
9	—	—	0	3.85	0.04	2
8	—	—	0	3.79	0.04	3
7	—	—	0	3.81	0.04	4
6	2.28	—	1	—	—	0
5	2.16	0.01	2	3.77	0.02	3
4	1.67	0.05	2	—	—	0
3	1.33	0.05	2	—	—	0
2	0.55	0.03	4	3.13	0.02	3
1	1.13	0.04	3	3.83	0.01	8
refractory velocity/(km s^{-1})	6.20			8.16	0.02	22

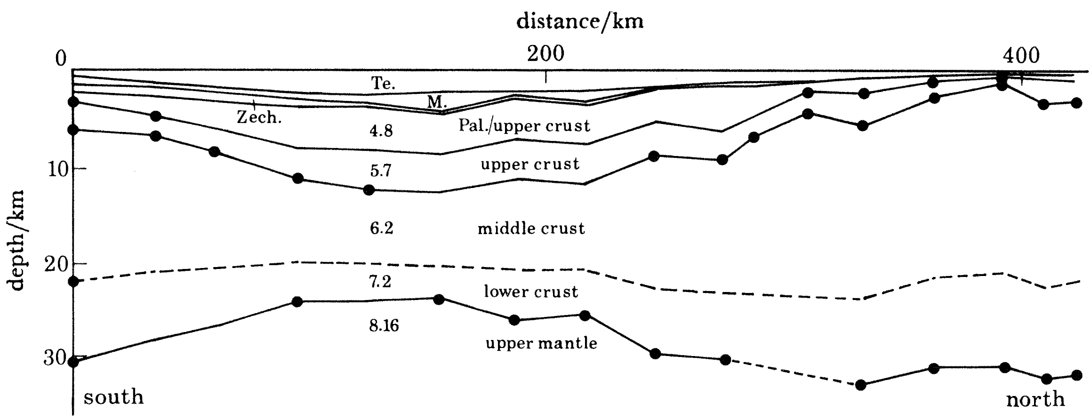

Figure 6. Velocity–depth section along the Main Line profile after inverting the time terms according to the procedure outlined in the text. Upper sedimentary sequence given by borehole information. Velocities are shown in kilometres per second. Time term control points are indicated by solid circles. Vertical exaggeration × 4. Te., Tertiary; M., Mesozoic; Zech., Zechstein; Pal., Palaeozoic.

(iv) although there is little control over the behaviour of the 5.7 km s^{-1} refractor, the interval between the base of the well control and the top of the 6.2 km s^{-1} refractor was assumed to be approximately equally divided between 4.8 km s^{-1} material and 5.7 kms^{-1} material. A velocity gradient without such an arbitrary division may be more appealing but there is good evidence for a distinct 5.7 km s^{-1} refractor from reversed short-range observations on the two crustal profiles.

Discussion

The most important feature of the velocity–depth profile is the anticlinal form to the Moho, which reaches its shallowest point, 24 km, beneath the deepest sediments. Although some broad assumptions have been made in the delay time inversion, they are not unreasonable. The average velocity of the crystalline crust is over 6.2 km s^{-1} and is somewhat greater than Solli's estimate of 6.09 km s^{-1}. The higher crustal velocity, in a time term inversion, will lead to a greater estimate of the Moho depth at all points along the profile. Although the contrast in terms of depth between the deepest and shallowest Moho soundings along the profile increases with average crustal velocity, the ratio between the two is independent of average crustal velocity if this is constant along the profile. It is the ratio of unstretched and stretched crustal thicknesses that is the attenuation or 'β' factor of the McKenzie model. If the same value of 32 km for the unstretched crustal thickness is taken for both Solli's line and the Cambridge profile, then the Cambridge profile results in a more conservative estimate of the attenuation factor. Furthermore, the Moho depths along the profile are in good agreement with those obtained by modelling gravity data over the same area (Smythe *et al.* 1980), where the shallowest Moho depth is also estimated at 24 km.

The anticlinal form to the Moho imposes considerable constraints upon the type of model used to explain North Sea Basin formation (Christie 1979). If it is assumed that the North Sea is an epicontinental basin and that the original crustal thickness in the region of the present North Sea was about 30 km, comparable with the crustal thickness beneath the Southern Uplands or the East Shetlands Platform (32 km), then a large class of models must be excluded. These include the classical graben formation mechanism of Vening Meinesz (1950), the viscoelastic loading model of Beaumont (1978) and mechanisms involving an increase in density of the lower crust such as that due to Haxby *et al.* (1976), all of which predict a deeper Moho beneath the centre of the basin than at the basin edges.

The gabbro–eclogite phase transition proposed by Collette (1968) is appealing in that it permits compensated subsidence to take place, but thermal balance is not maintained by the process, which predicts a smaller heat flow than normal in the centre of the basin, contrary to what has been measured (Evans & Coleman 1974).

The seismic evidence from all North Sea profiles appears to rule out the existence of a rift pillow of the form proposed by Illies (1970) in the context of the Rhine Graben and by Ziegler (1975) for the North Sea Graben, and indeed it should be noted that in the case of the Rhine Graben the existence of a rift pillow is strongly questioned by Edel *et al.* (1975) and other workers. According to this model, the rift pillow of fractionated upper mantle material is created during the extensional stage of graben formation and results in an uplifted rift dome. Supra-crustal erosion then creates the depression required for the deposition of material once the rift pillow starts to be absorbed back into the upper mantle. The absence of rift pillow velocities from the refraction data, and the difficulty of thinning the crust by the required amount to produce space for the subsequent sedimentary basin, effectively eliminates this model and other models appealing to subaerial erosion as a mechanism for crustal attenuation when they are considered in the context of the North Sea.

The most appealing mechanism to explain North Sea Basin formation is that due to McKenzie (1978), which relates the graben generation stage with lithospheric extension, to which the lower crust and upper mantle respond by ductile thinning, and the upper crust by brittle failure. Thinning the lower crust and upper mantle raises the isotherms and creates a thermal anomaly, which decays by conduction through the crust producing gently uniform subsidence with an exponentially decaying rate. The amount of extension required to produce the observed subsidence was estimated by Sclater & Christie (1980) from well log data to be 50–60% in the centre of the Main Line profile, which is consistent with the seismic evidence if an original crustal thickness of 32 km is assumed. However, recent work by R. Wood (personal communication) suggests that a value of 35% extension may be more appropriate. A local crustal attenuation factor of 1.3–1.5, especially if achieved by areal as opposed to simple linear extension, goes far towards meeting the amount of extension estimated by backtracking the faults interpreted from reflexion profiles (Smythe *et al.* 1980).

The temporal correlation between North Sea activity and the evolution of the North Atlantic (Ziegler 1978; Christie 1979) allows the McKenzie model as applied to the North Sea to be set against a background of extensional tectonics without the necessity of appealing to a catastrophic initiation event. With the possible exception of an as yet unresolved space problem in the fault pattern of the upper crust, the model satisfies the gross requirements of the observed North Sea data in terms of its deep velocity structure, subsidence history and present-day heat flow (Christie & Sclater 1980; Sclater & Christie 1980). Further refraction work currently in progress by the Cambridge Marine Group may help to define in more detail the velocity depth structure across the Central Graben, where the model predicts the greatest crustal attenuation.

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Discussion

A. S. Laughton, F.R.S. Dr Christie started by showing two completely different interpretations of the crustal structure beneath the North Sea. His own preferred model closely resembles one of them. Could he comment on why the interpretations were so different, and why he believes his own section is better constrained?

P. A. F. Christie. The first profile that I showed was obtained by Sørnes by using data from a number of different experiments carried out at different times. There may therefore, be internal inconsistencies in the data. Furthermore, Sørnes used his data only to produce time terms to the Moho and did not convert these into a crustal model. As I remember it was Willmore who made this conversion to Moho depths, about which he had certain reservations. Probably the principal difference between this profile and the second one that I showed, which was obtained by Solli, is caused by the values of the delay times introduced by the superficial sediments. When Sørnes made his analysis these delays were not well known. The more recent analysis by Solli made use of very detailed values of the delay times that Ziegler supplied, obtained from reflexion studies. Solli also used a velocity of about 6 km s^{-1} for the whole of the crystalline crust. His low crustal velocity and high sub-Moho velocity of 8.3 km s^{-1} combine to produce a much thinner crust beneath the graben than Sørnes obtained. The profile that I proposed had a two-layer crust beneath the sediments. The existence of the lower layer, which depends on the interpretation of the Firth of Forth line, increases the average velocity of the crystalline crust from 6 km s^{-1} to about 6.25 km s^{-1}. This change increased the crustal thickness. Hence my interpretation lies between that of Sørnes and Solli. Any increase in the mean crustal velocity would result in greater crustal thickness everywhere. Hence the change in crustal thickness going from the platforms on either side into the graben would also be increased, though the extension required to produce this change would not.

D. G. Roberts. Could Dr Christie comment on how much extension is required to account for his profiles, and how this compares with Ziegler's estimates for the central North Sea?

P. A. F. Christie. The minimum thickness of crystalline crust on the section is about 20 km The crustal thickness beneath both the Southern Uplands and the East Shetland Platform is about 32 km. If this is representative of the original crustal thickness beneath the graben, the maximum stretching factor required would be about 1.6. To produce the observed variation along the profile would then require a displacement of about 65 km if all of the stretching resulted from movement on faults striking east–west. This estimate is probably too large. If the extension is caused by movement of faults with a variety of strikes, as it may well do where the Moray Firth basin joins the Central Graben, then the resulting areal extension may require considerably smaller linear extension in any direction. To estimate the extension produced by areal extension requires detailed seismic coverage with lines run in several directions, which is not available to me.

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