Mapping of crustal heterogeneity in the North Sea basin via the propagation of $L_g$-waves

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Summary. The propagation of $L_g$-waves within the continental area in and around the North Sea basin shows strong dependence on the path between source and receiver. Paths lying within the British Isles and Norway show very clear $L_g$ phases, but paths which cross the graben zone lying in the middle of the North Sea basin have very weak $L_g$. Over 150 paths have now been studied across the region and the character of the $L_g$-wave has been described by comparison with the size of the $S_n$ phase. For shallow events this gives a stable measure of the efficiency of $L_g$ propagation. The regions which appear to block the transmission of $L_g$ are quite localized in the middle of the North Sea, in the region with graben structures, and extend on into The Netherlands. A weak zone of poor transmission appears to be associated with the Oslo graben.

With the relatively dense areal coverage provided by paths crossing the basin with a wide range of azimuths, it is possible to attempt to invert for the pattern of crustal heterogeneity which gives rise to the observed character of the $L_g$ propagation. An iterative scheme has been devised to find the propagation properties in cells of a $1^\circ \times 1^\circ$ grid, and a well-defined map of the heterogeneity is obtained. The strongest heterogeneities correlate very well with the major tectonic features of the Viking and Central Grabens running north–south through the basin. Where the path coverage is greatest, the position of the heterogeneity can be tightly constrained and lies within a rather narrow zone around 100 km wide. Despite the number of paths employed it is not possible to obtain this level of resolution over the whole region. Seen in the

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light of theoretical studies of $L_g$-wave transmission, the heterogeneity map gives an indication of the strength of horizontal gradients in seismic properties in the crust. These are most likely to be associated with crustal thinning beneath the graben structures.

Introduction

In a number of studies, the relative efficiency of propagation of high-frequency $S$ phases along different paths has been used to try to map out regions of structural complexity. The most commonly used phases have been $S_n$ and $L_g$. The phase $S_n$ (used by, e.g. Molnar & Oliver 1969) has a group velocity around 4.5 km s$^{-1}$ and is particularly sensitive to the seismic structure in the uppermost part of the Earth's mantle. However, the $L_g$ phase (used by Ruzaikin et al. 1977; Gregersen 1982) with group velocity close to 3.5 km s$^{-1}$ is mostly composed of waves trapped in the waveguide formed by the crust. Both of these phases can be viewed as being made up of a superposition of many higher modes of surface waves (see, e.g. Kennett 1983) which interfere to give the relatively complex waveforms observed on seismic records. On vertical and radial component records in stratified media these would be Rayleigh modes, whilst on the transverse component there would only be Love modes. However, the presence of three-dimensional velocity structure leads to a coupling between Rayleigh and Love modes (Kennett 1984) and thus a mixed character in three-component observed wave-trains (Kennett & Mykkeltveit 1984). For $L_g$-waves an alternative viewpoint is that the phase consists of a superposition of multiply reflected $S$-waves bouncing back and forth between the crust–mantle boundary and the free surface. Synthetic seismogram calculations for ranges out to 950 km at up to 5 Hz using the method described by Kennett (1980) show that up to 20 multiples are likely to be important. In addition scattering of energy adds to the complications of the waveform. For $S_n$, Menke & Richards (1980) have suggested that the velocity gradients in the uppermost mantle give a 'whispering gallery' effect to build up the phase by multiple reflections beneath the Moho, which again is consistent with the surface wave representation.

For each of the $L_g$ and $S_n$ phases, we therefore have descriptions which depend on the mutual interference of a variety of wave propagation mechanisms. In a horizontally stratified structure these interferences evolve smoothly with range to generate the characteristic group speeds for the phases. However, once the structure departs from horizontal stratification, this simple pattern with distance is disrupted and the interference patterns may be substantially altered. In particular, energy may be transferred between crustal and mantle propagation so that interconversion between $L_g$-type and $S_n$-type waves is possible (Stephens & Isacks 1975). In addition, when there are substantial changes in structure, there is the possibility of back reflection of energy so that the transmitted waveform may be significantly reduced in amplitude.

Such effects were first investigated for models with a sharp boundary between two different structures (see, e.g. Gregersen & Alsop 1976) but for high-frequency waves such a model is too simplified to give an adequate representation of most likely geological structures. A purely numerical attack has been mounted using finite element techniques (e.g. Lysmer & Drake 1972) but this approach does not lend itself readily to the tracking of modes as they cross a complex structure. However, Szelwis (1983) has proposed a hybrid computation scheme in which a pure Love mode was injected into a region with horizontally varying structure, within which the calculation was performed using a finite difference scheme. Once the resulting wavetrain emerged into a stratified zone it was split up into modal contributions so that the effect of the heterogeneity could be analysed.
Recently Kennett (1984) has introduced an approach in which the displacement field is described as a superposition of modal contributions for a reference structure. The redistribution of energy between the modes, corresponding to reflections and interconversions, is tracked by setting up a coupled set of differential equations for the modal amplitude coefficients as the waves pass through a laterally heterogeneous region. This technique has been applied by Kennett & Mykkeltveit (1984) to study the poor transmission of $L_g$-waves across the Central Graben of the North Sea and they were able to show that a velocity structure with substantial crustal thinning, as suggested by seismic refraction work (Wood & Barton 1983), would be sufficient to account for the observed transmission loss.

Now that we have a quantitative basis on which to assess the effect of structural heterogeneity on guided seismic waves such as $L_g$ and $S_n$, it is worthwhile trying to use detailed mapping of the relative efficiency of propagation of these phases as a way of mapping heterogeneity in areas which cannot readily be investigated by other methods.

In this paper we build on the work presented by Gregersen (1984a) to try to obtain a dense areal coverage of $L_g$-wave propagation paths in the North Sea basin, and to use the propagation characteristics as a means of mapping crustal heterogeneity in this region.

**Characterization of $L_g$ paths**

Gregersen (1984a) has presented seismograms from a number of events in the North Sea recorded at stations in Britain, Scandinavia and The Netherlands. These typically show poor propagation of $L_g$ across the North Sea basin itself but good propagation for $L_g$ around the periphery. By considering the sequences of events recorded at Copenhagen with almost the same azimuth, he was able to show that poor propagation was associated with propagation across the Viking Graben system in the northern North Sea. Events within the graben showed intermediate $L_g$ propagation, whilst those closer to the Norwegian coast had large amplitude $L_g$. A similar pattern was displayed by the set of explosions discussed by Kennett & Mykkeltveit (1984), which straddle the Central Graben at about $57^\circ$N. The explosions on the Norwegian side show clear $L_g$ phases at the Norwegian seismic array (NORSAR) but the explosions on the British side of similar size and firing pattern showed little discernible $L_g$ energy. These same shots did, however, show significant $L_g$ components at the LOWNET network in southern Scotland and the Eskdalemuir array (EKA).

These results suggest that the main crustal heterogeneity is concentrated in a relatively narrow zone in the centre of the North Sea basin but do not provide sufficient geographic coverage to refine the pattern. We have therefore collected as many observations of $S$-wave phases as possible for paths crossing the North Sea region and attempted to characterize these in a simple way which will allow direct comparison between many different events.

Although the detailed waveforms of the $S$ wavetrain are strongly dependent on the depth and focal mechanism of the event, we are able to minimize the dependence on such effects by comparing the relative amplitudes of phases within the same record. For shallow events, as considered here, this gives a stable means of characterizing the nature of the $L_g$ train and allows attention to be focused on the propagation paths (Gregersen 1984a).

We have assigned to each station record a code, based on the appearance of the $L_g$ train within the record, on a five point scale:

1. $L_g$ is the dominant phase within the $S$ wavetrain (i.e. the maximum amplitude occurs just after a group velocity of 3.5 km s$^{-1}$).
2. although $L_g$ is still clear, the amplitude of $S_n$ is significant and the peak amplitude of $L_g$ is not very much greater than that of $S_n$.
3. the amplitudes of $S_n$ and $L_g$ are comparable.
(4) $S_n$ is larger than $L_g$ but a surface wave arrival around 3.5 km s$^{-1}$ group velocity can be discerned.

(5) very little indication of an $L_g$-wave arrival.

This scheme represents an extension of the classification used and extensively illustrated by Gregersen (1984a) which included only codes 1, 3, 5. The new intermediate cases are most useful when one has a range of similar paths and can see the gradations associated with structure, or where, as with the records from the many similar stations of the British Geological survey network in Scotland or the subarrays at NORSAR, comparisons can be made with a wide range of other records.

Frequently, the $S_n$ wavetrain for paths which we would describe by codes 3, 4, 5 is drawn out in time, covering a span of group velocities from the usual value of 4.5 km s$^{-1}$ down to about 3.8 km s$^{-1}$. A possible explanation of this effect is provided by the theoretical studies of $L_g$-wave propagation through a crustal pinch by Kennett & Mykkeltveit (1984). They have shown that it is possible for energy which was originally propagating within the crust as $L_g$ to be converted into $S_n$-type energy travelling in the uppermost mantle by the effect of the crustal heterogeneity. If such a conversion occurs part way along the path from source to receiver the energy will have started with a group velocity of around 3.5 km s$^{-1}$ and then acquired a faster velocity of 4.5 km s$^{-1}$ on conversion; as a result its effective group speed will be intermediate between the pure $S_n$- and $L_g$-wave group velocities. Such waves would therefore appear in the coda to the true $S_n$ arrivals.

The pattern of $L_g$ propagation

We have attempted to obtain as dense an areal coverage of the North Sea region and its periphery as possible by using all available paths from regional events (300–1500 km) into the NORSAR array and the networks of stations run by the British Geological Survey in Scotland (Turbitt 1984), in addition to the propagation paths described by Gregersen (1984a) and Kennett & Mykkeltveit (1984). These have been supplemented where possible by records from other stations, and the recordings from the LISPB project of the Kintail Earthquake of 1974 (Kaminski et al. 1976). Virtually all the readings have been taken from short-period records, so that we are dealing with frequencies from 1 to 3 Hz in the $S$ wavetrain.

In all we have well over 150 different propagation paths, in many cases overlapping over part of their length so that we can place constraints on the location of possible heterogeneity. The results are summarized in Fig. 1, in which the paths are colour coded to conform to the classification scheme described in the previous section. We have used green for good $L_g$ propagation (code 1) and red for the poorest $L_g$ propagation (code 5) with intermediate hues for the other cases. Thus we have used light green for code 2 and yellow for code 3, where $S_n$ and $L_g$ are of comparable magnitude. The case of poor but still detectable $L_g$ (code 4) is in orange. The aim of this colour scheme is to enable an immediate qualitative assessment of the propagation pattern and so help with the localization of the crustal heterogeneity. By no means all the possible propagation paths are plotted, we have restricted the number of paths to the principal arrays to avoid unnecessary clutter. Thus only a single subarray is used at NORSAR for most events and only selected stations are shown for LOWNET.

The first thing that we notice is that the green paths (good $L_g$ propagation) occur within the British Isles, on almost all paths in Norway and on some paths from Germany into Copenhagen. On the other hand almost all red paths, indicating very poor $L_g$ propagation, cross the centre of the North Sea Basin. Thus we have paths from earthquakes in Britain,
near Hereford or in the Pennines, to NORSAR which give very clear \( S_n \) phases but very poor \( L_g \). These paths cross parts of England within which \( L_g \)-waves propagate well and after crossing the Central Graben follow closely the paths from the shots fired on the CANOBE project (Cassell et al. 1983) which gave clear \( L_g \) phases at NORSAR (Kennett & Mykkeltveit 1984). The dominant heterogeneity must therefore be confined to a region in the centre of the basin.

The consistency of the results from different events is excellent, paths from British events to Norway and Denmark and from events off the coasts of Norway and Denmark to the stations in Scotland (Shetland, Moray Firth, LOWNET) all show poor propagation for \( L_g \). Earthquakes with epicentres lying in the graben show intermediate quality of \( L_g \) propagation to stations on both the western and eastern margins of the basin. We cannot rule out the possibility that the apparent size of \( L_g \) for some of the paths could be strongly affected by the source radiation pattern, but it is clear that in general the dominant effects are structural.

Many of the paths cross the North Sea region with azimuths between 60° and 120° and as a result give little control on the east–west location of heterogeneity. Fortunately, the event near Liege (1983 November 8) was well recorded at NORSAR and in Denmark, as well as at most of the stations in the British Isles. The resulting paths show good \( L_g \) propagation to Ireland, East Anglia and southern Scotland, with a slight deterioration to the stations around the Moray Firth in the north of Scotland, whereas the three stations on Shetland show intermediate character with significant \( S_n \). At NORSAR, and in six locations spread all over Denmark (Gregersen 1984b) there was no indication of the \( L_g \) phase despite a strong \( S_n \) arrival. The underwater seismograph system at the Beryl oilfield also provides some useful constraints on \( L_g \) propagation on paths not covered by the land-based stations.

**Mapping of crustal heterogeneity**

The wide range of \( L_g \) propagation paths that we have been able to consider put a strong constraint on the location of crustal heterogeneity within the North Sea region. We have therefore attempted to produce a map of the zones of heterogeneity within the basin by fitting the observed pattern of \( L_g \) propagation.

Although the size of the \( L_g \)-wave packet is not simply related to the nature of the crustal structure along the path, we do know that the largest effects on \( L_g \) come from concentrated zones of strong horizontal change in seismic properties. Large-scale, slow, variations do not lead to interactions between the modes (Woodhouse 1974) and so would not lead to major changes in the transmissivity of the phase.

We have attempted to represent the heterogeneity within the region by assigning a value on a scale from 1 to 10 to each \( 1^\circ \times 1^\circ \) cell, with values constrained by the nature of the paths passing through each cell. We work with a scale with larger values assigned to stronger heterogeneity, to conform to the code used for the description of the records. Thus good \( L_g \) propagation corresponds to low heterogeneity values and poor propagation to large values.

As a starting model for further refinement, we used a simple back projection technique on the rather doubtful assumption of a linear relation between our heterogeneity scale factor and the original code assigned to each propagation path from the appearance of the \( L_g \) wavetrain. This led to large heterogeneity values occupying much of the basin and did not give adequate weight to the constraints provided by regions where \( L_g \) propagation is good.

We have therefore made the slightly subjective assumption that if any path through a cell represents good \( L_g \) propagation then the heterogeneity factor assigned to that cell should be small. Where it is clear that the dominant behaviour is for good propagation the heterogeneity is set at level 1. But if the sampling is only modest a slightly higher value is used.
Similarly we try to use the moderately efficient $L_g$ propagation (code 2) to constrain the next level of potential heterogeneity. Such regions occur off the British coast and up to the Shetlands, and to a lesser extent off the coast of Norway.

We are then faced with a decision about how intermediate propagation is to be treated for events within the graben system (represented schematically in Fig. 2 by yellow lines). From theoretical studies, using the approach described by Kennett (1984), propagation through one side of a crustal pinch structure underlying a sediment filled graben would give considerable disruption of the $L_g$ train but not extinguish it completely. Hence, such paths should be taken along with the poor propagation paths as a way of locating the strongest heterogeneity.

Once a rough general pattern of heterogeneity has been built up in this way it has to be checked for consistency with the original data on the character of the $L_g$ propagation. This leads to an iterative procedure on a cell-by-cell basis to update the model, to improve the picture for all the paths through that cell, whilst making appropriate modifications to other cells along the paths passing through the current target cell. The process converges quite quickly, giving sharply localized heterogeneity where data cover is good and a rather diffuse pattern where coverage is thinner.

The resulting pattern of heterogeneity factors is displayed in Fig. 2, once again using a colour coding for the properties. As in Fig. 1 we have reserved green for the regions with the best $L_g$ propagation which therefore have the least apparent heterogeneity in our $1-3$ Hz frequency band. The deepest reds indicate the most strongly localized heterogeneity in the Central graben zone and in the Viking Graben in the northern North Sea. The intermediate red tones attempt to convey the spread in the model associated with finite areal coverage. The ochre tones appear where there is some indication of heterogeneity in the pattern of propagation, but without the dramatic losses in transmission associated with the central features. Thus, for example, the group of paths arriving at NORSAR from the south (including fairly close events) imply the existence of some crustal heterogeneity in a narrow band of cells which corresponds to the location of the Oslo Graben. The zone extending into southern Denmark is associated with the group of paths with intermediate or poor $L_g$ propagation from events in the Low Countries and Germany. The lack of crossing paths means that there is little control on the location of the heterogeneity and so we perforce have a rather diffuse region. In northern Denmark, the $L_g$ propagation is much more efficient and approaches the level seen in the Fennoscandian shield.

Discussion

The pattern of heterogeneity found from our attempt to satisfy the patterns of observed $L_g$-wave propagation correlates very well indeed with the major tectonic features, even though we must stress that the model of the heterogeneity is definitely not unique. We are able to confirm Gregersen's (1984a) suggestions that the observed effects on $L_g$ arise from the Graben structures in the North Sea, and with a thorough areal coverage of $L_g$ propagation paths have been quite successful in localizing the positions of the heterogeneity. Even so there are some regions, notably in the south, where the data constraints are relatively poor.

We have indicated on Fig. 2, in yellow, the approximate outlines of the major graben zones running down through the centre of the North Sea basin. In the north we have the Viking graben which flares out at high latitudes, but we are able to pin down the main heterogeneous region by making use of sequences of events along similar paths which show a progressive change in the character of the $L_g$ train with source location. The region of strongest heterogeneity appears to be quite narrow, and confined to the centre of the
Figure 1. Map of the North Sea region showing a selection of the $L_g$ propagation paths studied. The character of the $L_g$ wave transmission along the various paths is indicated by colour coding. Paths for which $L_g$ propagates well are indicated in green and paths on which very poor transmission occurs are shown in red. Intermediate hues represent the gradation of behaviour between these extremes, see the text for details.

Figure 2. A representation of the crustal heterogeneity within the North Sea region as seen by $L_g$-waves. This pattern was derived by modelling the observed pattern of $L_g$-wave propagation shown in Fig. 1 with a model comprised of 1x1 cells. The heterogeneity level is colour coded so that the green regions correspond, as in Fig. 1, to good $L_g$-wave transmission. The heterogeneity levels grade through ochre to the strongest which are shown in red. The yellow lines in the middle of the North Sea outline the geologically well-known graben structures.
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graben. On either side there are some suggestions of slight heterogeneity effects but the principal effect lies within a 2° band in longitude. Further south in the Central graben, we are again able to pin down the feature quite tightly where we have maximum data coverage; the relatively broad red zone around 55°N simply reflects the lack of detailed constraints on the structure.

The break in the main heterogeneous region in the southern North Sea is dependent on a single path with intermediate $L_g$ propagation, so that it is possible that there is actually greater continuity than indicated. In Holland the suggested pattern fits in well with the gas-bearing inverted graben structure which represents the continuation of the main graben zone.

What then is the significance of these heterogeneous regions? For the Viking graben (Solli 1976) and for the Central graben (Wood & Barton 1983) the results of seismic refraction experiments suggest substantial crustal thinning under the regions with thickest sediments. The calculations of Kennett & Mykkeltveit (1984) show that a structure of this type would be sufficient to explain the major loss of $L_g$-wave energy in transmission through the graben zone. As a result it seems most likely that we are mapping horizontal gradients in crustal thickness. Slow smooth change will not give rise to significant transmission loss so that we cannot claim to map the actual crustal thickness. However, we can qualitatively correlate the main zones of heterogeneity with regions of thinner than normal crust.

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References


