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VII.2 Observation and modelling of regional phases recorded at NORSAR

A comprehensive study of propagation characteristics of regional seismic phases for paths to NORSAR is in progress. Such propagation paths intersect with a variety of tectonic provinces like shields and platforms with and without sedimentary covers, orogenic belts, ocean-to-continent transitions, major sedimentary basins and pronounced lateral Moho depth variations associated with graben structures. The study is accompanied by attempts at theoretical modelling of the observed features. The development of the new NORESS array with on-line location of recorded regional events necessitates proper understanding of the general occurrence of secondary phases in particular.

In this contribution, results from an observational and theoretical study on Lg waves across a graben structure in the North Sea are presented. Also included is a short report on the status of comprehensive mapping of regional phases recorded at NORSAR.

Lg waves across the Central Graben of the North Sea

Between 1977 and 1981 a number of large explosive charges were fired in the Central North Sea region in a sequence of seismic refraction experiments carried out by Cambridge University with the object of determining the deep structure of this extensional basin (Fig. VII.2.1). The locations of the shots are indicated on the map of the Central North Sea in Fig. VII.2.1 (top) which also indicates the main structural features and the region where sediment thickness exceeds 2 km. Wood and Barton (1983) have presented a structural model for the Graben region based on the P wave observation from these seismic experiments and detailed information on sedimentary deposits. In this model there is substantial crustal thinning beneath the deepest sediments (Fig. VII.2.1, bottom) with the Moho rising to nearly 20 km depth from 30 km at the flanks to create a crustal pinch. The thinning is accompanied by substantial horizontal gradients in the P wave velocities.

The shots were all clearly recorded at the NORSAR array. For the N shots on the Norwegian side of the Central Graben we get prominent Lg wave arrivals with a group velocity close to 3.5 km/s for ranges from 430 to 650 km. However, the shots to the west of the graben on the British side (D1, D2, F4), which show very clear P phases, have no distinct Lg arrivals.

The vertical component records for each of these explosions at the 02C03 seismometer at NORSAR are displayed in Fig. VII.2.2, after bandpass filtering with 3 dB points at 1.5 and 5 Hz. The traces are all normalized to the same maximum amplitude, the range is indicated to the right, and the time corresponding to a group velocity of 3.5 km/s is indicated by an arrow on each trace. The abrupt change in the character of the records as the shot points cross the Central Graben is very pronounced. For shots D1, D2 and F4 there is a slight increase in amplitude in the coda for group velocities around 4.2 km/s which is somewhat slower than a direct Sn path. For sources in Germany at similar ranges clear Lg waves are seen so that we do not have an explanation by range alone.

In order to try to understand the extinction of the Lg wave in crossing the graben zone, a number of numerical experiments have been conducted using the calculation scheme introduced by Kennett (1984). The S-wave train is represented as a superposition of higher mode surface waves for a reference structure and the way in which energy is transferred between modes as the wave train interacts with a heterogeneous zone is followed. The changes in relative modal amplitude modify the transmitted waves and there is also coupling to backward travelling modes giving rise to reflected waves. In view of the uncertainties in the shear wave speeds in the zone of crustal thinning, we have not attempted to use the Wood and Barton model directly. We have developed a simplified model shown in Fig. VII.2.3 with a sedimentary zone thickening from 2 km to 9 km with the same properties as the surface sediments. In the lower part of the crust we introduce material with properties close to those in the mantle (ρ = 3.2 Mg/m^3, β = 4.3 km/s) reducing the crustal thickness to 21 km. The reference stratified model outside the graben zone was the modified form of a model due to Bouchon (1982) discussed in Kennett (1984). In order to allow us to represent all shear waves with group velocities slower than 5.0 km/s by means of a modal representation, we have extended the model to 70 km depth and then introduced a half-space with shear wave speed 5.0 km/s.

The main trend of the structural features in the central North Sea is close to perpendicular to the paths to NORSAR. We are therefore able to use a two-dimensional model as a very good approximation to the actual situation. In order to simplify the already complicated calculations we have considered SH wave propagation through the model. As discussed in Kennett (1984) the close parallel between the behavior of the vertical component in Rayleigh mode propagation and the transverse component in Love mode propagation means that our results can be compared directly to the observations.

We have considered three different models for the effect of the graben structure. In the first (A) we have included only the thickening sediments and maintained the Moho depth at 30 km throughout, with no heterogeneity in the lower crust. The second model (B) was as illustrated in Fig. VII.2.3, with both sediment thickening and substantial crustal thinning. For both cases A and B we work with perfect elasticity. However, in order to give a better representation of the complex structure we also consider a further model (C) in which the structural model B is combined with a loss factor Q_β^{-1} = 0.02 over the span of the model from 0 to 110 km. The consequent attenuation is quite severe, but is intended to provide a measure of the effect of the complex, faulted structure to be found in the neighborhood of the crustal pinch.

Results of the detailed calculations for the three different models are presented in Kennett and Mykkeltveit (1984). We have illustrated the propagation of a 1 Hz wave train through the model; at this frequency there are 19 modes with group velocity less than 5 km/s. Of these, modes 1-10 represent Lg type propagation and modes 11-18 represent Sn waves with most of their energy in the upper mantle. This frequency provides a reasonable compromise between having a diverse collection of modes, representative of high frequency behavior, and reasonable computation cost. At 1 Hz, the fundamental mode is confined to the sediments and so we work with 18 x 18 matrices of reflection and transmission coefficients between the different modes. Once these matrices have been calculated we can determine the effect of any incident field by the action of the reflection or transmission matrix on the vector of incident modal amplitudes.

When we compare the results of these calculations with the record section in Fig. VII.2.2 we find (Kennett and Mykkeltveit, 1984) that we have been able to give a reasonable match to the observed behavior. The character of the modal train transmitted through the thinning crust models will be profoundly different from the incident wavefield and the energy in Lg will be much reduced compared with paths which do not cross the feature. By taking a simplified structural model of the central graben zone based on that proposed by Wood and Barton (1983) we find that it is possible to achieve a significant transfer of energy out of Lg type modes into upper mantle propagation. Such energy arrives quicker than before, so that the onset of Lg is obscured by earlier arrivals while the peak amplitude is reduced. The overall effect is to smear out the S wave energy over a wide range of group velocities and by transferring energy from the most energetic components to destroy the normal interference pattern which gives rise to the characteristic Lg arrivals. In addition to the bulk structural effects, attenuation due to wave scattering in the faulted central zone and enhanced anelastic loss due to higher heat flow through the thinner crust will help to diminish the transmitted Lg wave energy.

General mapping of regional phases recorded at NORSAR

In many circumstances where the Lg phase is not observed, crustal barriers to propagation are postulated, but it is often difficult to be precise about their location. With a sequence of shots crossing a structural feature, as in the results presented above, it is possible to identify the cause of the poor transmission of Lg waves with observations at a distant receiver. By using many events and stations it is possible to build up an areal picture of the pattern of crustal heterogeneity from the character of the Lg train. Gregersen (1984) has mapped Lg propagation in the North Sea region and identified features representing barriers to propagation of this phase. His data base is presently being supplemented with new (particularly NORSAR) data in order to obtain an even more complete picture of propagation characteristics in the North Sea and adjacent regions.

For a general study of propagation to NORSAR from regional distances, records from events up to 15^o-20^o away are now being compiled, and inspected for assessment of propagation characteristics of regional phases. A proper mapping and understanding of the relative strengths of the Lg and Sn phases is of particular importance to the performance of the on-line processing of regional events on the new NORESS array. Fig. VII.2.4 gives examples of NORSAR records for three events at approximately the same distance (12^o) but with differing azimuths, exhibiting marked differences in the occurrence of the secondary phases Sn and Lg. Processing of detected signals on the new NORESS array is based on FK-analysis for the phase identification, and since Sn and Lg cannot be separated on the basis of phase velocities alone, it will be necessary to invoke information on the general occurrence and relative strength of secondary phases for different source regions. Once such information has been compiled, it will be built into the event location part of the on-line processing package for NORESS.

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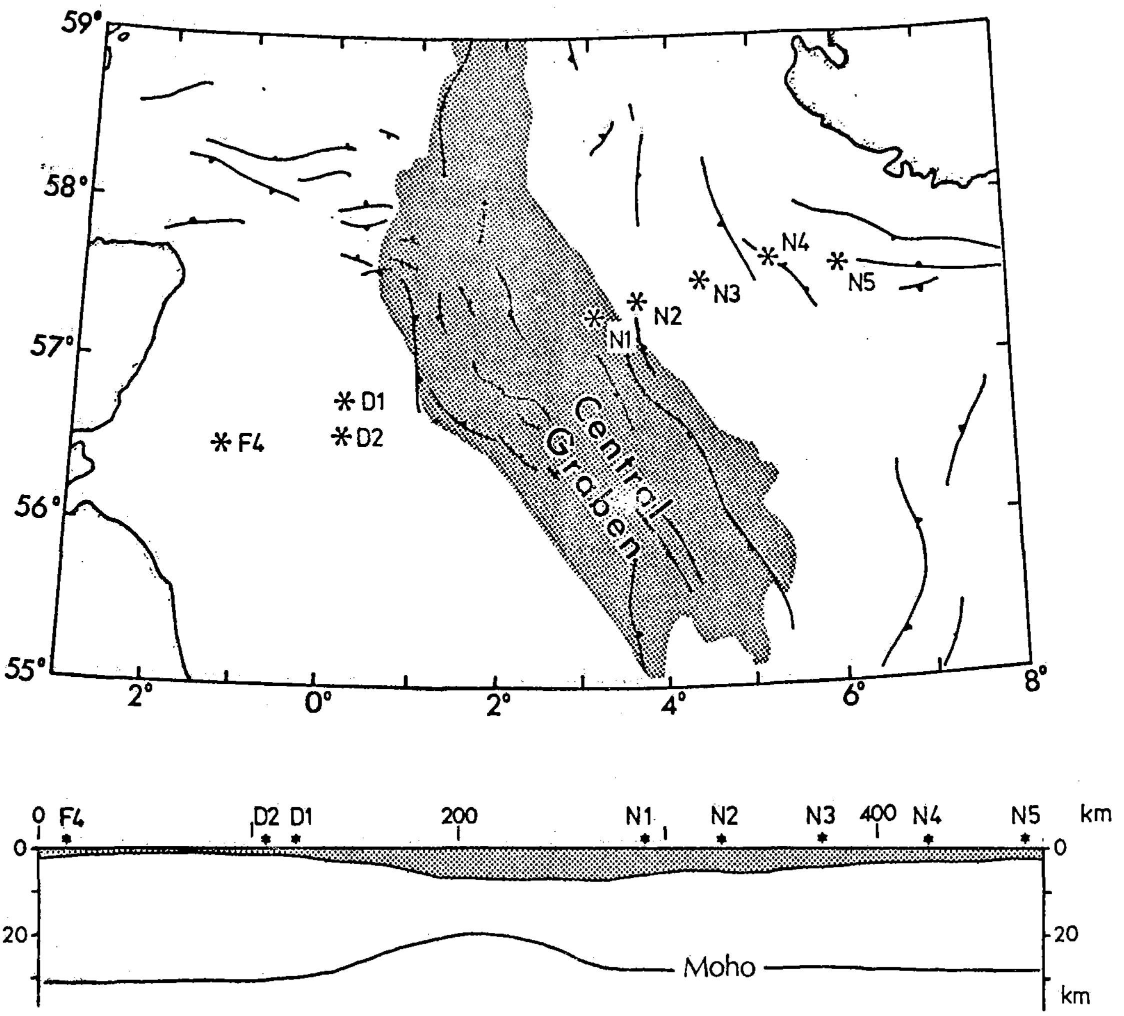

Fig. VII.2.1 Top: Map of the central North Sea basin showing the main structural features. The Central Graben zone with sediments thicker than 2 km is indicated by shading. The positions of the major shots in the seismic refraction experiments are indicated by stars.

Bottom: Cross section of structure across the graben zone along the line of the shots proposed by Wood and Barton (1983).

Sediments are indicated by shading.

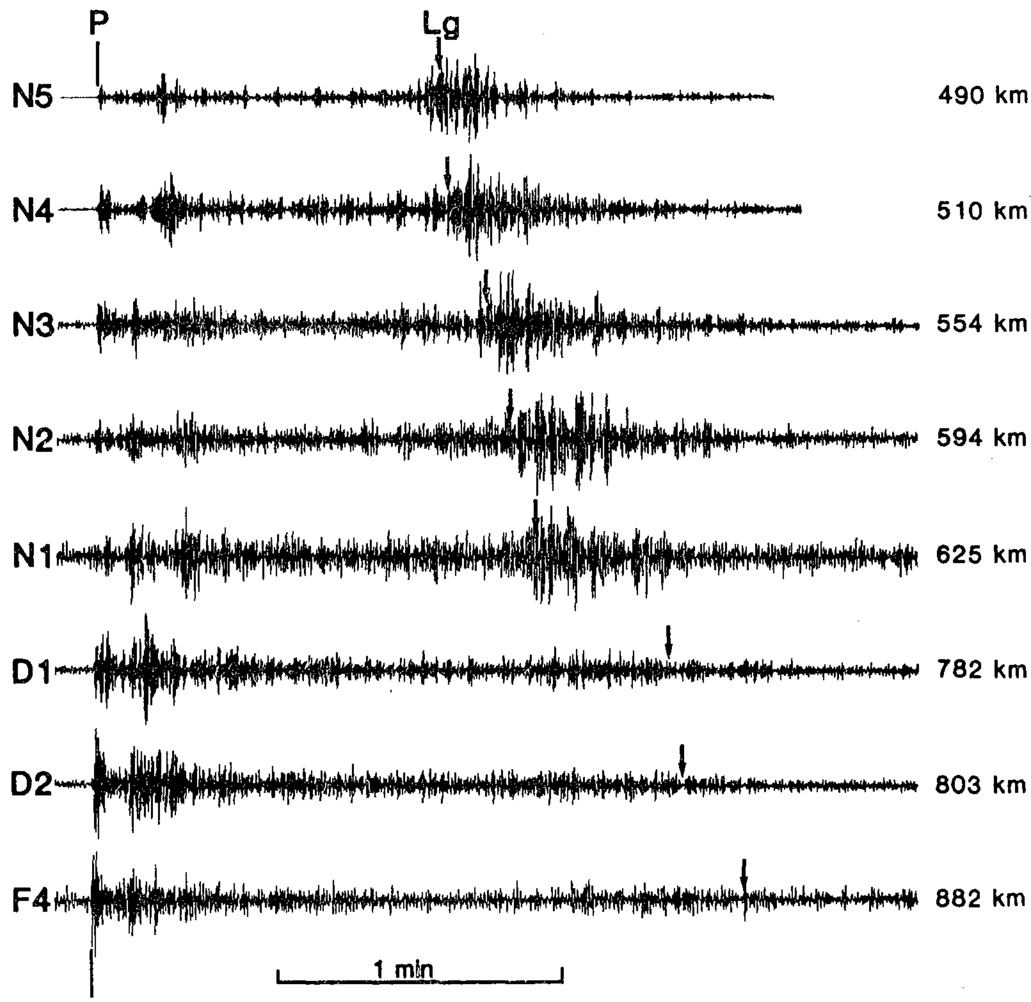

Fig. VII.2.2 Record section of seismograms from the major refraction shots spanning the Central Graben zone marked in Fig. VII.2.1. Each trace is normalized to the same maximum amplitude and aligned on the P wave onsets. An arrow indicates a group velocity of 3.5 km/s corresponding to Lg wave arrivals.

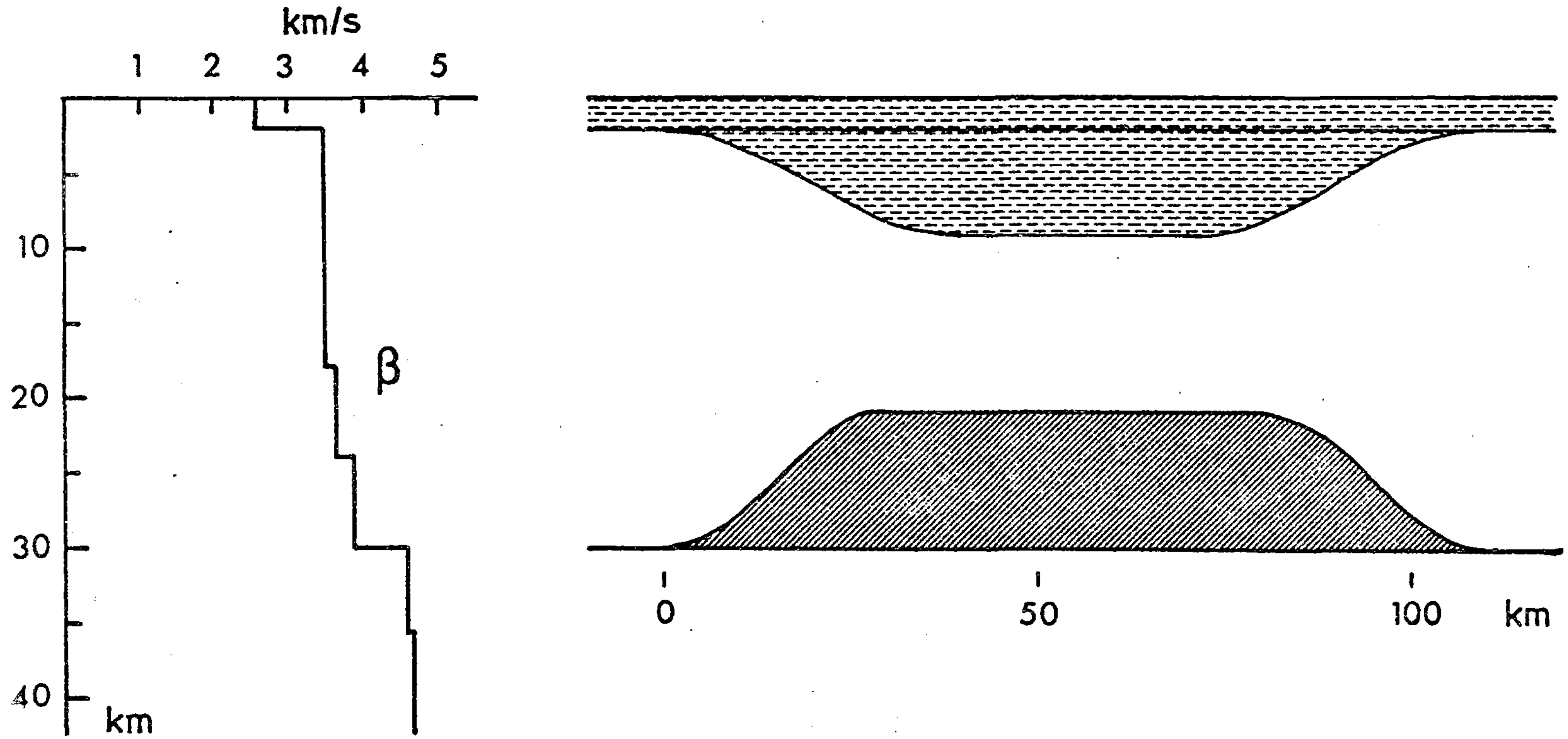

Fig. VII.2.3 Shear velocity model for the reference stratification and illustration of the structural model used in the study of Lg propagation across the graben zone.

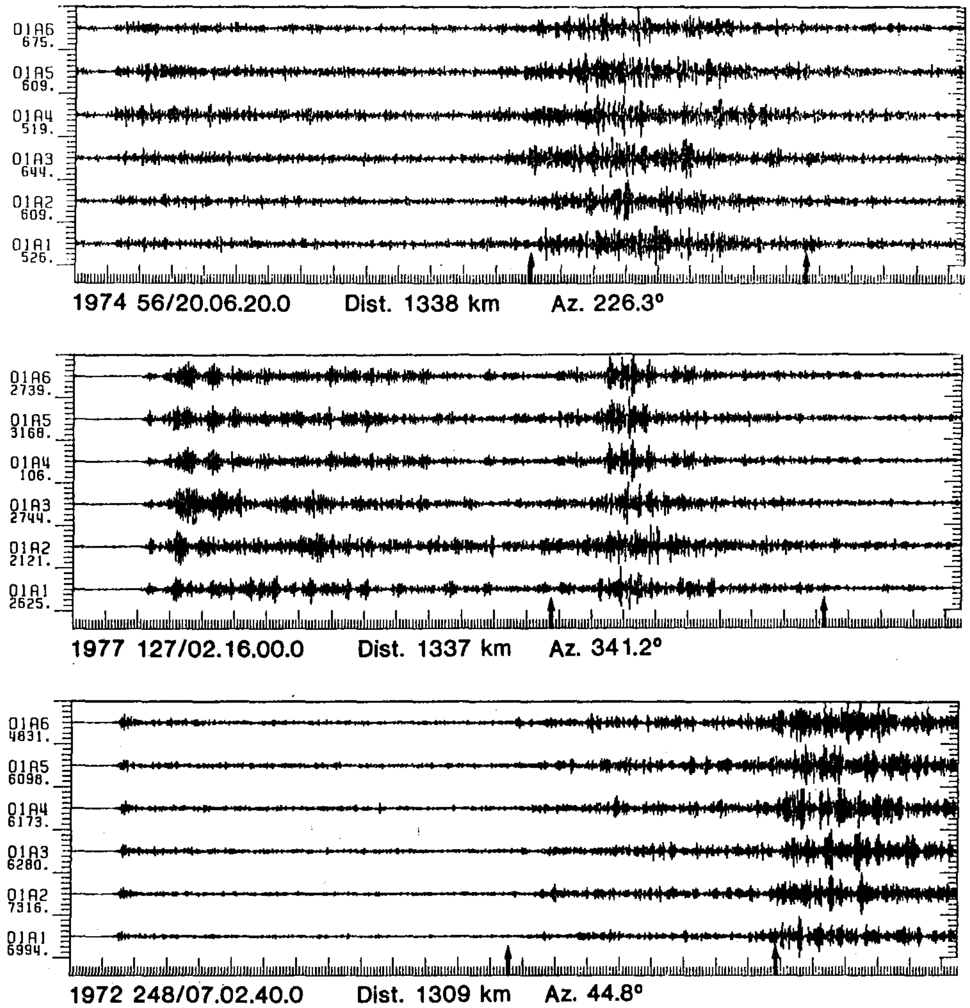

Fig. VII.2.4 Three events recorded at the NORSAR subarray 01A (6 instruments within a diameter of 10 km). All data have been bandpass fitered 1.2-3.2 Hz. For each event the two arrows indicate group velocities of 4.5 km/s and 3.5 km/s. Data start time, epicentral distance and station-to-epicenter azimuth are given for each event. The three events originated in the United Kingdom (top), in the Jan Mayen Island region (middle) and on the Kola peninsula in western Russia. As can be seen from the records, the relative strength of secondary phases Sn (standard group velocity about 4.4-4.5 km/s) and Lg (group velocity 3.5 km/s) varies drastically between various propagation paths to NORSAR. The traces are plot normalized with scaling factors given to the left. At the time of the 1977 event, channel 01A4 recorded data from channel 01A6, attenuated 30 dB. Data window length is 275 seconds in all three frames.