

## Deep seismic reflections in the Netherlands, an overview

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### Abstract

A project to study deep crustal structures was carried out by the Geological Survey of the Netherlands between 1986 and 1993. In this period deep seismic data were acquired on- and offshore the Netherlands. The data consist of stacked normal-incidence seismic lines with recording times of up to 16 s and wide-angle measurements. Interpretations show that the crust is composed of a transparent upper part and a reflective lower part. The base of the reflective zone coincides with the Moho discontinuity. The seismic lines cross several basins. The Roer Valley Graben was modelled with a pure-shear McKenzie model. The Mesozoic basins in the southern North Sea seem to have originated from pure-shear movements with an additional simple-shear component. The Moho depth map shows that the crust is thinner beneath the basins and thickens beneath the highs.

### Introduction

Since 1986, deep seismic reflection data, with recording times of 15 and 16 s, have been acquired in the Netherlands. The data consist of three onshore and two offshore seismic lines. During the acquisition of the offshore line MPNI-9101 wide-angle measurements have been recorded at four landstations. The locations of the lines and the landstations are given in Fig. 1. The general objectives of the deep seismic project were to study lower crustal structures and their relations with upper crustal geological features, like sedimentary basins and major faults, as well as the lateral relationship between the basins and the Caledonian London-Brabant Massif. The main issue was a better understanding of the genesis and evolution of the sedimentary basins in the Netherlands. This paper summarizes the results.

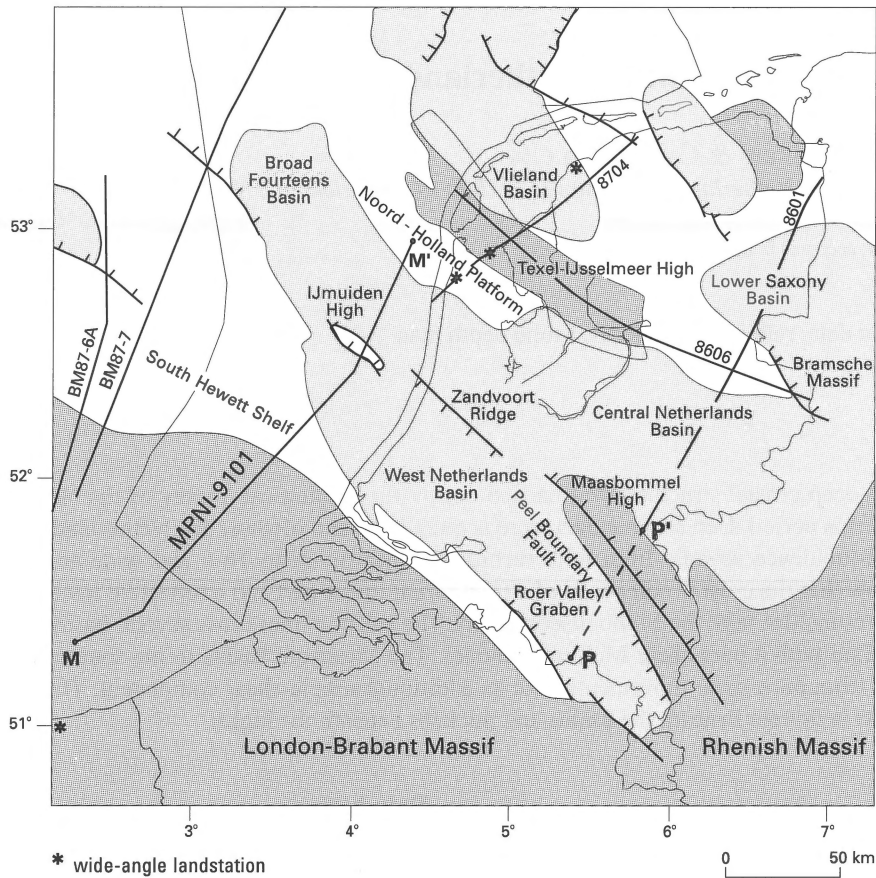
Figure 1 also presents the main Mesozoic structural elements in the Netherlands. The dominating geological trend is NW–SE. Most of the seismic lines are perpendicular to this trend.

### Data base

#### *Data acquisition*

The onshore data have been shot in 1986 and 1987 as a speculative survey by order of the Geological Survey of the Netherlands, in co-operation with Delft Geophysical. The results of this survey have been described by Remmelts & Duin (1990). In 1987 the British Institutions Reflection Profiling Syndicate (BIRPS) acquired the 'MOBIL-survey', of which line BM87-7 is partly situated in the Dutch part of the southern North Sea (Fig. 1; Blundell et al. 1991).

In 1991 a deep seismic line (MPNI-9101) was acquired in co-operation with the Belgian Geological Survey in the southern North Sea along the Dutch and Belgian coast (Rijkers & Duin 1994). Wide-angle measurements were recorded at three landstations in the Netherlands and one in France under supervision of the Department of Geological Sciences of the University of Durham. Although the wide-angle measurements suffered considerably from windy weather, the data from two stations in the Netherlands could be used to model the crustal velocities beneath the southern North Sea (Scott-Robinson 1993). During the acquisition of line MPNI-9101 an experiment was carried out to obtain a



Line	Year	Company / Institution
8601	1986	DG / RGD
8606	1986	DG / RGD
8704	1987	DG / RGD
BM87-6A	1987	BIRPS
BM87-7	1987	BIRPS
MPNI-9101	1991	RGD / BGD

Fig. 1. Location map of the deep seismic lines, the wide-angle landstations, and the main Mesozoic structural elements in the Netherlands. Lines with bars are main faults. The dashed line denotes the location of cross-section PP' in Fig. 3 (RGD = Geological Survey of the Netherlands, BGD = Belgian Geological Survey, DG = Delft Geophysical, BIRPS = British Institutions Reflection Profiling Syndicate).

deep common-midpoint, using a second recording ship sailing in opposite direction. Mainly due to bad weather no coherent reflections could be observed on these data below 5 s. By the end of 1992 the deep seismic project in the Netherlands was completed.

#### Data quality

A number of conspicuous features of the deep geology of the Netherlands is revealed by the recorded seismic data. Especially the high-quality offshore line MPNI-

9101 (Fig. 2) has yielded valuable information about the structures in the deeper crust. Unfortunately, not all of the acquired deep seismic lines have yielded such good results.

The quality of the deep seismic data, especially the onshore lines, has been degraded by a number of factors:

- Deep reflectors are badly imaged beneath the Zechstein salt province, which occupies the major part of the northern Netherlands. The salt attenuates the seismic signal, and fractured anhydrite and

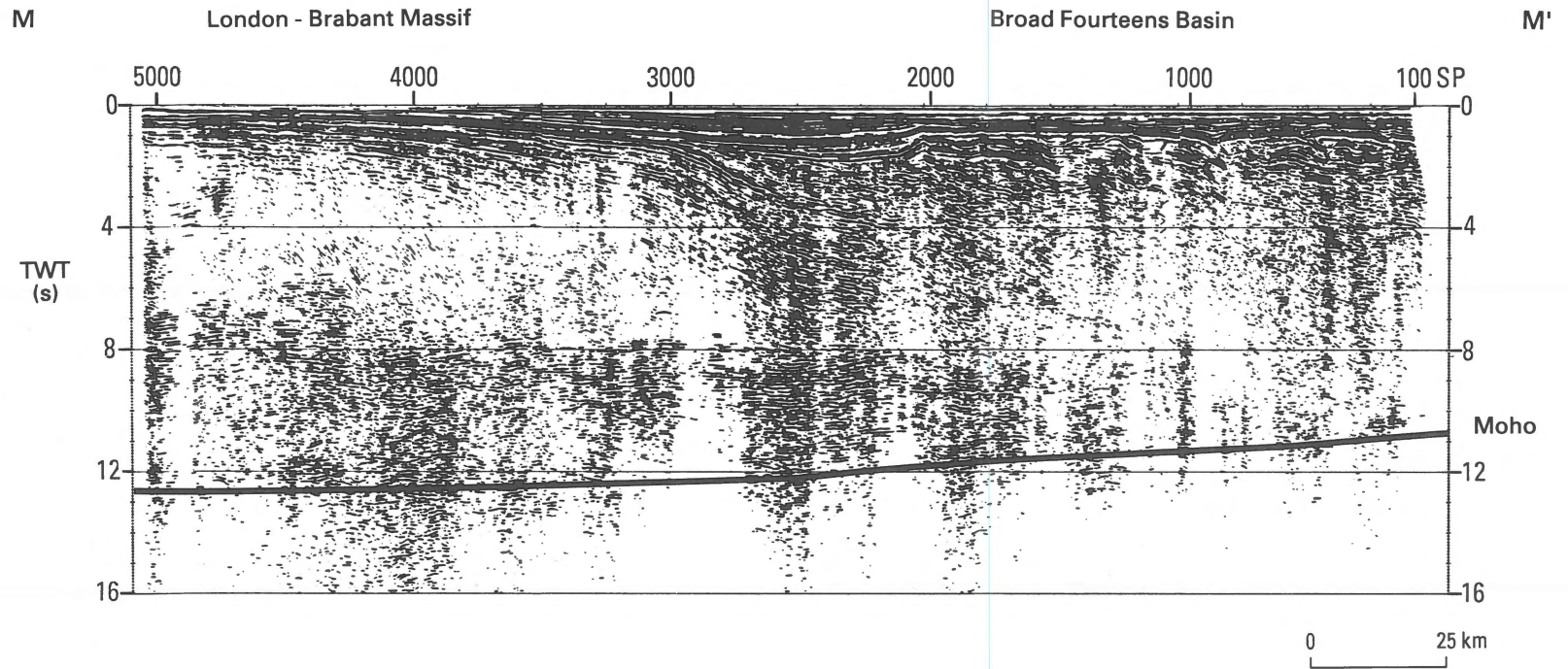


Fig. 2. Coherency-filtered stack of offshore line MPNI-9101 (Fig. 1). The base of the reflective lower crust, the Moho discontinuity, has been marked on the section. The transparent upper crust between approximately 3 and 7.5 s is clearly visible. In this interval numerous multiples from overlying strata can be observed between shotpoints 100–750 and between shotpoints 1500–2750. In the upper part of the section, between shotpoints 100–2500, the outlines of the Mesozoic basins of the southern North Sea are visible. The base Lower Carboniferous (Dinantian) reflection, at approximately 2 s beneath shotpoint 2800, strongly dips towards the basin area. The London-Brabant Massif can be identified between shotpoints 5000 and 3000.

dolomite layers act as strong signal scatterers. The deeper parts of line BM87-7 from the 1987 MOBIL survey are also largely obscured by side-swipes from salt piercement structures.

- Acquisition of the onshore lines was a combined effort to acquire both a regional seismic grid for hydrocarbon exploration and a set of deep seismic lines for crustal studies. This resulted in a number of concessions in acquisition parameters, which were not in favour of the quality of the deeper data. A split-spread source-geophones geometry with moderate offsets was chosen for the acquisition. No special efforts were undertaken to enhance the low frequencies of the source signal in order to obtain a deeper penetration of the seismic energy. The acquisition bandwidth was from 0 to 125 Hz.
- Due to legal and environmental restrictions, dynamite charges were low on land (1500 grams). In general these charges are too low to acquire good-quality deep seismic data. To compensate for this low-energy signal, a nominal fold of 120 was used. In areas where only vibroseis was allowed no reflections from the lower crust were observed on the sections. The airgun signal on the inland lake IJsselmeer, as part of the onshore survey, also did not penetrate the lower crust. Because of the limited source strength, no wide-angle or deep refraction measurements could be acquired on land.
- The normal-incidence offshore deep seismic line MPNI-9101 is of good quality (Rijkers & Duin 1994). The quality of the wide-angle measurements suffered from bad weather. Also the bad ground coupling of the landstations in the soft-rock environment of the Netherlands probably degraded the quality of the wide-angle measurements.

### Reflectivity patterns

One of the main results of the deep seismic surveys in the Netherlands is evidence that the crust consists of a seismically transparent upper part and a reflective lower part. This seismic pattern, which has been found in many parts of the world (Klemperer & Hobbs 1991), is independent of upper crustal structures. An example of this seismic fabric is shown in Fig. 2. Beneath the Mesozoic basins and highs and also beneath the Caledonian London-Brabant Massif, lower crustal reflections occur. The reflections are subhorizontal with an average length of about one kilometre. Refraction measurements in several parts of the world have shown that

the base of the reflective lower crustal zone coincides with the Moho discontinuity, the boundary between the crust and the upper mantle (Meissner et al. 1986).

The nature of the lower crustal reflections is still under debate. They may be caused by layered intrusives from the upper mantle, metamorphic layering (anatexis), dynamic layering (shear movements) or a combination of these factors. Seismic features, like faults or shear zones in the upper crust that link the supracrustal structures with lower crustal structures have not been observed in the data.

Rommelts & Duin (1990) observed a relation between the reflection amplitudes and heat flow anomalies. High reflection-amplitude values in the lower crust in the eastern Netherlands correspond with high heat-flow values, which may be related to the Late Cretaceous intrusions of the Bramsche Massif in western Germany.

### Interpretation

#### *Geological setting*

The Netherlands are part of an area that has been relatively stable during geological times. Although data are sparse, it is assumed that the area may have been partly affected by the Caledonian orogeny, but was not actually situated on a collision zone (Ziegler 1986). The London-Brabant Massif came into existence during this orogeny. Since the Carboniferous, the Netherlands are part of the northern foreland of this massif. The foreland was uplifted during the Variscan deformation phase and NW–SE striking faults developed. These faults have controlled in a later stage the formation of the Mesozoic basins. During Triassic, Jurassic and Early Cretaceous times, several Mesozoic basins, like the Central Netherlands Basin, the West Netherlands Basin and the Broad Fourteens Basin, developed in response to transtensional stresses (Kimmerian tectonic phases). The basins became inverted during the Late Cretaceous (Subhercynian phase) and the Early Tertiary (Laramide phase).

#### *Sedimentary basins*

The Roer Valley Graben in the southern Netherlands is a halfgraben with a complex multiphase deformation history. The most important rifting episodes occurred during the Late Permian–Early Triassic, the Middle Jurassic and the Late Cenozoic (Geluk et al. 1995,

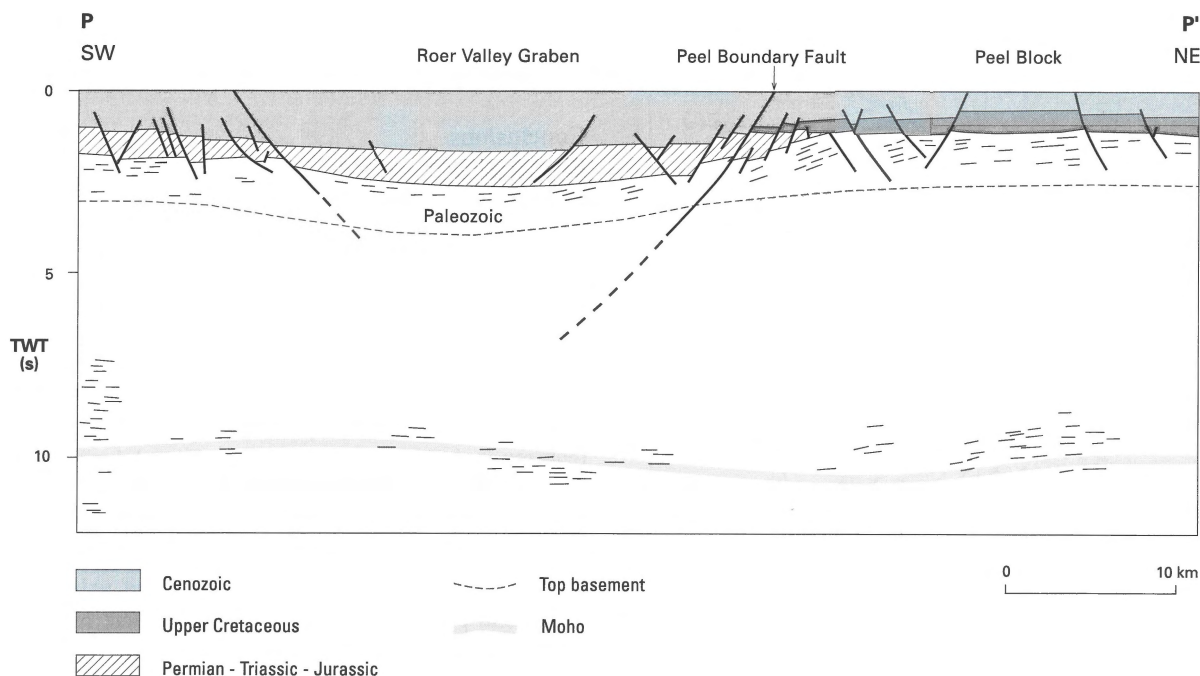


Fig. 3. Interpreted crustal section PP', based on seismic line 8601, crossing the Roer Valley Graben (Fig. 1).

Zijerveld et al. 1992). Extension is accommodated by a narrow fault zone in the northeast, the Peel Boundary Fault, and a number of parallel faults in the southwest. The recent earthquake of April 13th, 1992 in the Netherlands, with a magnitude of 5.8 on the scale of Richter, occurred along the Peel Boundary Fault. On the seismic data this fault can be traced with great confidence in the post-Carboniferous sediments. Figure 3 presents an interpretation of the southern part of onshore line 8601 that crosses the Roer Valley Graben. The fault is tentatively marked in the deeper sediments and the basement. A distinct uplift of the reflection Moho from an average depth of 30 km beneath the northeastern graben flank to a depth of 27 km below the graben centre is determined from the deep seismic line (Fig. 3). The time-to-depth conversion is described in the next section.

The  $\beta$ -factor for crustal stretching as derived from the change in crustal thickness, based on the pure-shear McKenzie model (McKenzie 1978), is estimated at approximately 1.17. Calculating the  $\beta$ -factor from fault heaves at base Tertiary gives a value of approximately 1.04. This discrepancy may be explained by the fact that variations in crustal thickness are the result of a polyphase deformation, while the fault heaves at base

Tertiary only relate to the Cenozoic extensional phase of the basin.

The Mesozoic basins in the southern North Sea, the West Netherlands Basin and the Broad Fourteens Basin, developed in response to transtensional stresses (Ziegler 1986). The basins are well imaged by the offshore line MPNI-9101 (Fig. 2). They are separated by palaeohighs and bounded by NW-SE trending faults. The depth of the reflection Moho, as described in the next section, decreases from more than 37 km beneath the London-Brabant Massif to less than 31 km beneath the northernmost part of the basin area. A crustal model based on the wide-angle measurements gives a Moho depth of  $31.5 \pm 1.5$  km for the basin area (Scott-Robinson 1993), which is in line with the interpretation of the normal-incidence seismic data. The depth of the reflection Moho is directly related to the occurrence of basins, and therefore probably also to stretching of the crust and upper mantle (pure-shear). Vertical offset of the Moho possibly occurs beneath the transition zone between the London-Brabant Massif and the northwestern part of the West Netherlands Basin, which may indicate that simple-shear processes have also been active in the lower crust. A combined mechanism of initial pure shear and subsequent simple

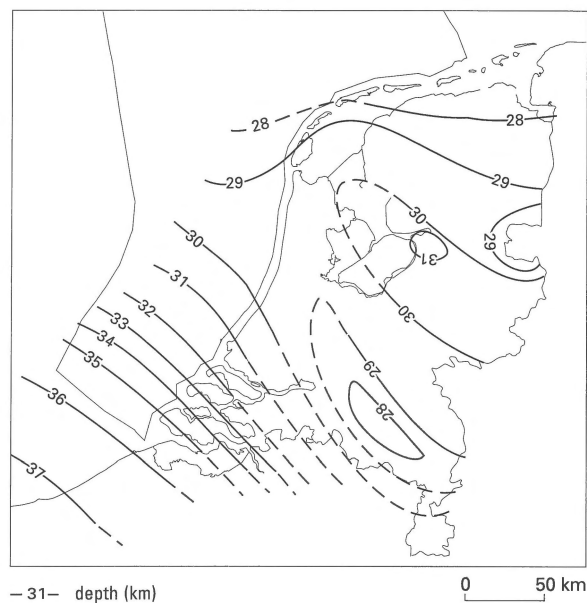


Fig. 4. Moho depth map of the Netherlands.

shear is possibly responsible for the deformation of the crust (Rijkers & Duin 1994).

Based on the measured lengths of the base Chalk and base Jurassic reflections,  $\beta$ -factors for the extensional and compressional phases have been calculated as 1.07 and 0.97 respectively.

### Moho depth map

A reflection Moho depth map of the Netherlands was compiled from the onshore survey and the offshore line MPNI-9101 (Fig. 4). Time-to-depth conversion was performed using a velocity model based on well data for the upper sedimentary column and a constant velocity of 6.2 km/s for the rest of the crust. The latter value was determined from the wide-angle measurements (Scott-Robinson 1993) and is in agreement with values found in the literature (Meissner et al. 1986).

The map gives a regional image of the depth of the Moho and shows that the trend seems to be dictated by the NW-SE orientation of the supracrustal structural grain. Minimum depth values of less than 28 km are found beneath the Roer Valley Graben and in the northernmost part of the Netherlands. A crustal thickness of more than 31 km is found beneath the Texel-IJsselmeer High. To the southwest the Moho deepens to more than

37 km beneath the London-Brabant Massif offshore Belgium.

### Conclusions

Apart from thickness changes of the crust, no major structural features have been found in the crust below the sedimentary column and in the upper mantle. The crust below the Netherlands is composed of a transparent upper part and a reflective lower part. This has been observed in many other areas around the world. The reflective layering of the lower crust seems to be post-orogenic, because it is independent of structural features in the upper crust, that originated during different tectonic phases. Even beneath the Caledonian London-Brabant Massif lower crustal reflections are present.

The Roer Valley Graben was modelled using the McKenzie pure-shear model, while the West Netherlands Basin can be modelled with a combination of the McKenzie pure-shear model and the local occurrence of simple-shear zones.

A Moho depth map of the Netherlands shows that the thickness of the crust relates to the large-scale supracrustal structural development: crustal thinning occurs beneath the sedimentary basins, whereas the crust is thicker beneath the highs. Minimum values of less than 28 km are found beneath the Roer Valley Graben, whereas a maximum crustal thickness of more than 37 km occurs beneath the London-Brabant Massif offshore Belgium.

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