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Seismic stratigraphy of the Mesozoic and Cenozoic in northern Belgium: main results of a high-resolution reflection seismic survey along rivers and canals

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Abstract

This paper presents the results of high-resolution reflection seismic surveys carried out between 1989 and 1996 along rivers and canals in northern Belgium. The seismic data penetrate down to 900 m in the sedimentary cover or to the Paleozoic basement. The reflection response of the acoustic basement provides clear indications with regard to the top of the Paleozoic: crystalline basement and Lower Paleozoic metasediments and volcanics of the London-Brabant Massif and NE-dipping Devonian and Carboniferous strata. The subhorizontal Mesozoic and Cenozoic sedimentary cover comprises 20 unconformity-bound seismic units: 5 in the Cretaceous and 15 in the Cenozoic. Based on borehole information, these units are correlated with lithostratigraphically defined formations or groups. Some of the unit-bounding unconformities are of regional importance. They are attributed i) to eustatic sea-level changes causing regional flooding during the Late Cretaceous or incision of deep valleys during the Late Oligocene and Late Miocene, ii) to regional tectonic tilting between Late Eocene and Early Oligocene, or iii) to a combination of eustasy and tectonics causing valley incisions during the Lutetian. Faults of the Roer Valley Graben have offset different stratigraphic levels by sometimes considerable amounts (up to 230 m in the Oligocene to Quaternary succession). Although the main tectonic phase took place during the Miocene, the activity has varied considerably through time, and also from fault to fault. Most faults seem to have a 10 to 30-m displacement since the Late Pliocene.

Introduction

Our knowledge about the geology of northern Belgium, the Flanders area, has been gathered over the past century by compiling information from outcrops, deep boreholes, and isolated geophysical surveys. The latter mostly aimed at determining the extent of Carboniferous coal measures in the now inactive mining areas in eastern Belgium.

Northern Belgium consists of a Paleozoic 'basement', covered by subhorizontal Mesozoic and Cenozoic sediments. It is tectonically relatively stable except for its easternmost parts.

The Paleozoic consists of two distinct units: the London-Brabant Massif in the west and centre, and the Campine Basin in the northeast (Figure 1). The London-Brabant Massif is a major, WNW–ESE trending structural unit composed of a Precambrian crystalline basement and of metasedimentary and volcanic rocks of Early Paleozoic age (De Vos et al. 1993b). The northern flank of the massif is covered by the thick, mainly Upper Devonian and Carboniferous sequences of the Campine Basin (Dreesen et al. 1987; Langenaeker & Dusar 1992). The Paleozoic in northern Belgium is presently buried to depths that range from 50 m below sea level (bsl) near Bossuit in the west, to over 1200 m bsl in the northeast (Legrand 1968) and east where it enters the Roer Valley Graben (Demyttenaere 1988).

Although some older Mesozoic deposits are present in the extreme east, i.e. in the area of the Roer Valley Graben (Demyttenaere 1988), the Paleozoic is in most areas directly overlain by the Upper

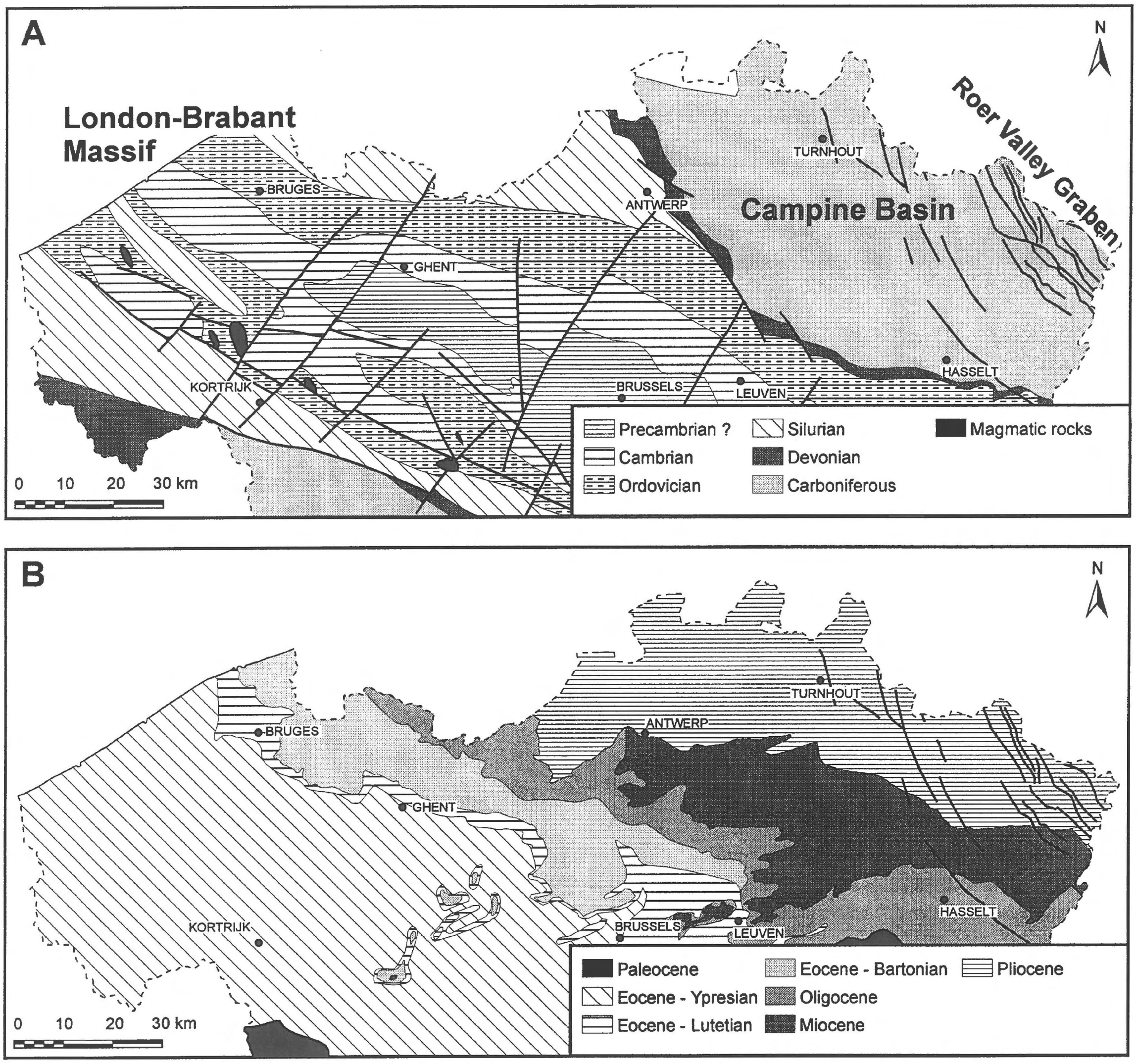

Figure 1. A) Simplified base-Mesozoic subcrop map of northern Belgium (compiled from Legrand 1968, Demyttenaere 1988, Langenaeker & Dusar 1992, De Vos et al. 1993b). B) Simplified geological map of the Tertiary (outcrop or base-Quaternary subcrop; after Marechal 1992).

Cretaceous, which is predominantly composed of carbonates (Felder et al. 1985). The thickness of the Cretaceous varies from 0 m in the area between Tielt and Oudenaarde on the crest of the massif to over 300 m northeast of Turnhout near the Roer Valley Graben (Legrand 1968).

The Cenozoic consists almost completely of siliciclastic, marine to marginal-marine sediments (Vinken 1988; Jacobs & De Batist 1996; Vandenberghe et al., in press). They result from periodical flooding of the area during periods of high relative sea level. While Paleogene strata were deposited in most of northern Belgium, the Belgian part of the Neogene depocentre became more and more restricted and confined to the northeast of the area. The Tertiary usually occurs at the outcrop (Figure 1) or is covered by Quaternary deposits of variable thickness (0–30 m). During the Quaternary, the sedimentation became almost entirely continental and confined to the northernmost and easternmost parts of the area. Marine influences affected the coastal areas in the west.

The accumulation of Neogene and Quaternary deposits in the northeastern parts of Belgium was favoured by tectonic subsidence. The area is transsected by the western border faults of the Roer Valley Graben (Rossa 1986; Demyttenaere & Laga 1988). This graben, that developed mainly in the Cenozoic, is still active tectonically (Geluk et al. 1994; Camelbeeck

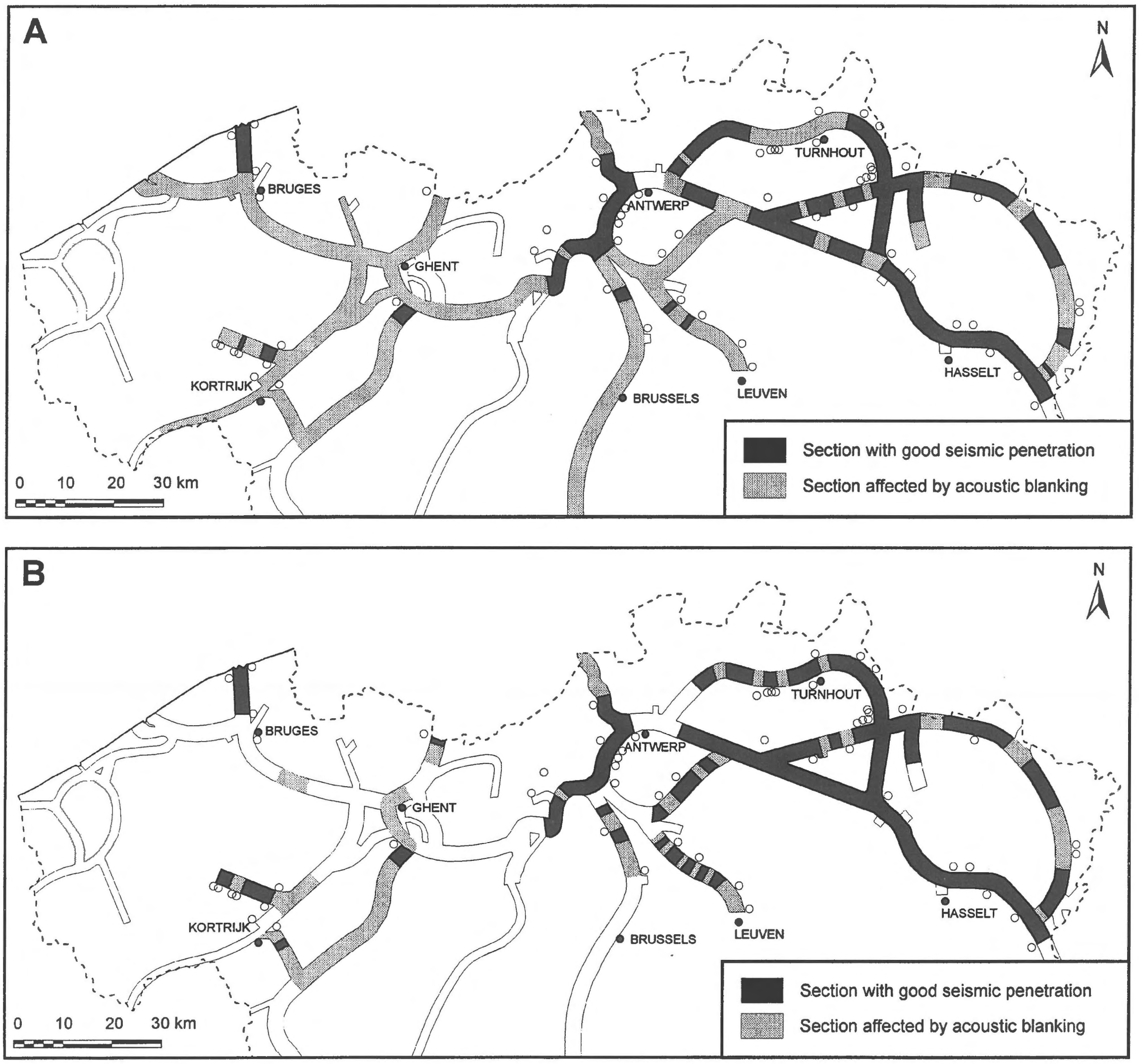

Figure 2. Schematic maps of northern Belgium showing the river and canal segments along which (A) analog, single-channel sparker profiles, and (B) digital, multi-channel watergun profiles were acquired, and showing the location of the boreholes (○) that were used for correlation. Segments with acoustic blanking are also indicated.

& Meghraoui 1996). Otherwise, no major tectonic structures active in Mesozoic and Cenozoic times are present in northern Belgium.

In recent years, new geophysical and geological data were acquired as the result of a renewed interest in the geology of northern Belgium. Four seismic surveys were conducted from 1989 to 1996 along most of the inland waterways in the area. The acquired data provide new, high-resolution information about the stratigraphy of the Mesozoic and Cenozoic overlying the Paleozoic basement and about the tectonic structure. In this paper we aim to present an overview of the main results of this study. We will not discuss the details of the seismic methods that were used, nor those of the stratigraphic and structural interpretations. These will be the subject of future publications. This paper is organised as follows. First, we present the background information about the acquisition and processing of the seismic data and about the data quality. In a second section, the seismic data are described, mostly so by using comprehensive tables. In the following sections, covering successively the Paleozoic, the Mesozoic and the Cenozoic, the origins of the unconformities, and tectonic aspects, the data will be interpreted and discussed in the framework of the regional geology.

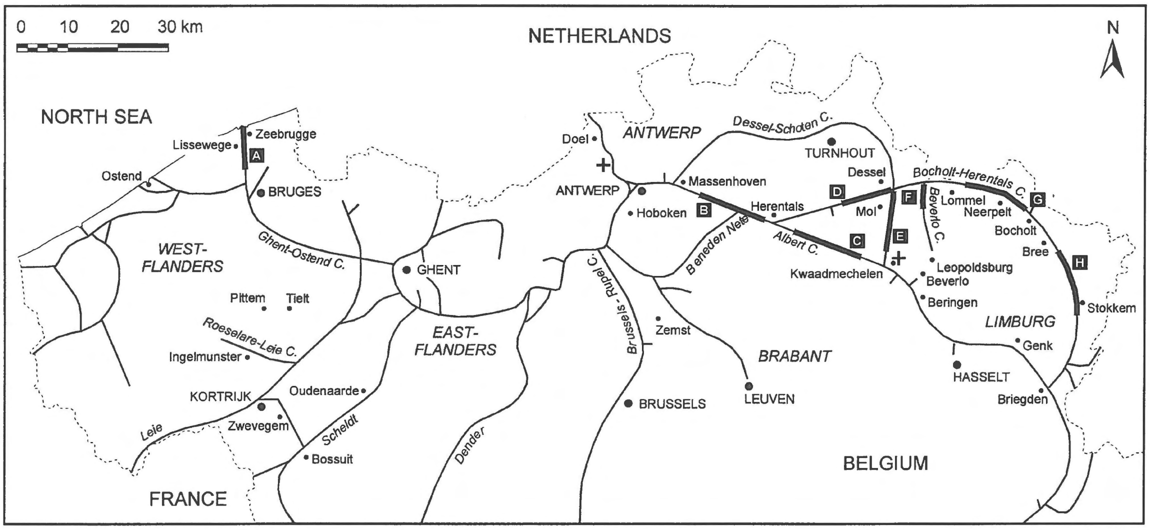

Figure 3. Map of northern Belgium showing the localisation of the main geographical names used in the text, and of the seismic profiles shown in the figures. A = Figure 5, B = 7, C = 6, D = 8, E = 9, F = 12, G = 13, H = 11. Crosses mark locations of velocity analyses shown in Figure 4.

Acquisition and processing of the seismic data

Virtually all of the high-resolution reflection seismic data used in this study were acquired, processed and interpreted by the Renard Centre of Marine Geology (RCMG) in the framework of four projects commissioned by the Belgian Geological Survey (Henriet et al. 1990) and by the Department of Natural Resources and Energy of the Flemish Government (De Batist et al. 1992, 1993, 1996). The data were shot on rivers and canals using 'marine' seismic sources and receivers, and the 'marine' continuous-profiling acquisition technique, which we adapted taking into account the limited towing depth of source and receiver, limitations on streamer length, reverberations in the water layer, etc. Similar surveys have since been conducted in the Netherlands, with limited success (Verbeek et al. 1994, 1995), and in Hungary (Tóth et al. 1997).

In total, we shot nearly 500 km of seismic profiles, along most of the rivers and canals in the provinces of West- and East-Flanders, Antwerp, Limburg and Brabant (Figures 2, 3). Along each section, we acquired two types of data:

1. analog, single-channel seismic profiles, using a 300 J 'Centipede' sparker or UNIBOOM boomer source and a 2.8 m single-channel streamer,
2. digital, multi-channel seismic (MCS) profiles, using a 0.25 l SODERA S15 watergun, a 100 m 8-channel streamer and an EG&G ES2420 seismograph.

Table 1. Overview of the acquisition parameters and data characteristics of the reflection seismic profiles used in this study.

Analog data	
Source	Centipede sparker
Energy	300 J
Depth of source	1.0 m
Receiver	2.4 m 1-channel streamer
Depth of receiver	surface
Shot interval	0.6 or 0.8 or 1.5 s

Digital MCS data	
Source	0.25 l SODERA S15 watergun
Energy	120–140 bar
Depth of source	1.5 m
Receiver	100 m 8-channel streamer
Depth of receiver	0.5 m
Shot interval	3.0 or 3.5 or 5.0 s
Record length	1.0 s
Sampling rate	0.25 ms

The acquisition parameters and data characteristics are listed in Table 1. The MCS data were processed at RCMG, using PHOENIX VECTOR software. The applied processing routines are listed in Table 2.

The quality of the processed data is generally good. The sparker and boomer data generally have a penetration of up to 100 ms two-way travel time (TWTT) and

Table 2. Overview of the processing routines applied to the MCS data.

Processing sequence
Demultiplexing and format conversion
Geometry definition
Pre-stack Butterworth filter (75-350 Hz)
Correction for spherical divergence
"Common depth point" (CDP) sorting
Static correction for watergun delay
Velocity analysis
"Normal Move-Out" (NMO) correction
Predictive pre-stack deconvolution
"Common depth point" (CDP) stacking
Post-stack Butterworth filter (75-350 Hz)
Scaling: "Automatic Gain Control" (AGC)

a resolution of 0.5 to 1 m, while the MCS data have a penetration of nearly 1000 ms TWTT and a resolution of about 5 m.

Some of the sections, however, are strongly affected by acoustic blanking. This is usually attributed to the presence of small gas bubbles, e.g. methane originating from the decomposition of organic material, contained within the surficial sediments (e.g. Davis 1992). Acoustic blanking affects our seismic records in varying degrees:

- partial absorption of the seismic energy, resulting in a reduced penetration;
- total absorption of the seismic energy, resulting in a total reduction of the penetration, i.e. complete blanking;
- (quasi) total reflection of the seismic energy at the gas-containing layer, resulting in a strong 'ringing' effect, caused by a series of high-amplitude reverberations in the water column.

These acoustic blanking effects have been avoided or reduced to some extent by using lower-frequency seismic sources and higher energies, or by applying adequate processing techniques. The profile segments affected by acoustic blanking are indicated on Figure 2.

Seismic-stratigraphic units

The processed MCS profiles and the analog sparker data were interpreted using the principles of seismic stratigraphy defined by Mitchum et al. (1977).

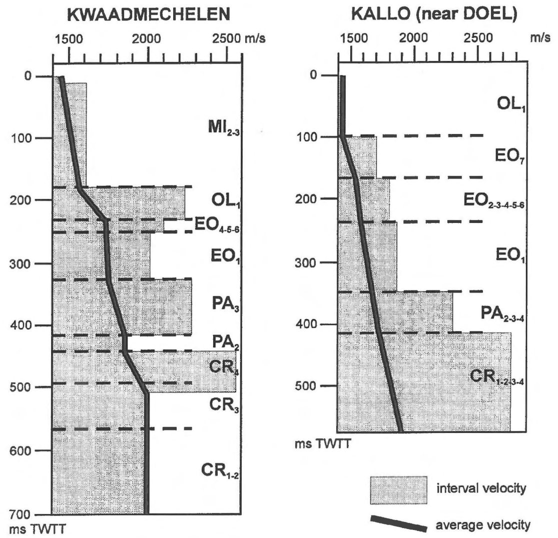

Figure 4. Two typical examples of velocity functions obtained by 'Normal Move-Out' (NMO) analyses of the MCS data, and used to tie the seismic stratigraphy to nearby boreholes. For location see Figure 3.

Twenty unconformity-bound seismic-stratigraphic units overlying the acoustic basement could thus be defined and correlated. Their seismic-stratigraphic characteristics (lower and upper unit boundaries, geometry, seismic facies, thickness, etc.) are summarised in Tables 3 to 5. Their symbols have a stratigraphic connotation.

Seismic-stratigraphic and geological interpretation

The seismically defined units were then correlated with borehole descriptions from the archives of the Belgian Geological Survey (e.g. Legrand 1968). We selected ca. 60 boreholes that were located in the vicinity of the profiles. Their position is indicated on Figure 2. In order to tie the seismic units to these boreholes, we used the velocity information obtained from 'Normal Move-Out' (NMO) analyses of the MCS data (Figure 4) and from wide-angle reflection experiments performed at selected sites (De Batist et al. 1996). In this way, the seismic stratigraphy was tied to the current Belgian litho- and chronostratigraphy (Marechal & Laga 1988).

This interpretation and correlation of the seismic data to the Belgian stratigraphy is discussed below with reference to eight interpreted profile segments

Table 3. Seismic-stratigraphic characteristics of the five seismic units in the Upper Cretaceous of northern Belgium.

Unit name	Lower boundary	Upper boundary	Geometry	Seismic facies	Occurrence	Thickness
CR$_4$	Conformity, distinct facies change	Erosional truncation or conformity	Continuous layer	Parallel, high-amplitude, continuous reflectors	Not in W and SW, continuous elsewhere	25-75 m (25-75 ms)
CR$_3$	Onlap	Weak erosional truncation or conformity, distinct facies change	Continuous layer	Some internal reflectors, homogeneous	Not in W and SW, continuous elsewhere	45-90 m (45-90 ms)
CR$_2$	Conformity	Erosional truncation or conformity	Continuous layer	Some internal reflectors, homogeneous	Not in W and SW, continuous elsewhere	variable
CR$_1$	Onlap against Paleozoic or conformity	Erosional truncation or conformity	Not clear or infill of morphological lows	Complex basin fill or incised channel fill facies	Not in W and SW, continuous to patchy elsewhere	0-30 m (0-30 m)
CR$_0$	Onlap against Paleozoic	Conformity and distinct facies change	Not clear	Some internal reflectors, poorly defined	W and SW	0-25 m (0-25 ms)

Table 4. Seismic-stratigraphic characteristics of the 11 seismic units in the Paleogene of northern Belgium.

Unit name	Lower boundary	Upper boundary	Geometry	Seismic facies	Occurrence	Thickness
OL$_2$	Onlap and downlap	Erosional truncation	Continuous layer, channel infill at the base	Complex incised channel fill facies	N and E, pinches out to SW and SE	0-75 m (0-85 ms)
OL$_1$	Conformity	Truncation by base OL$_2$, base MI$_1$ or base MI$_{2-3}$	Continuous layer	Generally reflection-free, or very weak, parallel and continuous reflections	Central and NE, pinches out to SE	0-150 m (0-160 ms)
EO$_7$	Conformity	Truncation by base OL$_1$	Continuous layer	not clear	NW and central	0-30 m (0-30 ms)
EO$_{4-5-6}$	Onlap and downlap	Conformity or erosional truncation by base EO$_7$ or base OL$_1$	Continuous layer, channel infill	E-ward prograding basin or incised channel fill facies	Everywhere, except in W, pinches out to E	0-125 m (0-130 ms)
EO$_3$	Not clear	Not clear	Continuous layer	Two strong, discontinuous reflectors	NW and central	not determined
EO$_2$	Conformity	Conformity or truncation by base EO$_{4-5-6}$	Continuous layer	Weak, parallel and continuous reflections	W and central, pinches out to E	0-50 m (0-50 ms)
EO$_1$	Conformity or erosional truncation	Conformity or erosional truncation by base EO$_{4-5-6}$ or base OL$_1$	Continuous layer	Weak, parallel and continuous reflections	Everywhere, pinches out to SE	0-130 m (0-150 ms)
PA$_4$	Onlap and downlap	Conformity or not clear	Channel infill	Onlapping incised channel fill facies	Patchy	0-15 m (0-15 ms)
PA$_3$	Distinct facies change	Erosional truncation by base PA$_4$ or by base OL$_1$	Continuous layer	Reflection-free with some high-frequency, continuous internal reflectors	Everywhere, pinches out to SE	0-100 m (0-100 ms)
PA$_2$	Distinct facies change	Conformity or erosional truncation by base OL$_1$	Continuous layer	Variable, or with parallel, high-amplitude, continuous reflectors	Central and E, pinches out to W and SE	0-50 m (0-50 ms)
PA$_1$	Onlap towards W	Conformity or erosional truncation by base OL$_1$	Continuous layer	Poorly defined	E, pinches out to W and SE	0-40 m (0-40 ms)

(Figures 5–9, 11–13), the locations of which are shown on Figure 3.

The London-Brabant Massif and its Paleozoic cover

On most of the acquired MCS data, the seismic signal penetrates the soft sedimentary strata overlying the Paleozoic quite well, even to depths down to 900 m (ca. 1000 ms TWTT). It, however, seldom penetrates into the Paleozoic, even where the Paleozoic occurs at relatively shallow depths. On our data, the Paleozoic is observed at depths below the surface that range between 110 m near Zwevegem on the London-Brabant Massif and 875 m near Dessel in the Campine Basin.

Table 5. Seismic-stratigraphic characteristics of the four seismic units in the Neogene of northern Belgium.

Unit name	**Lower boundary**	**Upper boundary**	**Geometry**	**Seismic facies**	**Occurrence**	**Thickness**
PL_2	Not clear	Not clear	Continuous layer	Various discontinuous undulating reflectors, one very high-amplitude, continuous reflector	Central and NE, pinches out to W	not clear
PL_1	Not clear or conformity	Not clear	Continuous layer	Various discontinuous undulating reflectors	Central and NE, pinches out to W	0-150 m (0-150 ms)
MI_{2-3}	Diffraction hyperbolae	Conformity or erosional truncation by base PL_1	Continuous layer, valley infill	MI_3: NW-ward prograding and aggrading foresets MI_2: chaotic and complex basin fill or incised valley fill facies	Central and NE, pinches out to W and SE	0-350 m (0-375 ms)
MI_1	Conformity	Erosional truncation by base MI_{2-3}	Continuous layer	Parallel, high-amplitude, continuous reflectors	NE, pinches out to W	0-180 m (0-200 ms)

The London-Brabant Massif

On the MCS data in the provinces of Brabant, Westen East-Flanders, in the western part of the province of Antwerp, and in the extreme southeast of the province of Limburg, the acoustic basement is characterised by a very high-amplitude reflection, that is usually associated with clusters of diffraction hyperbolae. In these areas the Paleozoic basement is composed of the pre-Caledonian, Cambrian to Silurian rocks of the London-Brabant Massif (Figure 1; Legrand 1968; De Vos et al. 1993b). The diffraction hyperbolae are most likely generated at small-scale irregularities in the basement topography. At some places, larger-scale paleoreliefs occur, such as near Hoboken and Zemst, south of Antwerp, or between Bruges and Zeebrugge (Figure 5). These paleoreliefs may exceed 30 m (ca. 25–30 ms). They are, however, too localised and too small to be correlated with features that show up on the regional aeromagnetic and Bouguer gravity anomaly maps of Belgium (Chacksfield et al. 1993; De Vos et al. 1993a).

These morphological irregularities often occur near areas where faults or magmatic rocks are inferred within the London-Brabant Massif (De Vos et al. 1993b). Near Ingelmunster, in West-Flanders, the top-basement reflector is remarkably irregular and complex. This is attributed to the presence of a major fault, running parallel with and practically underneath the Leie-Roeselare canal. This fault separates magmatic rocks of Late Ordovician, Ashgill, age from slightly metamorphosed sediments of Early Cambrian age (De Vos et al. 1993b). The presence of the fault and of the intrusive rocks can both account for the numerous diffraction hyperbolae. The high in the basement topography associated with this structure (Legrand 1968) corresponds with the local absence of Cretaceous deposits.

The Paleozoic cover of the London-Brabant Massif in the Campine Basin

The north flank of the London-Brabant Massif is covered by the post-Caledonian sediments of the Campine Basin, which are of Late Devonian to Carboniferous age (Figure 1). The seismic characteristics of the acoustic basement provide indications with regard to the nature of the top of the Paleozoic.

Near Massenhoven, just east of Antwerp, the top of the Paleozoic is characterised by a high-amplitude and laterally continuous reflection. Considering the borehole information (Legrand 1968; De Vos et al. 1993b), we attribute these characteristics to the Upper Devonian sandstones.

Further east, e.g. between Massenhoven and Kwaadmechelen (Figures 6, 7), the amplitude of this top-basement reflection decreases suddenly. Here, the acoustic basement is characterised by a pronounced and irregular erosion surface with paleoreliefs up to several tens of metres (up to ca. 80 ms, Figure 6). Based on the borehole information (Legrand 1968; De Vos et al. 1993b) we infer that the upper part of the Paleozoic in this area consists of Dinantian limestones. In the same area, a number of peculiar deformations affect the Mesozoic and part of the Cenozoic. They resemble 'sag' or collapse structures, and appear to find their origin in a heavily disturbed zone at the top of the Paleozoic, outlined by diffraction hyperbolae (Figure 7). These deformations are very localised and have widths of about 500 to 1000 m, and reliefs up to 50 m (ca. 40–50 ms). In accordance with the seismic-stratigraphic analysis of Dreesen et al. (1987) and with the seismic attribute studies (e.g. 'amplitude

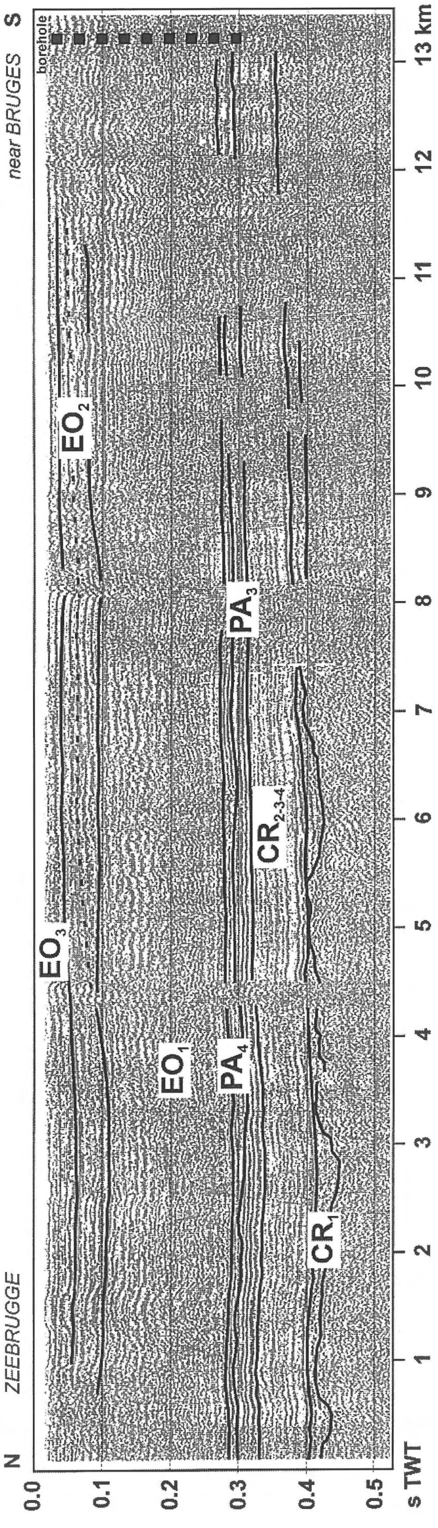

Figure 5. Part of an interpreted seismic profile along the canal Bruges-Zeebrugge, showing the irregular morphology i) at the top of the Paleozoic basement, below Unit CR_1, and ii) at the base of Unit PA_4. The internal reflector (dashed) within Unit EO_2 may represent the erosional base of the Vlierzele Sands Mbr. For location see Figure 3.

versus offset' analysis) of Vandenberghe et al. (1986) on similar features further to the north, we interpret them as dissolution or karst structures. They provide an additional argument for attributing the above seismic characteristics to Dinantian carbonate rocks. The collapse structures gradually fade out upwards, the youngest horizon affected by the sagging being the base of the Oligocene (Figure 7). This implies that the sagging (gradual in response to a continuing dissolution, or sudden due to collapse of a karst cavity?) ended in the Oligocene.

In the north and east of the Campine Basin, e.g. near Beringen and Dessel, the upper part of the Paleozoic is characterised by parallel, uniformly NE-ward dipping internal reflections below an erosion surface with a distinct cuesta-like morphology (Figure 8). Based on the borehole information (Legrand 1968; De Vos et al. 1993b), we attribute these characteristics to the alternating shales and sandstones of the Upper Carboniferous.

In some places in the Campine Basin, e.g. near Kwaadmechelen, the Paleozoic consists of faulted and tilted blocks (Figures 6, 9). These structures gradually die out in the overlying Mesozoic strata.

The Mesozoic

In most of northern Belgium, the Paleozoic is immediately overlain by the Upper Cretaceous. Older Mesozoic deposits are only present in the east (Demyttenaere 1988), but at depths that exceed the recording length of our data. The Upper Cretaceous reaches its maximum thickness (> 300 m) in the northeast, near Turnhout. Generally, this thickness decreases to the southwest, witnessing the gradual flooding of the London-Brabant Massif. Locally, e.g. between Pittem and Oudenaarde, on the crest of the massif, the Mesozoic is absent, and the Paleozoic is directly overlain by the Cenozoic.

The stratigraphy of the Upper Cretaceous is rather subtle (Felder et al. 1985). Rock types within the different formations tend to vary laterally and the same seems to apply to their appearance on our MCS data.

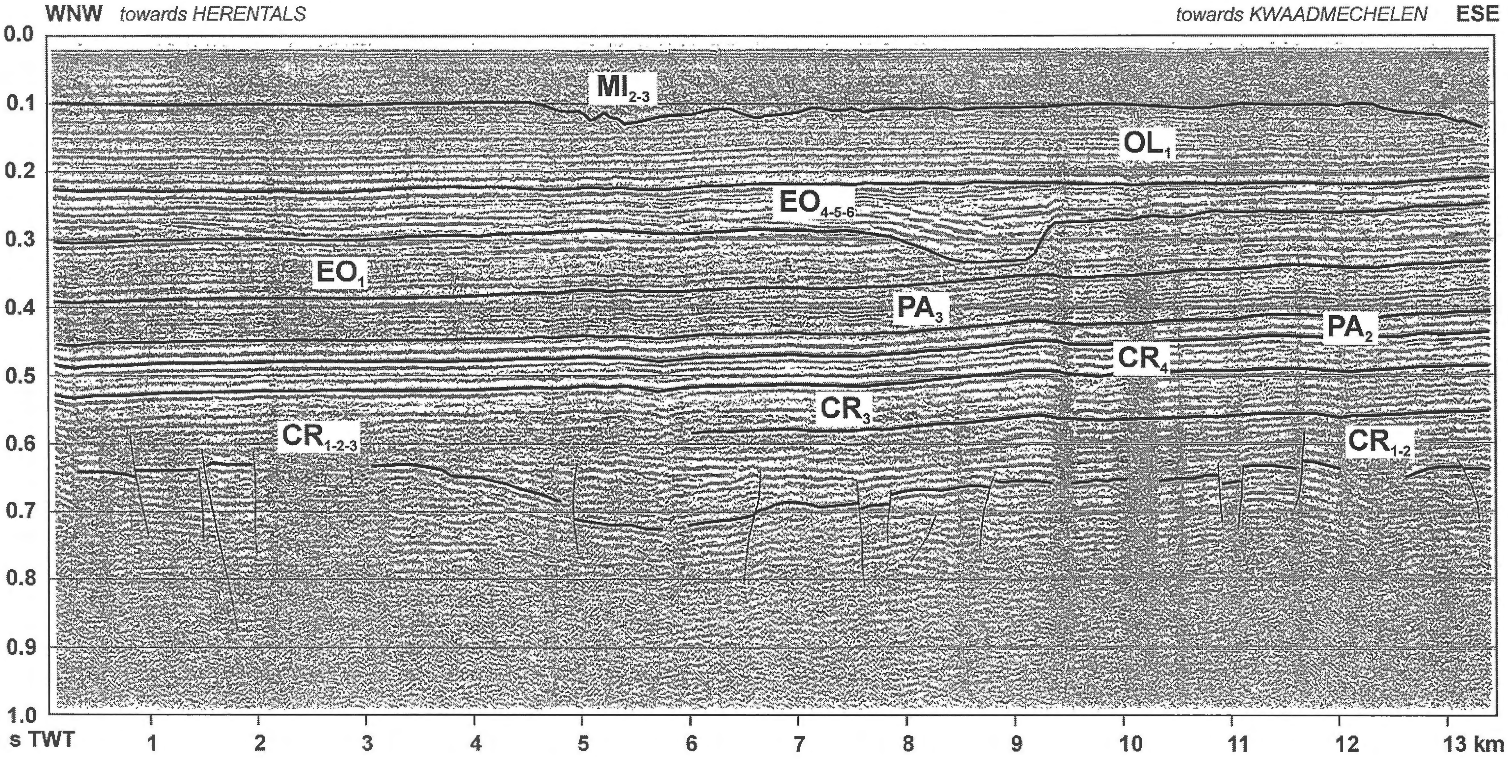

Figure 6. Part of an interpreted seismic profile along the Albert canal, between Herentals and Kwaadmechelen, showing i) the faulted Dinantian limestones at the top of the Paleozoic, below Unit CR_{1-2}, ii) the incised channel at the base of Unit EO_{4-5-6} (km 8–9.5), and iii) the incisions at the base of Unit MI_{2-3} (km 5.0–5.5 and 12.5–13.5). For location see Figure 3.

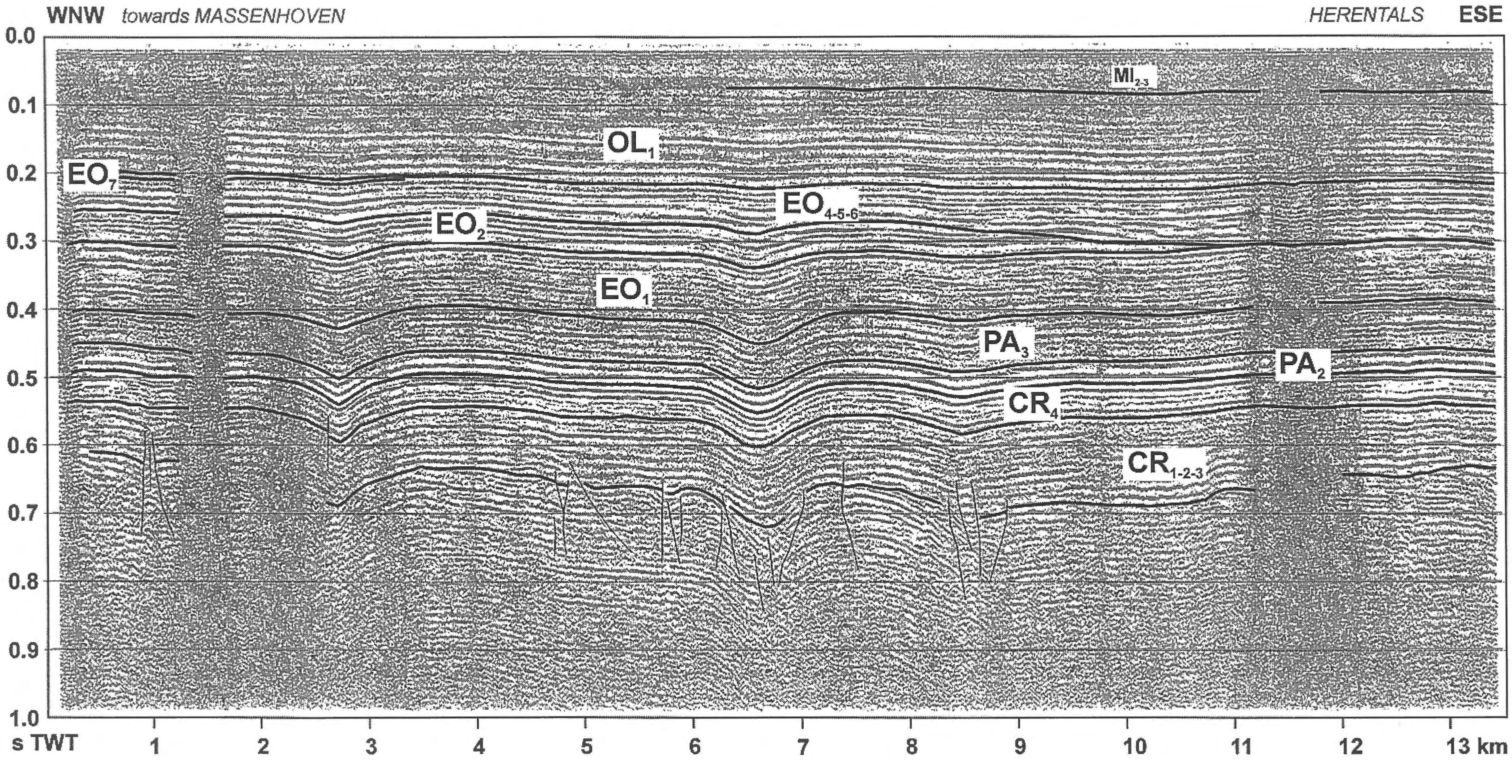

Figure 7. Part of an interpreted seismic profile along the Albert canal, between Massenhoven and Herentals, showing i) dissolution or karst structures within Dinantian limestones at the top of the Paleozoic, below Unit CR$_{1-2-3}$ (e.g. km 6.5–7.0 and km 8.5–9.0), and ii) truncation of Unit EO$_7$ by the base of Unit OL$_1$ (km 3.5). For location see Figure 3.

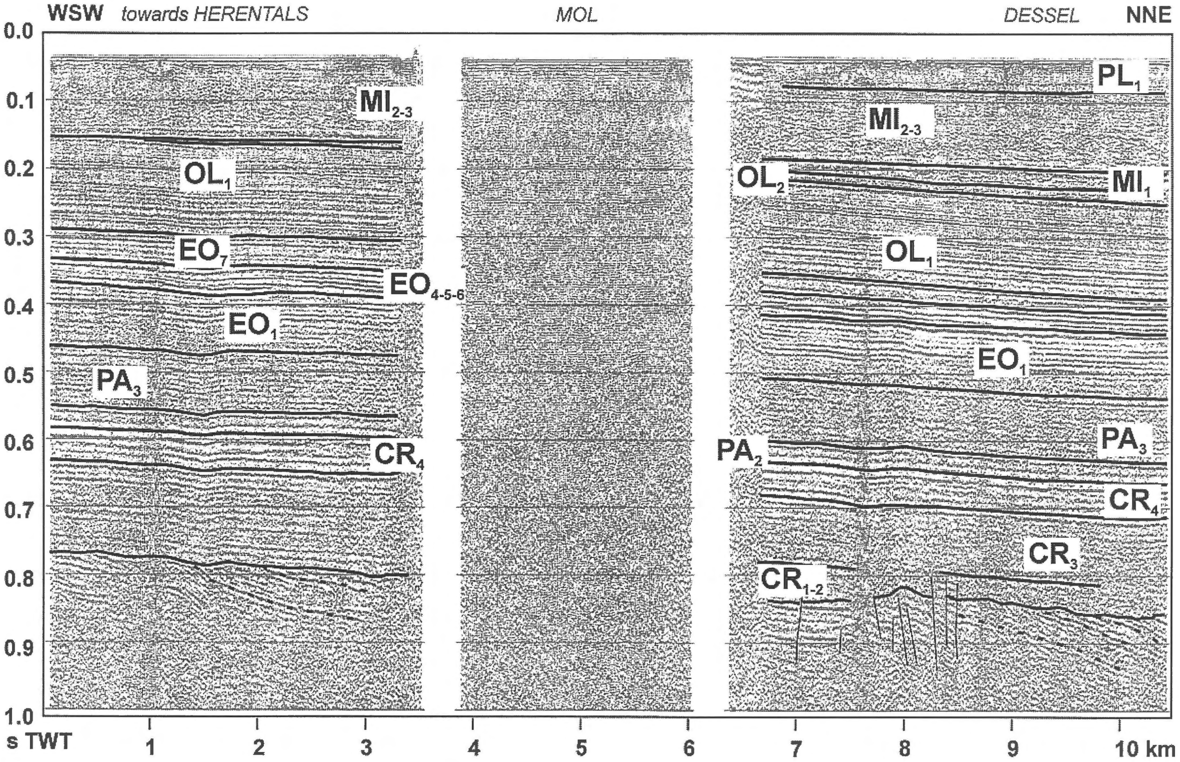

Figure 8. Part of an interpreted seismic profile along the Bocholt-Herentals canal, in the vicinity of Mol, showing i) the cuesta-like morphology at the top of the Paleozoic, below Unit CR_{1-2}, ii) the parallel, uniformly NE-ward dipping reflections underneath, which we attribute to Upper Carboniferous deposits, and iii) truncation of Unit EO_{4-5-6} by the base of Unit EO_7 (km 1.0–1.5). In the white sections no seismic data were recorded due to the presence of sluices. Section km 4–6 is characterised by complete blanking due to the presence of surficial gas. For location see Figure 3.

We have subdivided the Upper Cretaceous in northern Belgium into five seismic unit. Their seismic-stratigraphic characteristics are listed in Table 3. Due to lateral changes in seismic facies, this subdivision cannot, however, be maintained throughout the area. Figure 10 illustrates schematically the difficulties for seismic-stratigraphic correlation of these units.

Unit CR_0 only occurs in the westernmost part of northern Belgium, where seismic control is unfortunately rather poor and discontinuous. Based on borehole information, we correlate this unit with the Saint-Denis Formation (Fm) of Turonian age.

Elsewhere, the Paleozoic basement is overlain by *Unit CR_1*, which corresponds to the mainly sandy and clayey deposits of the Aachen Fm (Late Santonian). Locally, on top of the aforementioned paleorelief developed on Dinantian limestones, onlapping channel- and basin-fill facies can be observed at the base of this unit (Figure 6). This is in agreement with observations from the offshore of Belgium (De Batist 1989).

In most of the area, except in East- and West-Flanders, *Unit CR_2*, the Vaals Fm (Late Santonian), cannot be distinguished from the underlying Unit CR_1. Therefore, they are usually considered as one composite unit: Unit CR_{1-2}. In the Campine Basin, the top of this unit is marked by a clear seismic facies change and by erosional truncation (e.g. near Stokkem).

The overlying *Unit CR_3* corresponds to fine-grained white chalk of the Gulpen Fm (Late Campanian-Maastrichtian). Near Stokkem, it onlaps the erosion surface at the top of Unit CR_2 (Figure 11). Unit CR_2 is thickest (ca. 90 m, 90 ms) between Mol and Beringen and thins towards the east and west.

It is overlain in the whole of northern Belgium, except in the extreme west, by *Unit CR_4*, which corresponds to the Maastricht Fm (Maastrichtian), composed of relatively coarse calcarenite (central and eastern parts) or white chalk (western parts). The upper boundary of this unit is generally represented by a weak angular unconformity, except near Genk, where we interpret an irregular morphology and enhanced

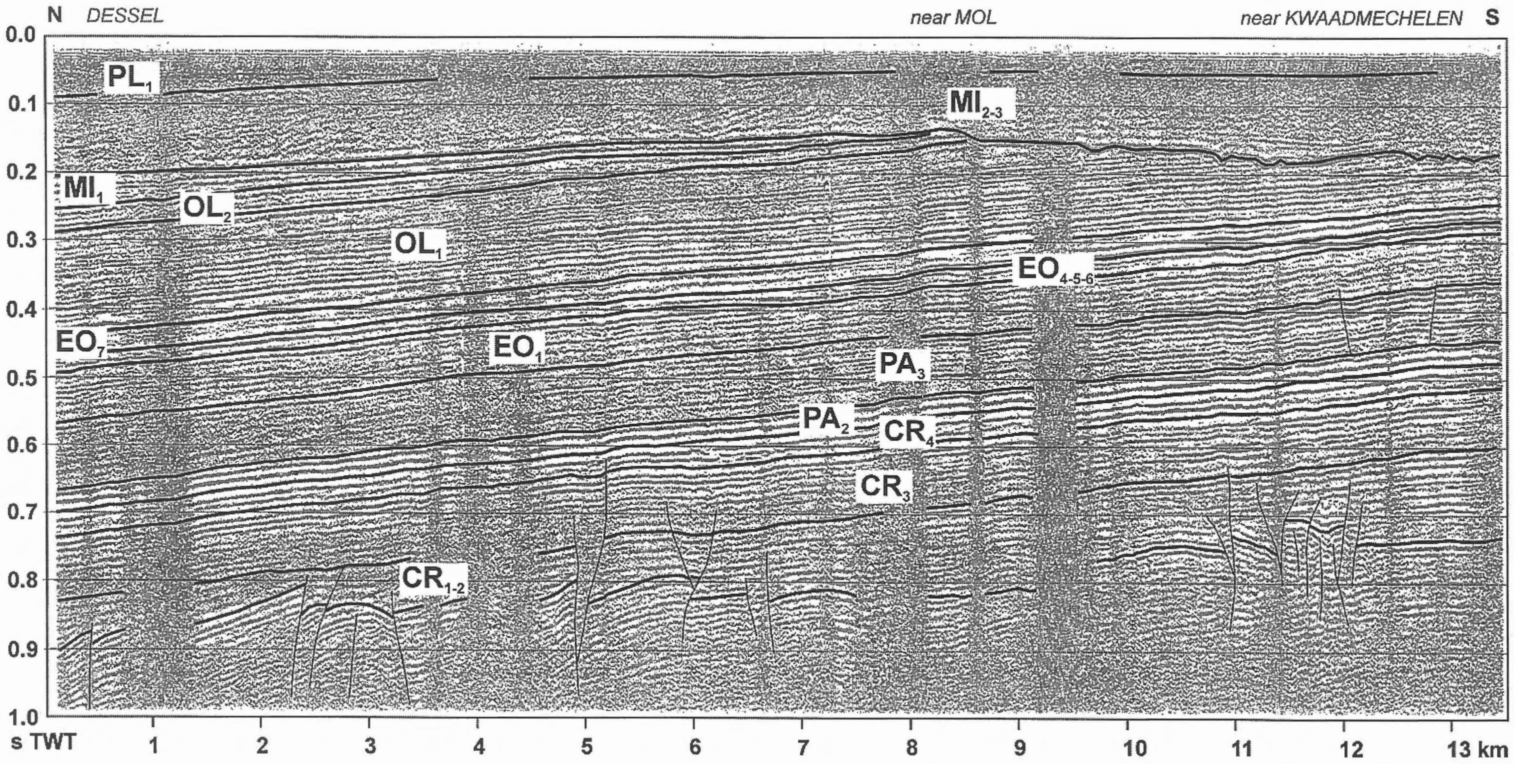

Figure 9. Interpreted seismic profile along the Lommel-Kwaadmechelen canal, between Dessel and Kwaadmechelen, showing i) faulted and tilted blocks in the Paleozoic, below Unit CR_{1-2}, ii) the truncation of Unit EO_{4-5-6} by the base of Unit EO_7 (km 7.5–8.5), iii) the truncation of unit EO_7 by the base of Unit OL_1 (km 11.5), and iv) the deep incision at the base of Unit MI_{2-3} (km 8.5–13.5). For location see Figure 3.

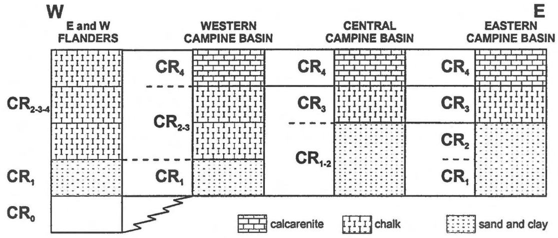

Figure 10. Schematic seismic-stratigraphic correlation for the Upper Cretaceous in northern Belgium, illustrating the lateral facies changes and the resulting difficulties for seismic-stratigraphic correlation.

amplitude as being caused by a subaerial (hardground?) erosion surface. The seismic facies of Unit CR$_4$, composed of a set of parallel, high-amplitude continuous reflections (silex horizons?) and comparable to that described by Demyttenaere (1988) for the Maastricht Fm, is very characteristic throughout the area (e.g. Figure 8).

The Cenozoic

The Late Cretaceous chalk is overlain by a series of predominantly siliciclastic, marine to marginal-marine Cenozoic deposits. The Paleogene onlaps the top of the Cretaceous in a western to southwestern direction. The Paleogene strata are exposed in numerous, classical outcrops in the western and south-central parts of northern Belgium, from where they generally dip less than 0.5% to the NNE. The overlying Neogene occurs mainly in the east and northeast. The total thickness of the Cenozoic in northern Belgium amounts to more than 700 m in the northeast, and to probably more than 1200 m in the Belgian part of the Roer Valley Graben (Marechal 1992).

The stratigraphy of the Cenozoic deposits has been studied in detail for over a century. Recently, the classical lithostratigraphy, summarised a few years ago by Marechal & Laga (1988), has been re-evaluated in a sequence-stratigraphic framework (Jacobs & De Batist 1996; Vandenberghe et al., in press).

Using the MCS data, we have subdivided the Cenozoic into 15 seismic units. Their seismic-stratigraphic characteristics are listed in Tables 4 (Paleogene) and 5 (Neogene and Quaternary). This seismic stratigraphy has been compared with that developed by De Batist & Henriet (1995) for the southern North Sea, offshore Belgium, and with that of Demyttenaere (1988) for the Campine Basin.

Paleogene

Unit PA$_1$ occurs only in the far southeast, between Beringen and Briegden. Although not unambiguously supported by borehole information, we correlate this unit with the combined Houthem Fm (calcarenite in lithological continuity with the underlying Maastricht Fm) and Opglabbeek Fm (siliciclastic, brackish-water and continental deposits), both Danian. They clearly onlap the Cretaceous in a western direction.

Unit PA$_2$, the Heers Fm (Early Thanetian), is present everywhere in the eastern part of the area; it overlies Unit PA$_1$ in the southeast and Unit CR$_4$ elsewhere. The seismic data do not allow to identify within this unit the Orp Sands below and the Gelinden Marls above, but a lateral seismic facies change within this unit, from a facies that resembles that of Unit PA$_1$ in the east to one that resembles that of Unit CR$_4$ in the west, may indicate the gradual thinning of the Orp Sands towards the west.

The overlying *Unit PA*$_3$, corresponding to the marine clays, silts and sands of the Hannut Fm (Thanetian), is present everywhere in northern Belgium (De Geyter 1981). In the east it overlies Unit PA$_2$, and in the west, in East- and West-Flanders, it is in direct contact with the Upper Cretaceous (Figure 5). Unit PA$_3$ gradually thickens towards the north, to about 100 m (ca. 100 ms) in the vicinity of Dessel and Lommel. Its seismic facies varies laterally, possibly indicating lateral variations in the shallow-marine depositions.

Unit PA$_4$ corresponds to the Late Thanetian Tienen Fm: sands, clays and marls with lignite and wood fragments, deposited in a fluvial to lagoonal environment (De Geyter 1981). The unit is generally relatively thin (ca. 5 m; 5 ms), almost at the limit of the resolution of our MCS profiles. Locally, however, the base of this unit is deeply incised into the underlying Unit PA$_3$. These incisions, e.g. near Leopoldsburg (Figure 12) and near Zeebrugge (Figure 5), can reach depths of 10 to 15 m (ca. 15 ms) and are filled with a typical onlapping facies. Similar localised incisions at the base of the Tienen Fm have been reported by Demyttenaere (1988), and by De Batist & Henriet (1995) for the southernmost North Sea.

The Hannut and Tienen Fms are overlain by the Early Ypresian Kortrijk Fm, which is composed of clayey and silty deposits in the west and of clays and sands in the east (see e.g. Steurbaut & Nolf 1986). Vandenberghe et al. (in press) distinguish several depositional sequences within the Kortrijk Fm, but this is, however, not at all reflected in our seismic data, in

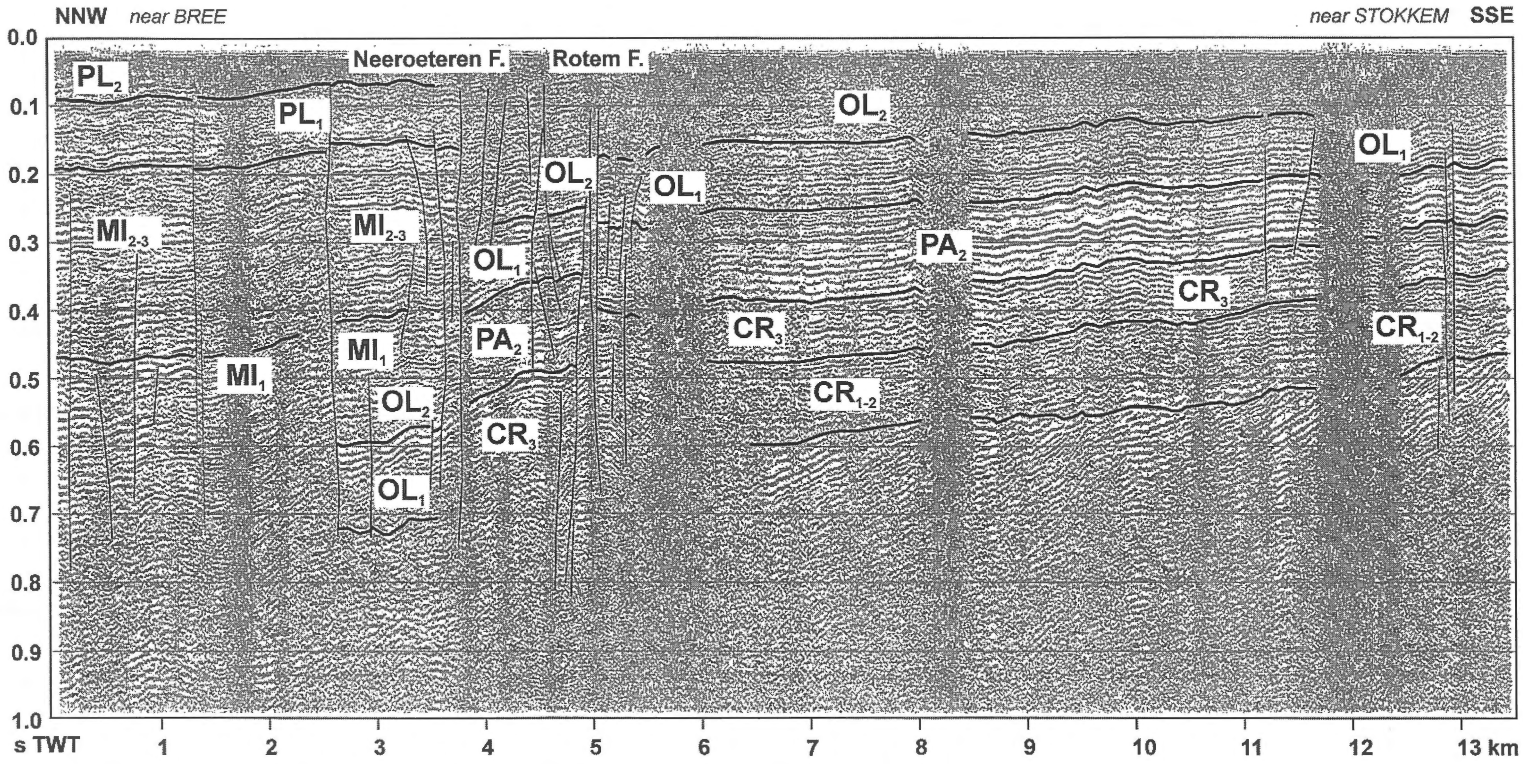

Figure 11. Part of an interpreted seismic profile along the Bocholt-Herentals canal, between Bree and Stokkem, showing i) onlap of Unit CR$_3$ on the top of Unit CR$_{1-2}$ (km 11.0–11.5), ii) the Neeroeteren and Rotem Faults at the margin of the Roer Valley Graben, and iii) the complex stratigraphy and thickness variations associated with these faults. For location see Figures 3 and 14.

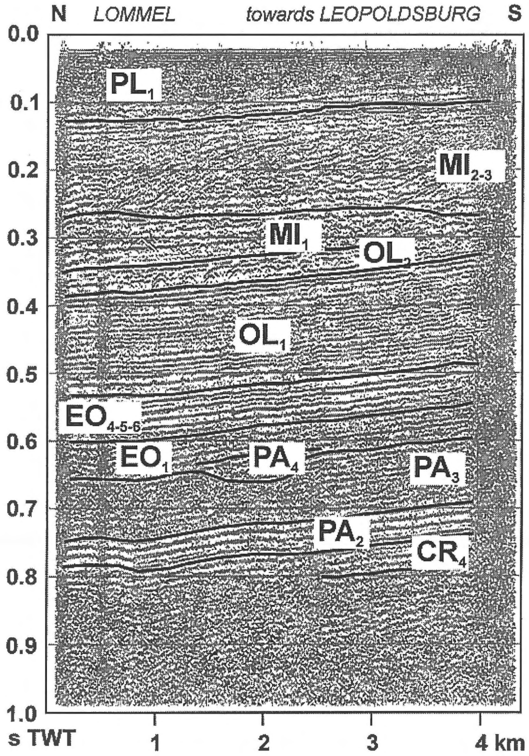

Figure 12. Part of an interpreted seismic profile along the Beverlo canal, in the vicinity of Lommel, showing i) the valley incisions at the base of Unit PA$_4$, and ii) the prograding facies of Unit MI$_{2-3}$. For location see Figure 3.

which the entire Kortrijk Fm, together with the silty Kortemark Member (Mbr) of the overlying Tielt Fm, forms one single seismic-stratigraphic unit: *Unit EO$_1$*. This is in agreement with observations by De Batist & Henriet (1995) in the North Sea, and by Demyttenaere (1988) in the Campine Basin. The total thickness of Unit EO$_1$ reaches locally 120 to 130 m (ca. 120–150 ms). In the west, e.g. near Lissewege, it can be subdivided into three seismic facies units:

- a lower facies unit (25 m thick) composed of weak, parallel and continuous reflections,
- a middle reflection-free facies unit (65 m thick),
- an upper facies unit (40 m thick) with disturbed reflection patterns and an internal tilted-fault-block geometry.

Such tilted fault blocks within the Kortrijk Fm are also observed in clay pits throughout West-Flanders (Henriet et al. 1991) and on seismic profiles in the southern North Sea (Henriet et al. 1988). They are generally attributed to post-depositional, intraformational, compaction-related processes (e.g. Henriet et al. 1988, 1991; Cartwright 1994).

Unit EO$_1$ is overlain in the western and central parts of the country by *Unit EO$_2$*, which corresponds to the sandy upper part of the Tielt Fm and the clayey and sandy Gent Fm, which are both Ypresian (Steurbaut & Nolf 1986). Unit EO$_2$ pinches out due to erosional truncation near Herentals. On our MCS data it is not possible to subdivide the unit. Only locally, near Zeebrugge, an internal reflector occurs that appears to cut down into the underlying strata (Figure 5). This reflector may represent the base of the Vlierzele Sands Mbr (Gent Fm), the erosional character of which is well-known from boreholes throughout East- and West-Flanders (Jacobs & De Batist 1996) and from seismic studies on the southern North Sea, e.g. the deeply incised, infilled channel off Ostend reported by De Batist & Henriet (1995).

Unit EO$_3$, the predominantly sandy Aalter Fm (Lutetian), occurs only in the northwest. Two discontinuous, sub-parallel, very high-amplitude reflectors in the upper part of the unit, only observed near Zeebrugge (Figure 5), correlate with the calcareous sandstone beds that occur in the top section of the Aalter Fm in this area (Henriet et al. 1982; Depret 1983; De Batist & Henriet 1995; Jacobs & De Batist 1996).

Unit EO$_{4-5-6}$ occurs only in the centre and east, where it is present mainly as the infill of a broad incised channel (Figures 6, 7). It consists of the sandy Brussel (= Brussels) and Lede Fms, which are both of Lutetian age. The seismic facies of this unit is that of a complex, eastward-prograding fill of a basin or incised channel. The unit can be subdivided into three subunits prograding onto each other from west to east: EO$_4$ as the lower litho-facies unit of the Brussel Fm (Houthuys 1990), EO$_5$ as the upper lithofacies unit of the same formation (Houthuys 1990), and EO$_6$ as the Lede Fm. This observation, which is, however, not entirely in agreement with all borehole data, places the Lede Fm into the same Lutetian depositional sequence as the Brussel Fm. Vandenberghe et al. (in press) tentatively postulate that the erosion surface at the base of Unit EO$_{4-5-6}$ may be correlated with the one at the base of the Vlierzele Mbr in Unit EO$_2$ further to the west. This would imply that not only the Brussel and Lede Fms (EO$_{4-5-6}$), but also the Vlierzele Mbr and the Aalter Fm (Unit EO$_3$) would constitute together the total infilling of a regional erosion surface during a single long-term transgression, directed from west to east. An additional argument in favour of this hypothesis is the striking similarity between the eastward prograding channel-fill facies of Unit EO$_{4-5-6}$ and the equally eastward-prograding channel-fill facies of the

Vlierzele Sands in the southern North Sea (De Batist & Henriet 1995). Unfortunately, our MCS data do not allow to resolve the complicated stratigraphic relationships between these deposits, due to insufficient coverage in key areas.

The stratigraphic complex represented by Units EO_3 and EO_{4-5-6} is overlain by *Unit* EO_7, the Maldegem Fm, which is composed of a characteristic alternation of clayey and sandy deposits of Late Lutetian to Bartonian age (Jacobs 1978), and which occurs only in the north and northwest. Its lower boundary is a distinct marker reflector that locally, e.g. near Mol, truncates underlying strata (Figures 8, 9). The thickness of Unit EO_7 is quite variable; it is generally thicker in the west, pinches out east of Massenhoven and reappears near Mol to disappear again further to the east.

Unit OL_1, corresponds to the Tongeren and Rupel Groups: i.e. the Zelzate and Boom Fms in the west and centre, and the Sint-Huibrechts-Hern, Borgloon, Bilzen, Boom and Eigenbilzen Fms in the east. These formations are all Priabonian to Rupelian and consist mainly of clayey and sandy deposits (Vandenberghe 1978; Steurbaut 1992). The lower boundary of Unit OL_1 is a pronounced erosion surface that truncates from west (near Antwerp) to east (near Briegden) all underlying units, and this down to the base of the Tertiary. Examples of truncations of Units EO_{4-5-6} and EO_7 can be seen on Figures 7, 9 and 13. The resulting angular unconformity, also observed by Demyttenaere (1988), is a prominent marker horizon. Vandenberghe et al. (in press) distinguish several depositional sequences within the Tongeren and Rupel Groups. This is, however, not reflected in our seismic data. Only a weak, but relatively continuous internal reflector at about 20 m (ca. 25 ms) above the base of Unit OL_1 may be interpreted as the boundary between the sandy Zelzate Fm and the clayey Boom Fm. Detailed high-resolution reflection seismic studies on the Scheldt river near Antwerp enabled Henriet & Heldens (1982) and Henriet et al. (1986) to identify within the Boom Clay the septaria-bearing (concretions) layers studied by Vandenberghe (1978), and even to discover some new ones.

In the north and northeast, *Unit* OL_2 represents the Voort Fm, the last Paleogene unit. The maximum observed thickness is about 75 m (ca. 85 ms). The lower boundary of this unit is a well-developed erosion surface, locally showing deep incisions, such as between Lommel and Bocholt (Figure 13). De Batist (1989) reported a comparable incised morphology at the top of the Boom Fm in the southern North Sea. These incisions are attributed to the major eustatic sea-level drop (Haq et al. 1987) of the Late Oligocene (Chattian).

Neogene and Quaternary

Unit MI_1 only in the north of the Campine Basin and represents the sandy Berchem (mostly to the west) and Bolderberg (mostly to the east) Fms. Both have a Late Aquitanian to Burdigalian age. Unit MI_1 locally truncates the underlying strata, such as near Neerpelt. The unit is thickest in the far northeast of the area, e.g. > 180 m (ca. 200 ms) near Bocholt, and thins toward the southwest. Vandenberghe et al. (in press) distinguish several sequences within these deposits, but this is not reflected in our seismic data. The seismic facies of Unit MI_1 is composed of distinct, parallel and continuous internal reflections. Such a seismic facies is not really in agreement with the continental to fluvial depositional environment that is usually attributed to these deposits (Vandenberghe et al., in press), as continental to fluvial deposits generally tend to show a highly discontinuous and variable seismic facies (Sangree & Widmier 1977).

Unit MI_{2-3}, the sandy Diest Fm of Tortonian to Messinian age, is present in most of northeastern Belgium as the spectacular prograding fill of a broad and deep valley (Figures 6, 9, 12, 13). This valley, with a general SW-NE direction, is incised into the underlying units MI_1, OL_2 and OL_1 and in places even down into EO_{4-5-6}. The unit's lower boundary represents in most places a distinct erosional unconformity, often emphasised by the presence of numerous diffraction hyperbolae (e.g. between Lommel and Bocholt; Figure 13), and is a prominent marker horizon. This is in contradiction with the findings of Demyttenaere (1988) who reported difficulties to identify this reflector. The erosional character of this reflector decreases towards the Roer Valley Graben, suggesting that during Late Miocene times this area was tectonically subsiding. This would also explain why Unit MI_{2-3} reaches thicknesses of up to 350 m in this area (near Bree), while its maximum thickness outside the graben amounts to only 180 m in the deepest incisions (near Kwaadmechelen). Our MCS data enable us to subdivide this unit into two seismic facies units that are separated by an unconformable boundary: MI_2 (Dessel Sands Mbr) and MI_3 (Diest Sands Mbr). Unit MI_2 is characterised by an irregular, chaotic and complex basin-fill or incised-valley-fill facies (Figure 13). Unit MI_3 forms a spectacular sedimentary wedge, consisting of several prograding and aggrading sub-

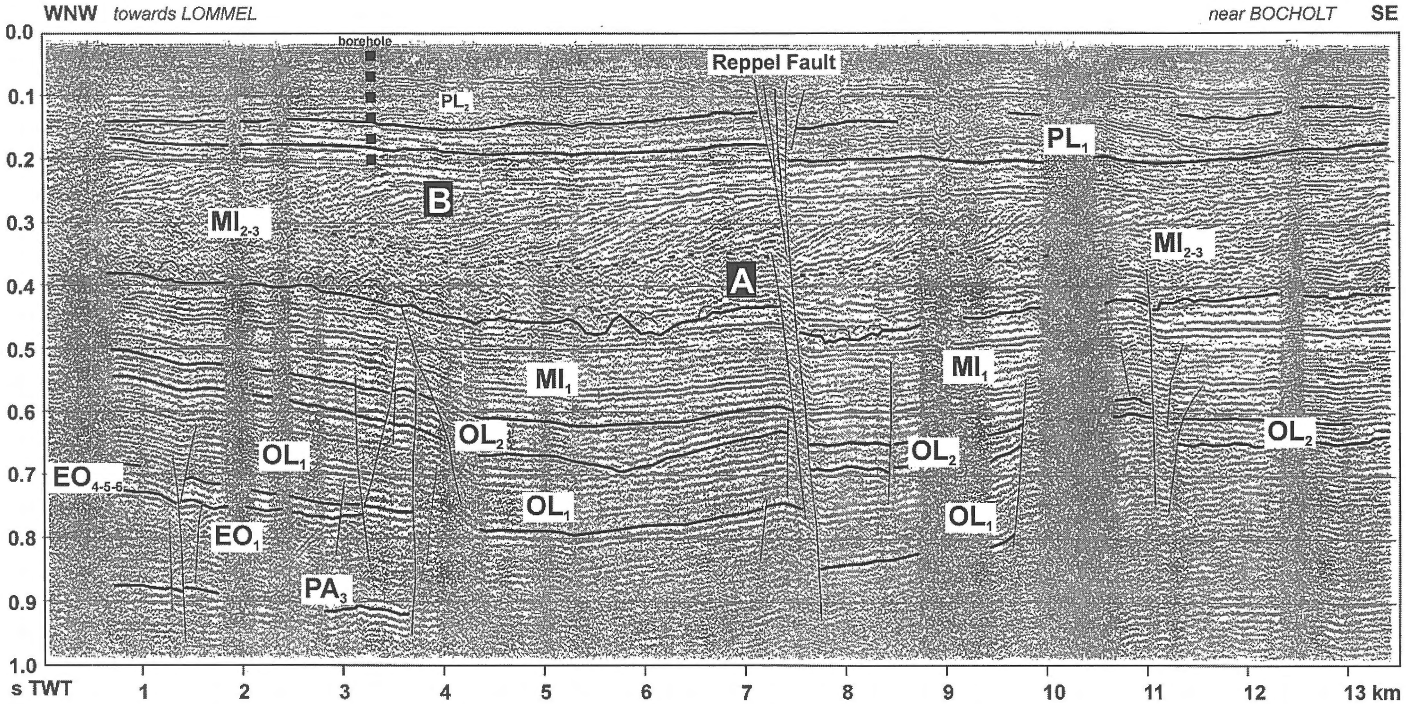

Figure 13. Part of an interpreted seismic profile along the Bocholt-Herentals canal, between Lommel and Bocholt, showing i) the truncation of Unit EO_{4-5-6} by the base of Unit OL_1 (km 3.5), ii) the erosional unconformity at the base of Unit OL_2 (km 6.0), iii) the spectacular incision marked by diffraction hyperbolae at the base of Unit MI_{2-3}, iv) the prograding facies of Unit MI_{2-3}, and v) the Reppel Fault. Segments with acoustic blanking occur at e.g. km 8.7–9.5 and 10.0–10.5. A = Lower, and B = upper seismic facies of Unit MI_{2-3} (see text). They are separated by a downlap unconformity (dashed line). For location see Figures 3 and 14.

units, each composed of large northwestward-dipping clinoforms in a distinct offlap-configuration (Figure 13).

Unit MI_{2-3} is overlain in the north by *Unit PL_1*, that corresponds to the sandy Kasterlee (in the west) and Kattendijk (towards the east) Fms. They are both Early Pliocene. The lower boundary of this unit is a poorly defined, undulating erosional unconformity, that truncates the topsets of Unit MI_{2-3}, such as observed between Lommel and Beverlo (Figure 13). Unit PL_1 reaches a maximum thickness of 150 m (ca. 150 ms), near Bocholt.

The youngest identified seismic-stratigraphic unit is *Unit PL_2*. It corresponds to the continental sands of the Mol Fm, the Poederlee Fm and the Neeroeteren Fm, of which the chronostratigraphic position is at present still unclear. As a whole, this unit would be Late Pliocene to Early Pleistocene. It occurs only in the northernmost part of the study area. Its lower boundary is an undulating and laterally discontinuous reflector, the unconformable nature of which is difficult to establish. In many places, e.g. near Lommel, a distinct reflector of very high amplitude and strong continuity can be observed within Unit PL_2. It occurs at an almost constant depth of 80 m (90–100 ms) below the surface (Figure 13), except where it is displaced by the faults of the Roer Valley Graben. The borehole information does not provide any conclusive evidence as to what this reflector could represent (lignite horizons, pebble layers, . . .).

Unconformities within the sedimentary cover

A number of the above-mentioned unconformities are of regional importance, viz. the bases of the Cretaceous, the Tertiary, Unit PA_4 (Tienen Fm), Unit EO_{4-5-6} (Brussel Fm), Unit OL_1 (Tongeren and Rupel Groups), Unit OL_2 (Voort Fm) and Unit MI_{2-3} (Diest Fm).

These unconformities can be attributed to various causes, such as discussed by Vandenberghe et al. (in press) and, to some extent, by Jacobs & De Batist (1996). Some reflect clearly the major eustatic sea-level trends (Haq et al. 1987): i.e. the progressive flooding of vast continental areas during the Late Cretaceous 2nd-order highstand (onlap on the Paleozoic of Units CR_0 and CR_1 at the base of the Cretaceous), the incision of deep valleys in response to the major 3rd-order lowstands of the Late Oligocene (valley incision at the base of Unit OL_2 or Voort Fm) and late Miocene (Valley incision at the base of Unit MI_{2-3} or Diest Fm). Others, which appear not to have an obvious link to the eustatic sea-level changes, have presumably a tectonic signature: i.e. the angular unconformity at the base of Unit OL_1 (Tongeren and Rupel Groups). Still others result probably from a combined effect of eustasy and tectonics: i.e. the incision at the base of Unit EO_{4-5-6} (Brussel Fm) and its still enigmatic correlation with the incisions locally observed within Unit EO_2 (the base of the Vlierzele Sands Mbr).

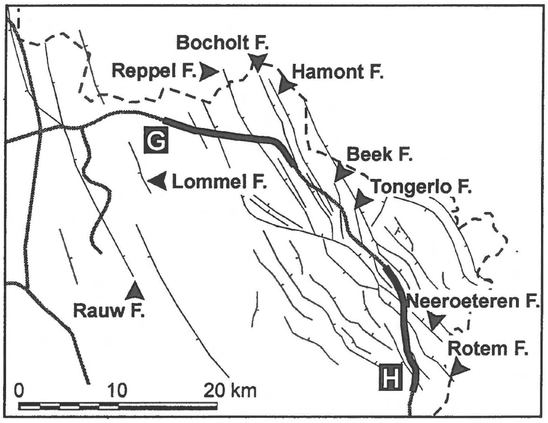

Figure 14. Map showing the location of the main faults of the Roer Valley Graben within northeastern Belgium (after Demyttenaere 1988) and their intersections with the seismic profiles of Figures 11 (G) and 13 (H).

Structural deformations

Faults in the Paleozoic basement

Despite the fact that northern Belgium is generally regarded as tectonically stable and quiescent, it is transsected by several faults and fault zones. Most of these are of Paleozoic age and have been virtually inactive since that time, in which case they are covered by undisturbed Mesozoic and Cenozoic strata. Examples of such faults are observed on our seismic records in Doel, in Ingelmunster and in many places in the Campine Basin.

Faults of the Roer Valley Graben

The eastern part of the Campine Basin is transsected by a number of younger faults that are part of the Roer Valley Graben (Figure 14). This graben is tectonically still active as illustrated by the Roermond earthquake of April 13, 1992 (Camelbeeck & Meghraoui 1996). Most faults appear as vertical or quasi-vertical on our seismic sections, and it is difficult to determine their dip. Also, they usually do not appear as single faults, but as groups of closely spaced faults that distribute the total displacement among them (Figures 11, 13). For the sake of simplicity, we will however treat them here as single features. For the names of the faults, for their detailed description and mapping and for an analysis of their tectonic history, we refer to the work of Demyttenaere & Laga (1988) and Rossa (1986). Because of the better resolution of our MCS data, our observations can help to assess in more detail the deformation history of some of these faults.

The throw of the Rauw Fault gradually increases with depth; reference horizons in the Cretaceous are offset by about 50 m, in the Paleogene by 40 to 30 m, in the lower Neogene by 20 to 10 m, and the basal unconformity of Unit PL_1 is affected by a flexure of merely 5 m. This suggests that the fault has been more or less continuously active throughout the Late Cretaceous and Tertiary, up until the beginning of the Pliocene.

Near Lommel, we distinguish a fault that was not reported by Demyttenaere & Laga (1988). We interpret this fault as the northern prolongation of the Lommel Fault. The fault offsets the basal unconformities of Units MI_{2-3}, MI_1, OL_2, OL_1, EO_{4-5-6}, EO_1 and even PA_2. The observed throw amounts to 10 m for each of these reference levels. This puts the last pulse of activity in or after the Late Miocene.

The Reppel Fault can be distinguished clearly as a single fault on the MCS data near Neerpelt. The fault splays towards the surface (Figure 13). The basal unconformities of several units are all offset with apparent throws that amount to 20 m (PL_2), 30 m (PL_1), 20 m (MI_{2-3}), 75 m (MI_1), 75 m (OL_2) and 100 m (OL_1). This suggests that the main tectonic activity took place during the Oligocene and before the incision at the base of Unit MI_{2-3} (Diest Fm), i.e. before the Late Miocene, but also that there has been a fairly recent Quaternary phase of deformation.

The Bocholt Fault cannot be exactly located on our data due to acoustic blanking. Its presence can, however, be inferred from the offset of the basal unconformities of several units at either side of the zone of blanking. The apparent throws are 30 m (PL_2), 150 m (PL_1), 230 m (MI_{2-3}) and 175 m (MI_1), which suggests that the main tectonic activity took place during the Late Miocene and Early Pliocene, and that there was a phase of tectonic inversion in the Early or Middle Miocene.

The Beek Fault is not visible either for the same reason. The apparent continuity of the basal unconformity of Unit PL_2 at either side of this supposed fault suggests that it has not been active during or after the Late Pliocene.

The Tongerlo Fault offsets the basal unconformities of Units MI_{2-3} to OL_2 with a throw of about 20 m. The displacement gradually dies out towards the base of Unit PL_1. This puts the last pulse of activity in the Late Miocene.

By far the most distinct structural feature on our seismic profiles is the heavily faulted zone between Stokkem and Bree (Figure 11). According to Demyttenaere & Laga (1988) and Rossa (1986), this disturbed zone should be the expression of the Rotem and Neeroeteren Faults (Figure 14), which form the northward prolongations of the Heerlerheide and Geleen Faults in the Netherlands respectively. Both faults appear as complex fault zones (800 and 500 m wide, respectively) in which a number of sub-faults make up for the total throws (Figure 11). According to Rossa (1986), these throws amount to respectively ca. 100–200 m and ca. 400 m for the base of the Tertiary.

Summary

The observations and results of our high-resolution reflection seismic investigations in northern Belgium can be summarised as follows:

- Nature of the Paleozoic basement: The seismic characteristics, i.e. reflection amplitude, reflector continuity and morphology, etc., provide information on the top of the Paleozoic substratum. Different rock types appear to have distinctly different reflection responses:
  1. The Cambrian to Silurian, pre-Caledonian intrusive or metasedimentary rocks of the London-Brabant Massif: a very high-amplitude reflection, often associated with clusters of diffraction hyperbolae;
  2. Upper Devonian sandstones, a high-amplitude, regular and laterally highly continuous reflection;
  3. Dinantian limestones, a low-amplitude reflection corresponding to an irregular erosion surface;
  4. Upper Carboniferous shales and sandstones: a series of parallel, NE-ward dipping reflections below an erosion surface with a cuesta-like morphology.
- Seismic stratigraphy of the sedimentary cover: The Mesozoic and Cenozoic succession in northern Belgium can be subdivided into 20 seismic units,

bound by unconformities or their correlative conformities: 5 in the Cretaceous and 15 in the Cenozoic. Based on borehole information, these seismic units can be correlated with lithostratigraphically defined units as is discussed above.

- Unconformities within the sedimentary cover: A number of the unit-bounding unconformities are of regional importance. The unconformities at the bases of Units CR_0, CR_1, OL_2 and MI_{2-3} are attributed to eustatic sea-level changes, e.g. the Late Oligocene and Late Miocene lowstands causing incision of deep valleys. The angular unconformity at the base of Unit OL_1 (Tongeren and Rupel Groups) has presumably a tectonic signature. The unconformity and incision at the base of Unit EO_{4-5-6} (Brussel Fm) probably results from a combined effect of eustasy and tectonics.
- Tectonic activity: The Mesozoic and Cenozoic strata in the east of northern Belgium are affected by faults that belong to the Roer Valley Graben. Different stratigraphic levels in the Oligocene to Quaternary succession are offset by sometimes considerable vertical displacements (e.g. ≥ 230 m for the base of Unit MI_{2-3} along the Bocholt Fault). The tectonic activity has varied considerably through time, with distinct phases of normal and sometimes even reverse fault displacement, but also from fault to fault so that no regional tectonic scenario can be presented. The main tectonic activity took place during the Miocene, and most faults seem to have a 10 to 30-m displacement since the Late Pliocene. This is in agreement with the recent findings of Camelbeeck & Meghraoui (1996).

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