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Plio-Pleistocene fault pattern of the Feldbiss fault system (southern border of the Roer Valley Graben, Belgium) based on high resolution reflection seismic data

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Abstract

A high-resolution reflection seismic survey was carried out in 1999 over the Feldbiss fault system, the southern border of the Roer Valley graben, in Belgium. Six profile-lines with total length of 13982 m provided information on the 40-600 m depth range, covering Lower Pleistocene to Miocene strata with special emphasis on the Plio-Pleistocene Kieseloolite formation. Data quality depends on near-surface conditions and on degree of deformation in some fault zones, with better results for seismic detonator sources compared to vibroseis sources. The new data confirm the segmented character of the fault system with occurrence of fault bends, relay ramps and branching of overlapping fault sequences, testifying of the strong tectonic activity during the lower Pleistocene. Antiform structures along the Bichterweerd scarp, relaying the Feldbiss to the Geleen fault in the Meuse valley, are presented as a model for the Tertiary evolution of the Bree Uplift.

Keywords: Belgium, Campine basin, faults, Roer Valley graben, seismic prospecting, Tertiary

Introduction

The present structure of northeastern Belgium is connected to the formation of the Mid-Jurassic (Kimmerian) incipient North Sea rift. The Roer Valley Graben originated as part of this rift and was reactivated during the Late Tertiary to Quaternary (Geluk et al., 1994). The adjacent structural units (Brabant Massif / Campine basin) were uplifted during the Kimmerian deformation and are differenciated by the net result of the subsequent Jurassic/Cretaceous erosion (Legrand, 1961; Patijn, 1963).

The Campine basin forms the graben shoulder and is characterised by a gradual thickening of the Mesozoic-Tertiary cover towards the Roer Valley Graben, enhanced by a series of downstepping faults with similar histories but less importance than the graben boundary faults (Table 1). The Feldbiss Fault system defines the southwestern boundary of the Roer Valley Graben (traditionally known as Roermond Graben in Belgium) – (Fig. 1).

This boundary is characterised by a series of parallel faults (Paulissen, 1997). Faults may link and split at different places during successive tectonic phases. Faults can be expressed as morphological scarps which are proven to be active faults by the work of the Royal Observatory of Belgium on the Bree scarp (Camelbeeck & Meghraoui, 1998). The connection between the faults recognised on Dutch and Belgian territories is not always clear, which is due either to confusion of fault names or to changing directions and offsets along strike (Tab. 2-3). The Heerlerheide, Geleen, Feldbiss faults known in Dutch South Limburg, have been unfortunately renamed Rotem, Neeroeteren, Elen faults in Belgium (Demyttenaere & Laga, 1988), after the hypothetical faults inferred from borehole stratigraphy before any geophysical data were known (Stainier, 1911). It is suggested here to

Table 1. Stratigraphic overview of post-variscan deposits in Campine basin (= graben shoulder) and Roer Valley graben, NE. Belgium (average thickness in meters of fully preserved units)

Chronostratigraphic unit	Graben shoulder	Graben
younger Quaternary	10	30
Plio-Pleistocene	20	240
Mio-Pliocene	150	550
Oligocene	110	330
Eocene	20	0 (not deposited)
Paleocene	150	145
Maastrichtian	125	30
Campanian-Santonian	120	0 (not deposited)
Lias	0 (eroded)	450 (minimum)
Keuper	0 (eroded)	120
Muschelkalk	0 (eroded)	80
Buntsandstein	550	650
Zechstein	30	30

abandon this scheme. Due to changing fault splits and junctions through time, no simple scheme can be proposed, beyond the general denomination of Feldbiss fault system.

The rate of subsidence along the graben boundary faults can be measured by the completeness and cumulative thickness of the stratigraphic record at the termination of each major phase of deformation. Seismic exploration for coal has indicated that maximal throw was located at the external Heerlerheide fault during the Kimmerian deformation phase, and at the Feldbiss fault during the Quaternary and Upper Tertiary. Total downthrow of the top Carboniferous and the Upper Tertiary amounts to 800 m and to 400 m, respectively. Transfer of movement between these faults has not been elucidated, however (Rossa, 1986; Langenaeker, 1998).

The main objective of the present study is the connection of the active Quaternary faults to deeper faults, recognised on previous seismic surveys containing information from pre-Pliocene strata. A second objective was the exact nature of faults and shallow deformation structures below the Meuse river gravels. A preliminary version of this study was presented at the HAN2000 Paleosis conference (Dusar et al., 2001).

Highlights and pitfalls in the reconnaissance of the fault system

The sudden changes in landscape and geological con-

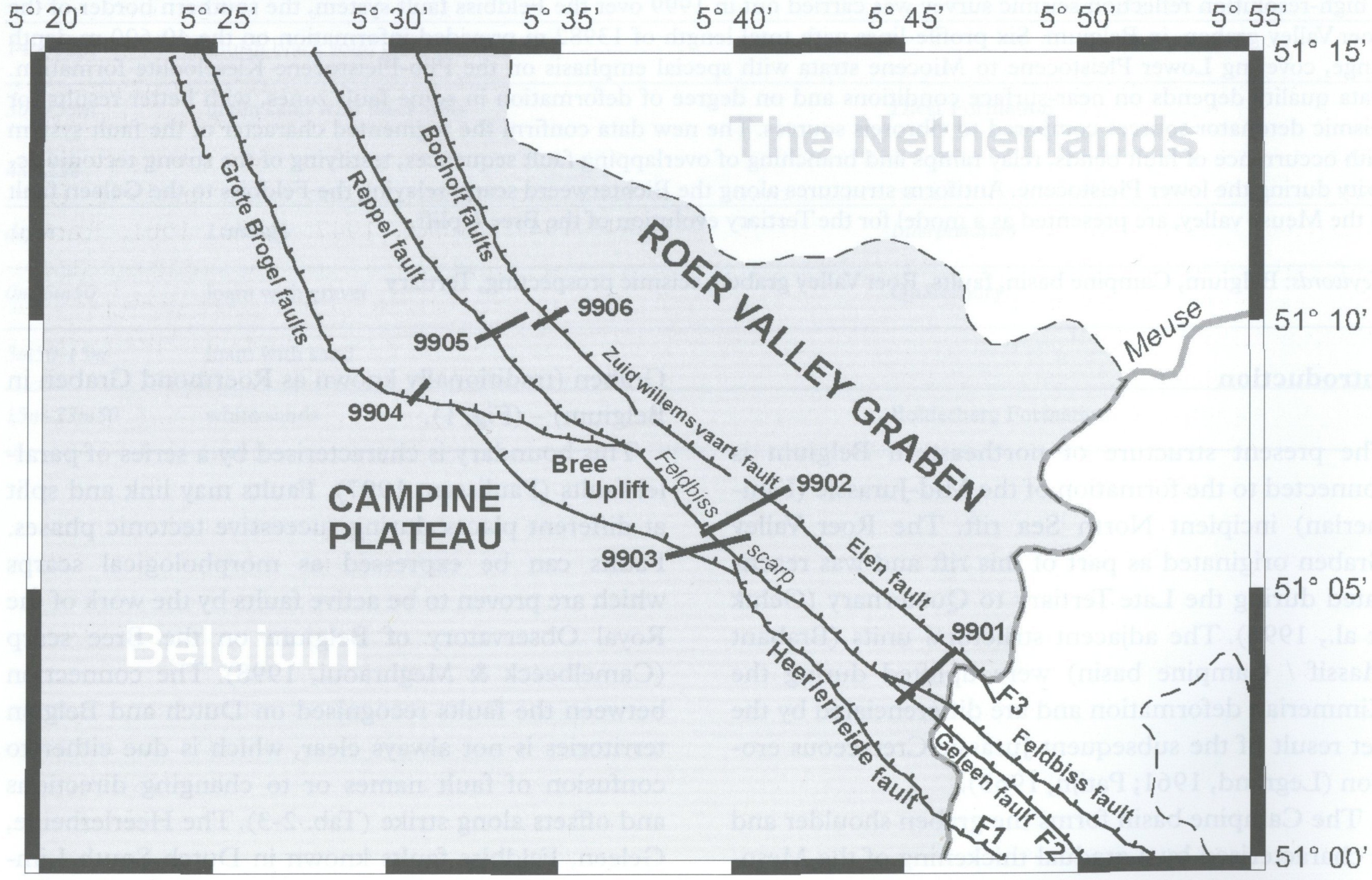

Fig. 1. Location map of the 1999 high resolution seismic survey with synthetic overview of the Feldbiss fault system at the southern border of the Roer Valley Graben, active during Plio-Pleistocene times (by courtesy of K. Vanneste). Most notable changes with respect to previous fault maps reflecting other time intervals are: the relay between the Feldbiss and Geleen (F2) faults at the Bichterweerd scarp (Meuse river crossing, line 9901), and the equivalence of the Bocholt - F3 (Elen) and the Reppel - F2 (Geleen-Feldbiss) fault segments respectively. The southern border of the Bree Uplift shows only moderate fault activity during the Tertiary-Quaternary.

Table 2. Approximate fault correspondence in the Meuse valley for different studies and connection with South Limburg faults (Geluk et al., 1994). Bichterweerd is a transfer fault between Feldbiss, east of the Meuse, and Geleen, west of the Meuse. Elen probably is a split of Feldbiss, starting already east of the Meuse. Fault F3 (Beerten et al., 1998) starts at the same place as the Bichterweerd but continues as an independent fault in NW direction, parallel to faults F1 and F2, similar to the Elen fault as defined by Demyttenaere & Laga (1988). Elen in Langenaeker (1998) starts at the same place as Elen in this work, but bends more to the north.

Langenaeker (1998)	Demyttenaere & Laga (1988)	this work	Beerten et al. (1998)	Geluk et al. (1994)
Elen		Elen		
	Elen	Bichterweerd	F3	Feldbiss
Feldbiss	Neeroeteren	Geleen	F2	Geleen
Heerlerheide	Rotem	Heerlerheide	F1	Heerlerheide

Table 3. End of Pliocene fault connections in the Belgian part of the Roer Valley graben along a NW-SE transect (fault splitting indicated by { mark). The fault along the Zuidwillemsvaart is considered as a time-restricted connection between the Elen and Bocholt-2 faults.

line 9905-9906		line9902		line 9901		east of the Meuse
Bocholt-2		(Zuidwillemsvaart)		Elen	}	
Bocholt-1	}		{	Bichterweerd = Feldbiss	}	Feldbiss
Reppel	}	Feldbiss = Bree scarp	{	Geleen		Geleen

stitution along the southern border of the Lower Rhine graben have long struck geologists who were delimiting reserves of brown coal, located to the North of these faults, and hard coal, located to the South (e.g. van Waterschoot van der Gracht, 1914). Fault maps for the Lower Rhine Graben, east of the river Meuse, already exist since the beginning of the 20th century (Holzapfel, 1903). The morphological break associated with the sharp transition from the Campine Plateau to the Roer Valley Graben near Bree on Belgian territory, was first identified as a fault scarp and correlated with the Feldbiss fault in Dutch South Limburg by Briquet (1907, 1908) and confirmed by Klein (1914), despite their absence on the first Belgian geological maps. Stainier (1911) deduced the existence of several large faults, named after salt exploration borehole sites Rotem, Neeroeteren, Elen. Their traces remained hypothetical. Stainier was unintentionally at the origin of much confusion because his faults have been located at different places with different directions for different tectonic events.

Exploration for coal in the Campine coalfield posed the question of the northern limit to the accessible coal deposits, which are progressively buried under thickening sequences of Permian to Jurassic and Cretaceous to Quaternary towards the north. The Rotem fault initially was constructed to separate the productive coal measures to its south from all Permo-Triassic 'Red Beds' to its north, thus bending in an east-west direction into the heart of the coalfield (Stainier, 1931). This vision retarded development of the Campine mining basin in a northern direction until the borehole series 110-117 southeast of Bree proved that the Heerlerheide = Rotem fault is effectively extending towards the NW (Grosjean, 1939, 1942).

Revision of mining sections combined with gravity data for the South Limburg coalfield enabled de Sitter (1942) to present a coherent reconstruction of the Heerlerheide-Feldbiss fault system which was subsequently confirmed by boreholes and mining galleries, crossing the faults (Dikkers & Patijn, 1944; Heybroek, 1947; Müller, 1947; Patijn, 1961; Rutten, 1945). Tectonic and mining maps produced for the South Limburg coalfield during the post-war coal production boom integrated geophysical prospecting, exploration borehole and mining data to show 3-D fault structures at the level of coal mining (Müller, 1945; Sax, 1946; Patijn & Kimpe, 1961; Patijn, 1963).

The exploration development in the Campine basin showed clear similarities, although the exploited coalfield remains at some distance from the graben boundary faults. Geophysical (electrical and electromagnetic) prospecting during the war years contributed less to the advancement of knowledge on fault patterns in the Campine but confirmed the NW-SE direction of the Heerlerheide fault in the area west of Rotem (de Magnée, Centre belge d'Etudes de Prospection géophysique, unpublished data 1942-1944). Two seismic campaigns carried out over the Campine basin in 1953-56 and 1961-63 proved decisive in deciphering the general fault pattern and confirmed the de Sitter model, even though they did not yield detailed information on post-Oligocene deposits (cf. Legrand, 1961). Seismic surveys for coal exploration during 1980-1982 extended towards the graben boundary faults and threw new lights on the deformation history, especially on the importance of Upper Cretaceous to Tertiary inversion tectonics (Rossa, 1986). The 'Bree Uplift' whose origin as intrabasin high is still a matter of debate, was discovered this way (Bouckaert et al., 1981; Rossa, 1986; Langenaeker, 1998). A seismic survey for deep aquifers in the Belgian part of the Roer Valley graben carried out in 1984, was again not able to discriminate the post-Miocene stratigraphy but resulted in Tertiary subcrop maps (Demyttenaere, 1989; Demyttenaere & Laga, 1988). The fault pattern established in this work and schematically copied in Geluk et al. (1994) unfortunately used the names introduced by Stainier (1911) in another context: Rotem for Heerlerheide, Neeroeteren for Geleen, Elen for Feldbiss. It was revised by Langenaeker (1998) as Heerlerheide, Feldbiss (including Geleen) and Elen. Fault connectivity and kinematic mechanisms clearly remain a matter for debate.

Meanwhile, mapping of different terrace gravel deposits and of fault scarps in the Meuse valley, the Campine Plateau and the Roer Valley graben defined the outline of the Quaternary fault system as marked by scarps, both visible and buried (Paredis, 1968; Paulissen, 1973, 1997). Fault connection on both sides of the river Meuse, between Belgium and The Netherlands, remains a major problem. The Heerlerheide, Geleen and Feldbiss faults, as defined on the northern margin of the South Limburg coalfield, extend right towards the Meuse river; Geleen and Feldbiss may either join or diverge. Based on geoelectrical surveys and gravel thickness measurements in quarries and boreholes, the Bichterweerd scarp was documented as the main event in the Meuse valley, and apparently connected the Feldbiss and Geleen faults from the Dutch side of the Meuse to the Bree scarp, thus justifying its original name Feldbiss (Paulissen et al., 1985), which was further confirmed by high-resolution seismics on the Zuidwillemsvaart canal (Vanneste et al., 1997). This concept was questioned by Beerten et al. (1998), restoring the Geleen-Feldbiss fault doublet as their faults F2-F3, with F2 (Geleen) as the major fault. The interpretation of the Heerlerheide = F1 fault has never been questioned again, only the timing of latest period of activity is a matter for discussion. Fortunately, the Opitter-Bree scarp generally has retained its original attribution to the Feldbiss (Paulissen, 1997 vs. Demyttenaere & Laga, 1988)-(Tab. 2-3).

The new geological maps of the Belgian part of the Roer Valley graben make clear that importance of the faults is not only derived from vertical offset at given times, but also from changes in dip and in thickness of the different lithostratigraphical units which were deposited during time of activation of the faults. The resulting picture is very complex, and clearly indicates that fault importance may not be judged from the deformation of a single stratigraphic horizon (Buffel et al., 1999; Sels et al., 1999).

The Roermond earthquake of 13.4.1992 triggered off several research activities, the most important of which was the programme for the paleoseismological study of active faults by geophysical means and by trenching at the initiative of the Royal Observatory of Belgium (cf. Camelbeeck & Meghraoui, 1998; Vanneste et al., 1999).

Two major problems thus remain: connecting the morphological fault scarps and Quaternary faults to the deeper faults recognised by seismic surveying, and determining the exact nature of faults and shallow deformation structure below the Meuse river gravels.

High-resolution reflection seismic survey of the Feldbiss fault system

A 2-D high-resolution seismic survey was conducted by TNO-NITG on behalf of the Geological Survey of Belgium and NIRAS/ONDRAF between April 6-28, 1999 for a total shot-length of 12983 m divided over 6 profile-lines (Fig. 1, Tables 4-6). The main objective of this survey was to integrate the morphological and near-surface very high-resolution geophysical data, attaining a 0-30 meter depth range, to existing seismic sections with low resolution, generally not providing geological information in the 0-300 meter interval. Geologically useful data were effectively obtained between time-depths of 50 to 700 ms (or about 40-600 m vertical depth).

Different quality problems beset the operation, mainly due to the surface geology – which also impedes other geophysical surveys: presence of coarse gravels and locally deep groundwater table, causing extremely low velocities and reverberations. The station length was increased from 2 to 3 m after it was observed that the first line 9901 had a markedly lower signal to noise ratio in the interval 200-500 ms, due to multiple reflections from the groundwater surface.

Lines 9901and 9906 were obtained with seismic detonators of 2 gram dynamite each, placed in hand-drilled boreholes with average depth 2 m for line 9901 and 4 m for line 9906. The charges were covered by at least 0.8 m of sand and all holes were refilled up to the surface with sand or gravel, except for those on fields which had to be plowed. Lines 9902 to

Table 4. Overview of seismic sections.

profile-line	location	length	direction	Lambert coordinates (x; y; z in m)
9901	Elen-Rotem	3032 m 729 shots over 2912 m	ENE-WSW-SSW	start station 101 248657; 195782; 33.40 end station 1619 246675; 193883; 32.44
9902	Solterheide-Voorshoven	3495 m 553 shots over 3315 m	WSW-ENE	start station 101 239896; 199564; 63.60 end station 1267 242898; 201258; 34.83
9903	Neerglabbeek-Waterloos	2991 m 469 shots over 2811 m	WSW-ENE	start station 101 238715; 198757; 73.01 end meas. station 1085 241548; 199523; 55.51
9904	Grote Brogel Ooievaarsnest	1065 m 148 shots over 885 m	SW-NE	start station 101 230268; 204265; 61.48 end station 455 230967; 205059; 55.56
9905	Reppel Leukeneinde	2040 m 310 shots over 1860 m	SW-NE	start station 101 232133; 206115; 50.95 end station 781 233928; 207068; 45.96
9906	Bocholt Schuitelbeek	1359 m 200 shots over 1200 m	SW-NE	start station 101 234103; 206598; 44.56 end station 555 235261; 207311; 41.55

9905 were obtained with a minivibrator with peak force of 2200 kg, emitting 4 identical sweeps with frequency content of 8-248 Hz. The reference sweep was regularly adapted to changing soil conditions or deteriorations of signal-noise ratio. A seismic source was preferably used over the minivibrator, whenever depth to groundwater table and absence of gravels allowed drilling the required boreholes. Unfortunately, this could only be applied to 2 of 6 profile-lines: line 9901 following an abandoned meander of the Meuse river, silted up during the Middle Ages, and line 9906, located on the sandy Bocholt plain. These two profile-lines are indeed the most satisfactory: superior quality of data obtained by seismic detonator is demonstrated by the better quality of line 9906 over 9905 when comparing two almost overlapping sections in similar terrain on similar geology. Data quality strongly deteriorated on freshly plowed fields and above some of the major fault zones, ultimately resembling 'no-data areas'. As the same was observed on earlier seismic surveys (e.g. the 1982 'Meeuwen-Bree' and 1984 'Poppel-Lommel-Maaseik' surveys by Prakla-Seismos and the 1991 high-resolution survey on canals by RCMG Ghent, De Batist & Versteeg,

Table 5. Data acquisition parameters.

	line 9901	lines 9902-9905	line 9906
channels	60	60	60
station interval	2 m	3 m	3 m
shot interval	4 m	6 m	6 m
spread type	split-spread	split-spread	split-spread
sampling interval	0.5 ms	1 ms	0.5 ms
sampling time	1024 ms	1536 ms	1024 ms
receivers	10 Hz sensor 6 linear over 2 m	10 Hz sensor 6 linear over 3 m	10 Hz sensor 6 linear over 3 m
source	seismic detonators 2 gr dynamite	minivibrator sweep 8-248 Hz length 12.288 sec	seismic detonators 2 gr dynamite
instrument	Summit	Summit	Summit

Table 6. Data processing steps.

proces	steps
geometry	x, y, z
trace editing	no reverse polarity, zero traces
statics	elevation statics
	time depth 0 equals 50 m above Ostend level
filtering	bandpass 25-40-400-500 ms
	AGC
	deconvolution 3 ms lag, 40 ms operator length
	F-K filter
velocity analysis	constant velocity stacks
display date	vertical scale 100 ms = 3 cm
	horizontal scale 1:3750 and 1:7500

1999), it is assumed that severe tectonic dislocation is the main reason for the poor data quality over these areas.

Stratigraphic framework

The lithostratigraphic subdivision from new 1:50.000 Belgian geological maps 18-10, Maaseik-Beverbeek (Sels et al., 1999) and 26, Rekem (Buffel et al., 1999) is followed. As this slightly differs from the Dutch stratigraphic nomenclature, the basic characteristics are summarised:

Quaternary sensu stricto

Cromerian to Weichselian heterogeneous sand, gravel and loam; occasionally covered by Holocene brook (sand with some peat) or Meuse (gravel, clay or loam) deposits; thickness average 25-30 m, maximum 40 m.

Kieseloolite Formation (Middle/Upper Pliocene-Pleistocene)

Jagersborg sand Member (corresponding to Dutch Schinveld Sand Member): thickness minimum 18 m, average 60 m, maximum 110 m

Brunssum I clay and lignite Member: thickness minimum 10 m, average 35 m, maximum 60 m

Pey sand Member: thickness extremely variable minimum 5 m, average 40 m, maximum 95 m

Brunssum II clay and lignite Member: thickness minimum 8 m, average 30 m, maximum 60 m

Waubach sand Member: thickness minimum 15 m, average 70 m, maximum 130 m.

Mol Formation (Middle/Upper Pliocene)

White quartz-rich sands, stratigraphically equivalent to at least part of the Kieseloolite Formation.

Kasterlee Formation (Lower Pliocene)

Slightly glauconitic medium sand (Kasterlee to Bolderberg formations correspond to Dutch Breda formation).

Diest Formation (Upper Miocene)

Poorly sorted glauconitic sands. The transition between Kasterlee and Diest formations may be sharp or gradual; it is not certain whether at all places the same boundary bed is picked out.

Bolderberg Formation (Middle/Lower Miocene)

Genk Member (corresponding to Dutch Heksenberg member of Ville formation): white to yellow heterogeneous sands. May contain lignite and silicified sandstone.

Houthalen Member: glauconitic fine sand.

Voort Formation (Upper Oligocene)

Glauconitic clayey sands; Veldhoven Clay Member at top.

Geophysical well logs provide a sound basis for this stratigraphic subdivision; contrasting sand and clay-dominated members are also differenciated on seismic sections with sufficient resolution. The Quaternary-Tertiary boundary is probably crossed by the Kieseloolite formation. Palynological dating suggests a Pleistocene age for the Jagersborg Member and Quaternary affinities for the Brunssum I Member (Em. Roche, MRAC Tervuren, personal communication).

Both fault-driven subsidence and northward-increasing regional subsidence combine to increase the thickness of the Neogene to Quaternary sediments to a maximum in the deepest part of the graben, north of the Bocholt-Elen faults. Thickness increases irregularly affect all members of the Kieseloolite formation and underlying units, showing that major fault activity was contemporaneous with deposition. Inverse tectonic movements have occurred, leading to great changes in thickness distribution between the 5 members of the Kieseloolite formation whereas the complete formation does not necessarily vary much in thickness.

Interpretation of seismic lines

Line 9901

Profile-line 9901 is located in the Meuse valley, starting at the river bend with rapids near Elen, running in

SW direction and crossing the new Bichterweerd dyke and then following an abandoned Meuse meander now occupied by the Kogbeek in SSW direction till the early medieval ruin Bergkelder southeast of Rotem. The line was programmed to cross the F2-F3 fault system (also known as Neeroeteren-Elen or Geleen-Feldbiss) and to make the junction between known faults on Belgian and Dutch territory (Fig. 1). The profile-line effectively shows strongly fractured and deformed strata but only one fault presents a large offset, near station 1417, between the centres of Rotem and Grevenbicht, neatly corresponding to recent mapping of fault F2 (Beerten et al., 1998). Displacement for the base Miocene attains 200 ms or approx. 170 m. This difference is due for almost equal parts to the absence of the Plio-Pleistocene Kieseloolite formation south of the fault and to thickness increase of the Mio-Pliocene formations, especially the Genk Member of the Bolderberg formation.

The Bichterweerd scarp (Paulissen et al., 1985) near station 1102 is the most conspicuous near-surface feature because it coincides with updoming strata, immediately underlying the late-Quaternary Meuse gravel bed (Fig. 2).

The updoming exceeds 50 m for the base of the Kieseloolite formation (time difference 105-170 ms), corresponding to an average dip of 6° over 500 m. This structure remains similar for most of the Kieseloolite and Kasterlee formations but seems to flatten towards the base of the Miocene. The unexpected result is that the Kieseloolite formation reaches its greatest thickness (120 ms or approx. 100 m) near the southern end of the profile-line, just north of fault F2, on the back of the Bichterweerd scarp.

Equally striking is the almost flat nature of the base Miocene over the whole length of the profile-line north of station 1417 (fault F2), occurring at around 450 ms. Cumulative vertical displacement for the base Miocene along the series of faults accompanying the Bichterweerd scarp attains a mere 90 m, which is largely offset by a SW vergent fault intersecting the profile-line near station 490, where passage of the Elen F3 fault was supposed. Borehole information indicates an abrupt doubling in thickness of the Kieseloolite formation just north of Elen, implying the passage of a large fault (Sels et al., 1999). This 'Elen' fault probably crosses the river Meuse at the rapids just north of the seismic section.

Line 9902

Profile-line 9902 (Fig. 3) starts on the Campine

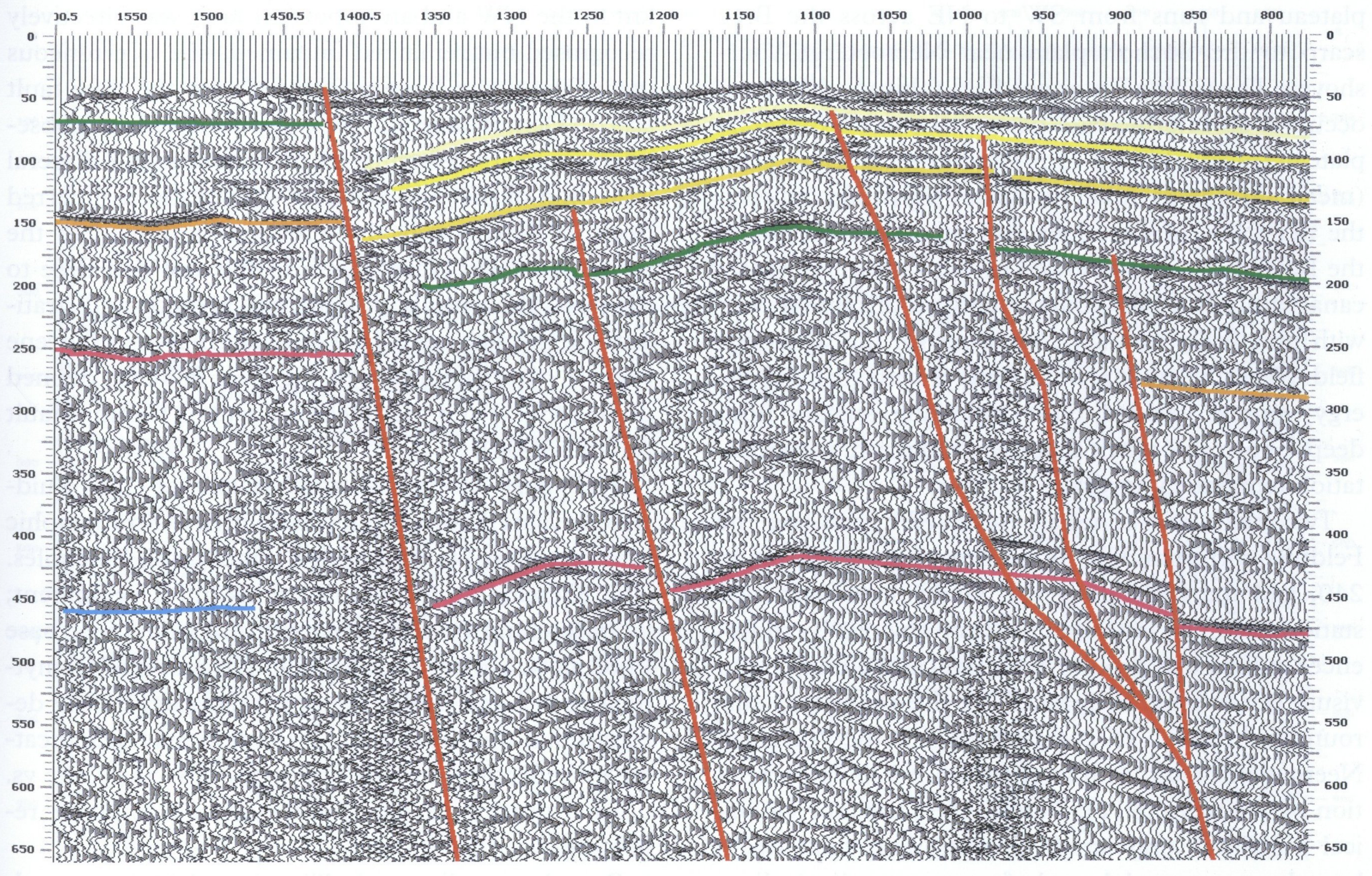

Fig. 2. Seismic section 9901 east of Rotem (Meuse valley) – (from SSW to NNE from left to right, total length 1500 m). Two faults reach the Meuse gravels (represented by topmost continuous reflector): the Geleen fault (F2) near CDP 1420 to the left, and the Bichterweerd scarp (representing the relay between the overlapping Feldbiss and Geleen faults) near CDP 1100 in the middle of the section.

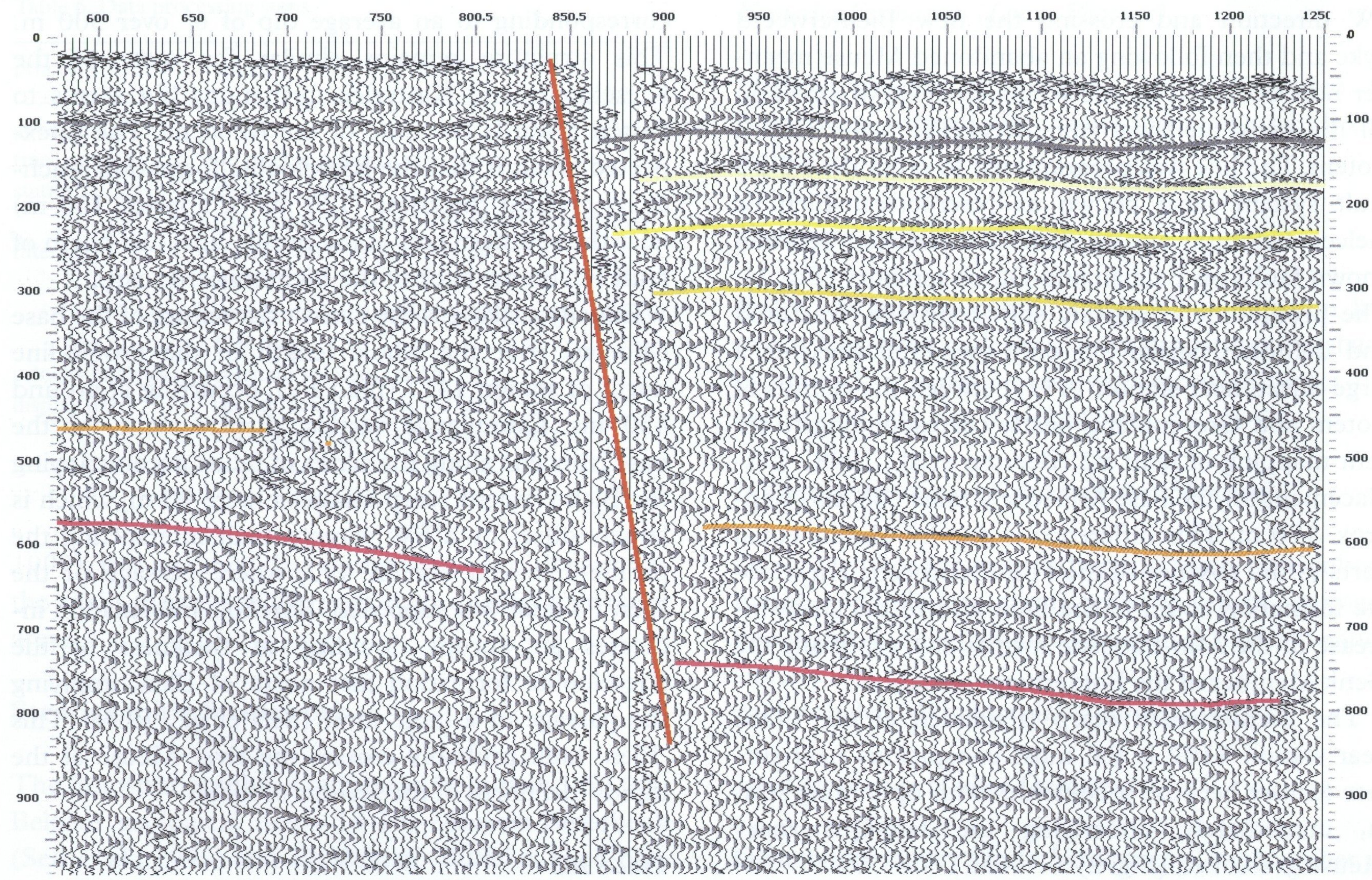

Fig. 3. Seismic section 9902, Zuidwillemsvaart canal crossing (from SW to NE from left to right, total length 1500 m). The newly defined Zuidwillemsvaart (ex-Neeroeteren) fault runs parallel to the canal. The Waterloos field south of the canal is almost devoid of reflection data.

plateau and runs from SW to NE across the Bree scarp to the Bocholt plain near Neeroeteren-Voorshoven. The rolling Waterloos field (altitude 45-55 m) occupies an intermediate position between Campine plateau (mean altitude 75 m) and lower Bocholt plain (mean altitude 35 m). The abrupt transition between the dry fields of Waterloos and the wet meadows of the Bocholt plain is followed by the Zuidwillemsvaart canal (altitude 40 m). Data quality on this line is poor with practically no-data conditions on the Waterloos field. Nevertheless, previous surveys with stronger energy sources yielded clear reflecting signals from deeper horizons, albeit that the stratigraphic interpretation remained imprecise.

Two major fault zones are traversed by this line: the Feldbiss corresponding to the Bree scarp near station 240, and the fault along the Zuidwillemsvaart near station 840. The latter fault is very obvious by differences in land use, groundwater level and elevation but visual observation is masked by the canal and surrounding dykes. It corresponds to the 'original' Neeroeteren fault, as inferred from borehole correlation by Stainier (1911). Despite the clear morphological transition, only small discontinuous fault traces have been mapped here before: most seismic lines stayed on either one side of the canal. Line 8412 (survey Poppel-Lommel-Maaseik) crossed the canal 2.4 km to the NW and an important fault was effectively recognised but remained unnamed, due to erroneous use of the name Neeroeteren fault for the Bree fault scarp (Demyttenaere, 1989, also followed by subsequent authors referring to his publication). Lateral extension of the 'Neeroeteren' fault plane, as inferred from its morphological expression, is limited to the stretch between Neeroeteren to the east and Bree to the west. However, both structural position and stratigraphic displacement for the Quaternary to Pliocene suggest correspondence to the Elen fault (as defined on line 9901) and the Bocholt-north or Hamont fault (on line 9906).

The part of the section north of the Zuidwillemsvaart shows better reflectivity. Stratigraphic interpretation fits well with neighbouring boreholes. The Kieseloolite formation attains full development; its base could be correlated with horizon 16 or base Pliocene sensu base Kieseloolite formation of Demyttenaere & Laga, 1988. Tectonic relaxation during deposition of the Kieseloolite formation may be indicated by reflectors dipping south towards the fault vs. normal northward dips for the deeper Miocene reflectors.

Poor data quality on the Waterloos field does not allow to recognise strong downdip towards the Feldbiss, as was observed for the Miocene on adjoining seismic sections 8412 (survey Poppel-Lommel-Maaseik) and 8201 (survey Meeuwen-Bree). The short section with better reflectivity on the Campine plateau, south of the Bree scarp, can be correlated with the Tertiary sequence of profile-line 9903 and shows generalised updip towards the fault hinge.

Line 9903

Completing line 9902 and located about 1 km further east, profile line 9903 (Fig. 4) runs from the Campine plateau across the Bree scarp to the Waterloos field with special purpose to pass over the eastern extremity of the Bree Uplift. Previous seismic surveys had interpreted the Bree Uplift as a Cretaceous inversion structure, although small-scale inversion continued into the Miocene (Rossa, 1987). However, the new 1:50.000 geological map indicates marked vertical displacement along the margins of the fault block, besides thinning and facies change of the sedimentary sequences within (Sels et al., 1999; Sintubin et al., this volume). Line 9903 confirmed that the Tertiary strata have practically not been displaced vertically along the southern margin of the Bree Uplift, even though the Cretaceous inversion fault (station 385) and two satellites (stations 225 and 160) locally have upthrusted and fractured all Tertiary strata. Within the Bree Uplift all Tertiary strata are tilted with increasing dips towards the north. Updoming rather than vertical fault displacement thus is responsible for the structural high in Tertiary strata. The seismic interpretation by Demyttenaere (1989) could be confirmed for the base Cretaceous till lower part of the Bolderberg Formation (younger stratigraphic units were not discernible seismically).

The no-data interval between stations 650 and 740 corresponds to the section between the Heerlerheide and Feldbiss faults (named Op-den-Berg block in Langenaeker, 1998). The brute stack suggests a strong southward dip on this block. The data quality of the remaining part of the section is rather poor in comparison with adjoining coal exploration lines 8002 and 8201. The interpretation of the Kieseloolite formation therefore is tentative. Noteworthy again is the southward dip, in direction of the Feldbiss of 6° for line 8201, 4° for line 9903 and 7° for line 8002, all measured for the Brunssum II member.

Line 9904

Profile-line 9904 (Fig. 5) runs along the Hoogstraat in Grote Brogel (municipality Peer) along the historic

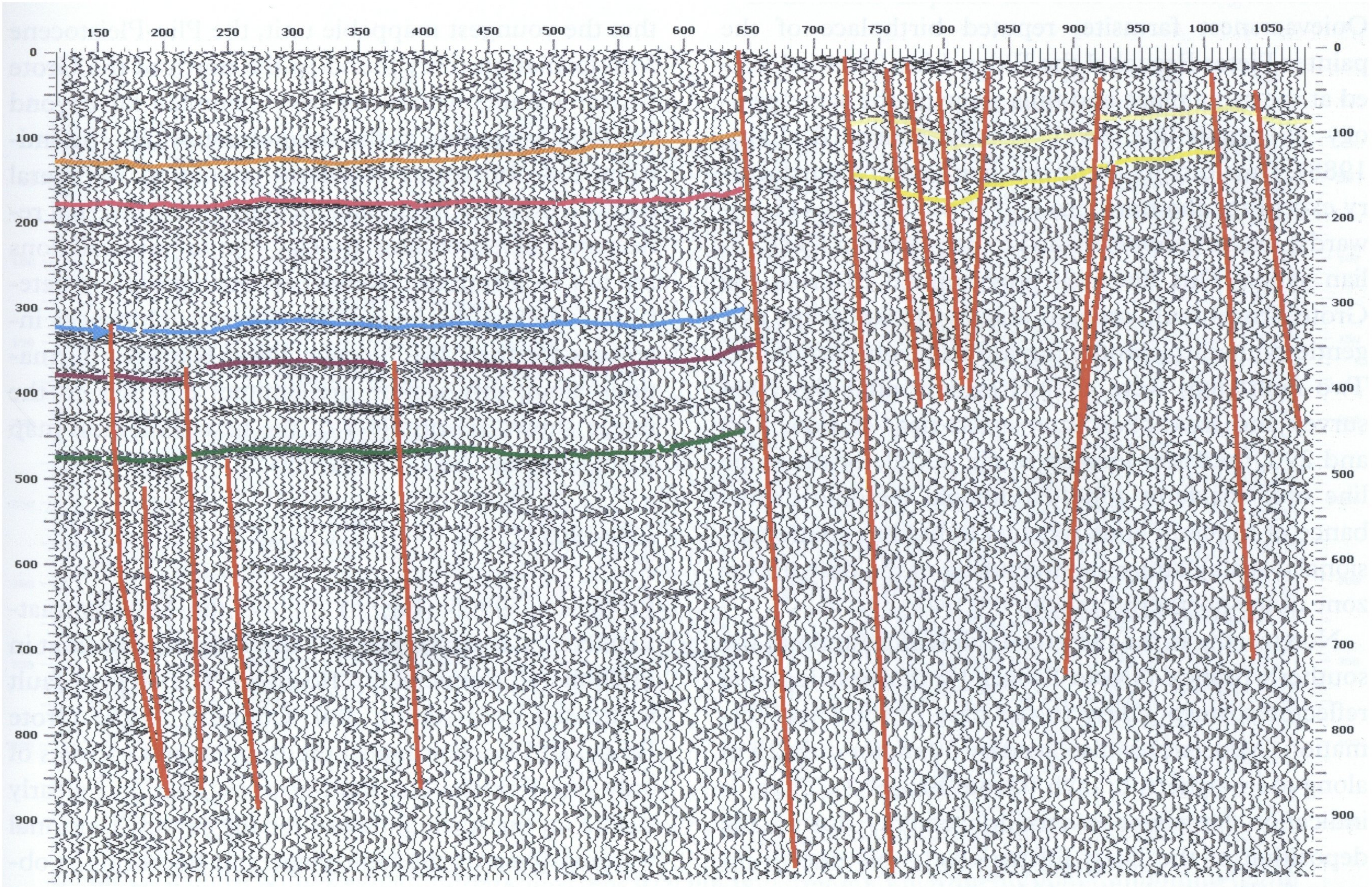

Fig. 4. Seismic section 9903 from Solterheide on the Campine plateau to the Waterloos field on the Bocholt plain (from SW to NE from left to right, total length 2800 m). Quaternary faults reaching the surface represent the Heerlerheide and Feldbiss faults at CDP 600 and 760 respectively. A series of minor faults affecting Tertiary reflectors at the SW end of the section represent the southern boundary of the Bree Uplift.

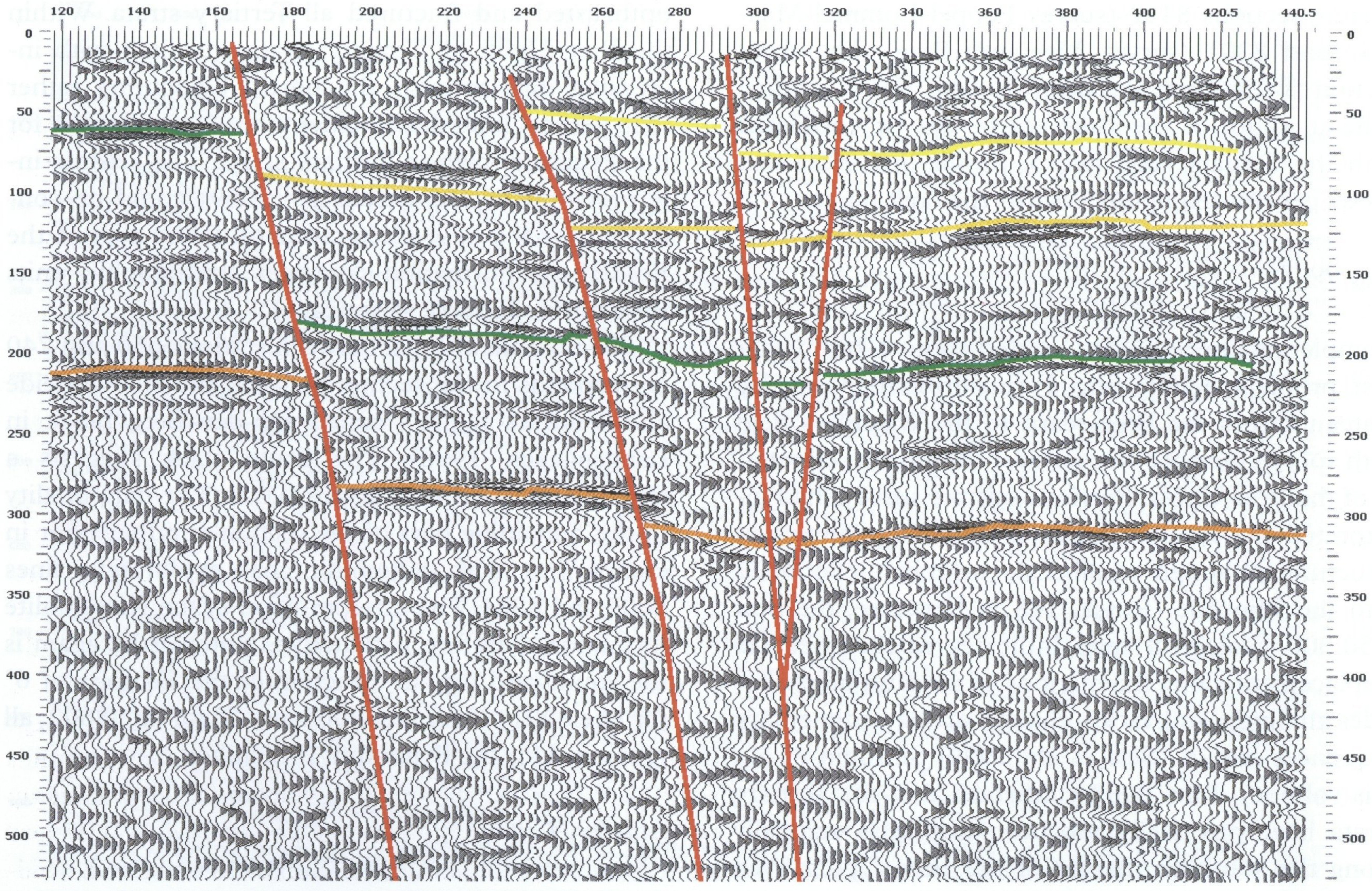

Fig. 5. Seismic section 9904 across the Grote Brogel fault system (from SW to NE from left to right, total length 960 m). The main branches reach the surface at CDP 165 and 240.

Ooievaarsnest farmsite, reputed birthplace of the painter Pieter Breughel the Elder. Line 9904 is located at the same place and thus showing the same geology as profile-line 8411 (Demyttenaere & Laga, 1988). Data quality along this line remains satisfactory except for the northern end (from station 415 onwards) where geophones had to be placed in loose eolian sands. This line was programmed to cross the Grote Brogel fault, recognisable in the landscape as a gentle faultscarp, producing a 6 m height difference. Two fault steps were already evident after the 1984 survey and have been intersected near stations 165 and 290, the latter located in the middle of the slope line over the fault zone. Additional tectonic disturbance of the fault zone remains limited to gentle tensional warping and some fracturing of the downthrow zone of the northern branch.

Noteworthy is the the greater downthrow along the southern branch (Grote Brogel 1): the best regional reflector corresponding to the base of the Diest formation (Miocene) is displaced by 60 m, for only 25 m along the northern branch (Grote Brogel 2). There is indication for slight inverse movements during the deposition of the Diest formation. Is this due to inverse fault tectonics or to depositional environment (absence of channel fills)? Downthrow differences are maintained into the Quaternary, which could indicate that the youngest mappable unit, the Plio-Pleistocene Mol formation (only found to the north of the Grote Brogel 1 fault) would not have extended far beyond the fault hinge line at the time of deposition. Seismically, this formation is clearly related to its lateral equivalent, the Kieseloolite formation; the internal reflectors corresponding to clay-lignite intercalations are not so distinctive. Reflection quality rapidly deteriorates below the base Diest horizon. Thickness increases for the Mio-Pliocene Diest-Kasterlee formations along this section are limited, contrary to the image shown on profile 1 of the new geological map sheet Maaseik (Sels et al., 1999).

Line 9905

Profile-line 9905 (Fig. 6) follows the Leukenstraat-Leukeneindestraat in Reppel and Bergerheidestraat in Bocholt (all municipality Bocholt). The Reppel fault is crossed near station 380. Contrary to the Grote Brogel and Bocholt faults, the Reppel fault consists of only one branch. The fault scarp is neat and clearly visible on the track, followed for the survey. Tensional warping towards the fault plane and fracturing is obvious, at least of comparable intensity to the Grote Brogel faults (however, the Reppel fault was generally represented as a simple fault plane in previous reconstructions, cf. Demyttenaere & Laga, 1988). The quality of the reflections deteriorates north of the fault. This cannot be due to changing surface conditions since it was observed on variable land conditions. Possibly the new incoming reflector representing the Brunssum 1 clays and lignite member is responsible for strong additional attenuation of the signal.

Rapid thickness differences are observed in the Diest formation immediately south of the Reppel fault: the basal part of the formation increases 20 m over 500 m distance in direction of the fault and becomes at the same time almost seismically transparant. This thickness gain is lost again in the upper part of the formation which decreases 15 m in the same direction (note that the stratigraphic boundary between Diest and Kasterlee formations may show some discrepancies between seismic and borehole interpretation). All seismic sections are too short to distinguish regional unconformities from fault warps.

The Kieseloolite formation is complete north of the Reppel fault. The middle sand unit, the Pey sand member, is very distinctive between the Reppel and Bocholt 1 faults by being seismically transparant.

Line 9906

Profile-line 9906 (Fig. 7) is located east of the centre of Bocholt, on the left bank of the Schuitelbeek, streaming in a straight bed almost perpendicular to the regional tectonic setting. The line was programmed to cross the Bocholt fault which was observed as a double fault reaching the surface near stations 315 (Bocholt-1) and 428 (Bocholt-2). Station 315 is situated on a 2 m scarp with wet soil conditions on the upthrown side, characterised by thin peat remains not found anywhere else along the profile line, at 1 m depth. Station 428 is situated near the main road Bocholt-Bree running parallel to the fault, which probably obscures the passage of a small scarp. Structural deformation associated with these faults is limited to slight tensional warping close to the fault planes; therefore these faults are preferential candidates to be recognised as morphological scarps. It is suggested here that the Bocholt active fault scarps may pass along the Gena and Mariëndaal watermills on the river A, whereas the Bocholt-2 scarp lines up with the scarps passing between Beek and Bree and continuing in direction of the fault along the Zuid-willemsvaart canal, appearing between Tongerlo and Neeroeteren.

Both faults displace the base Miocene reflector in

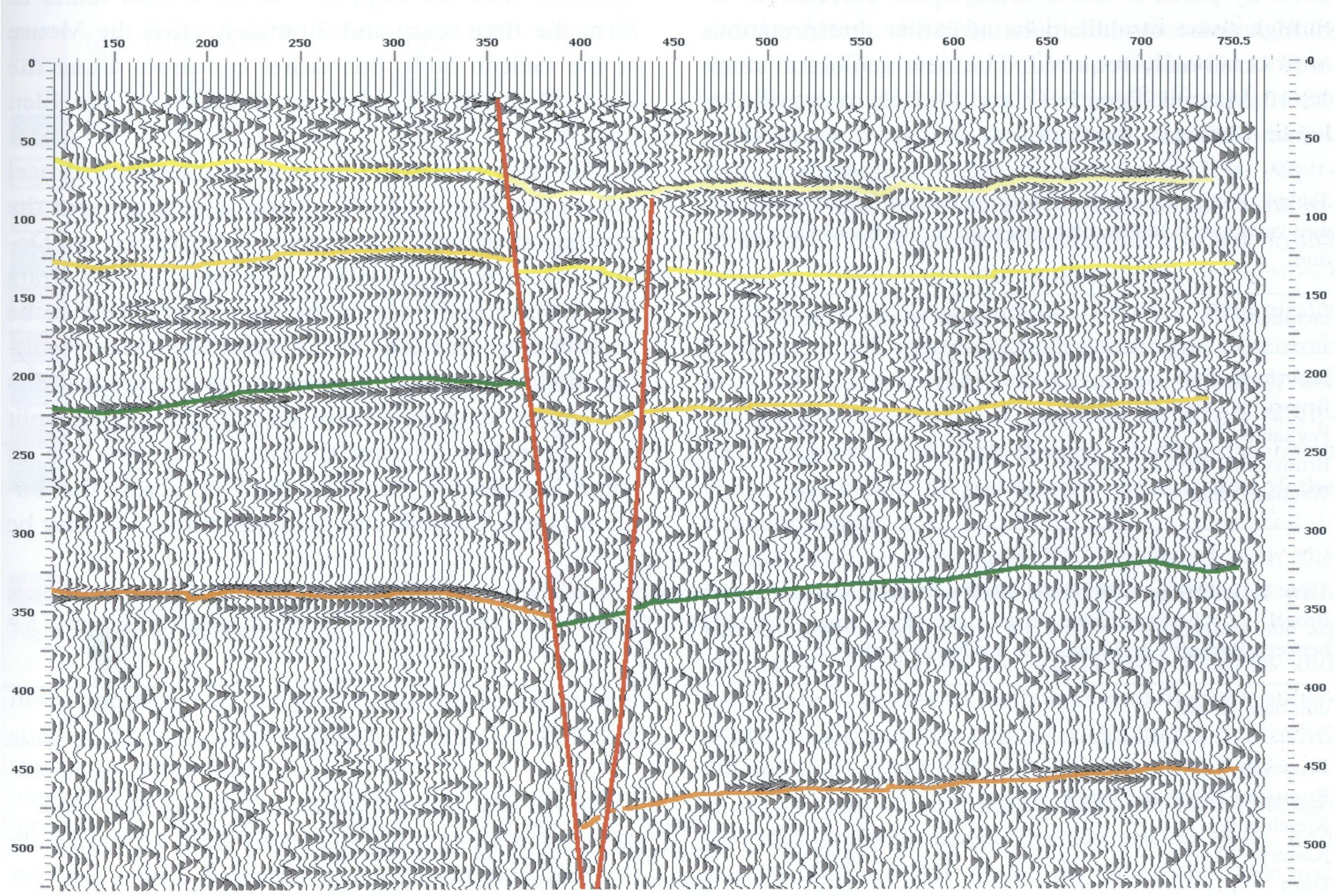

Fig. 6. Seismic section 9905 across the Reppel fault (from SW to NE from left to right, total length 1920 m).

equal way, descending from 425 ms over 530 ms to 635 ms (about 180 m). The base of the Plio-Pleistocene Kieseloolite formation (time-equivalent to the Mol formation) descends from 205 ms over 270 ms to 335 ms (about 110 m). The Kieseloolite formation increases from ca 155 ms over 220 ms to 280 ms (or about 105 m additional thickness resulting in a total of 240 m). The thickness difference with the displacement of its base is due to a slight increase in thickness of the late Quaternary sediments. This indicates that late Quaternary fault activity, however marked in the landscape, is limited in scope when compared to early Pleistocene downthrow. The seismic character changes mostly along the southern fault branch which is due to apparent thickness changes of its members. As far as can be judged from the reflection pattern, and consistent with neighbouring borehole information, thickness variations between the southern and northern blocks are mostly incorporated in the upper and lower sand units, at the detriment of the inverse-moving intermediate Pey sand unit (Tables 7-8). The legend for figures 2 to 7 is shown in Fig. 8.

Discussion and conclusions

Deeper reflectors in this high-resolution survey can be compared to previous seismic surveys. Similar reflectivity patterns allow stratigraphic correlation, although some modifications of earlier interpretations are occasionally required. The new geological maps 18-10 Maaseik-Beverbeek and 26 Rekem provide reliable borehole stratigraphy, as shown in different cross-sections (Buffel et al., 1999; Sels et al., 1999). Rapid lateral thickness changes, even within fault blocks, make correlation between offset boreholes and seismic sections somewhat insecure. Fortunately, some lithological changes, such as the clay-lignite intercalations in the Plio-Pleistocene Kieseloolite formation and the base of the Miocene Diest formation, are seismically strongly expressed.

Table 7. Profile-line 9906, crossing the Bocholt fault system: thickness variations in millisecond time-units for the Kieseloolite formation.

members	south block	north block
Jagersborg sands	15	70
Brunssum 1 clays and lignite	15	25
Pey sands	40	25
Brunssum 2 clays and lignite	15	35
Waubach sands	70	125

The Kieseloolite formation is equivalent of the Mol formation, the main difference being the much clearer distinction of the clay-lignite intercalations in the former. Whereas full stratigraphic succession is attained north of the F2 (Geleen + Feldbiss) and Reppel faults, maximal thickness is reached north of the Elen, 'Neeroeteren' and Bocholt faults. The Feldbiss and Reppel faults were already set in equivalence by Langenaeker (1998).

The fault pattern presents a segmented character; long continuing fault planes on structural maps are based on morphological similarities. However, each phase of renewed graben activity has to be considered independently; many branches and relay zones are present, and subsidence rates vary along fault planes (cf. Peacock & Sanderson, 1996).

Based on morphological observations and subsidence evolution, the hypothesis is forwarded here that at least the northern Bocholt fault does not combine with the Reppel – Grote Brogel faults to form the Bree scarp and ultimately cross the Meuse at the Geleen fault, but rather continues along the Zuidwillemsvaart heading in direction of the Elen fault.

Profile-lines 9904-9905-9906 across the Grote Brogel – Reppel – Bocholt fault systems largely confirm the existing structural interpretation, published in Demyttenaere & Laga (1988). The intermediate strata are downwarped towards the faults and appear to be slightly more fractured at the downthrow side, resulting in slight doming between the faults. Vertical displacement is quite evenly distributed among split fault branches. Varying thickness and inversion of some Kieseloolite members show up across the Bocholt faults. Variability in the Diest formation may be

Table 8. Profile-lines 9904-9905-9906: time-depth changes in milliseconds between adjacent fault blocks (from SW to NE) 1 = SW of Grote Brogel 1; 2 = between Grote Brogel 1 and Grote Brogel 2; 3 = between Grote Brogel 2 and Reppel; 4 = between Reppel and Bocholt 1; 5 = between Bocholt 1 and Bocholt 2; 6 = NE of Bocholt 2.

unit base (in ms)	1	2	3	4	5	6
Brunssum 1 clays and lignite	–	–	–	80-55	110-105	135-125
Brunssum 2 clays and lignite	–	–	85-65	145-120	?	180-170
Kieseloolite	–	85-105	125-105	235-205	270-280	335-330
Kasterlee/Diest	60-65	170-185	215-200	320-285	?	?
Diest	210-215	280-290	315-350	465-425	525-540	635

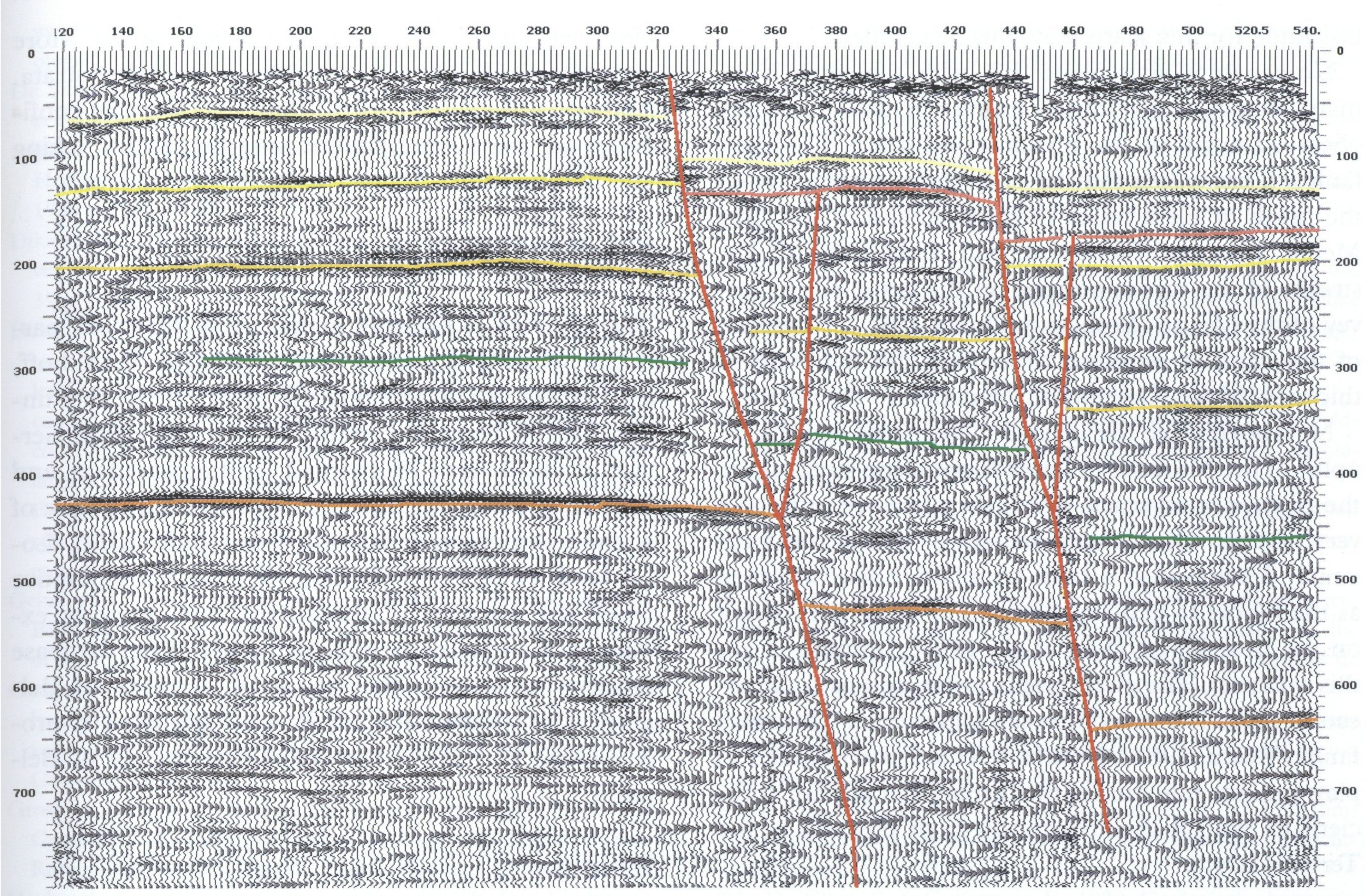

Fig. 7. Seismic section 9906 east of Bocholt (from SSW to NNE from left to right, total length 1350 m). The Bocholt fault system encompasses both fault planes which each produce almost identical vertical displacement of the Miocene to early Pleistocene strata (CDP 325 and 430). Although late Quaternary displacement is modest, morphological scarps are formed over both fault intersections.

🟧	top Brunssum II	horz	●
🟨	Brunssum II	horz	●
🟫	top Brunssum I	horz	●
🟨	Brunssum I	horz	●
🟨	base Kieseloolite	horz	●
🟩	base Kasterlee	horz	●
🟧	base Diest	horz	●
🟥	base Miocene	horz	●
🟦	base Boom	horz	●
🟪	base Tongeren	horz	●
🟩	base Tertiary	horz	●
🟥		fault	×

Fig. 8. Legend for figures 2 to 7.

more controlled by regional base level and sediment supply changes (Demyttenaere, 1988; De Batist & Versteeg, 1999).

The main drainage pattern across the southern margin of the Roer Valley Graben is at right angles to the fault scarps. Remarkably, watermills are almost always located at the passage of the Quaternary faults. On the Abeek, the Slagmolen, Reppelermolen, Mariëndal and Genamolen coincide with the Grote Brogel, Reppel, Bocholt and Bocholt-2 (or Hamont) faults respectively. On the Itterbeek, the Pollismolen and Keiaartermolen coincide with the Feldbiss (Opitter scarp) and newly defined 'Neeroeteren' faults respectively. The Neeroeteren watermill also lies on the presumed trace of the Neeroeteren fault.

The Meuse valley situation remains structurally complex; it will require a much denser grid of seismic lines to elucidate the 3-D structure. Possibly, the changing tectonic style is inherited from the NNE-SSW trending Visé-Puth flexure affecting Paleozoic strata and linked to the eastern termination of the Brabant Massif.

Line 9901 crosses fault F2, associated with the Geleen fault. The striking antiform associated with the Bichterweerd scarp probably originated as an overlap zone between the pre-Tertiary Feldbiss and Geleen fault segments with maximal Tertiary subsidence in opposite directions (cf. Anders & Schlische, 1994; Childs et al., 1995). Within this 'horse' the strata are strongly tilted towards the southwest. Through the Bichterweerd scarp, the eastern Feldbiss and western Geleen (F2) faults join in a bent fault and head towards the Bree scarp. Use of the name 'Feldbiss fault' for this scarp may thus be justified.

No separate fault plane 'F3' with the same kinematic history as the South Limburg Feldbiss fault was observed north of the Bichterweerd scarp. The Elen fault – if extending that far eastwards – should lay to the north of Elen, north of the eastbend of the river Meuse between Elerweerd and Illikhoven, downstream of the rapids noticed on the geo-electric survey of the Meuse (Brabers & Dusar, 1999). Existence of this fault is required to explain the doubling in thickness of the Kieseloolite formation to the north.

Noteworthy are the inverse movements causing an uplift of the Miocene to lower Pleistocene strata along the Bichterweerd scarp, which therefore seems to be a very young, Quaternary structure. These antiform strata, developed as a fault-bounded 'horse' are seen as the model to explain the window of Tertiary strata on the Bree Uplift (Sels et al., 1999; Sintubin et al., this volume). The Bree Uplift originated as a Cretaceous inversion structure on Cimmerian (Jurassic) faults (Rossa, 1986). Inversion tectonics continued to play a minor role during the tertiary but are not sufficient to explain the structurally high position of the Tertiary strata.

Recommendations

The high-resolution seismic survey of the Feldbiss fault system was intended to image selected 2-D sections of geological formations in the depth range 40-600 m, covering the early Pleistocene to base Miocene interval. Seismic coverage is still insufficient to fully elucidate the 3D-fault pattern. However, new insights are provided on the relation between the different fault branches, on the fault-controlled development of the Kieseloolite formation and on the strong and variable tectonic activity during the Pleistocene. Data quality depends on near-surface conditions, with explosive sources giving the best results, at least when applicable. Drilling through the Meuse river gravel may be too costly for this kind of operation, but the Bocholt plain may be suitable for lightly powered drilling equipment.

The 2 m station interval applied to section 9901 yielded highest-resolution data down to 150 ms; low signal to noise ratio observed at greater time-depths was induced by multiple reflections at the groundwater level but was partly influenced by the poor reflectivity within Upper Miocene sequences. Therefore the switch to a 3 m station interval, suppressing this noise, produced mixed effects on data quality.

The area north of the Bree scarp remains a poor data zone, probably due to bad surface conditions (presence of gravel beds and deep water table) combined with highly-fractured and dipping strata. More energy is needed to get information on deeper strata. Additional borehole control would allow more confidence in seismostratigraphic interpretations, taking into account quick lateral changes in subsidence.

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