Netherlands Journal of Geosciences — Geologie en Mijnbouw | **85 – 4** | **245 - 276** | **2006**

Subsurface structure of the Netherlands – results of recent onshore and offshore mapping

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Manuscript received: September 2006; accepted November 2006

Abstract

This paper presents depth maps for eight key horizons and seven thickness maps covering the onshore and offshore areas for the Late Permian to recent sedimentary section of the Netherlands. These maps, prepared in the context of a TNO regional mapping project, are supported by nine regional structural cross sections and a table summarizing the timing of tectonic activity from Carboniferous to recent. These new regional maps enable the delineation of various structural elements but also reveal the development of these elements through time with improved detail.
Since the latest Carboniferous the tectonic setting of the Netherlands changed repeatedly. During successive tectonic phases several pre-existing structural elements were reactivated and new elements appeared. The various identified regional structural elements are grouped into six tectonically active periods: Late Carboniferous, Permian, Triassic, Late Jurassic, Late Cretaceous and Cenozoic. This study demonstrates that many structural elements and fault systems were repeatedly reactivated and that a clear distinction exists between long-lived elements, such as the Roer Valley Graben, and short-lived structural elements, such as the Terschelling Basin.

Keywords: geological maps, structural elements, Permian, Triassic, Jurassic, Cretaceous, Cenozoic, Netherlands

Introduction

This paper presents the results of a regional geological mapping project of the Dutch onshore and offshore subsurface at a scale of 1 : 2,500,000 that was carried out by TNO at the request of the Ministry of Economical Affairs with the following objectives:

- to promote exploration efforts in the Netherlands;
- to obtain a regional framework for a detailed geological mapping program 2006 - 2010;
- to enhance research for the use of the subsurface for CO_2 storage and geothermal energy production.

The onshore part of the maps presented, was recently published in the Geological Atlas of the Subsurface of the Netherlands – *onshore* (TNO-NITG, 2004), while the offshore part is being published for the first time. In this paper we present these new integrated maps and cross sections and briefly discuss the main regional structural elements.

Depth and thickness maps have been created for the Zechstein Group (Late Permian), the Lower and Upper Germanic Trias groups, the Altena Group (Early and Middle Jurassic), the Schieland-Scruff-Niedersachsen groups (Late Jurassic), the Rijnland Group (Early Cretaceous), the Chalk Group (Late Cretaceous), the Lower and Middle North Sea groups (Paleogene) and the Upper North Sea Group (Neogene) (Fig. 1). These maps provide an overview of the geological development of the deep subsurface of the Netherlands since the Carboniferous. In this paper the presented maps are discussed in two paragraphs for each lithostratigraphic group by describing (a) depth, thickness and basin development and (b) structural development (faults, erosion and salt movements).

Figure 1 shows the geological time scale of Gradstein et al. (2004) together with the mapped lithostratigraphic intervals that are discussed in this paper. For detailed information on the lithostratigraphy of the mapped intervals and a discussion on regional structural elements readers are referred to earlier publications by TNO-NITG (2004) and Van Adrichem Boogaert

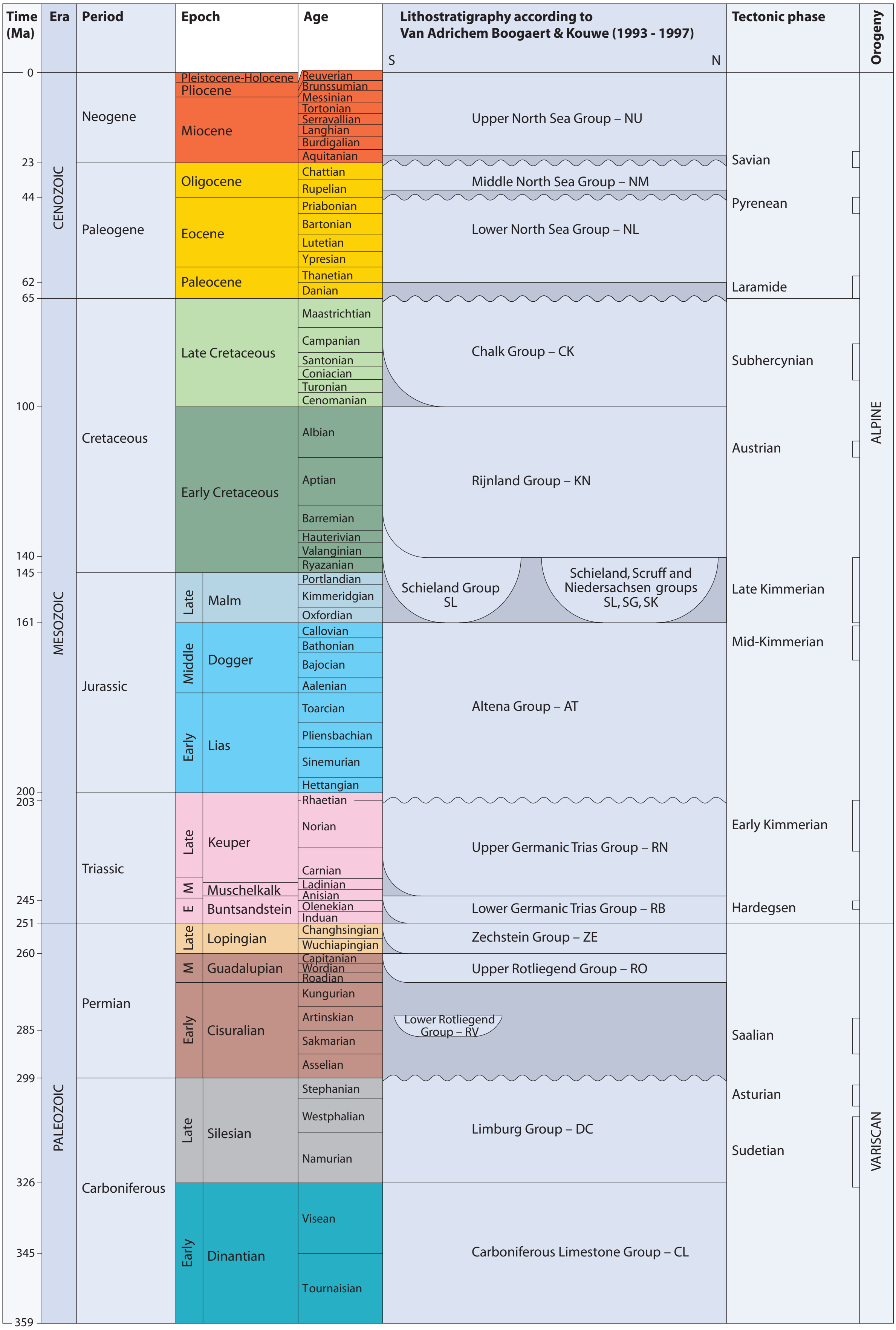


Fig. 1. Geological time scale (after Gradstein et al, 2004) and lithostratigraphic column (after Van Adrichem Boogaert & Kouwe, 1993 - 1997) showing main tectonic deformation phases.

& Kouwe (1993 - 1997). Earlier structural geological models and studies of basin evolution in the Netherlands have been published by Heybroek (1974), Van Wijhe (1987), Rijkers & Duin (1994), Racero-Baena & Drake (1996), Rijkers & Geluk (1996), Dirkzwager (2002), Wórum (2004), Van Balen et al. (2005) and De Jager (in press). All depth maps, thickness maps and figures that are presented in this paper can be downloaded from *www.nlog.nl*.

Further improvement of the structural reconstruction is necessary to explain geological distribution of aquifers, reservoirs and hydrocarbon systems. In particular the reconstruction and timing of salt tectonics in the Netherlands can be improved strongly. Regional maps are also required for analysis of paleo-stress fields and timing of salt movement and contribute to an improved understanding of fault patterns, reservoir configuration and burial evolution on a local scale.

Data base and map reliability

The data used for the construction of the maps were acquired from various oil companies during their exploration and production activities since the beginning of the 20th century. For this project, only publicly released seismic and borehole data have been used (Fig. 2). The stratigraphic information of 1756 boreholes has been incorporated in the interpretation of the seismic data. The interpreted seismic data were converted from time to depth using the seismic velocity model of Van Dalfsen et al. (this volume). In contrast to the onshore area, the offshore part shows a lower density of used seismic lines. In the onshore area much more seismic data were available than in the offshore region resulting in a higher reliability of the map data in the onshore area. Offshore areas in which 3D seismic data have been interpreted are the Cleaver Bank High (CBH), Ameland Block (AB) and Terschelling Basin (TB) (Figs 2 and 4d). In these areas the maps show more detail and are more reliable than the areas with a low coverage of 2D seismic data. In the southern part of the offshore region the thickness map of the Zechstein Group is largely based on well data. In this area, the depth map of the Zechstein Group was constructed by adding the Zechstein thickness to the Triassic depth map. For the period 2006 - 2010, a detailed geological mapping project is programmed during which more recently released (3D) seismic and well data will be accessed, which will result in the improvement and higher reliability of the depth and thickness maps.

Structural elements

Nine regional geological cross sections were constructed to illustrate the main structural elements of the Netherlands (Fig. 3). In this paper the term 'structural element' is given to regional structures with a uniform deformation history in terms of subsidence, faulting, uplift and erosion during a specific time interval. The structural element maps have been reconstructed from the depth and thickness maps presented in this paper. In order to map these regional structural elements systematically, the following structural types are used: basin, high, platform and fault (-zone). The boundaries of structural elements, including basins, are delineated by subcrops, (major) faults or salt structures. In this study a *high* is defined as an area with significant erosion down into Carboniferous or Permian strata (Rotliegend and/or Zechstein). A *platform* is characterized by Late Jurassic erosion into the Triassic and the absence of Lower and Upper Jurassic strata. The term *graben* is used for subsided structural elements that are clearly delineated by major linear faulting. Exceptions on this systematical methodology in nomenclature of structural elements are the Ems Low (EL), Lauwerszee Trough (LT), Netherlands Swell (NS) and Zandvoort Ridge (ZR). These names are not changed because of their common use in literature.

The regional structural elements have been reconstructed for six tectono-stratigraphic periods, namely Late Carboniferous - Early Permian (Variscan phases), Middle and Late Permian, Triassic (Early Kimmerian phase), Late Jurassic (Late Kimmerian phase), Late Cretaceous (Subhercynian phase) and Cenozoic (Laramide, Pyrenean and Savian phases) (Figs 4a - 4f). Improved delineation of basin structures is obtained by using the subcrops of the Lower and Upper Jurassic strata. Table 1a indicates the active geological period for each structural element with regional significance that is recognized in these new maps. Major fault zones that are indicated in the deformation scheme in Table 1a are recognized both in the maps and the cross sections. In Table 1b the geological description and the used abbreviations of these main structural elements are given. It is strongly recommended not to mingle names of structural elements that have been active during different geological periods. For instance, the larger part of the Mid North Sea High (MNSH) is a Variscan structure, while the Elbow Spit High (ESH), at more or less the same location, is of Late Jurassic origin (Figs 4a and d).

The structural grain has been strongly influenced by fault systems in the basement that came into existence during the Variscan orogeny (Late Carboniferous - Permian phases). It is obvious from the structural element maps that the Late Jurassic - Early Cretaceous extensional tectonics dominates the structural configuration of the Dutch subsurface, involving Kimmerian reactivation of pre-existing Permo-Carboniferous faults. Late Jurassic and Early Cretaceous subsidence of basins and uplift of flanking platforms, combined with effects of salt movement, reflect the development of a complex structural setting. The geological setting during the Late Jurassic was characterized by erosion of elevated platforms together with the accumulation of sediment in the local basins along the edges of the uplifted blocks. It is emphasized that Late Jurassic depositional areas are relatively small as compared to

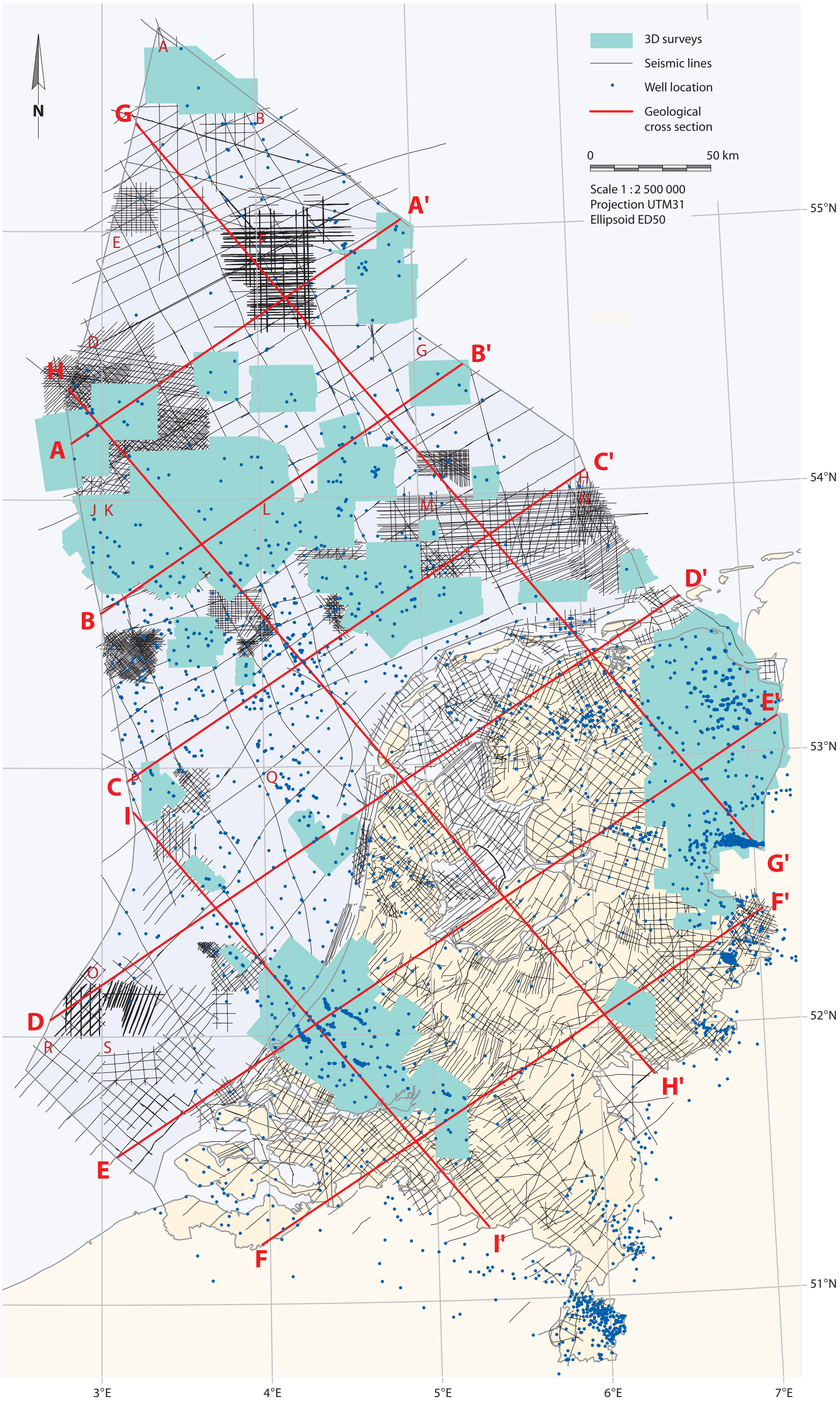


Fig. 2. *Map showing the locations of seismic lines and wells used, and geological cross sections given in Fig. 3.*

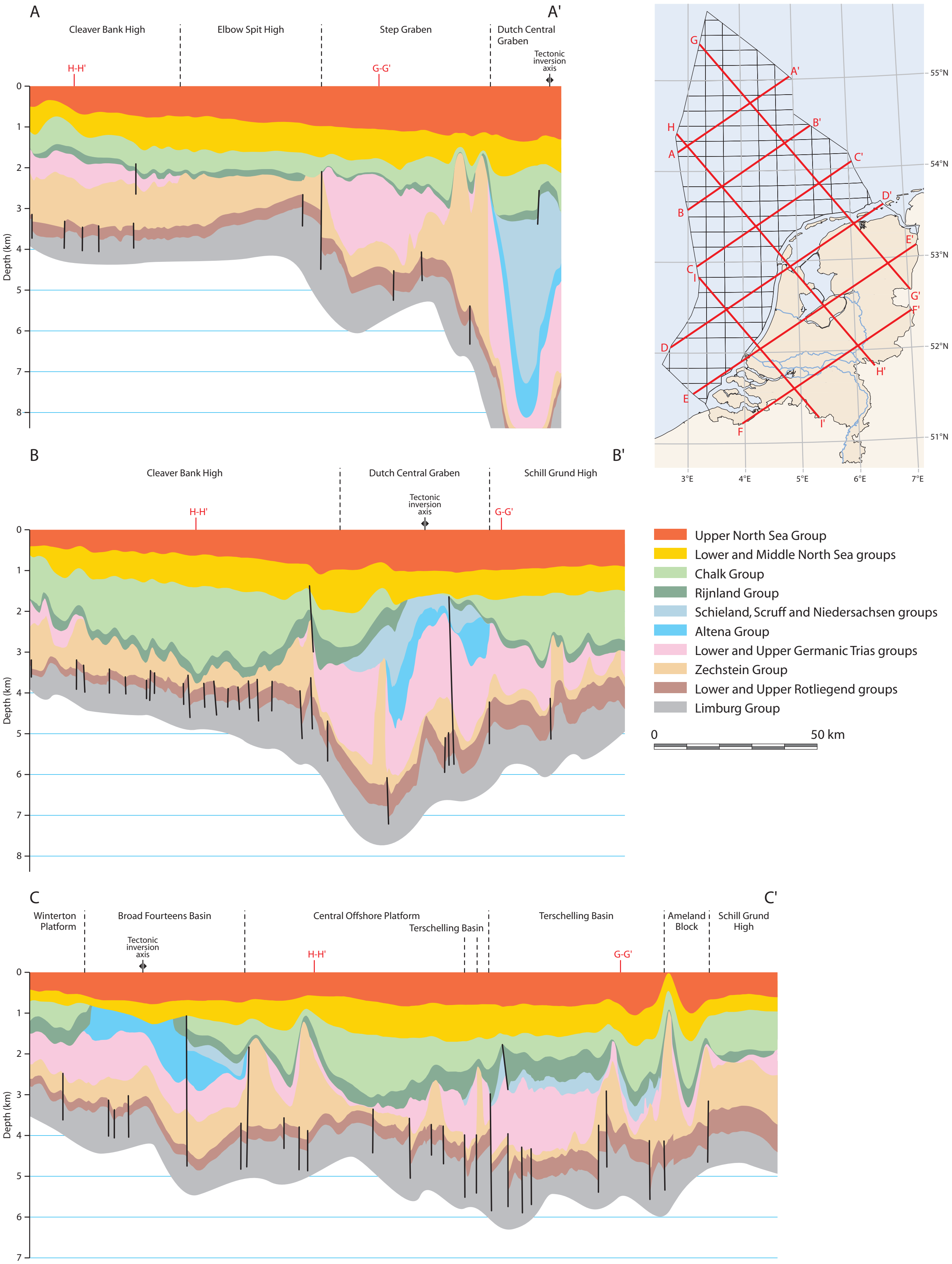


Fig. 3a. SW-NE geological cross sections A-A', B-B' and C-C'.

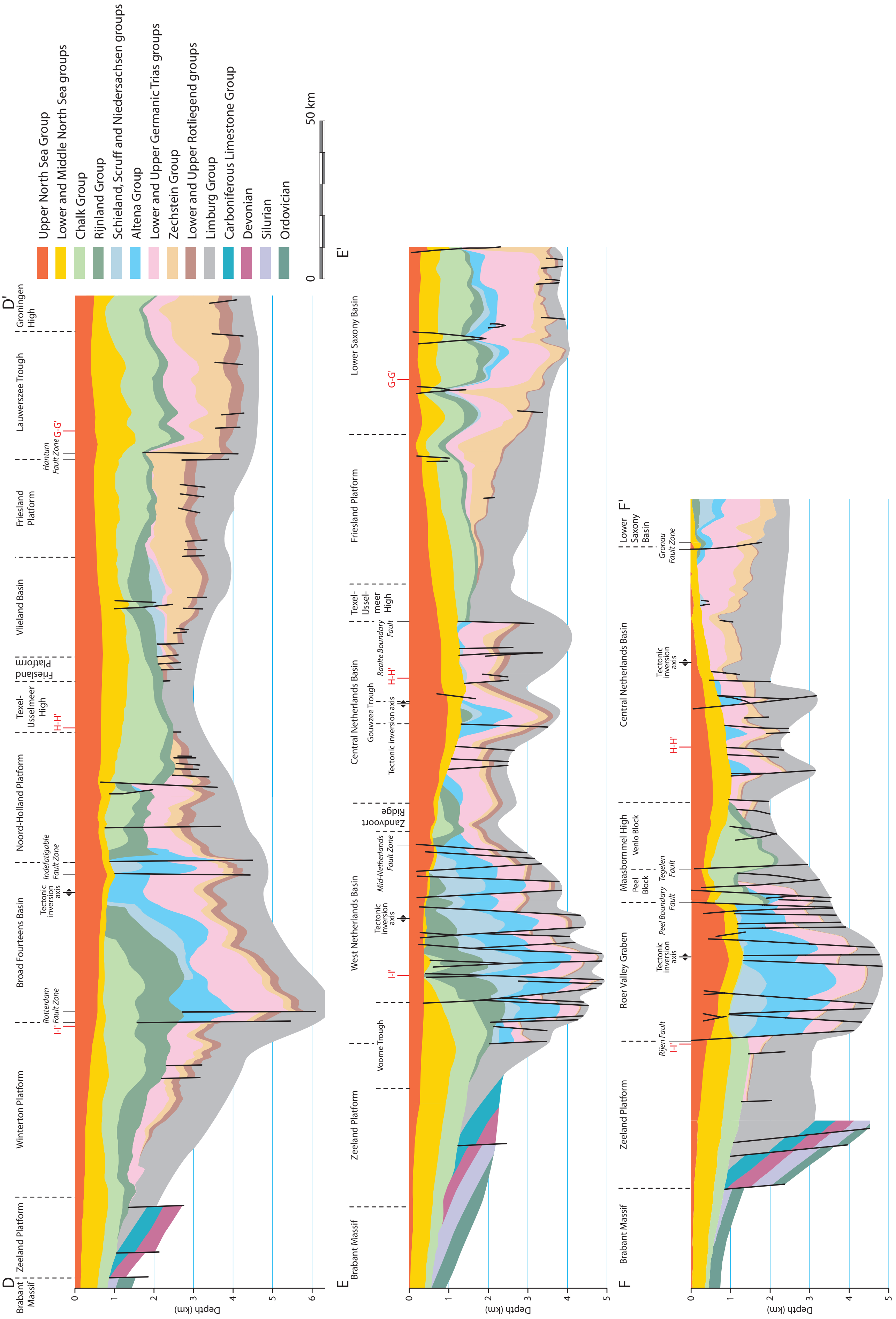


Fig. 3b. SW-NE geological cross sections D-D', E-E' and F-F'.

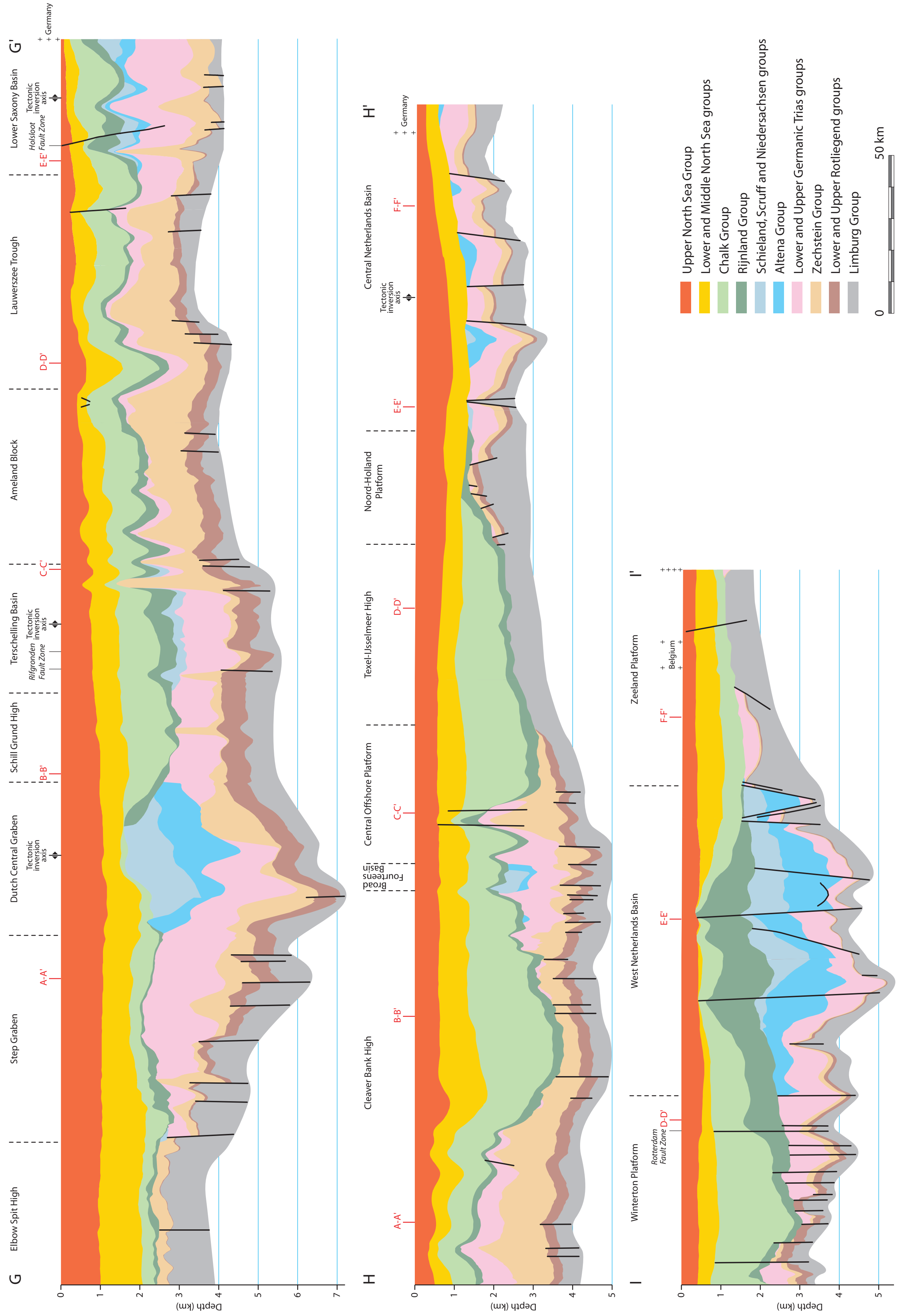
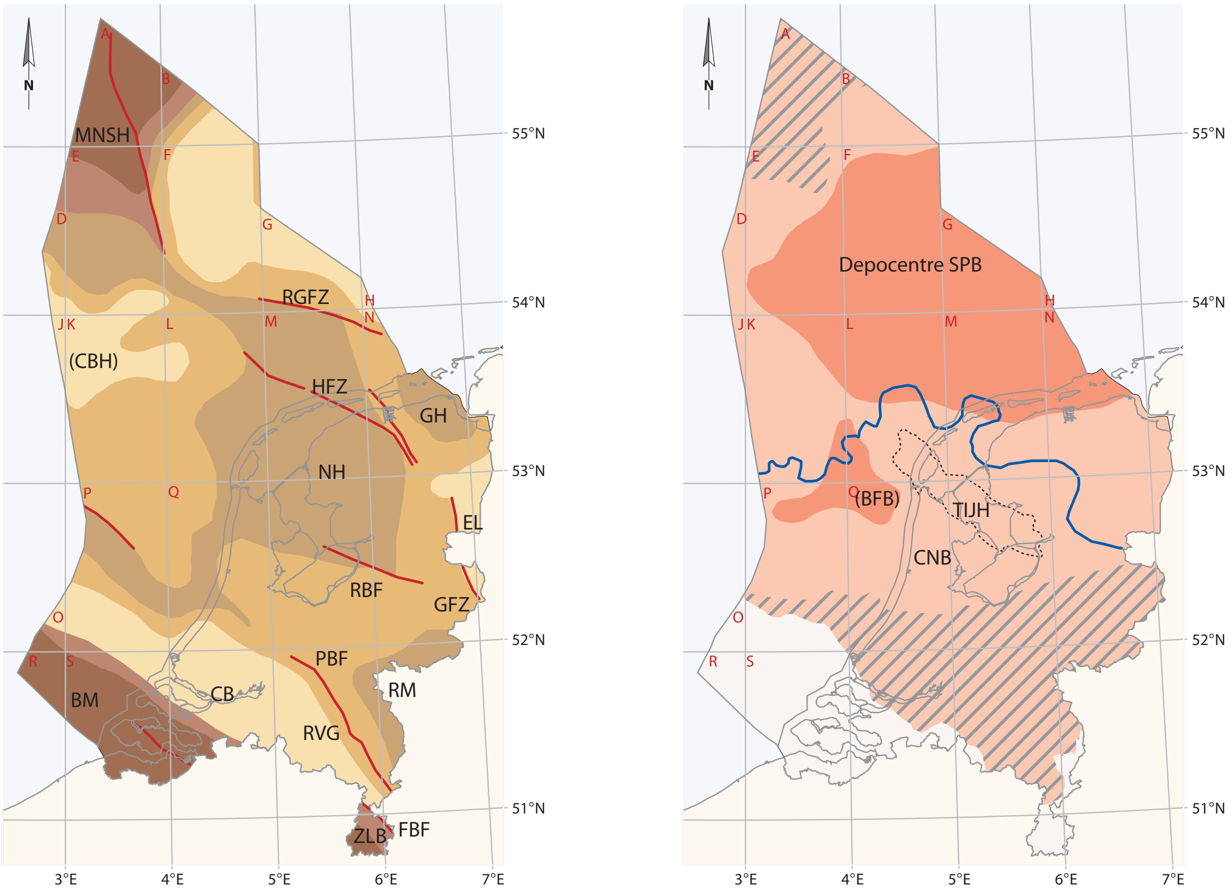
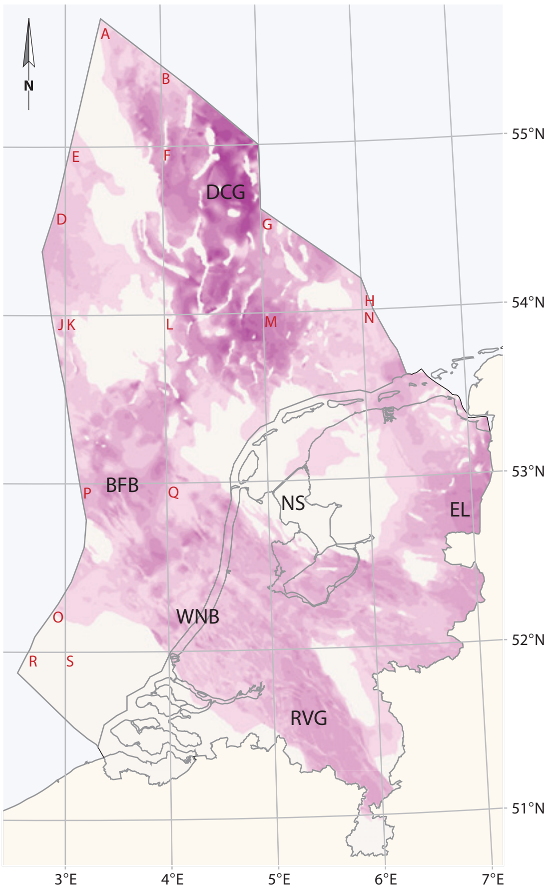


Fig. 3c. NW-SE geological cross sections G-G', H-H' and I-I'.



a. Variscan structural elements

b. Late Permian structural elements



c. Triassic structural elements (Early Kimmerian phase)

Legend

— Major fault

Fig. 4a

■ Dinantien – Namurian and older

■ Westphalian A/B

■ Westphalian B/C

■ Westphalian C

■ Westphalian D - Stephanian

Fig. 4b

■ Southern Permian Basin

■ Depocentre, thickness Rotliegend >300 m

▨ Permian basin fringe

□ Non-deposition

— Southern limit halokinesis (Zechstein salt)

Fig. 4c

Thickness of Triassic deposits in m

■ 0 - 250 ■ 500 - 750 ■ >1000

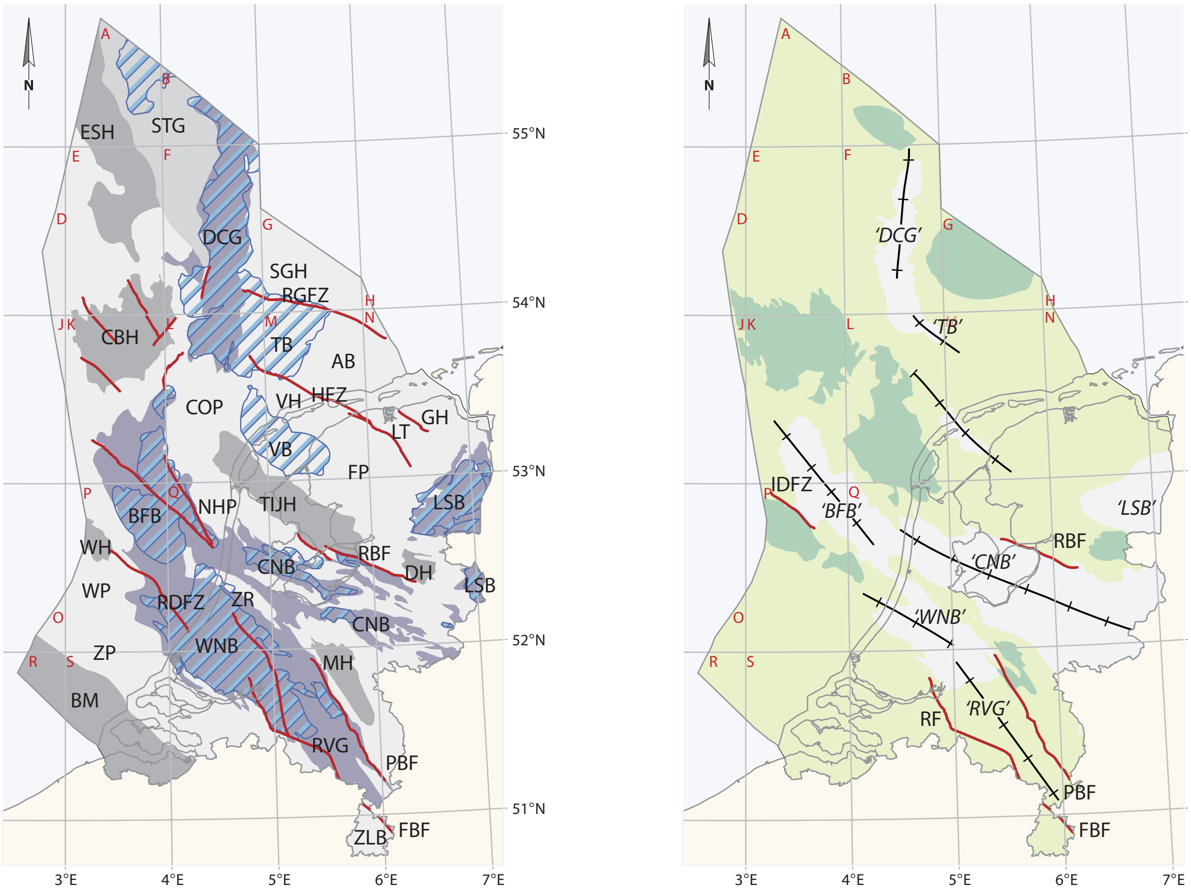
■ 250 - 500 ■ 750 - 1000

□ Triassic deposits absent by erosion or non-deposition

0 100 km

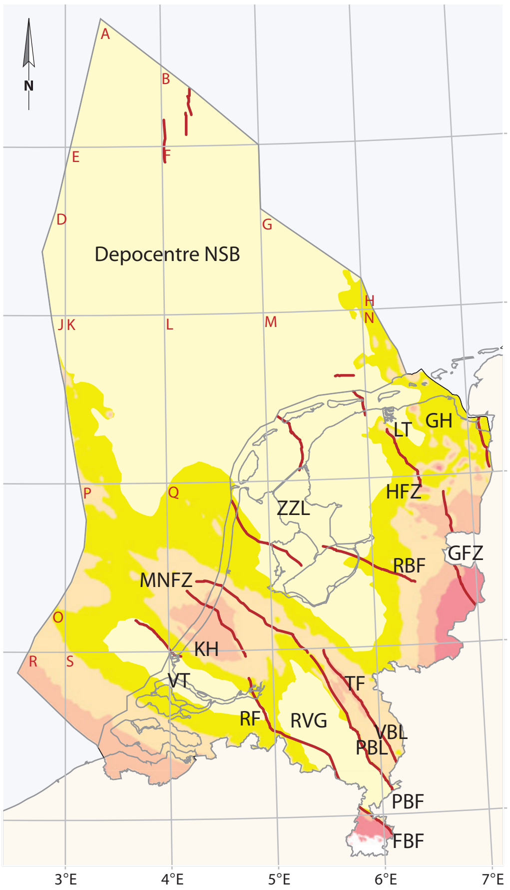
Scale 1 : 5 000 000
Projection UTM31
Ellipsoid ED50

Fig. 4 Structural element maps (1 : 5 000 000) summarizing main structural features active during the six tectono-stratigraphic periods (4a - 4f). The structural elements are mainly based on the present-day thickness maps in Figs 5 - 12. For explanation of the abbreviations of the structural elements and the faults see Table 1.



d. *Late Jurassic - Early Cretaceous structural elements (Late Kimmerian phases)*

e. *Late Cretaceous-Early Tertiary structural elements and basins (Subhercynian and Laramide phases)*



f. *Cenozoic structural elements (Pyrenean and Savian phases)*

Legend

—	Major fault

Fig. 4d

■	Basin: Lower Jurassic present
▨	Basin: Upper Jurassic present
□	Platform: Jurassic deposits absent
■	Half graben: Lower Jurassic absent, Triassic partly eroded
■	High: Triassic absent, Rotliegend and/or Zechstein absent

Fig. 4e

🟩	Thickness Chalk >1000 m
🟩	Thickness Chalk <1000 m
□	Subhercynian/Laramide inverted basins
+—+	Tectonic axis

Fig. 4f

🟥	Depth base North Sea Supergroup <250 m
🟧	Depth base North Sea Supergroup 250 - 500 m
🟧	Depth base North Sea Supergroup 500 - 750m
🟨	Depth base North Sea Supergroup 750 - 1000 m
🟨	Depth base North Sea Supergroup >1000 m

0 100 km

Scale 1 : 5 000 000
Projection UTM31
Ellipsoid ED50

Table 1a. Deformation scheme of regional structural elements in the subsurface of the Netherlands onshore and offshore. The scheme indicates for each structural element individually the minimum age and the periods that tectonic activity occurred can be assigned. Included with 'tectonic activity' are basin subsidence, (reverse) faulting and uplift. Excluded from this table is doming and piercing from halokinetic activity. E.g. the Cleaver Bank High has been tectonically active during Variscan phases. During the Permian, Triassic and Early and Middle Jurassic no significant tectonic activity occurred. During the Late Kimmerian phase (Late Jurassic) until the Laramide phase, resp. uplift inversion and erosion occurred on the Cleaver Bank High.

Depth maps presented in this paper			**Rotliegend Group**	**Zechstein Group** Fig. 5	**Lower and Upper Germanic Trias groups** Fig. 6			**Altena Group** Fig. 7
Orogeny		***Variscan orogeny***			***Alpine orogeny***			
Tectonic phase and unconformity		**Saalian**		-		**Hardegsen**	**Early Kimmerian**	
Age of tectonic phase		**290 - 280 My**				**245 - 247 My**	**213 - 204 My**	
Regional stress field		*compression*		*extension*		*extension*	*extension*	
Tectonic expression		*wrench faulting*		*subsidence*		*subsidence*	*subsidence*	
Time		**Late Carboniferous**		**Permian**		**Early Triassic**	**Late Triassic**	
Basins, platforms and highs	***Abbreviation***							
Ameland Block	AB							
Brabant Massif	BM	🟫						
Broad Fourteens Basin	BFB					🟪	🟪	
Campine Basin	CB	🟫						
Central Netherlands Basin	CNB			🟥		🟥	🟥	
Central Offshore Platform	COP							
Cleaver Bank High	CBH	🟫						
Dalfsen High	DH							
Dutch Central Graben	DCG					🟪	🟪	
Elbow Spit High	ESH							
Ems Low	EL	🟫		🟫		🟫		
Friesland Platform	FP							
Groningen High	GH	🟫						
Kijkduin High	KH							
Lauwerszee Trough	LT	🟫						
Lower Saxony Basin	LSB							
Maasbommel High	MH							
Mid North Sea High	MNSH	🟫		🟫				
Netherlands High	NH	🟫		🟫		🟫		
Netherlands Swell	NS					🟪		
Noord-Holland Platform	NHP							
North Sea Basin	NSB							
Peel Block	PBL							
Rhenish Massif	RM	🟫						
Roer Valley Graben	RVG	🟫				🟫	🟫	
Schill Grund High	SGH							
Southern Permian Basin	SPB			🟥				
Step Graben	STG							
Terschelling Basin	TB							
Texel-IJsselmeer High	TIJH							
Venlo Block	VBL							
Vlieland Basin	VB							
Vlieland High	VH							
Voorne Trough	VT							
West Netherlands Basin	WNB						🟪	
Winterton High	WH							
Winterton Platform	WP							
Zandvoort Ridge	ZR							
Zeeland Platform	ZP							
Zuiderzee Low	ZZL							
Zuid-Limburg Block	ZLB	🟫						
Faults and fault zones								
Feldbiss Fault	FBF	🟫						
Gronau Fault Zone	GFZ	🟫						
Hantum Fault Zone	HFZ	🟫				🟫		
Indefatigable Fault Zone	IDFZ							
Mid-Netherlands Fault Zone	MNFZ							
Peel Boundary Fault	PBF	🟫				🟫		
Raalte Boundary Fault	RBF							
Rifgronden Fault Zone	RGFZ							
Rijen Fault	RF	🟫				🟫		
Rotterdam Fault Zone	RDFZ					🟪		
Tegelen Fault	TF							

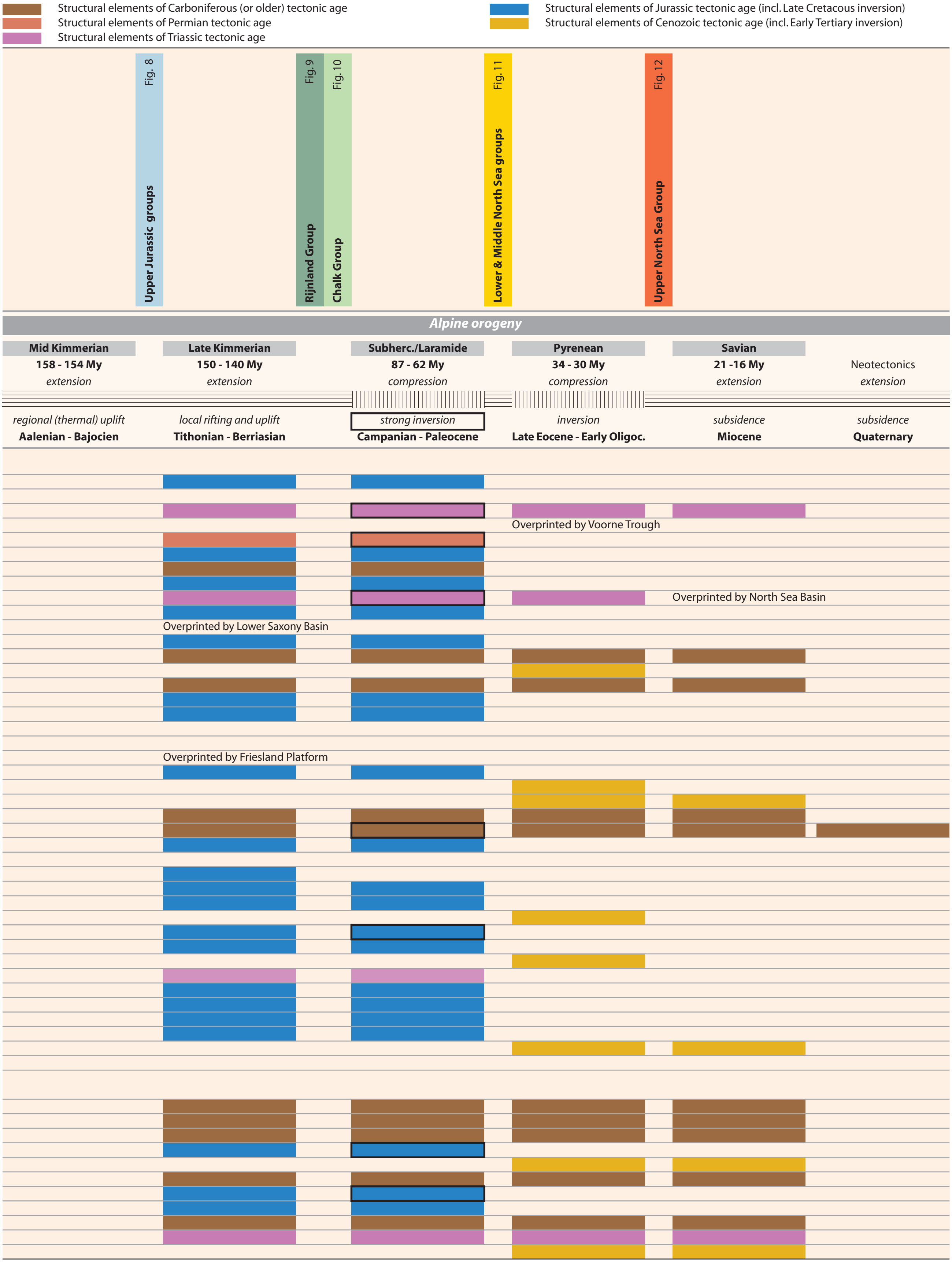

Structural elements of Carboniferous (or older) tectonic age
Structural elements of Permian tectonic age
Structural elements of Triassic tectonic age
Structural elements of Jurassic tectonic age (incl. Late Cretacous inversion)
Structural elements of Cenozoic tectonic age (incl. Early Tertiary inversion)
Fig. 8
Upper Jurassic groups
Fig. 9
Rijnland Group
Fig. 10
Chalk Group
Fig. 11
Lower & Middle North Sea groups
Fig. 12
Upper North Sea Group
Alpine orogeny
Mid Kimmerian
158 - 154 My
extension
regional (thermal) uplift
Aalenian - Bajocien
Late Kimmerian
150 - 140 My
extension
local rifting and uplift
Tithonian - Berriasian
Subherc./Laramide
87 - 62 My
compression
strong inversion
Campanian - Paleocene
Pyrenean
34 - 30 My
compression
inversion
Late Eocene - Early Oligoc.
Savian
21 -16 My
extension
subsidence
Miocene
Neotectonics
extension
subsidence
Quaternary
Overprinted by Voorne Trough
Overprinted by North Sea Basin
Overprinted by Lower Saxony Basin
Overprinted by Friesland Platform

Table 1b. Geological description and abbreviations of regional structural elements.

Geological descriptions of structural elements		
Basins, platforms and highs	***Abbreviation***	
Ameland Block	AB	Stable area between Schill Grund High, Terschelling Basin and Friesland Platform
Brabant Massif	BM	Lower Paleozoic structural element of folded Caledonian rocks, unconformably overlain by Cretaceous rocks; locally overlain by Upper Paleozoic rock
Broad Fourteens Basin	BFB	Depositional basin during the Triassic that was strongly activated during the Jurassic
Campine Basin	CB	Basin flanking the northern border of the Brabant Massif, indicated by thick sequence of Westphalian C/D and Stephanian
Central Netherlands Basin	CNB	Permian and Jurassic basin trending WNW-ESE
Central Offshore Platform	COP	Jurassic erosional area between Vlieland Basin, Terschelling Basin, Dutch Central Graben, Cleaver Bank High and Noord-Holland Platform
Cleaver Bank High	CBH	Area uplifted and eroded during Late Jurassic and Early Cretaceous
Dalfsen High	DH	High structure between Friesland Platform and Central Netherlands Basin
Dutch Central Graben	DCG	Triassic and Jurassic depositional area, delineated as subcrop of Lower Jurassic; southern extension of northerly Viking Graben
Elbow Spit High	ESH	NNW-SSE structure with Kimmerian erosion down to Carboniferous and Devonian; high area during Permian
Ems Low	EL	N-S trending basinal structure along the Dutch-German border, active in Westphalian C and Triassic
Friesland Platform	FP	Stable platform area with significant Jurassic erosion, situated between Texel-IJsselmeer High, Lower Saxony Basin and Central Netherlands Basin
Groningen High	GH	Stable structural high between Lauwerszee Trough and Ems Low delineated by normal faults and by Pre-Permian subcrop map
Kijkduin High	KH	High area in the centre of the WNB due to inversion in Late Eocene, NW-SE trend
Lauwerszee Trough	LT	Fault block between the Friesland Platform and the Groningen High, flanked by the Hantum Fault Zone in the west
Lower Saxony Basin	LSB	Jurassic basin defined by occurrence of Upper Jurassic and Lower Cretaceous deposits
Maasbommel High	MH	Jurassic erosional area where Lower Cretaceous unconformably overlies Triassic, Permian and Carboniferous
Mid North Sea High	MNSH	Structural high during Late Carboniferous and Permian age
Netherlands High	NH	Erosional area in northern Netherlands during Late Carboniferous and Early Permian
Netherlands Swell	NS	Erosional area in northern Netherlands during the Triassic, delineated by absence of Volpriehausen Member
Noord-Holland Platform	NHP	Jurassic erosional area where Lower Cretaceous unconformably overlies Triassic, Permian or Carboniferous
North Sea Basin	NSB	Present-day North Sea Basin
Peel Block	PBL	Stable fault block, northeast of the Roer Valley Graben
Rhenish Massif	RM	High structure, SE Netherlands at German border. Rocks deformed during the Variscan and uplifted during Jurassic and Cenozoic
Roer Valley Graben	RVG	Graben system in southwest Netherlands located between Brabant Massif and Peel Block
Schill Grund High	SGH	Stable platform area southerly of the Rynkøbing Fyn High, flanking the Dutch Central Graben
Southern Permian Basin	SPB	Permian depositional area located between Brabant Massif and Rynkøbing Fyn High
Step Graben	STG	Intermediate fault block between Elbow Spit High, Cleaver Bank High and Dutch Central Graben; Upper Jurassic locally present
Terschelling Basin	TB	Upper Jurassic basin in the Netherlands offshore, delineated between the Dutch Central Graben and the Friesland Platform; Lower Jurassic is absent
Texel-IJsselmeer High	TIJH	Tilted and uplifted structure between Central Netherlands Basin and Friesland Platform, where Carboniferous was eroded during the Jurassic
Venlo Block	VBL	Stable fault block, northeast of the Peel Block and Roer Valley Graben
Vlieland Basin	VB	Late Jurassic and Early Cretaceous basin in the Netherlands offshore area
Vlieland High	VH	Platform area between Terschelling and Vlieland Basin
Voorne Trough	VT	Early Tertiary subsidence area, between West Netherlands Basin and Zeeland Platform
West Netherlands Basin	WNB	Depositional area during Triassic and Jurassic, between Brabant Massif and Netherlands Swell
Winterton High	WH	Stable structural unit between Brabant Massif and Broad Fourteens Basin, Triassic completely eroded
Winterton Platform	WP	Platform area surrounding the Winterton High, Triassic partly eroded
Zandvoort Ridge	ZR	Fault block between Central Netherlands Basin and West Netherlands Basin defined by severe faulting
Zeeland Platform	ZP	Jurassic erosional area between the Brabant Massif and the West Netherlands Basin
Zuiderzee Low	ZZL	Early Tertiary basin in the central onshore area
Zuid-Limburg Block	ZLB	Stable fault block at northern flank of the Brabant Massif that was strongly uplifted during Variscan pulses
Faults and fault zones		
Feldbiss Fault	FBF	Southern fault of the Roer Valley Graben trending NW-SE
Gronau Fault Zone	GFZ	Separating Central Netherlands Basin and Lower Saxony Basin
Hantum Fault Zone	HFZ	Separating the Ameland Block from the Vlieland High and the Friesland Platform, active since Carboniferous
Indefatigable Fault Zone	IDFZ	Separating Broad Fourteens Basin and the Winterton Platform
Mid-Netherlands Fault Zone	MNFZ	Separating the Central Netherlands Basin and the West Netherlands Basin and flanks the Zandvoort Ridge
Peel Boundary Fault	PBF	Northern border of Roer Valley Graben, active since Carboniferous and Brabant trending NW-SE
Raalte Boundary Fault	RBF	Separating the Texel-IJsselmeer High and Central Netherlands Basin
Rifgronden Fault Zone	RGFZ	Separating the Terschelling Basin and the Schill Grund High
Rijen Fault	RF	Southwestern limit of the northwestern part of the Roer Valley Graben
Rotterdam Fault Zone	RDFZ	Fault zone in the axis of the inversion zone of the West Netherlands Basin
Tegelen Fault	TF	Separating the Peel Block and the Central Netherlands Basin

the Permian, Triassic and Cretaceous basins. Strong halokinetic movements took place in the northern offshore and the north-eastern onshore area. The thickness variation of Zechstein salt can be easily observed in the geological profiles and the thickness map of the Zechstein (Fig. 5b). Salt structures are revealed by thicknesses of Zechstein larger than 1300 m (Fig. 5b). Salt pillows, walls and diapirs have been active since the Late Triassic. Both intensity and (re-)activation of salt movement varies locally very strongly.

Pre-Zechstein

Carboniferous

In the Netherlands, Early Carboniferous (Tournaisian and Visean) sediments are only known from a few wells. In the southern part of the Dutch onshore and offshore these sediments consist of black limestones whereas in the northern offshore Early Carboniferous rocks are of clastic origin. Upper Carboniferous deposits (Namurian, Westphalian and Stephanian) are widely distributed in the subsurface of the Netherlands (Van Adrichem Boogaert & Kouwe, 1993 - 1997). The total thickness and distribution of the Carboniferous strata is not known in detail due to their deep burial. In large parts of the Netherlands the Carboniferous subcrop is well-documented as it is the source rock of many gas fields and a target of gas exploration (Mijnlieff, 2005).

The depth of the top of the Carboniferous can be greater than 6000 m and the Carboniferous deposits locally reach thicknesses of more than 4000 m (TNO-NITG, 2004). Hence, in many locations these deposits are thicker than the total thickness of the cumulative Permian to Cenozoic deposits. The

Carboniferous deposits are overlain by Middle and Late Permian sediments of the Upper Rotliegend and Zechstein groups (Fig. 3). The Carboniferous is unconformably overlain by the Early Cretaceous Rijnland Group on structural high elements, such as the Texel-IJsselmeer (TIJH) (Fig. 3c), and Winterton highs (WH) or by the Chalk Group in the southern parts of the Netherlands. Carboniferous strata are absent in the southernmost part of the onshore and offshore and locally on the Elbow Spit High, where Devonian strata directly are overlain by the Late Cretaceous Chalk Group.

The Variscan structural elements map (Fig. 4a) shows the Campine Basin (CB), Roer Valley Graben (RVG), Ems Low (EL) and the Cleaver Bank High (CBH) that developed in response to Permo-Carboniferous wrench tectonics (Mijnlieff, 2005). Westphalian D strata are present in these synclinal structures which resulted from Variscan tectonics (Schroot & De Haan, 2003). Most large fault zones that have come into existence during the Permo-Carboniferous have been reactivated repeatedly later, such as the Hantum Fault Zone (HFZ), Gronau Fault Zone (GFZ), Raalte Boundary Fault (RBF) and Peel Boundary Fault (PBF). According to Schroot & De Haan (2003) the Carboniferous fault system of the Cleaver Bank High shows NW-SE and NE-SW orientations. The orientation of Variscan faults in NW-Europe is generally developed in a NW-SE to WNW-ESE direction (Scheck-Wenderoth & Lamarche, 2004; Schroot & De Haan, 2003; Ziegler et al., 2004).

Lower and Upper Rotliegend (Early and Middle Permian)

After the transpressional tectonics of the Variscan orogeny, Lower and Upper Rotliegend sediments were deposited under continental conditions during the Early and Middle Permian in the Southern Permian Basin (SPB) (Fig. 4b). The Southern Permian Basin is defined by the occurrence of Rotliegend and Zechstein deposits, south of the Mid North Sea High (MNSH) and the Ringkøbing Fyn High. The thickness of the Rotliegend section reaches a maximum value of more than 900 m in the G-block in the northeastern offshore area (Fig. 4b; Geluk, 2005). Subsidence of the central parts of the Southern Permian Basin took place during the Middle and Late Permian, in conjunction with the pre-cursor of the Broad Fourteens Basin (BFB) and the Central Netherlands Basin (CNB). The Southern Permian Basin has developed in a WNW-ESE direction north of the Brabant Massif (BM). The local absence of the Rotliegend deposits within the Southern Permian Basin, such as on the Texel-IJsselmeer High (TIJH) and on the Winterton High (WH), is the result of Jurassic erosion. However, it was also shown by Rijkers & Geluk (1993) that the Texel-IJsselmeer High was a high structure during the Permian, which is indicated by the thickness development and sedimentary facies changes of the Upper Rotliegend and Zechstein groups around the high.

Zechstein Group (Late Permian)

Depth, thickness and basin development

The outlines of the Zechstein basin coincide largely with the occurrence of deposits of the Upper Rotliegend Group (Fig. 3b). The southernmost occurrence of Zechstein sediments defines the southern margin of the Southern Permian Basin. The present-day depth of the base of the Zechstein Group ranges from almost 700 m in the southeastern part of the Netherlands to more than 5000 m in the Dutch Central Graben, the Broad Fourteens Basin and the West Netherlands Basin (Fig. 5a). Basins that have subsided further during the Early and Late Kimmerian phases, such as the Dutch Central Graben (DCG), Terschelling Basin (TB), Broad Fourteens Basin (BFB), Ems Low (EL) and Roer Valley Graben (RVG), are clearly outlined in the depth map of the base of the Zechstein Group (Fig. 5a). The thickness of the Zechstein Group increases strongly to the north up to more than 900 m on Late Jurassic platforms (Fig. 5b).

Structural development

At the Maasbommel (MH), Winterton (WH), Texel-IJsselmeer (TIJH), Dalfsen (DH) and Elbow Spit highs (ESH) the Zechstein is absent due to Mid- and Late Kimmerian erosion (Figs 5a and 5b). The absence of Zechstein deposits on the Texel-IJsselmeer High is the result of strong Mid- and Late Kimmerian uplift and erosion (Rijkers & Geluk, 1994). In the southern part of the Netherlands only thin Zechstein deposits are present due to shallow basin development.

The Dutch Central Graben and the Terschelling Basin show pronounced occurrences of salt diapirs and walls. The northeastern onshore and northern offshore areas are characterized by the widespread occurrence of salt structures with local thicknesses of more than 1300 m (Fig. 5b). The area of mobilized Zechstein salt is clearly visible by the lateral thickness variations. In the areas that have been tectonically active, such as the Terschelling Basin and the Dutch Central Graben, the original Zechstein depositional thickness is obscured by halokinesis (Fig. 5b). On platforms like the Cleaver Bank High and the Ameland Block, where post-Zechstein tectonics have been relatively quiet, the Zechstein is thicker than 900 m, which indicates the minimum depositional thickness of the Zechstein sequence for the offshore E, F, K, L and M-blocks. The absence of Zechstein deposits on Kimmerian highs in the northern salt province is the result of strong Kimmerian uplift and erosion. In the Dutch Central Graben (DCG), Terschelling Basin (TB) and the western part of the Schill Grund High (SGH) the Zechstein salt is locally absent due to salt movement (Fig. 5b). The thin Zechstein sections in these halokinetic areas consist of residual carbonates and anhydrites.

Lower and Upper Germanic Trias groups

Depth, thickness and basin development

The present-day depth of the base of the Lower Germanic Trias Group ranges from approximately 500 m in eastern Netherlands to over 5000 m in the Dutch Central Graben (Fig. 6a). As the result of Jurassic subsidence, thick Triassic deposits have only been preserved in the Dutch Central Graben, Terschelling, Broad Fourteens, Central Netherlands, Lower Saxony basins and Roer Valley Graben (Figs 6a and 6b). In the other areas the Triassic deposits were eroded during the Late Jurassic. The total thickness of Triassic deposits amounts to more than 1800 m in the Dutch Central Graben (Fig. 6b). During the Triassic the Dutch Central Graben, Roer Valley Graben and the Broad Fourteens Basin have subsided relatively faster than the surrounding highs which resulted in greater thicknesses in these basins (Fig. 6b; Geluk, 2005). The Netherlands Swell is the area in the northern part of the Netherlands that is strictly defined by the subcrop of the Volpriehausen Sandstone Member in the Lower Germanic Trias Group (Geluk, et al., 2005). The Netherlands Swell was a relative high during the Early Triassic and was paralleled by the Hardegsen event in the Early Triassic (Geluk, 2005; Fig. 4c).

Structural development

Erosion of Triassic deposits occurred on structural highs such as the Elbow Spit (ESH), Cleaver Bank (CBH), Texel-IJsselmeer (TIJH), Dalfsen (DH), Winterton (WH) and Maasbommel highs (MH) and Friesland Platform (FP), sometimes removing the entire Triassic succession (Figs 6a and 6b). The greater part of the erosion of Triassic deposits occurred in response to Late Jurassic uplift. Moreover, salt walls and erosion obscure such faulting. The borders of the Dutch Central Graben and the Terschelling Basin appear to be preferential sites for the development of thrust (inversion) faults together with salt walls and diapirs. The faults in the Triassic maps in Figs 6a and 6b are the cumulative result of Jurassic rifting and Late Cretaceous inversion tectonics. Triassic extensional tectonics in the Netherlands was paralleled by rifting in the Arctic-North Atlantic domain (Ziegler, 1988).

Altena Group (Early and Middle Jurassic)

Depth, thickness and basin development

The depth of the base of the Altena Group ranges from less than 1000 m in the eastern Netherlands to more than 5000 m in the Dutch Central Graben and the Broad Fourteens Basin (Fig. 7a). In the easternmost part of the Central Netherlands Basin, strata of the Altena Group outcrop. The Central Netherlands Basin has developed in a WNW-ESE direction and the Dutch Central Graben in a N-S direction (Fig. 4d). The Broad Fourteens Basin, Roer Valley Graben and West Netherlands Basin have developed in NW-SE to NNW-SSE directions (Fig. 4d). The Hantum Fault Zone, as the southern boundary of the Terschelling Basin, is considered to be the feature link between the Lower Saxony Basin and the southern parts of the Dutch Central Graben. In addition, the Vlieland Basin (VB) has been activated in response to a Late Jurassic dextral strike-slip faulting (Herngreen et al., 1991).

Structural development

Due to Late Cretaceous basin inversion and uplift, Lower Jurassic deposits have been partly eroded in the Central Netherlands Basin, especially on higher fault blocks (Figs 7a and 7b; Fig. 3). The Central Netherlands Basin and the Roer Valley Graben have been strongly inverted during the Subhercynian/Laramide phase removing most of its Jurassic (and Cretaceous) infill (Figs 7a, 9a and 10a). Local uplift and subsequent erosion during Middle Jurassic to Early Cretaceous tectonic phases have almost completely removed Altena deposits on the structural highs and platform areas (Fig. 7a). In the transition zone between the West Netherlands Basin and the Roer Valley Graben, subtle but distinct structural NNW-SSE and WNW-ESE fault directions can be observed on the depth and thickness maps of the Altena Group (Figs 7a and 7b).

Schieland, Scruff and Niedersachsen groups (Late Jurassic)

Depth, thickness and basin development

Upper Jurassic deposits are only found in depocentres of the Dutch Central Graben (DCG), Roer Valley Graben (RVG), Vlieland (VB), Terschelling (TB), Broad Fourteens (BFB), West Netherlands (WNB) and Central Netherlands basins (CNB) (Figs 8a and 8b). The geographical extension of Late Jurassic deposits is very similar to those of the Early Jurassic deposits (Fig. 7a). The depth of the Upper Jurassic sediments ranges from almost 100 m in the eastern Netherlands to over 3000 m in the Dutch Central Graben, Terschelling Basin, Vlieland Basin and Broad Fourteens Basin (Fig. 8a). The thickness of the Upper Jurassic deposits is strongly influenced by inversion and erosion during the Late Cretaceous. A thickness of over 1000 m is only present in the most active Late Jurassic structures, such as the Dutch Central Graben and the Broad Fourteens Basin (Fig. 8b). These basins were deformed by strong local rift tectonics of the Late Kimmerian phases. Complex Late Jurassic tectonics obscure the earlier geological deformation history because Late Kimmerian tectonics initiated both basin subsidence and uplift of platforms and highs. Upper Jurassic deposition started in the Dutch Central Graben during the Oxfordian in continental and lacustrine facies. These depositional environments of the

Kimmeridgian in the Dutch Central Graben expanded towards the south into the Broad Fourteens and the West Netherlands basins during the Portlandian (Van Adrichem Boogaert & Kouwe, 1993 - 1997; Herngreen & Wong, 1989).

Structural development

On the Late Jurassic structural highs the deposits of the Triassic, Zechstein and Rotliegend are completely eroded (Fig 4d). Late Jurassic platforms are delineated by complete erosion of Altena and/or Upper Jurassic deposits. Late Jurassic basins in the southern offshore and onshore of the Netherlands are controlled by NW-SE trending fault systems, with WNW-ESE and NNW-SSE trending faults playing a subsidiary role (Fig. 8a). Periods of enhanced salt flow correspond with tectonic phases (Remmelts, 1996). Late Jurassic faulting together with sea level fluctuations resulted in a large variety of facies systems ranging from open marine to continental deposits (Herngreen & Wong, 1989; Van Adrichem Boogaert & Kouwe, 1993 - 1997). The Zuidwal volcanic complex in the Vlieland Basin was active during the Late Jurassic, dividing this basin into a continental and a marine part (Figs 8a and 8b). Volcanic activity in the Vlieland Basin was coupled to transpressional wrench tectonics during the Oxfordian (Herngreen et al., 1991). Late Jurassic rifting and wrench tectonics in the Netherlands was paralleled by a major extensional event in the central and northern North Sea as well by the Arctic-North Atlantic rifting phase (Ziegler, 1988, 1990), locally referred to as Late Kimmerian rifting phase.

Rijnland Group (Early Cretaceous)

Depth, thickness and basin development

The present-day depth of the Rijnland Group ranges from the outcrops in the eastern part of the Netherlands to more than 3000 m in the West Netherlands Basin, the Central Offshore Platform (COP), the Schill Grund High (SGH) and the northern offshore (Fig. 9a). The thickness map of the Rijnland Group shows the Lower Cretaceous depocentres in the Broad Fourteens and the West Netherlands basins. The Vlieland, Terschelling and Lower Saxony basins formed minor depocentres (Fig. 9b). The present-day depth and occurrence of deposits of the Rijnland Group is strongly influenced by Late Cretaceous inversion (Fig. 9a). Erosion of Rijnland deposits occurred in the Roer Valley Graben, Central Netherlands Basin and Dutch Central Graben (Fig. 9a). The present-day depth of the Rijnland Group of more than 3000 m in the A- and B-blocks is partly due to the large basin subsidence of the North Sea Basin during the Cenozoic (Fig. 9a).

Structural development

As a result of Late Cretaceous inversion, the Rijnland Group is locally absent or reduced in thickness in the areas of strongest inversion, especially in the West Netherlands Basin (Fig. 9a). From the depth maps it can be concluded that inversion has also occurred in the Roer Valley Graben, Central Netherlands Basin and Broad Fourteens Basin (Figs 9a and 9b). The thickness map of the Rijnland Group also reveals intense salt tectonics on the Central Offshore Platform and in the Terschelling Basin and the southern part of the Dutch Central Graben, where the Rijnland Group is locally thin or absent.

Chalk Group (Late Cretaceous)

Depth and thickness

The Chalk Group comprises sediments of Cenomanian to Danian age (Van Adrichem Boogaert & Kouwe, 1993 - 1997). The base of the Chalk Group outcrops in the eastern and southern parts of the Netherlands (Figs 10a and 10b). The depth increases towards the north to more than 2800 m in the northern offshore blocks. The base of the Chalk Group is uplifted to 1500 m in the inverted Dutch Central Graben (Fig. 10a). More than 1800 m of sediments of the Chalk Group have been preserved on the Jurassic platforms, whereas Late Cretaceous inversion has partly and completely removed the sediments across the axial parts of the West Netherlands (WNB), Broad Fourteens (BFB), Central Netherlands (CNB), Vlieland (VB) and Lower Saxony basins (LSB) and Dutch Central Graben (DCG) (Figs 4e and 10b). Thin deposits of Danian age, that are stratigraphically the top of the Chalk Group, have been deposited in the inverted basins after the Subhercynian phase. These occurrences are absent on the presented maps (Figs 10a and 10b) due to their small thickness.

Structural development

The axes of maximum inversion are deduced from the regional distribution and thickness of the Upper Cretaceous (Fig. 4e). The tectonic inversion phases seem to have been active simultaneous in most basins. Inversion of these basins appears to have been synchronous during the Subhercynian (Santonian-Campanian), Laramide (Paleocene) and Pyrenean (Eocene) phases of intraplate compression that is attributed to collisional coupling of the Alpine orogenic wedge with its northern foreland (Heybroek, 1974; Ziegler, 1990; De Jager, 2003; Heybroek, 1974; Ziegler, 1990; Van der Molen, 2004). The strongest inversion occurred in the Central Netherlands Basin where the Raalte Boundary Fault has a reversed offset of more than 2000 m (Fig. 3b: E-E').

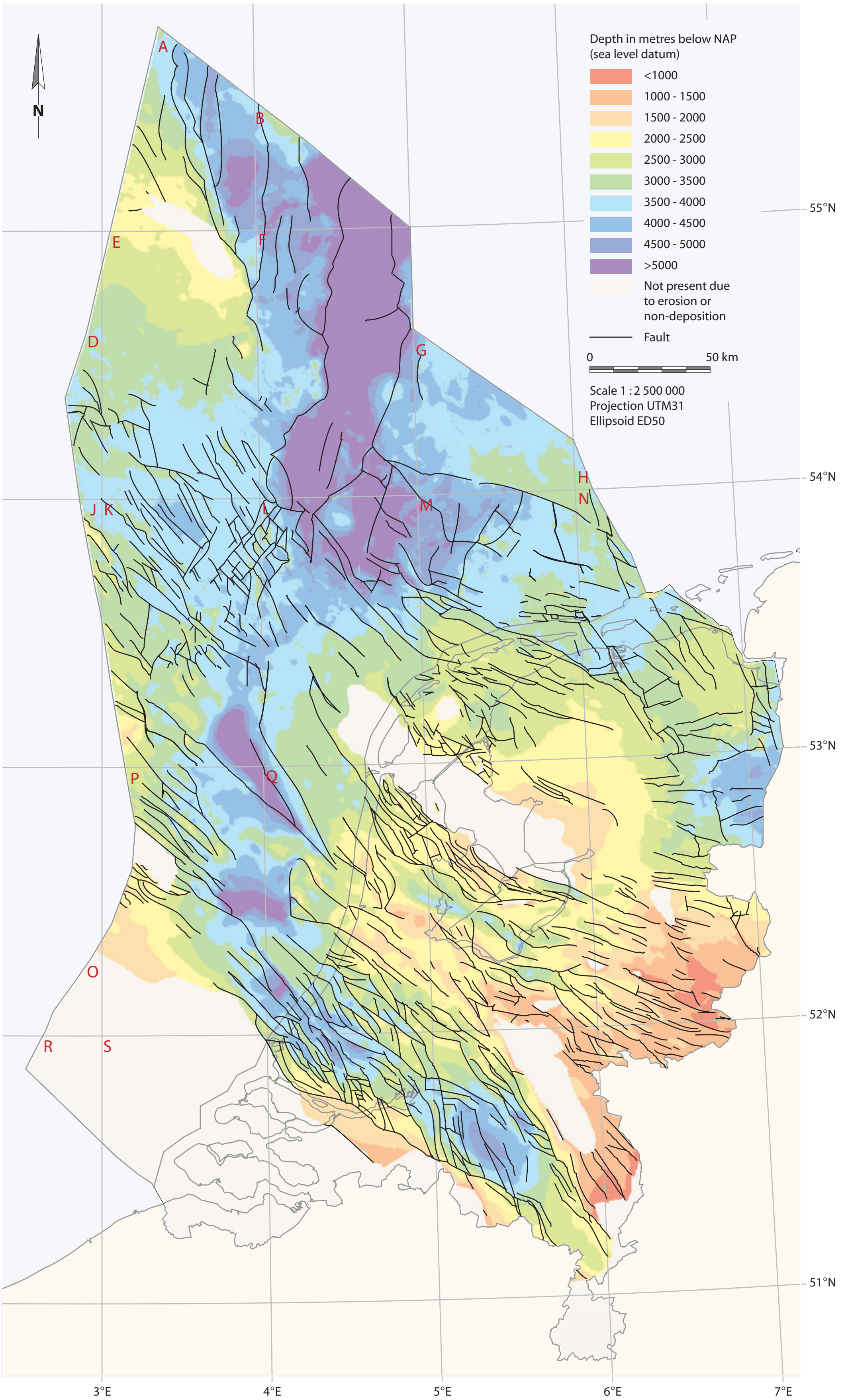


Fig. 5a. Depth map of the base of the Zechstein Group (Late Permian).

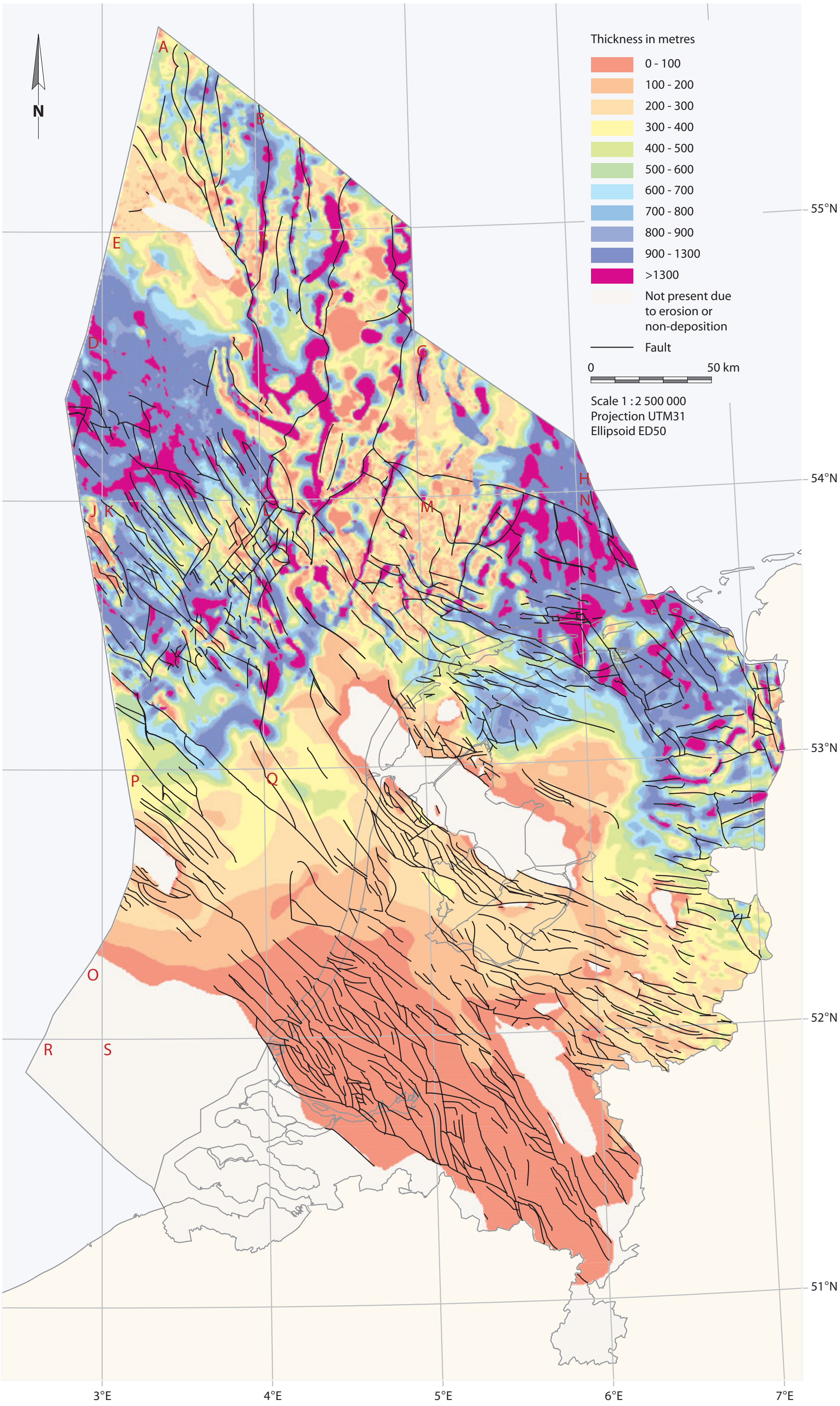


Fig. 5b. Thickness map of the Zechstein Group (Late Permian).

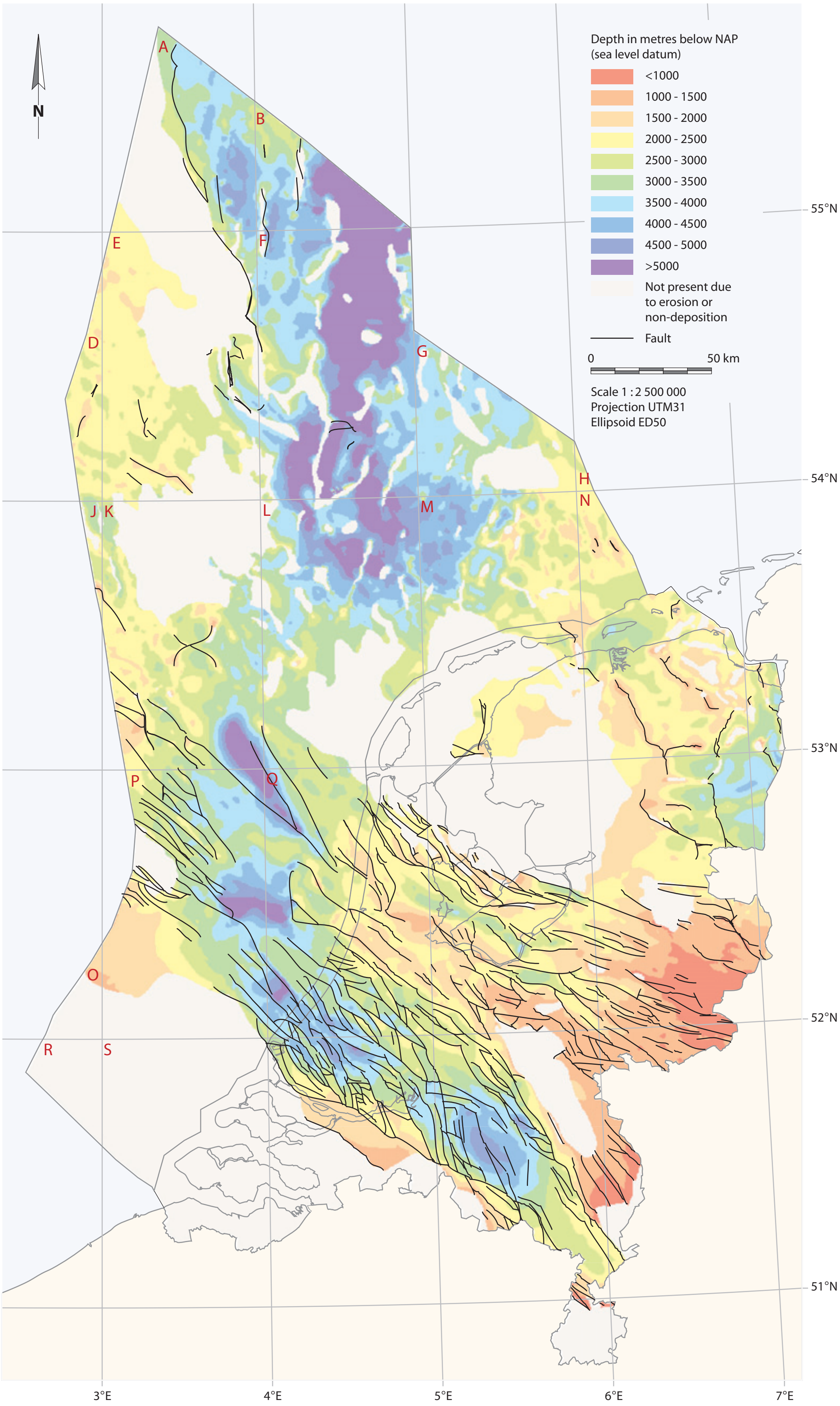


Fig. 6a. *Depth map of the base of the Lower Germanic Trias Group.*

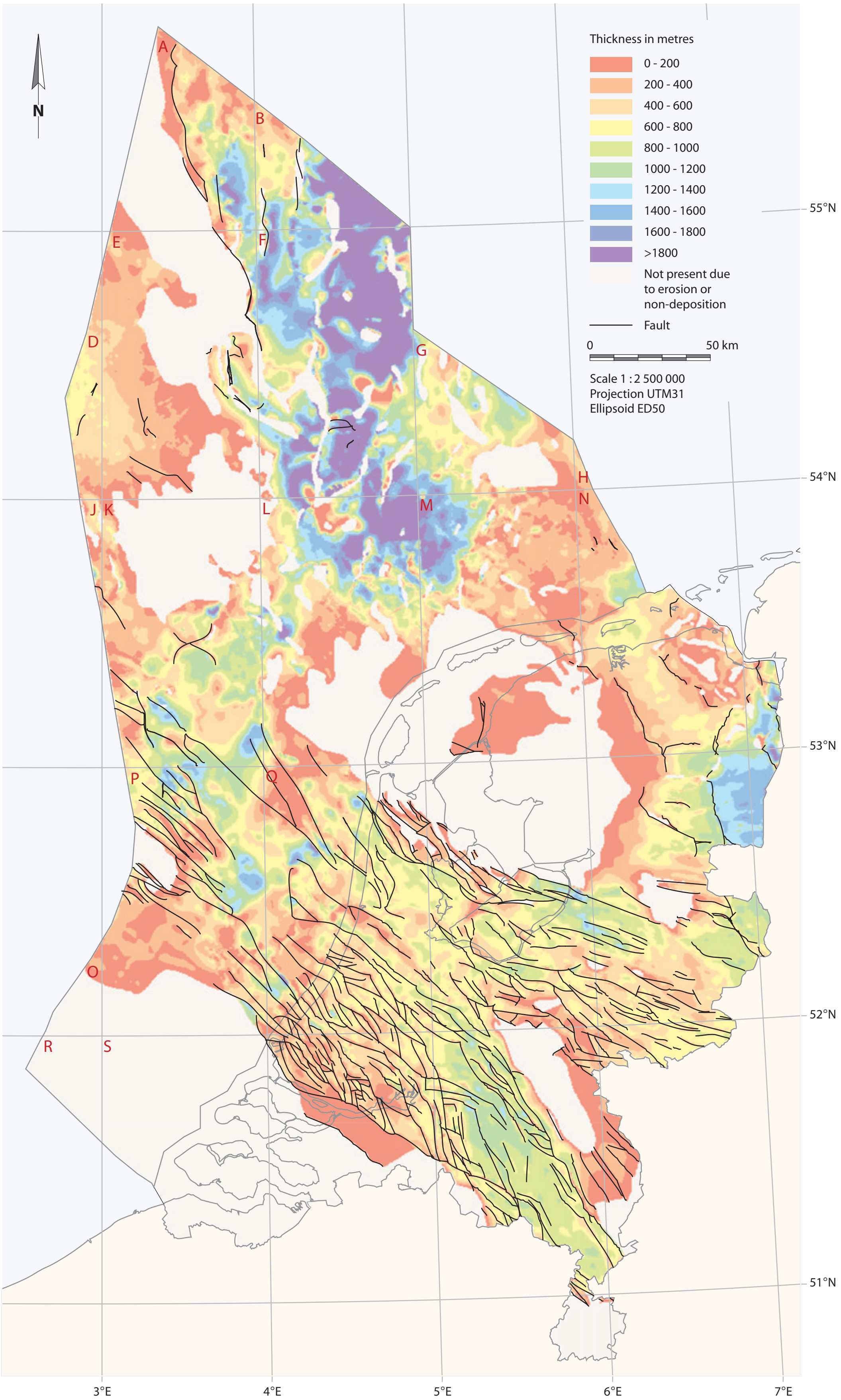


Fig. 6b. Thickness map of the combined Lower and Upper Germanic Trias groups.

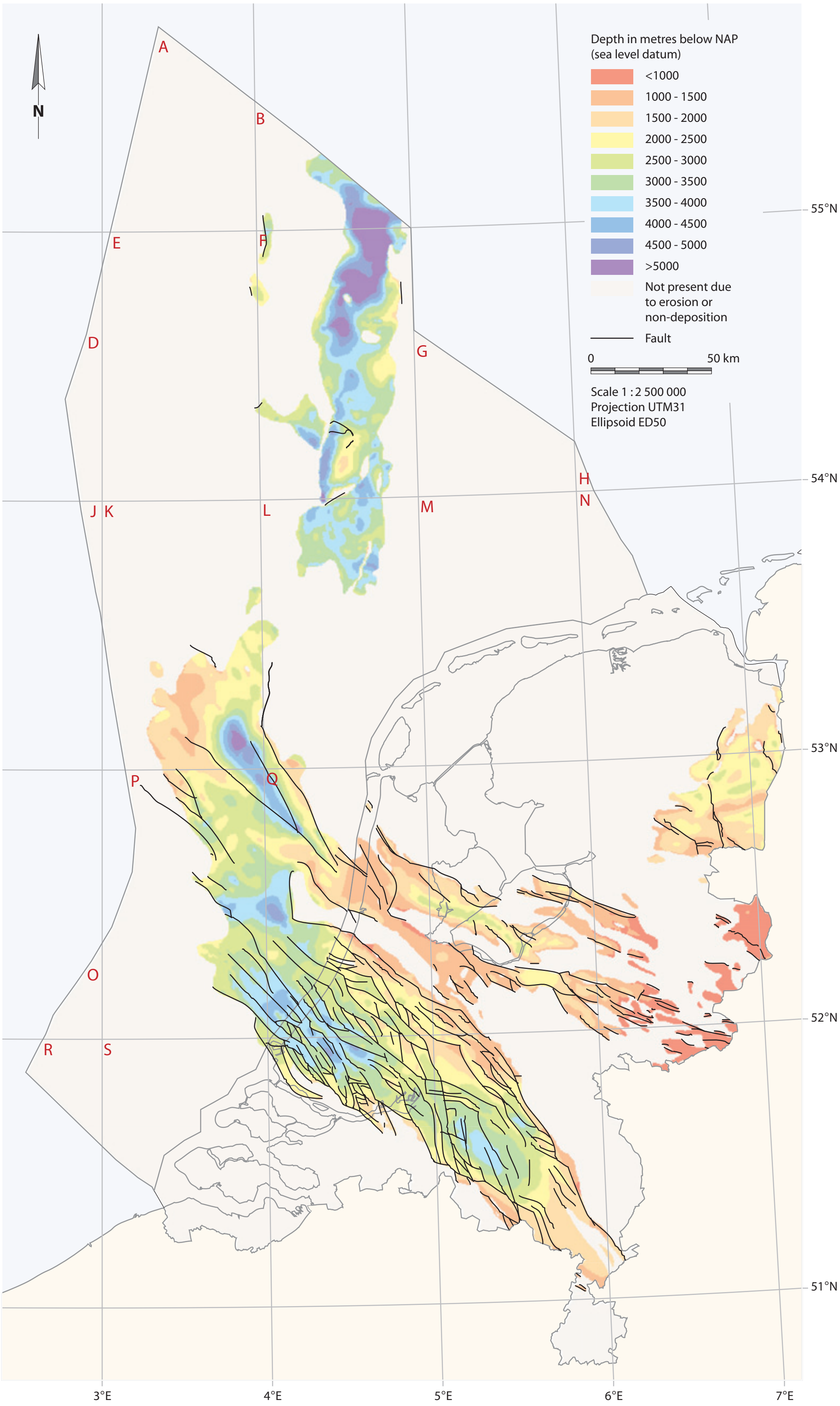


Fig. 7a. Depth map of the base of the Altena Group (Early and Middle Jurassic).

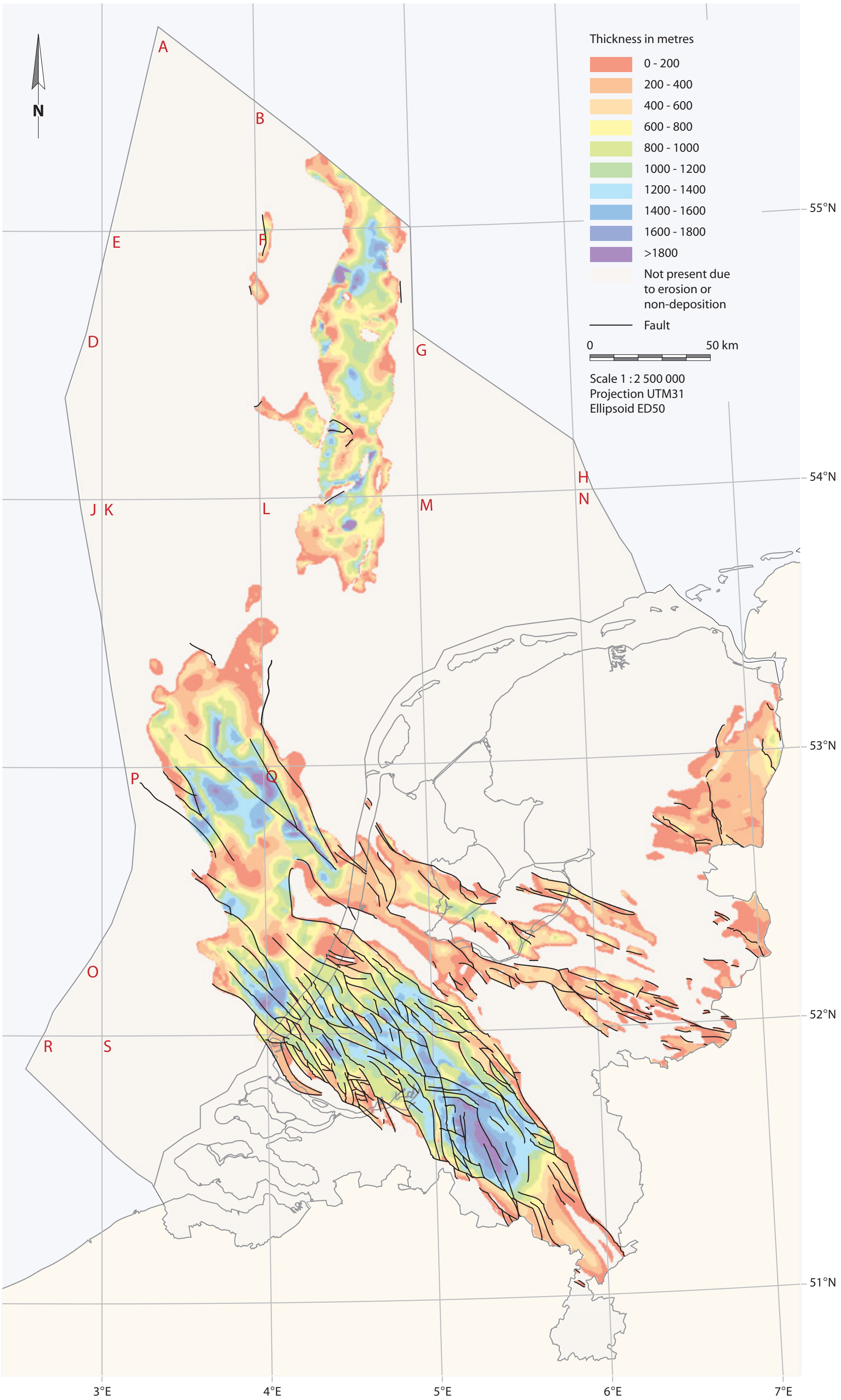


Fig. 7b. *Thickness map of the Altena Group (Early and Middle Jurassic).*

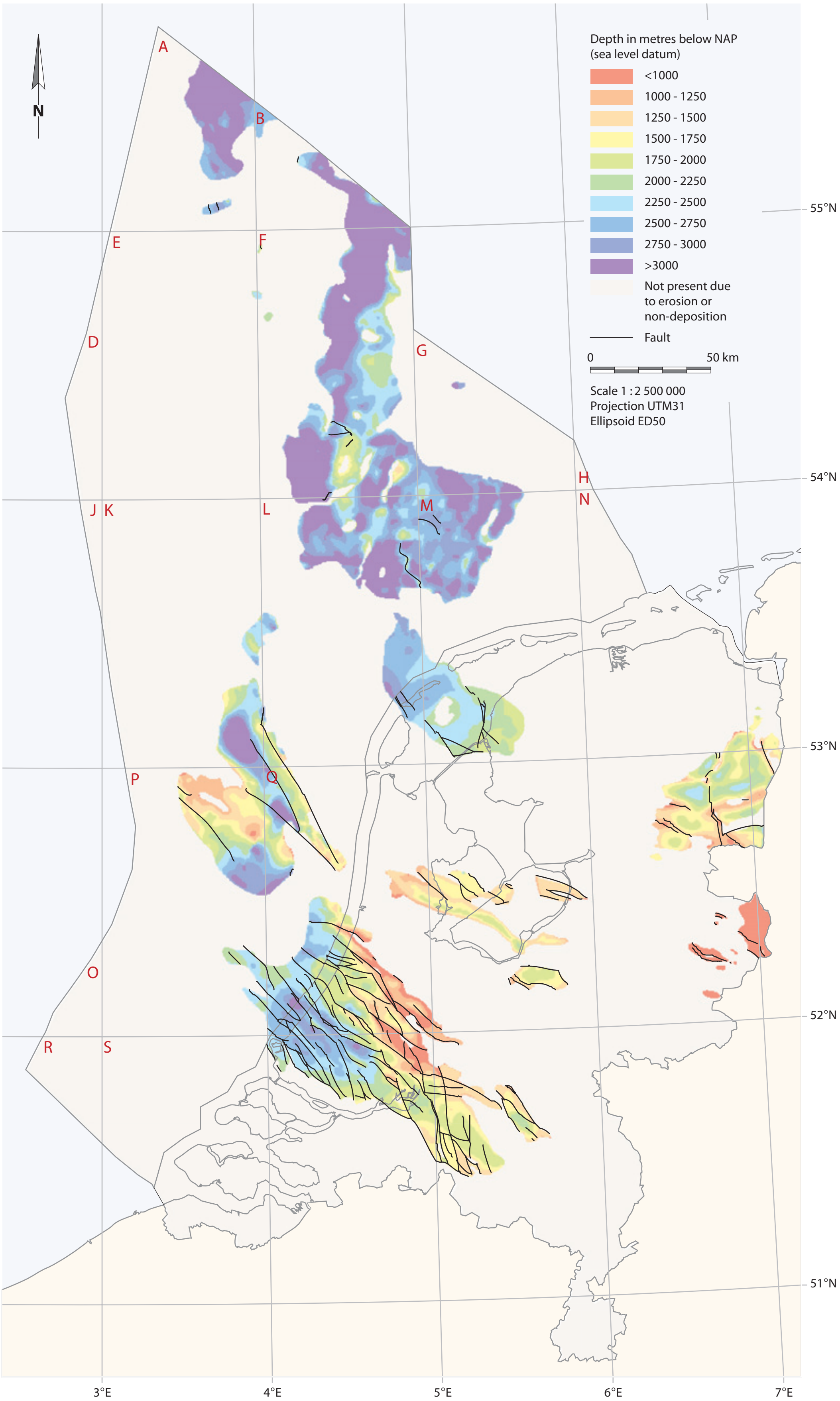


Fig. 8a. Depth map of the base of the Schieland, Scruff and Niedersachsen groups (Late Jurassic).

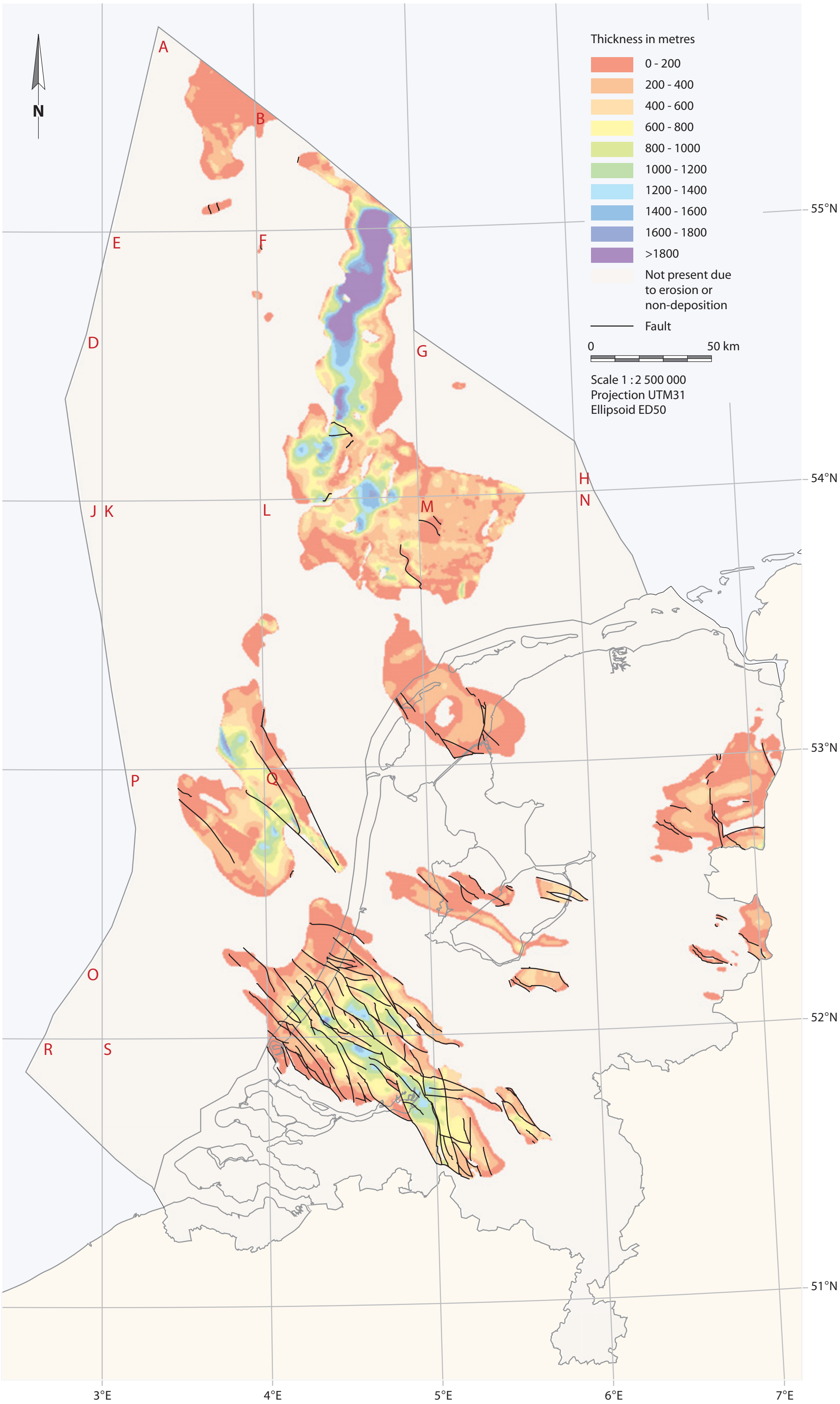


Fig. 8b. Thickness map of the Schieland, Scruff and Niedersachsen groups (Late Jurassic).

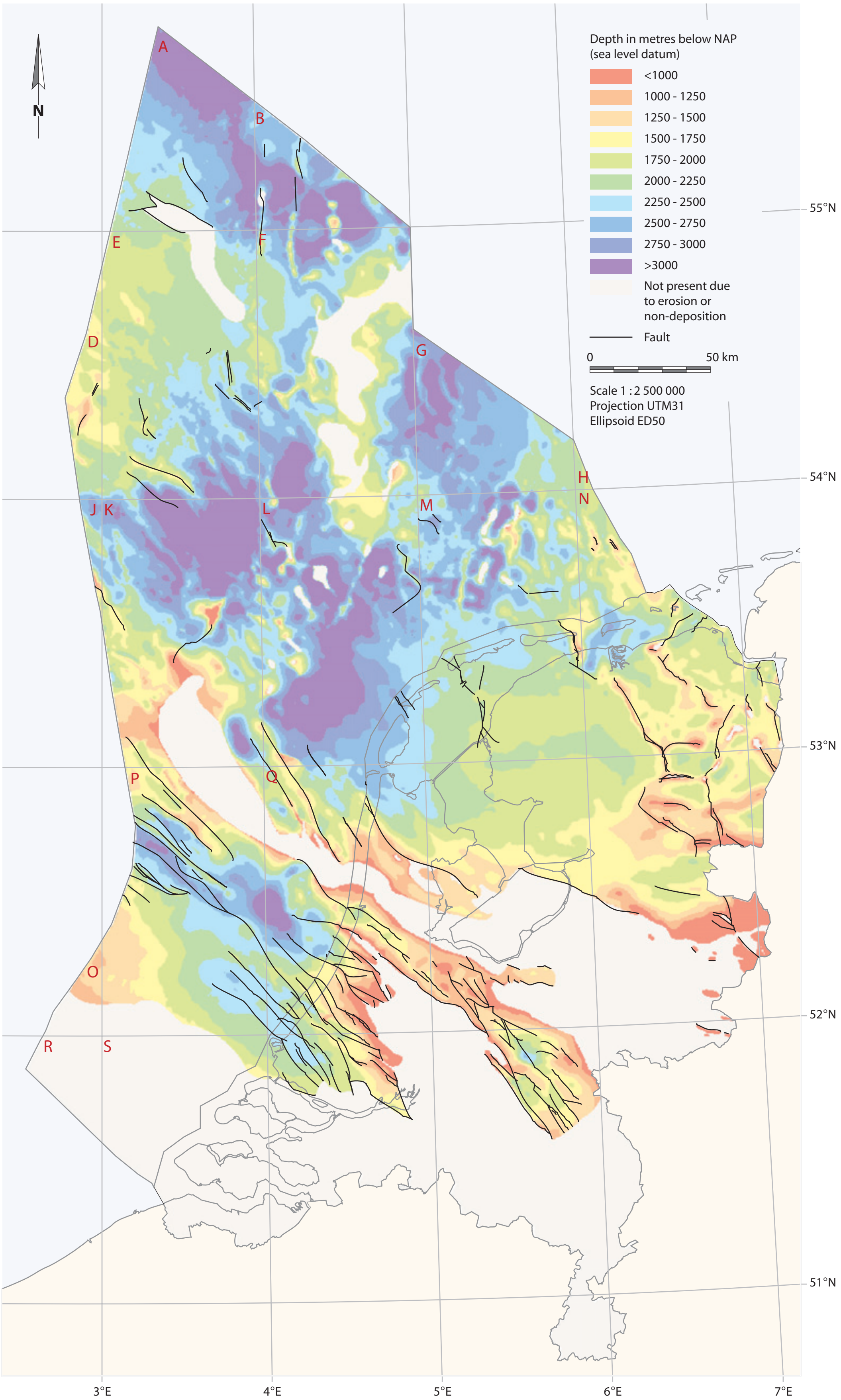


Fig. 9a. Depth map of the base of the Rijnland Group (Early Cretaceous).

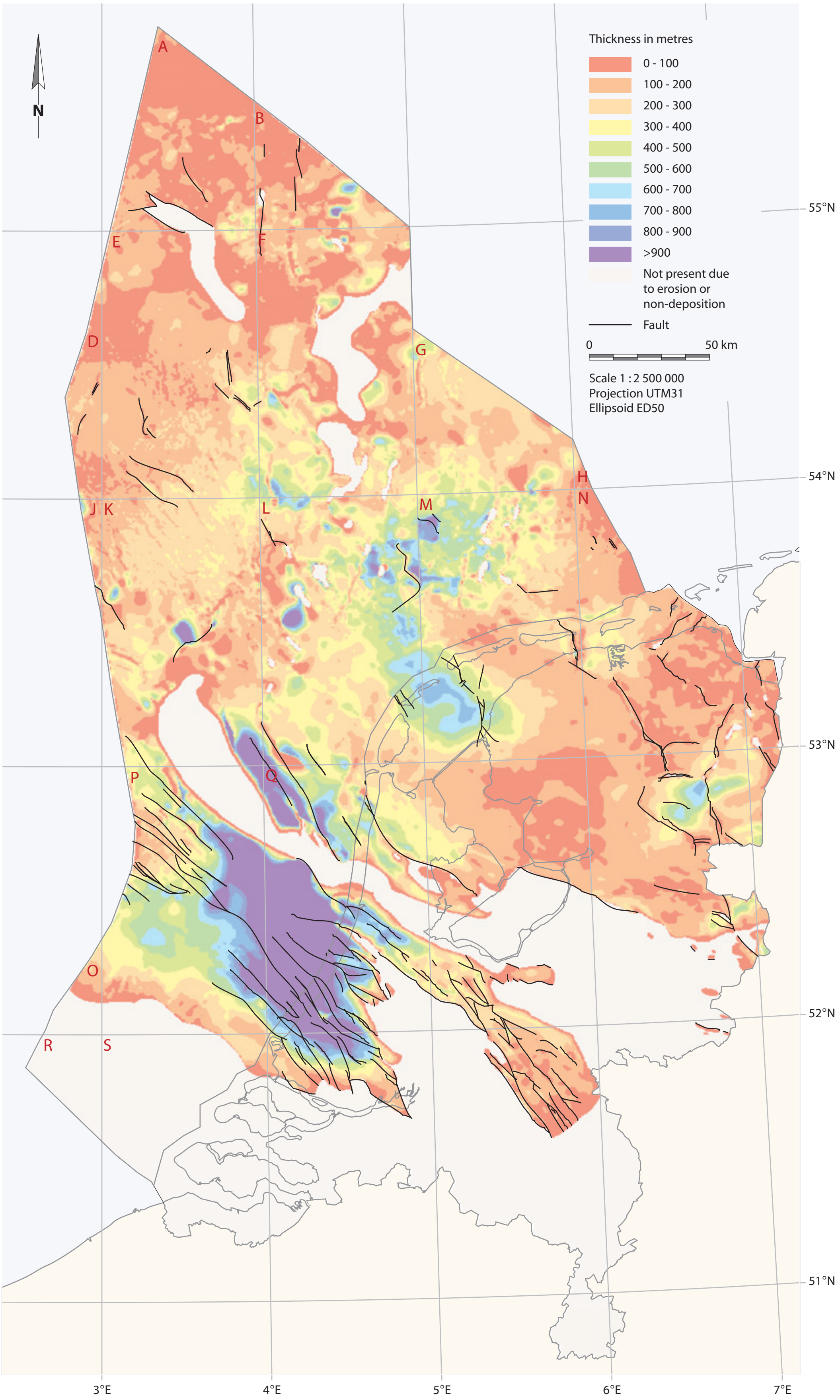


Fig. 9b. Thickness map of the Rijnland Group (Early Cretaceous).

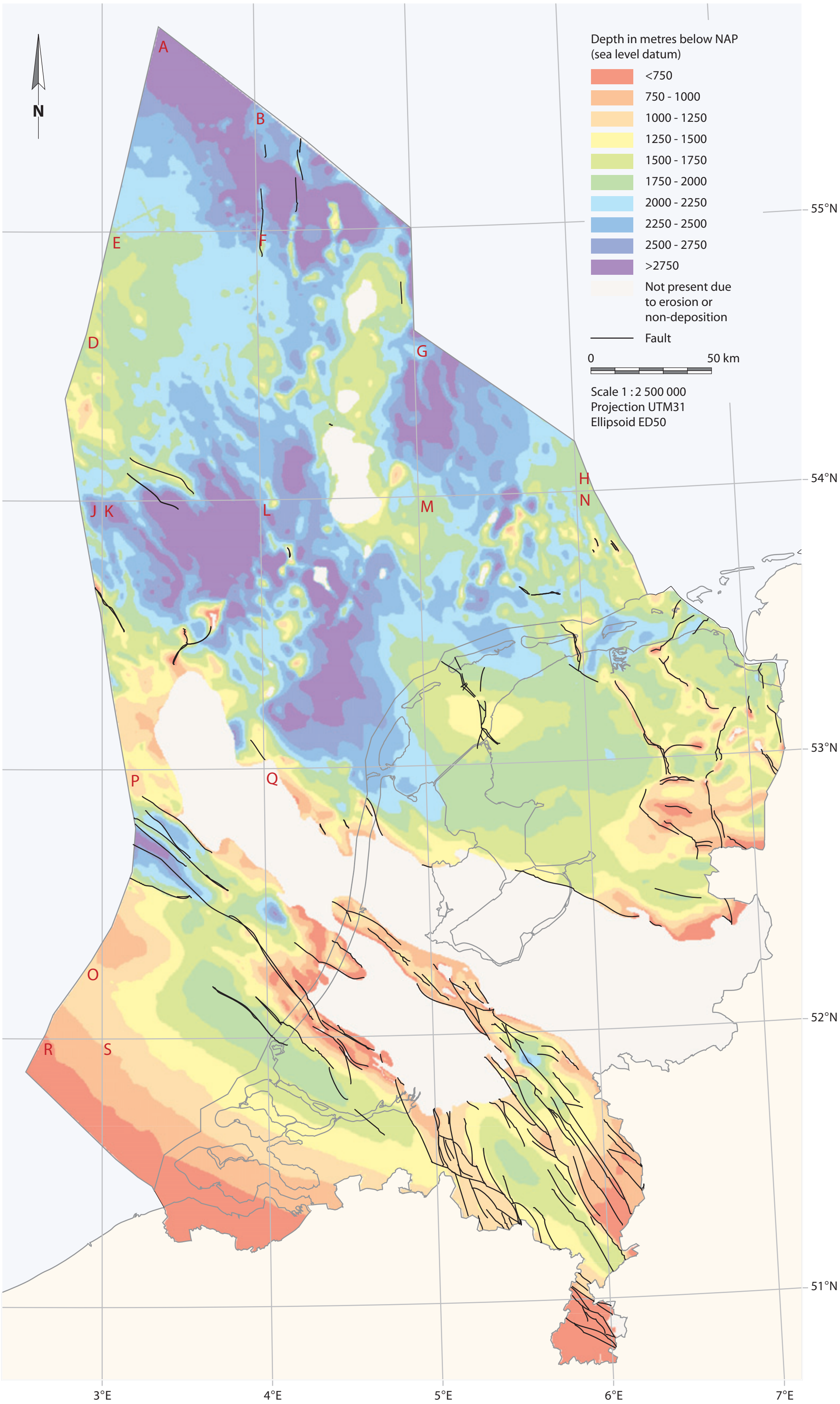


Fig. 10a. Depth map of the base of the Chalk Group (Late Cretaceous).

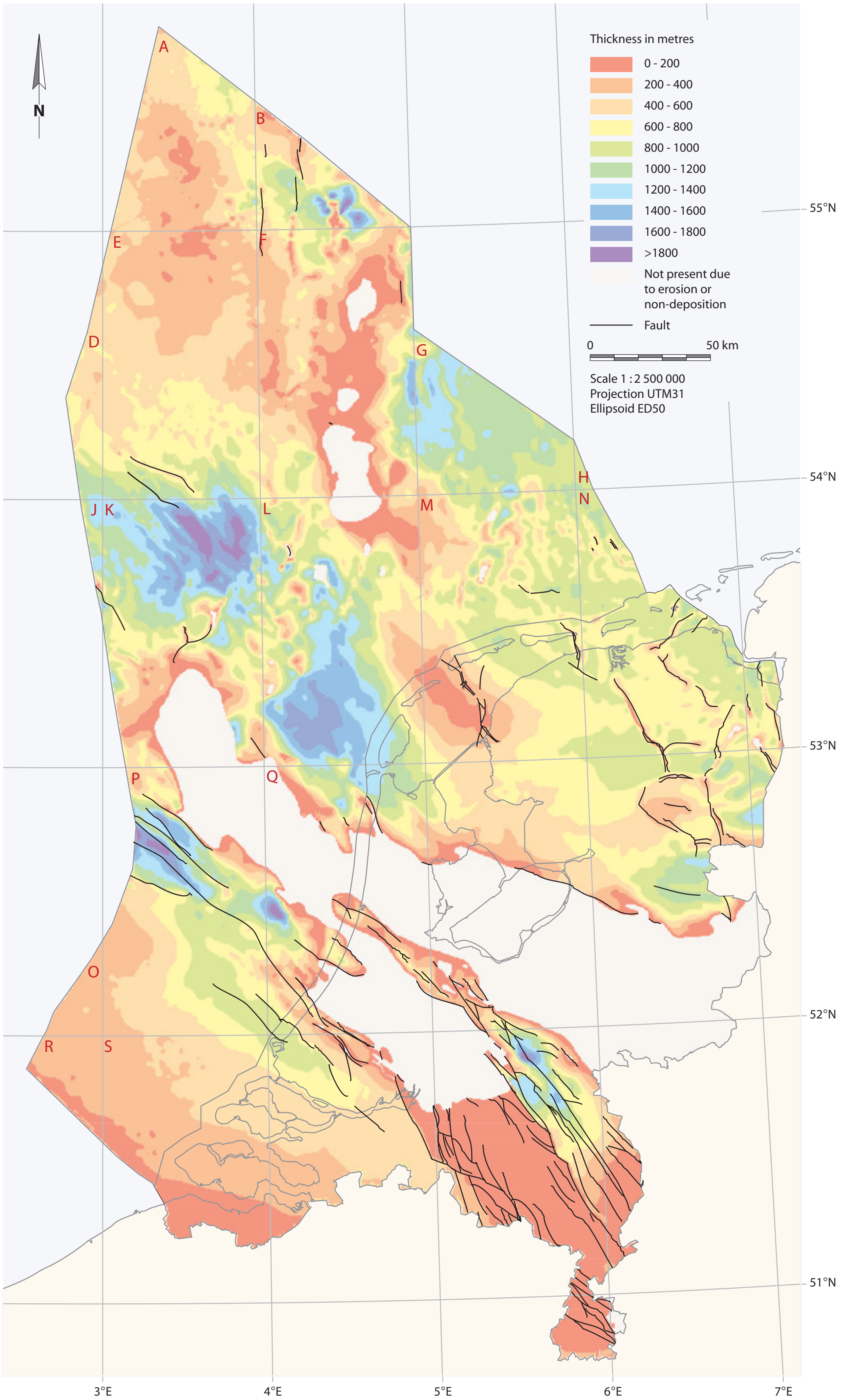


Fig. 10b. Thickness map of the Chalk Group (Late Cretaceous).

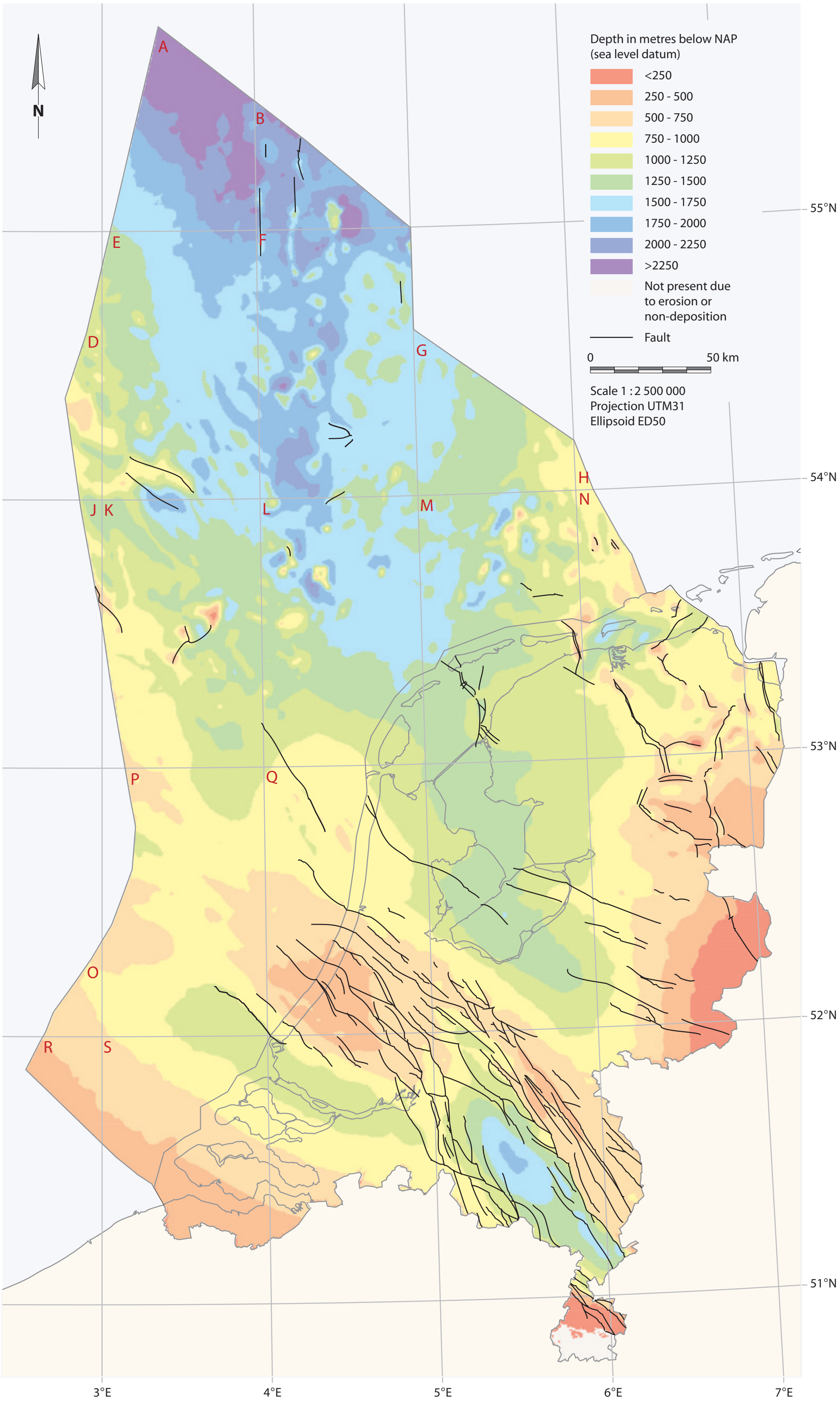


Fig. 11a. Depth map of the base of the Lower and Middle North Sea groups (Paleogene).

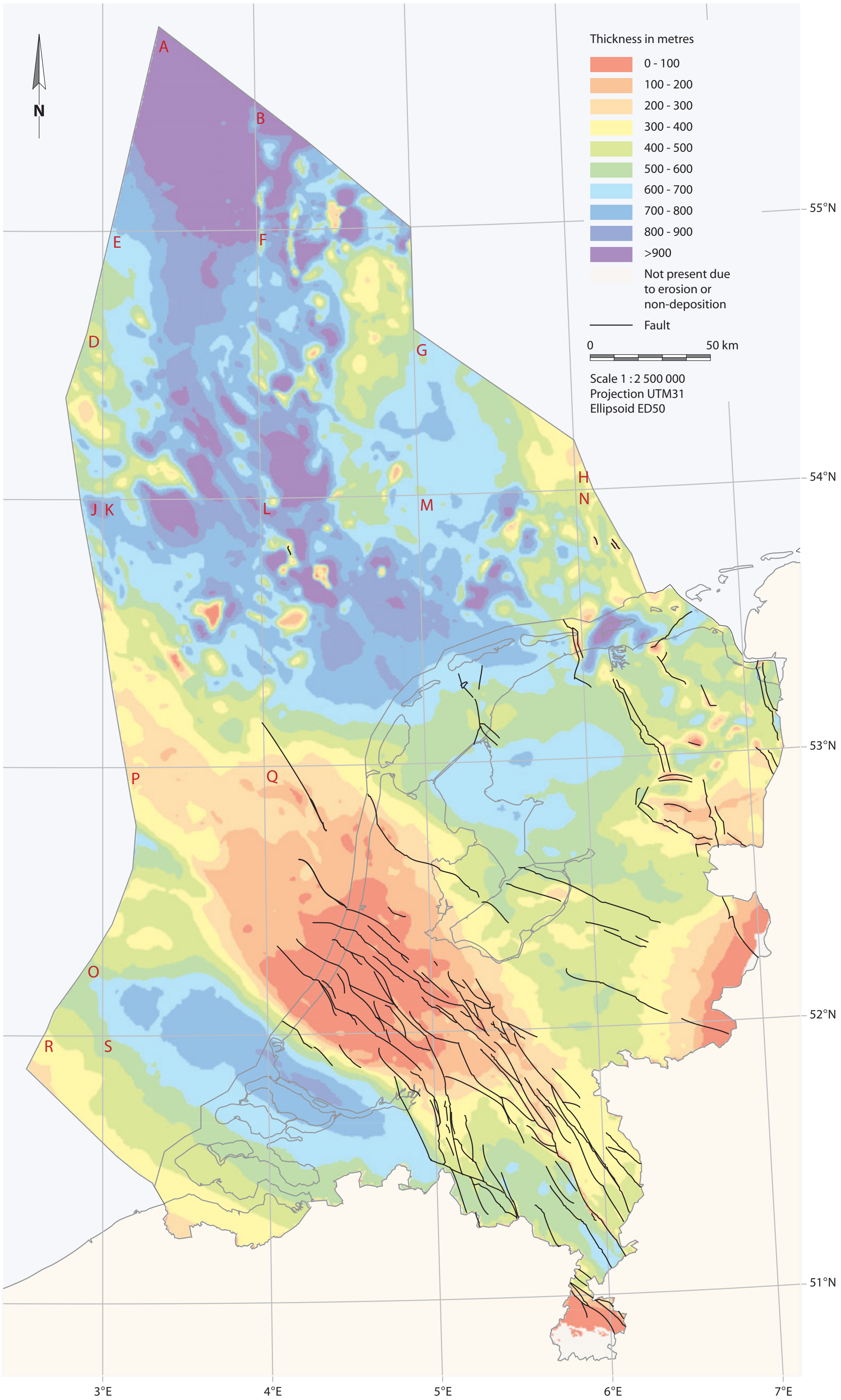


Fig. 11b. Thickness map of the Lower and Middle North Sea groups (Paleogene).

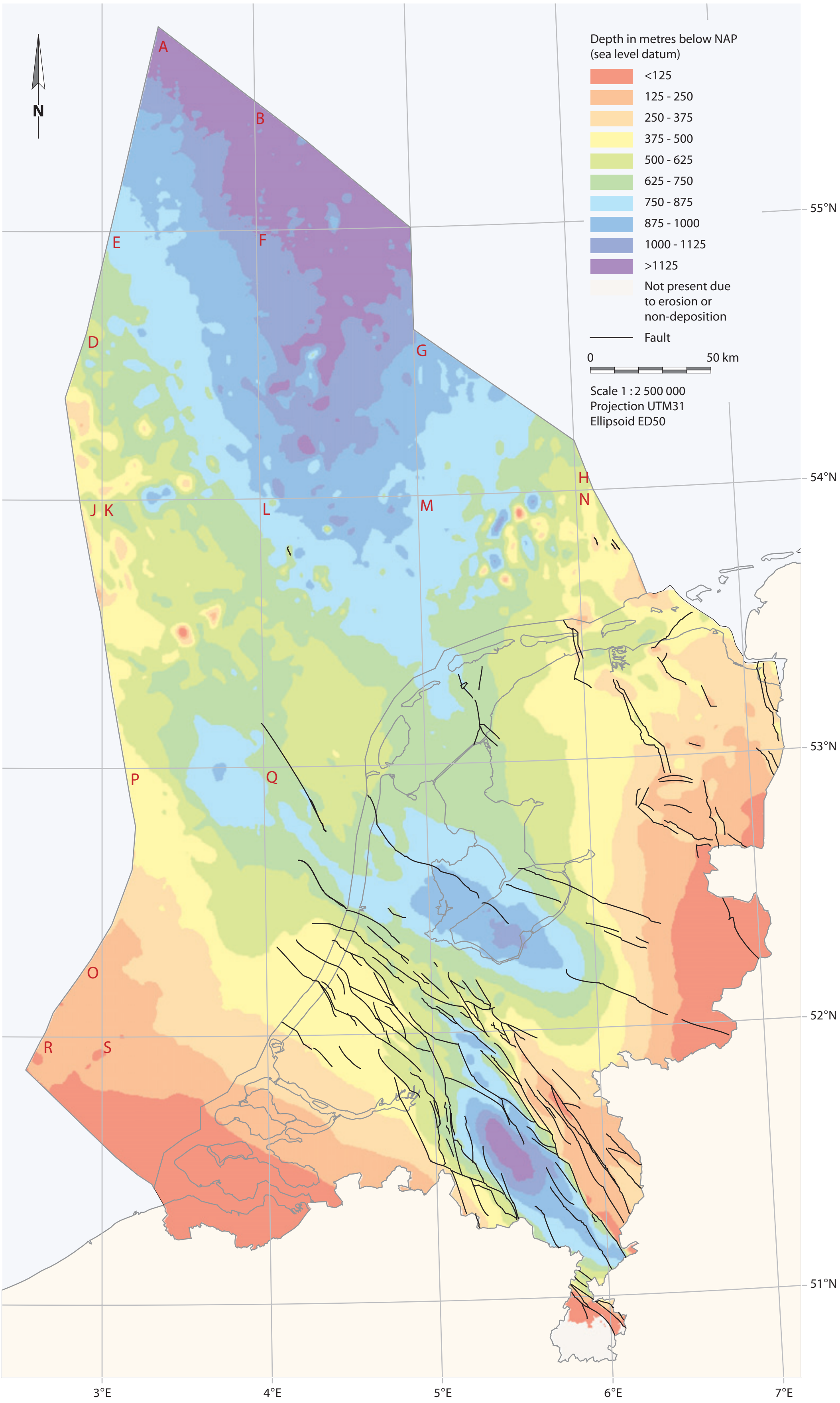


Fig. 12. Depth (and isopach) map of the Upper North Sea Group (Neogene).

North Sea Supergroup (Cenozoic)

Depth, thickness and basin development

The base of the North Sea Supergroup outcrops in the eastern and southern parts of the Netherlands and is located at depths of more than 2000 m in the Dutch part of the Cenozoic North Sea Basin (NSB) (Fig. 11a). The outlines of this basin roughly coincide with the present-day North Sea (Van Adrichem Boogaert & Kouwe, 1993 - 1997). The depth map of the base of the North Sea Supergroup shows the strong Cenozoic subsidence in the Roer Valley Graben and the offshore part of the North Sea Basin, while the Voorne Trough (VT), located on the SW-flank of the inverted part of the West Nederlands Basin (the Kijkduin High), underwent only moderate subsidence (Fig. 11a). Whilst differential subsidence of the Voorne Trough ceased at the beginning of the Miocene, the Roer Valley Graben continued to subside (Figs 12 and 11b; De Jager, 2003; Kuhlmann, 2004). On the other hand, subsidence of the Central Netherlands Basin, Broad Fourteens Basin and North Sea Basin accelerated during the Neogene (Fig. 12). This has also been observed by Michon et al. (2003), who conclude that the Late Eocene inversion was restricted to the southern North Sea.

Structural development

Uplift of the West Netherlands Basin resulted in depositional thinning and in erosion of the Upper Cretaceous Chalk and Paleogene clastics, as well as in local truncation of older sediments (De Jager, 2003). Strong halokinesis was active during the Paleogene in the Dutch Central Graben, Cleaver Bank High, Central Offshore Platform, Ameland Block, Hantum Fault Zone and Lower Saxony Basin (Fig. 11b). In the northern parts of the Dutch offshore subsidence has continued strongly and Neogene deposits reach a thickness of 1400 m.

Cenozoic regional thermal subsidence of the North Sea Basin was from the Middle Eocene paralleled by the evolution of the Rhine rift system that propagated during the Oligocene northwards (Ziegler, 1988). This is evidenced by the subsidence of the Roer Valley Graben and activation of the Hantum, Mid-Netherlands and the Peel Boundary Fault (Figs 12 and 11b). Further growth of salt diapirs during the Cenozoic continued in the northern offshore area, as can be seen on the thickness maps of the Lower and Middle, and Upper North Sea groups (Figs 12 and 11b).

Acknowledgements

The presentation of the maps given in this paper is the result of the work of many colleagues at TNO Built Environment and Geosciences, especially within the regional mapping team. We thank Nora Witmans and Carla Elmers for their assistance in collecting, interpreting and processing the data into integrated maps and figures. The authors thank the reviewers Mark Geluk and Peter Ziegler for their technical comments to improve this manuscript.

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