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The late Maastrichtian to Late Paleocene tectonic evolution of the southern part of the Roer Valley Graben (Belgium)

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Abstract

The late Maastrichtian to Late Paleocene seismostratigraphic record of the Roer Valley Graben provides new data on the timing and dynamics of stress changes related to the intra-plate deformation of northwestern Europe. During the deposition of late Maastrichtian to middle Danian limestones, no severe tectonic movements occurred in the southern part of the Roer Valley Graben. Around the late Danian, a known fundamental change in the European intra-plate stress field initiated an increase in subsidence of the southern part of the Roer Valley Graben. Subsidence along the graben border zone enabled relatively thick accumulations of the latest Danian to mid-Selandian siliciclastics in the intra-graben zone. Subsidence was not bounded by large offsets along faults, but rather by flexuring within and along the borders of the Roer Valley Graben. The intensity of these dynamics diminished after the middle Selandian. Most likely due to inherited intra-basinal structural differences, the northern and southern part of the Roer Valley Graben experienced distinctly different late Maastrichtian to Late Paleocene tectonics.

Keywords: Paleocene, Roer Valley Graben, flexural subsidence, relaxation tectonics

Introduction

From Late Cretaceous to Early Paleocene, Western and Central Europe underwent two regional inversions in response to compressional intra-plate stresses exerted by an advancing Alpine front and north Atlantic rifting (Ziegler, 1990). The Sub-Hercynian inversion phase cumulated during the Santonian to Campanian and was followed by the Laramide inversion phase, which ranged from the Maastrichtian to Middle Paleocene. In some southern North Sea Basins, like the Broad Fourteens Basin, both inversion phases were identified (De Lugt et al., 2003). In other southern North Sea Basins, however, one of both phases was lacking (De Jager, 2003) or, in the case of the Roer Valley Graben (RVG), remained a matter of debate. One of the main reasons that debate still exists is the lack of sufficient data for the late Maastrichtian to Late Paleocene interval in the RVG.

In the southwestern or Belgian sector of the RVG, for example, only one well (with well logs) has penetrated the late Maastrichtian to Late Paleocene interval of interest. This Molenbeersel well (Geological Survey of Belgium file 049W0226) was drilled in 1987 along a 2D seismic line of the Poppel–Lommel–Maaseik survey of 1984. Demyttenaere & Laga (1988) correlated the data from this survey to their Molenbeersel well interpretations and created depth maps of the Cenozoic strata in the Belgian sector of the RVG. Their efforts were hindered, however, by the wide spacing (> 5 km) of the NE–SW oriented seismic lines.

Research of underground gas storage potential renewed the interest in the region and triggered the reprocessing of the Poppel–Lommel–Maaseik survey and the acquisition of new 2D seismic data in the Belgian sector of the RVG by VITO in 2007 (hereafter called the VITOLIM survey). The VITOLIM survey consists of relatively closely (mutual distance < 3 km) spaced SW–NE and NW–SE oriented seismic lines. This survey was used, amongst others, to create new depth maps for the Cenozoic siliciclastic formations in the Belgian sector of the RVG. In order to create these maps, former seismic and lithostratigraphic interpretations were revised and a new seismostratigraphic model was defined by Broothaers et al. (2012). The first objective of this study is to use this seismostratigraphic model as a tool to study structural deformation and thereby gather new information on the late Maastrichtian to Late Paleocene dynamics of the RVG. The second objective is to link this information to existing regional tectonic models.

Geological background

The Roer Valley Rift System initiated in the Late Oligocene as a northwest trending branch of the Rhine Graben System (Ziegler, 1988), which covers a small part of northeastern Belgium (Fig. 1). Structurally, it can be subdivided into the Campine Basin in the west, the RVG in the centre and the Peel Block in the east. The RVG is roughly 30 km wide and 130 km long, and orientated NW–SE. The current southwestern RVG border fault system (or Feldbiss fault system in Dusar et al., 2001) consists of numerous laterally branching and bending fault segments (Fig. 2).

The Meso- and Cenozoic stratigraphic distribution indicates a graben border fault system that has been repeatedly active since Paleozoic times (Demyttenaere, 1989; Langenaeker, 2000). The oldest deposits known from boreholes in the RVG are of Carboniferous age. These are unconformably overlain by Permian–Triassic–Jurassic sequences. The RVG was a fault-bound platform during the Permian and a broad subsiding basin during the Triassic (Geluk et al., 1994). Based on stratigraphic onlap relationships, Demyttenaere (1989) argues that differential movements of the southern part of the RVG occurred at the transition from the Early to Middle Jurassic. In this part of the RVG a hiatus, corresponding to the Late Kimmerian tectonic phase, covers the timespan between the Middle Jurassic and Early Cretaceous (Geluk et al., 1994). Upper Cretaceous carbonate sediments are also largely absent due to an episode of uplift and erosion of the RVG during the Santonian to Maastrichtian related to the Sub-Hercynian inversion phase (Demyttenaere, 1989). Apatite fission track data and model simulations of Late Cretaceous basin inversion suggest a strong variation in exhumation in the RVG (Luijendijk et al., 2011). By late Maastrichtian times, the RVG turned into a shallow net subsiding basin with deposition of limestones up to the Early

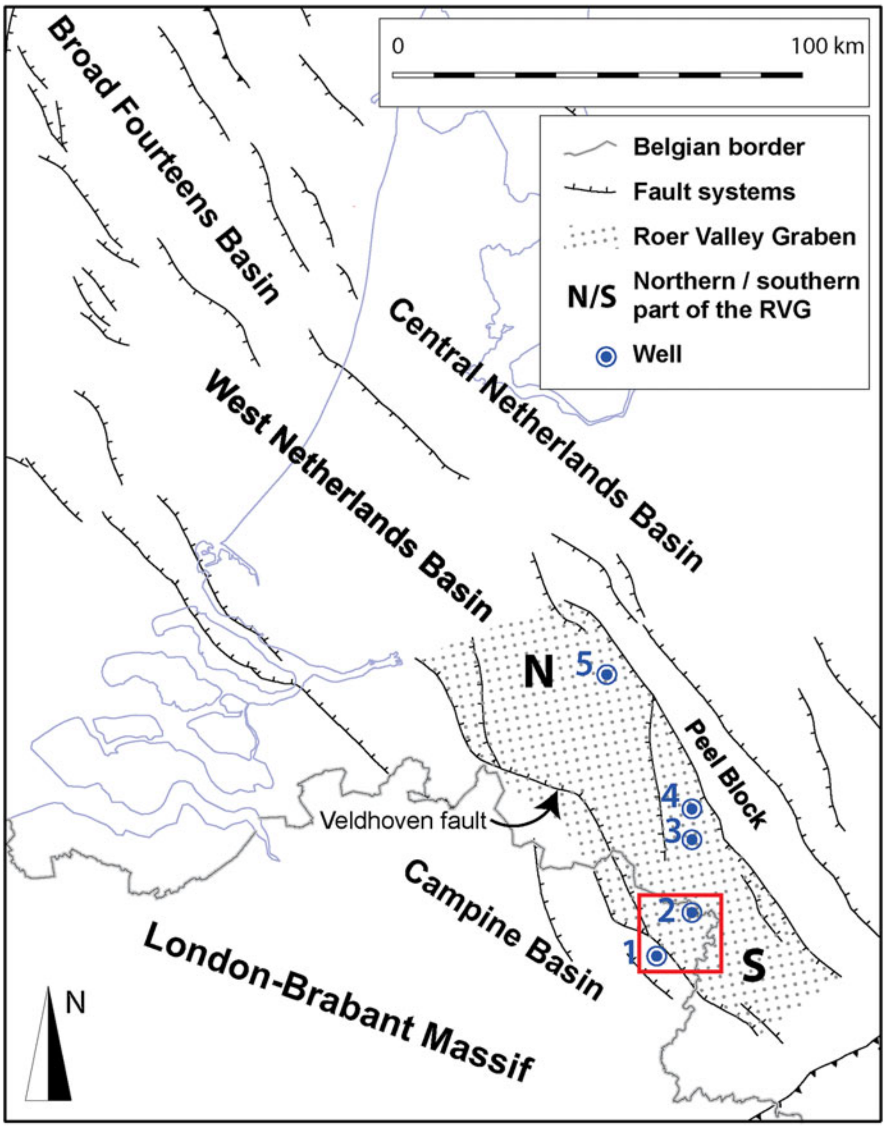

Fig. 1. Structural elements map of the Netherlands and northern Belgium showing the Jurassic and Early Cretaceous basins, highs and platforms (modified after De Jager, 2007). The Roer Valley Graben is divided into northern and southern parts separated by a transition zone located near the Veldhoven fault (following Geluk et al., 1994). The boundary between the Roer Valley Graben and the West Netherlands Basin has been taken at the pinch-out line of Upper Cretaceous sediments after Kombrink et al. (2012). The locations of the correlation panel of Fig. 6 are given: 1, Opitter; 2, Molenbeersel; 3, Nederweert-01; 4, Asten-02; 5, Keldonk-01. The study area is indicated by the red square.

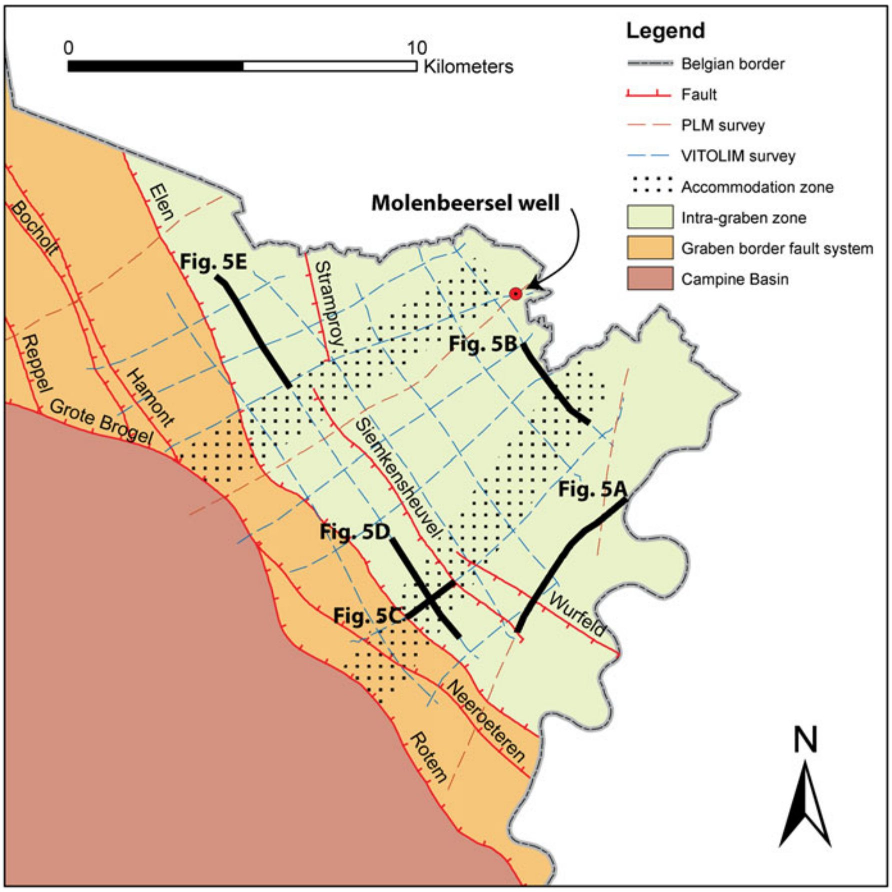

Fig. 2. The Belgian sector of the RVG enclosed within its border fault system in the southwest and the border with the Netherlands. The fault traces presented in this figure are extracted and modified after Broothaers et al. (2012) and represent the intersections between the reactivated Mesozoic faults (during Late Oligocene rifting) and the top of the Chalk Group. The indicated sections along the seismic lines are shown in Fig. 5.

Paleocene (Gras & Geluk, 1999) followed by siliciclastic deposition (Fig. 3). Apart from a latest Maastrichtian episode of regional uplift and erosion (Dusar & Lagrou, 2007) and a mid-Paleocene increase in graben subsidence, no significant tectonic movements were interfered for this period in the southern part of the RVG (Demyttenaere, 1989). Most North Sea basins, however, were subject to compression related to the Early Paleocene Laramide inversion phase (De Jager, 2003). Contrary to De Jager (2003), both Verbeek et al. (2002) and Michon et al. (2003) claimed that the Laramide inversion phase also affected the RVG. Luijendijk et al. (2011) did not exclude that the RVG was affected by the Laramide inversion phase, but stated that its impact was small in comparison to the Sub-Hercynian inversion phase.

Around Late Eocene times, the RVG and its shoulders were progressively uplifted from north to south by the Pyrenean inversion phase (Geluk et al., 1994). Models from apatite-fission track analyses indicate that the uplift in the western part of the RVG varied between 200 and 600 m (Van Balen et al., 2002). In the southern part of the RVG, the Pyrenean inversion phase resulted in erosion of all post-Paleocene strata. Subsidence resumed at the end of the Eocene and strongly increased from the Late Oligocene start of rifting onwards (Demyttenaere, 1989; Geluk, 1990). Tectonic movements still continue at present as indicated by, for example, earthquakes in the region (Ahorner, 1994; Camelbeek et al., 1994).

Stratigraphy

In the Molenbeersel well, the late Maastrichtian to Paleocene interval is identified between 1107 and 1283 m depth. It is divided into a lower 60 m of limestones and an upper 114 m of siliciclastic sediments (Fig. 4). The Mesozoic formations underlying the limestones will be referred to as 'Mesozoic strata' to simplify their description.

The base of the late Maastrichtian to Paleocene interval starts with a 2-m thick sequence of reworked material (conglomerates) that covers the Mesozoic strata (Bless et al., 1993). This sequence is overlain by the late Maastrichtian to middle Danian limestones that characterise the entire region. With the exception of the upper 9 m, the limestone interval of the Molenbeersel well was entirely cored, which enabled highly detailed lithological, biostratigraphic and petrographic studies by Bless et al. (1993), Swennen & Dusar (1997) and Lagrou et al. (2011).

The Maastricht Formation was deposited during the late Maastrichtian in a shallow subtidal (sometimes high-energy) environment at the transition from nearshore to more open marine conditions (Bless et al., 1993). The overlying Houthem Formation was deposited during the early to middle Danian in an initially repeatedly emergent environment that gradually deepened, but ended in renewed shallow subtidal conditions. The sudden transformation from an open marine to repeatedly

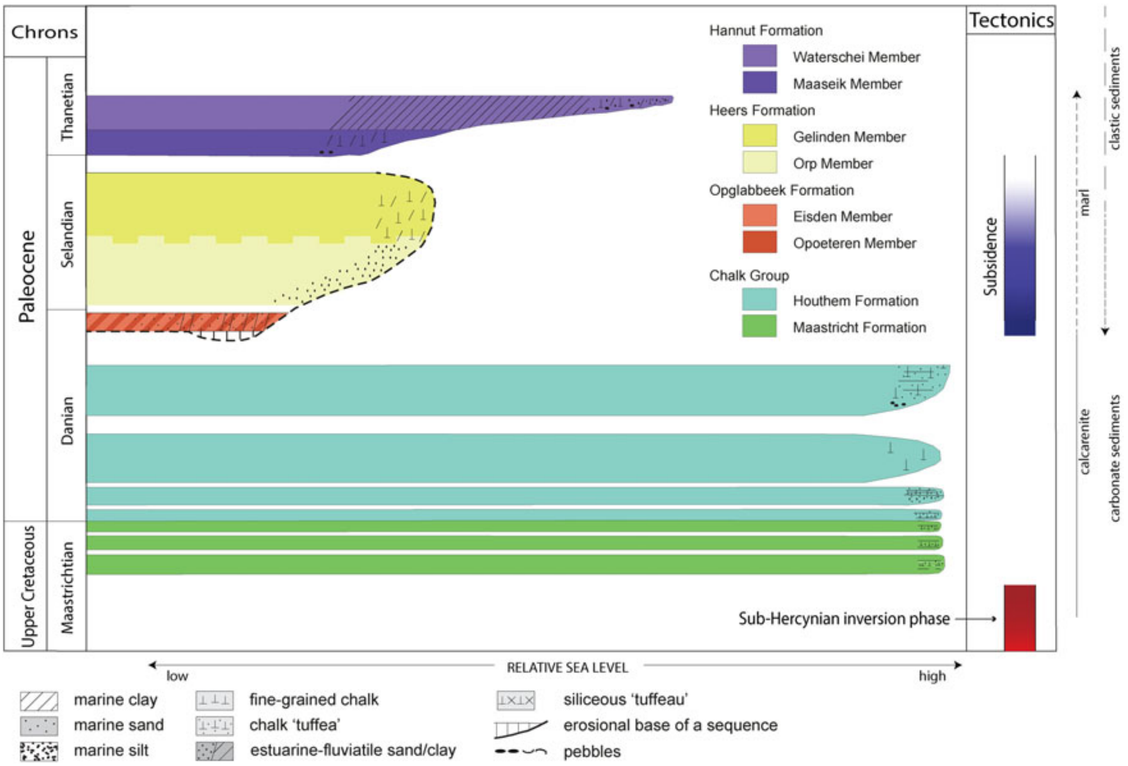

Fig. 3. The sediment sequences for this study and their relative sea-level positions (modified after Vandenberghe et al., 2004). The most distinct tectonic phases are indicated on the right-hand side.

emergent environment is formed by a karstified horizon at the Cretaceous/Paleogene boundary. Well data suggest that the Houthem Formation attains a rather uniform thickness of some 30 m throughout the region (Geluk et al., 1994).

Limestone deposition ended due to a regional regression after the middle Danian. During the latest Danian, the lowstand siliciclastics of the Opglabbeek Formation were laid down on top of the limestones (Fig. 3; Steurbaut & Sztrákos, 2008). The Opglabbeek Formation consists of multicoloured lignitic silty claystone with intercalated sandy levels of the Opoeteren Member, and medium to coarse sand(stone)s of the Eisden Member (Steurbaut, 1998). Well data suggest that the Opglabbeek Formation reached its maximum thickness of 40 m in the Molenbeersel well (De Koninck et al., 2011), which is more (i.e. 10 m) than in wells in the eastern part of the Campine Basin (Demyttenaere, 1989).

The Opglabbeek Formation is overlain by the early to late Selandian Heers Formation (Fig. 3; Steurbaut, 1998; De Bast et al., 2013), which consists of a lower Orp Member and an upper Gelinden Member. The Orp Member consists of fine glauconitic marine sands which are interpreted as early to mid Selandian transgressive deposits, whereas the shallow marine marls of the Gelinden Member are thought to represent the subsequent mid to late Selandian highstand deposits (De Bast et al., 2013). Well data suggest that the Heers Formation reaches its maximum thickness of 55 m in the Molenbeersel well (De Koninck et al., 2011), which is again more (i.e. 10 m) than in wells in the eastern part of the Campine Basin (Demyttenaere, 1989).

The Heers Formation was in turn covered by the early to middle Thanetian Hannut Formation (Fig. 3; Steurbaut, in press). Because of uplift and erosion during the Late Eocene Pyrenean inversion phase, the clayey marls of the informal Maaseik Member (Steurbaut, 1998) and clays of the Waterschei Member are the only remains of the Hannut Formation in the Molenbeersel well. The Maaseik Member is around 7 m thick in the southern part of the RVG and the easternmost part of the Campine Basin (De Koninck et al., 2011).

Dataset and methodology

Seismic data

The Poppel–Lommel–Maaseik survey of 1984 consists of 41 km of 2D seismic reflection data in the RVG with exclusively NE–SW oriented lines (Fig. 2) that were reprocessed in 2008. The VITOLIM survey of 2007 adds another 133 km of 2D seismic reflection data to the RVG, with both NW–SE and NE–SW oriented lines (Fig. 2). All seismic data is displayed with normal (SEG) polarity so that a downward increase in acoustic impedance is represented by a peak (black) and a downward decrease in acoustic impedance by a trough (white).

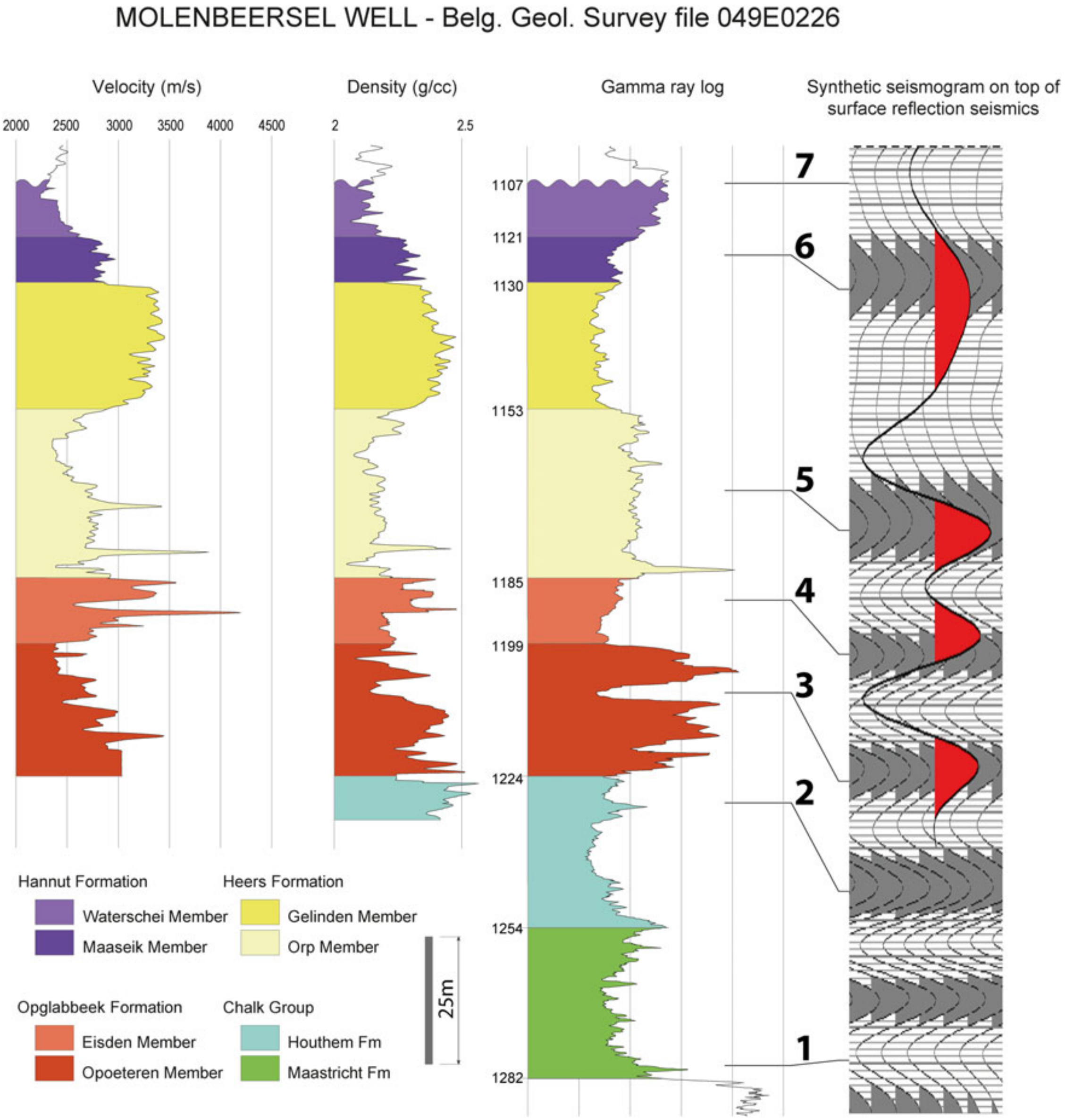

Fig. 4. Well log (left) and seismic (right) interpretations of the Late Cretaceous to Late Paleocene interval of the Molenbeersel well. The well log interpretations are extracted from Broothaers et al. (2012). These interpretations correspond (as indicated by the black lines in the centre) with the red wiggles of the synthetic seismogram on the right. In turn, the red wiggles of the synthetic seismogram are displayed on part of a reflection seismic line. 1, base Chalk Group reflector; 2, top Chalk Group reflector; 3, lower Opglabbeek Formation reflector; 4, upper Opglabbeek Formation reflector; 5, lower Heers Formation reflector; 6, top Heers Formation reflector; 7, top Hannut Formation reflector.

Well log- and seismic interpretations

Seismic interpretation was based on correlation with data from the Molenbeersel well (Fig. 4). For the Paleocene siliciclastics, the gamma-ray, density and sonic-log responses were correlated with wells in the eastern part of the Campine Basin and used to identify three key markers with litho- and chronostratigraphic significance: the top Opglabbeek, top Heers and top Hannut Formations. The seismic horizons are tied to geophysical contrasts in these formations by using a synthetic seismogram from sonic and density log data. The following horizons were interpreted on the reflection seismic data: lower and upper Opglabbeek Formation, lower and top Heers Formation, top Hannut Formation.

For the late Maastrichtian to Danian limestone interval, litho- and biostratigraphic data (from the cored interval) were used to identify three key surfaces: the base Maastricht Formation, and the base and top Houthem Formation. Since sonic log data is absent underneath the top of this interval, the first two key surfaces could not directly be interpreted on the seismic data. The base of the limestone interval was indirectly tied to the seismic data based on the contrast in seismic facies with the underlying

Jurassic shales. Since only the top and base of the limestone interval were seismically interpreted, it will be studied as a whole and referred to as the 'Chalk Group' (Van Adrichem Boogaert & Kouwe, 1993–1997).

Fault interpretations

Since all available seismic data is 2D, only small fault segments are actually imaged and their interpretation as one large fault plane remains speculative. The Mesozoic faults shown in Fig. 2 and discussed in the section below should therefore not be considered as single fault planes, but can also represent fault systems, each of which represents one tectonic feature made up of different fault segments that can be either linked or isolated (following Rypens et al., 2004).

The southwestern part of the RVG can be divided into a border zone or border fault system and an intra-graben zone. The border fault system is delimited in the east by the large synthetic Elen fault and in the west by the synthetic Grote Brogel, Neeroeteren and Rotem faults (respectively from northwest to southeast). The flank of the intra-graben zone is characterised by a series of antithetic Mesozoic faults with lengths of over 6 km, called the Stramproy, Siemkensheuvel and Wurfeld faults. A seismic section across the zone of overlap between the Siemkensheuvel and Wurfeld faults is shown in Fig. 5A. At further distance from the flank of the intra-graben zone, deformation is restricted to fault zones that segment the Mesozoic strata (Fig. 5B).under Segmentation of faults (or fault zones) in the flank and centre of the intra-graben zone occurs along the same zones of weakness that trend quasi perpendicular to the graben border fault system. Two of these zones were identified in the study area (Fig. 2).

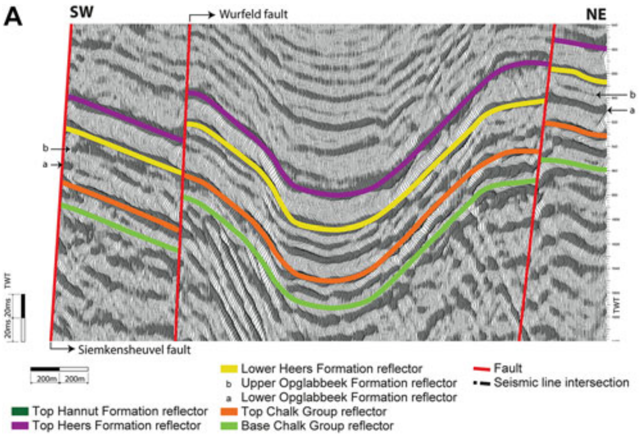

Fig. 5A. NW–SE section across the southern study area. This section shows that the thicknesses of the late Maastrichtian to Late Paleocene sequences remain rather uniform in the centre of the RVG, even across the pre-existing Wurfeld fault. The faults drawn in this section breached the late Maastrichtian to Late Paleocene sequences during Late Oligocene rifting.

Seismostratigraphic results

Chalk Group

The Chalk Group is present throughout the study area. Across most of the study area, the top and base Chalk Group reflectors run parallel (Figs 5A, C, D and E). Locally, this parallel pattern changes by convergence of the Chalk Group reflectors (Fig. 5B). These changes are, however, very subtle, and do not affect the two-way-travel time thickness of the Chalk Group by more than 15 ms. Although the changes often occur near pre-existing zones of weakness (Fig. 5B), the thickness of the Chalk Group is not affected by consistent vertical movements along more than one segment of the large Mesozoic faults.

Opglabbeek Formation

The Opglabbeek Formation is present throughout the study area. In most of the area, it is represented by two very weak to weak reflectors (a and b in Fig. 5A). In the southeastern part of the study area these reflectors sometimes merge into one strong reflector (a and b in Figs 5B, C and D). The lower Opglabbeek Formation reflector is weak in the central study area and very weak in the southeastern study area. The switch in strength of this reflector consistently takes place above a zone that segments the Mesozoic strata in the RVG (Fig. 2 and a in Figs 5B and D).

When the lower Opglabbeek Formation reflector is present, it either conformably covers or onlaps the top Chalk Group reflector. The most distinct onlap occurs along the flank of the

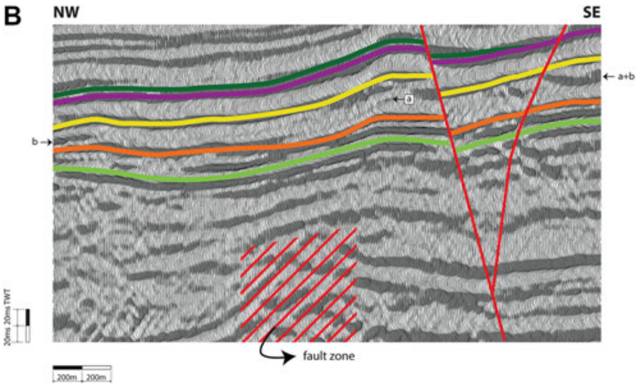

Fig. 5B. NW–SE section across a Mesozoic fault zone on top of which the top Chalk Group reflector converges with the intra-Chalk Group reflector. The lower Opglabbeek Formation reflector onlaps the top Chalk Group reflector to the northwest of the Mesozoic fault zone. Southeast of the fault zone, the lower Opglabbeek Formation reflector becomes very weak. In the northwestern part of this section, the lower and upper Opglabbeek Formation reflectors are merged into one strong reflector. At the top of this section, the Hannut Formation is gradually truncated towards the southeast. The faults that were drawn in this section were all active during Late Oligocene rifting. See Fig. 5A for legend.

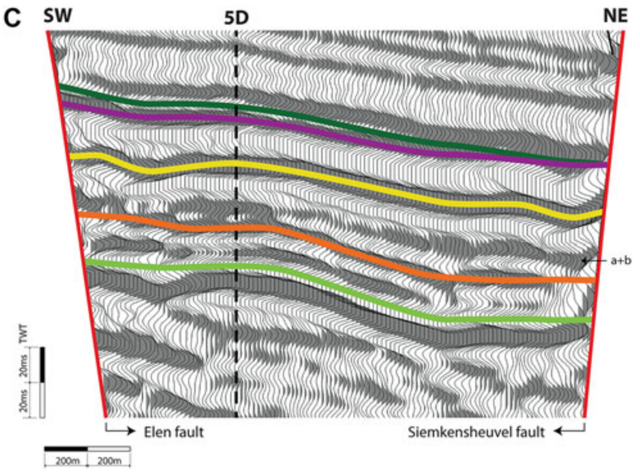

Fig. 5C. SW–NE section across the hangingwall block to the Elen and Siemkensheuvel faults. This section shows how the merged lower and upper Opglabbeek Formation reflectors onlap the top Chalk Group reflector towards the southwest or towards the graben border fault system. At the top of this section, the Hannut Formation is gradually truncated towards the northeast. The Elen and Siemkensheuvel faults breached the late Maastrichtian to Late Paleocene sequences during Late Oligocene rifting. See Fig. 5A for legend.

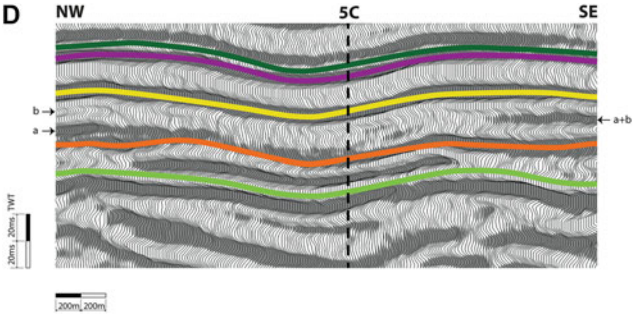

Fig. 5D. This NW–SE section shows the irregular thickness of the Opglabbeek Formation (in between the lower Heers and top Chalk Group reflector) along the hangingwall to the Elen fault. In the northwest, for example, the lower Opglabbeek Formation reflector onlaps the top Chalk Group reflector. The lower Opglabbeek Formation reflector becomes very weak and merges with the upper Opglabbeek Formation in the centre and southeastern part of this section. See Fig. 5A for legend.

intra-graben zone in the direction of the Elen fault (Fig. 5C). Fig. 5D shows that the onlap is rather irregular along the hangingwall block to the Elen and Siemkensheuvel faults. In the most northwestern part of the study area or in the hangingwall block to the Elen and Stramproy faults, the lower Opglabbeek Formation reflector is absent (Fig. 5E). Further within the graben, the lower Opglabbeek Formation reflector only locally and less distinctly onlaps the top Chalk Group reflector (Fig. 5B).

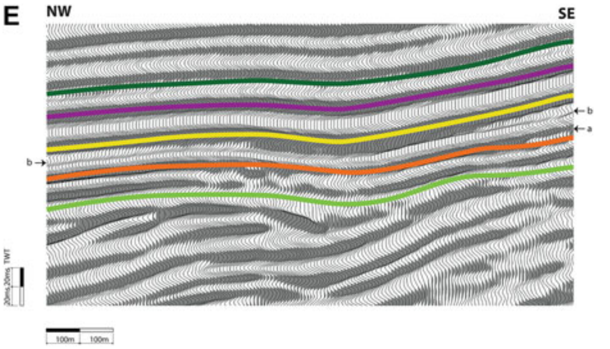

Fig. 5E. NW–SE section along the hangingwall block to the Elen and Stramproy faults. In the southeastern part of this section, the lower Opglabbeek Formation reflector onlaps the top Chalk Group reflector towards the northwest. Throughout this section, the upper Opglabbeek Formation and lower Heers Formation reflectors tend to merge. See Fig. 5A for legend.

The upper Opglabbeek Formation reflector is present throughout the study area and conformably overlies the lower Opglabbeek Formation reflector or, when the latter is absent, the top Chalk Group reflector (Figs 5B and E).

Heers Formation

The Heers Formation is represented throughout the study area by continuous and high-amplitude reflections (Figs 5A–E). The lower Heers Formation reflector conformably overlies the upper Opglabbeek Formation reflector. In the northwestern part of the study area or in the hangingwall block to the Elen and Stramproy faults, the latter reflectors converge without merging at any point (Fig. 5E). The top Heers Formation reflector runs quasi parallel with the lower Heers Formation reflector (Figs 5A–E).

Hannut Formation

Uplift and erosion of the RVG during the Late Eocene Pyrenean inversion phase caused a strong reduction in thickness of the Hannut Formation in the study area. As a result, the interval between the top Hannut Formation reflector (angular unconformity, see Figs 5B and C) and the top Heers Formation reflector is too small to extract information about possible deformation during the deposition of the Hannut Formation.

Discussion

Tectonics in the southern part of the RVG

Structural inheritance

The Mesozoic strata are segmented from the large faults along the flanks up to the centre of the intra-graben zone. Segmentation occurs in zones of weakness that trend quasi perpendicular to the graben border fault system. Two of these zones were identified in the study area and interpreted as accommodation zones (Fig. 2). These zones clearly played a major role in the Mesozoic evolution of the graben. After the Mesozoic, the accommodation zones were still able to affect Late Oligocene to recent rifting. The northern accommodation zone, for example, crosses the southwestern graben border fault system at the location where the Neeroeteren fault currently branches into the Grote Brogel, Bocholt–Hamont and Reppel faults. The southern accommodation zone in turn crosses the southwestern graben border fault system where Vanneste et al. (2002; 2008) identified a Quaternary stepover.

Late Maastrichtian to middle Danian tectonics

Based on stress-field data of other southern North Sea basins and the type of basin deformation south of the RVG, Michon et al. (2003) estimated that the region was subjected to a north–south oriented compressional stress-field during the Early Paleocene. The quasi parallel pattern of the top and base Chalk Group reflectors shows that this compression had no severe effect on the thickness of the Chalk Group in the southern part of the RVG (Figs 5A–E). At some locations, however, the parallel pattern of the base and top Chalk Group reflectors is subtly disrupted, often near pre-existing zones of weakness (Fig. 5B). Since all available seismic data is 2D, we are unable to gather sufficient information on the 3D geometry of deformation and therefore to make reliable interpretations of possible mechanisms that might have caused it.

Latest Danian to early Thanethian tectonics

Well data show that the Opglabbeek Formation and the lower part of the Heers Formation (i.e. Orp Member) attain larger thicknesses in the southern part of the RVG than in the Campine Basin and northern part of the RVG (Fig. 6). The large thicknesses were no local fault-bound phenomenon at the location of the wells, but widespread in the southern part of the RVG (Fig. 5A). This suggests that the southern part of the RVG was subsiding with respect to its surroundings from the late Danian to middle Selandian. The seismic results of this study show that subsidence was not taken on by large displacements along faults. Instead, the intra-graben zone experienced flexural subsidence, predominantly along the graben border zone (Fig. 5C). Deckers & Matthijs (in press) show that flexural subsidence extended beyond the RVG border zone into the Campine Basin. Based on the lack of substantial fault activity or subsidence bounding the RVG, Michon et al. (2003) argued that it is likely that subsidence of the RVG was a result of stress relaxation and lithospheric sagging after the main compressive phase. The results of this study show that the start of stress relaxation

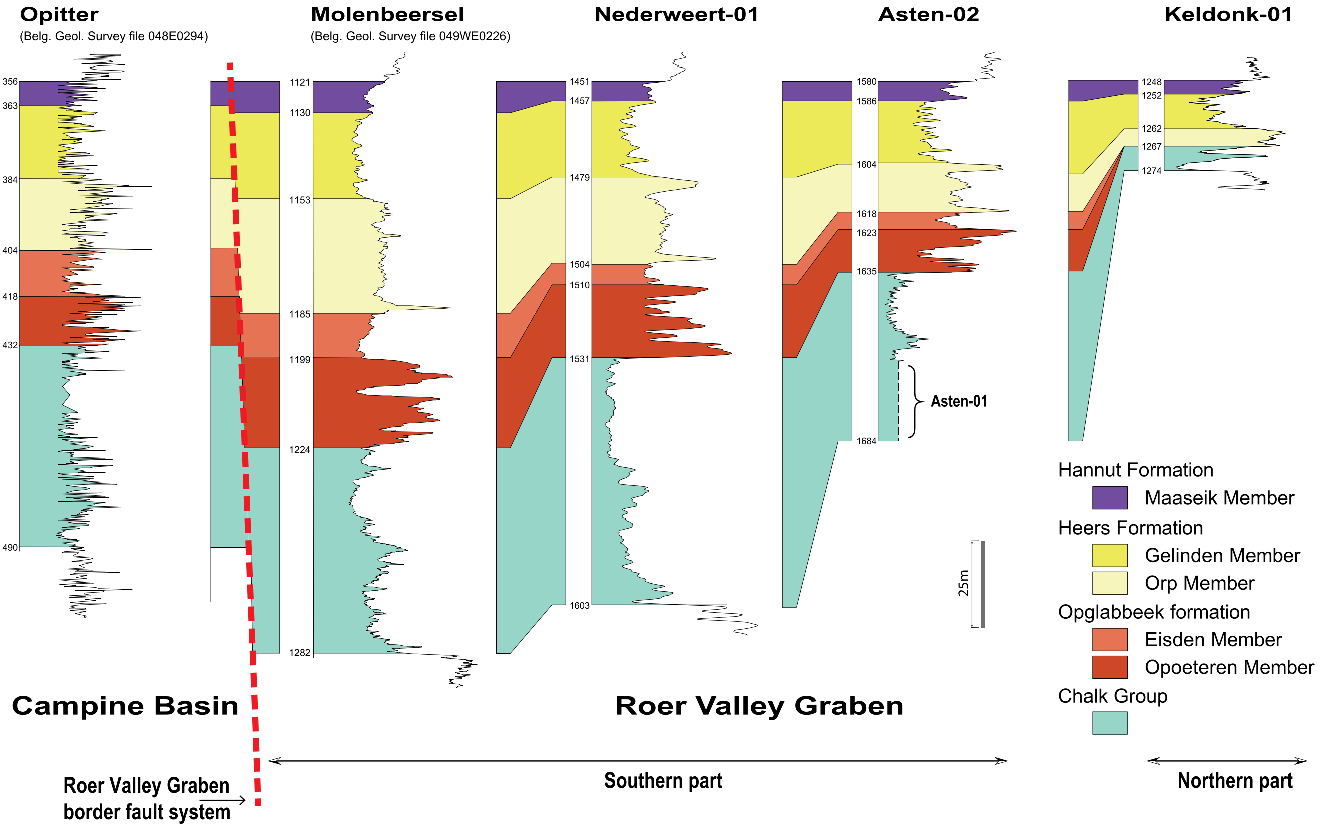

Fig. 6. Log correlations through the Roer Valley Graben and the southeastern part of the Campine Basin. Well AST-02 did not reach the base of the Chalk Group, so the thickness of the Chalk Group in nearby well AST-01 was used to estimate its thickness. The location of the wells is shown in Fig. 1.

coincides with the boundary between the Houthem Formation and the Opglabbeek Formation or roughly the late Danian (Fig. 3). This age interval coincides with the estimated timing (i.e. 62 Ma) of a fundamental change in the European intra-plate stress field related to North Atlantic rifting (Nielsen et al., 2007). Nielsen et al. (2005) stated that the stress change ended the 20-Ma long contractional intra-plate deformation of Europe and replaced it with low-amplitude intra-plate stress-relaxation features. Both the age and expression of late Danian to middle Selandian subsidence in the southern part of the RVG can thus be reconciled with established regional tectonic models. At the start of stress relaxation, the magnitude of subsidence locally varied in the intra-graben zone, enabling the development of paleo-highs, which were onlapped by the lower part of the Opglabbeek Formation (Fig. 5B). The coverage of the paleo-highs by the upper part of the Opglabbeek Formation (Fig. 5B) and the quasi parallel pattern of the Heers Formation reflectors (Figs 5A–E) show that the relative rates of subsidence became progressively more uniform within the intra-graben zone.

Well data show that the upper part of the Heers Formation (i.e. Gelinden Member) and the lower part of the Hannut Formation (i.e. Maaseik Member) only gradually change in thickness within and across the borders of the RVG (Fig. 6). This suggests that the intensity of stress-relaxation tectonics diminished after the middle Selandian (cf. Deckers & Matthijs, accepted).

Contemporaneous tectonics in nearby regions

Contrary to the southern part of the RVG, the Chalk Group is thin or absent in the northern part of the RVG (Fig. 6). It is still uncertain whether this is the result of erosion during compression or of non-deposition due to pre-existing topography (Luijendijk et al., 2011).

The seismic results of this study show that the Opglabbeek and Heers Formations thin towards the northwestern part of the study area (Fig. 5E). Well data show that both formations continue to thin in the northwestern direction throughout the RVG (Fig. 6). The absence of the Opglabbeek Formation and the thin Heers Formation indicate that the northern part of the RVG hardly experienced any subsidence during the late Danian to Selandian interval. The late Maastrichtian to Selandian tectonic evolution of the southern and northern parts of the RVG therefore strongly differed. Because of a general lack of detailed information on the tectonics of the northern part of the RVG, possible explanations for these differences remain hypothetical. Mazur et al. (2005) have shown that inherited basement structures play an important role in controlling the Late Cretaceous to Early Paleogene strain pattern within the European basins. In the RVG, these inherited structures are of Mesozoic age. Geluk et al. (1994) argued that based on the Mesozoic structural development, the RVG could be divided into a northwestern part and a southeastern part. The boundary between the two parts is gradual and located near the west–east striking Veldhoven fault (for location see Figs 1 and 7). It is therefore likely that the differences in tectonic movements in the RVG are related to inherited structural differences between its northern and southern halves. The importance of inherited structures is illustrated in this study by the abrupt change in seismic facies of the Opglabbeek Formation across the southern accommodation zone (Figs 5B and D).

With erosion or non-deposition of the Chalk Group and absence of the Opglabbeek Formation, the late Maastrichtian to Selandian tectonic evolution of the northern part of the RVG seems similar to that of the Central and West Netherlands Basins. In the Central and West Netherlands Basins, the reduced late Maastrichtian to Selandian thickness is interpreted as the result of uplift and erosion during the Laramide inversion phase (De Jager, 2003). The Laramide inversion phase occurred at the transition from limestone to siliciclastic deposition (De Jager, 2007) or simultaneous with flexural subsidence of the southern part of the RVG (i.e. late Danian). This simultaneity of uplift and subsidence of European Basins is explained by Nielsen (2005, 2007) as the result of late Danian relaxation of in-plane tectonic stress.

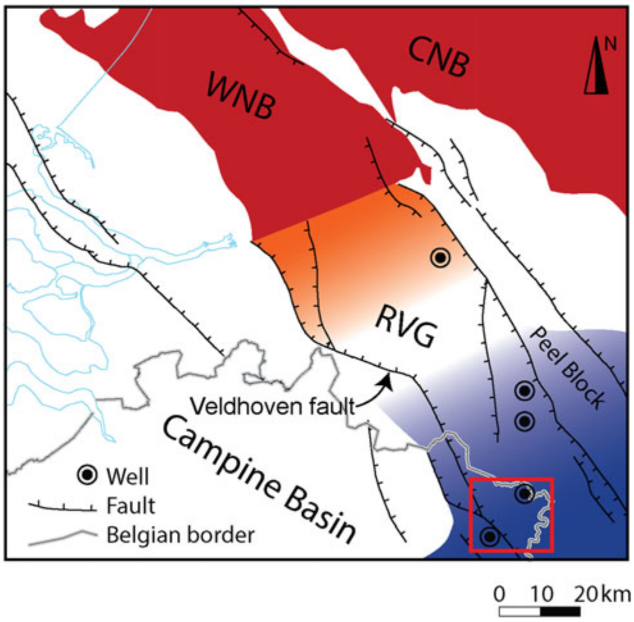

Fig. 7. Schematic presentation of inverted and subsiding southern North Sea basins during the late Danian (modified after De Jager, 2007). Dark-red shading shows strongly inverted areas, where the Chalk Group is not preserved, orange shading shows the mildly inverted areas, where the Chalk Group is thin and not covered by latest Danian siliciclastics, blue shading shows the subsiding areas, where the Chalk Group is not affected by strong erosion and covered by the latest Danian siliciclastics. WNB, West Netherlands Basin; CNB, Central Netherlands Basin. The names of the wells are given in Fig. 1. The study area is indicated by the red rectangle.

The model of Nielsen et al. (2005) states that this Middle Paleocene stress relaxation phase was characterised by a dome-like uplift of a wider area with only mild fault movements, and the formation of more distal and shallow marginal troughs. If we apply this model to the RVG, its northern part was (together with the Central and West Netherlands Basins) subjected to a low-amplitude smooth dome-like uplift with erosion of the Chalk Group and limited coverage by Selandian siliciclastics, while its southern part (together with parts of the Campine Basin and Peel Block) turned into a shallow trough or depocenter with deposition of relatively thick latest Danian to Selandian siliciclastics (Fig. 7).

Conclusions

Based on a new 2D seismic model, it has been demonstrated that no severe tectonic movements occurred during the deposition of late Maastrichtian to middle Danian limestones of the Chalk Group in the southern part of the Roer Valley Graben. The seismic facies of the Chalk Group was locally disturbed, often near pre-existing zones of weakness, but 3D seismic data are needed for detailed analysis of the geometry and origin of deformation.

During the late Danian, a fundamental change in the intra-plate stress field of Europe triggered low-amplitude subsidence of the southern part of the RVG. Our model shows that subsidence was not bounded by large offsets along pre-existing fault systems, but rather by flexuring. Flexural subsidence along the graben border zone enabled the deposition of relatively thick latest Danian to Selandian siliciclastsic sequences in the intra-graben zone. The magnitude of subsidence initially locally varied within the intra-graben zone, but progressively became more uniform during the Selandian.

In several other southern North Sea basins, including the northern part of the RVG, the late Danian stress change most likely caused uplift and erosion of the Chalk Group and only thin coverage by siliciclastic sequences. The late Maastrichtian to Late Paleocene tectonic evolution of the southern and northern part of the RVG thus distinctly differed. These differences are probably related to inherited structural differences. Even in the southern part of the RVG, inherited accommodation zones were able to affect the seismic facies of the latest Danian deposits. The intensity of stress-relaxation tectonics diminished after the middle Selandian.

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