GEOLOGICA BELGICA (2014) 17/3-4: 236-243

A late Danian change in deformation style in the south-eastern part of the Campine Basin

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ABSTRACT. The combined use of newly interpreted well data and reprocessed 2D seismic data provides new insights in the Early to Middle Paleocene tectonic evolution of the south-eastern part of the Campine Basin.
A late Danian fundamental change in the intra-plate stress-field of Europe changed the deformation style in several southern North Sea basins, including the Campine Basin and neighboring Roer Valley Graben. In the south-eastern part of the Campine Basin, this stress change ended an early to middle Danian tectonic quiet phase with calcarenite deposition and started a late Danian to middle Selandian phase of differential subsidence and restricted deposition of continental to shallow marine siliciclastics. Onlap patterns and associated thickness variations in the siliciclastics indicate that the south-eastern part of the Campine Basin experienced flexural subsidence in the direction of the downthrown Roer Valley Graben. Simultaneously, in the footwall to the Roer Valley Graben border fault system, the Bree Uplift was deformed by subtle (re)activation of faults, possibly in strike-slip mode. After the middle Selandian, former dynamics diminished throughout the region.

KEYWORDS: Differential subsidence, Campine Basin, Paleocene, Bree Uplift

1. Introduction

Around the Early to Middle Paleocene boundary, several Western European basins were characterized by an abrupt shift from inversion to tectonic relaxation (Nielsen et al., 2007). A recent study by Deckers et al. (in press) revealed that this shift initiated a Mid-Paleocene phase of differential subsidence of the southern part of the Roer Valley Graben. Data on subsequent movements of the graben shoulder or south-eastern part of the Campine Basin (SECB) are scarce. Although documentation is provided by several studies (Rossa, 1986; Demyttenaere, 1989; Vandenberghe et al., 1998; De Batist & Versteeg, 1999), these were either limited due to the fact that they were based exclusively on well data, on interpretation of seismic data with poor regional coverage or on low-resolution interpretation of broad time-intervals.

In the past, seismic surveys in the SECB were mainly designed to image its coal-rich Carboniferous strata. In the south-eastern part of the CB two of these surveys were reprocessed and thereby reached a resolution that is sufficient for a detailed study of its Early to Mid-Paleocene strata, which are located a few hundred meters above the Carboniferous strata.

Recently, well data was used to map the Early to Mid-Paleocene strata and to present them, amongst others, in the 2.5D G3Dv2-model of northern Belgium (Flanders) (Matthijs et al., 2013). De Koninck et al. (2011) reveal in this model that each of the Early to Mid-Paleocene sequences strongly contrasts from its predecessor and is characterized by a regionally very similar log-response. This allows the seismic and lithological framework to be tightly coupled and, therefore, seismostratigraphic modeling to be conducted of relatively thin sequences across large areas.

This quality will be used in this study to reconstruct the Early to Mid-Paleocene tectonic evolution of the SECB. Seismostratigraphic models were obtained for this purpose by correlating the two reprocessed seismic surveys in the SECB to the interpreted well data of the G3Dv2-model. The G3Dv2-model was furthermore used to upscale the extracted knowledge on the tectonic evolution of the SECB near the survey areas into the broader or more regional context of north-eastern Belgium.

2. Geological background

The Campine Basin is located in north-eastern Belgium, in between the West Netherlands Basin in the north, the Roer Valley Graben in the north-east and the London-Brabant Massif in the south (Fig. 1). The Campine Basin is characterized by the presence of coal-rich Upper Paleozoic strata that were intensely mined during the 20th century. The upper Paleozoic strata of the Campine Basin were covered in the east by a wedge of Permian to Jurassic strata that thickens into the Roer Valley Graben (Fig. 2).

The southern part of the Campine Basin, located on the shoulder of the south-western part of the Roer Valley Graben, is the focus of this study. The SECB is separated from the Roer Valley Graben by a border fault system (Feldbiss fault system in Dusar et al., 2001) that most likely developed during the transition from the Early to Middle Jurassic (Demyttenaere, 1989).

A thick cover of Upper Cretaceous strata overlies the Carboniferous to Jurassic basement of the SECB. In the Roer Valley Graben, this cover is much thinner due to uplift and erosion during the Late Cretaceous Sub-Hercynian inversion phase (Fig. 2). During inversion, the dextral transpressional deformation in a restraining bend of the graben border fault system resulted in the formation of a dome structure in its footwall (Langenaeker,

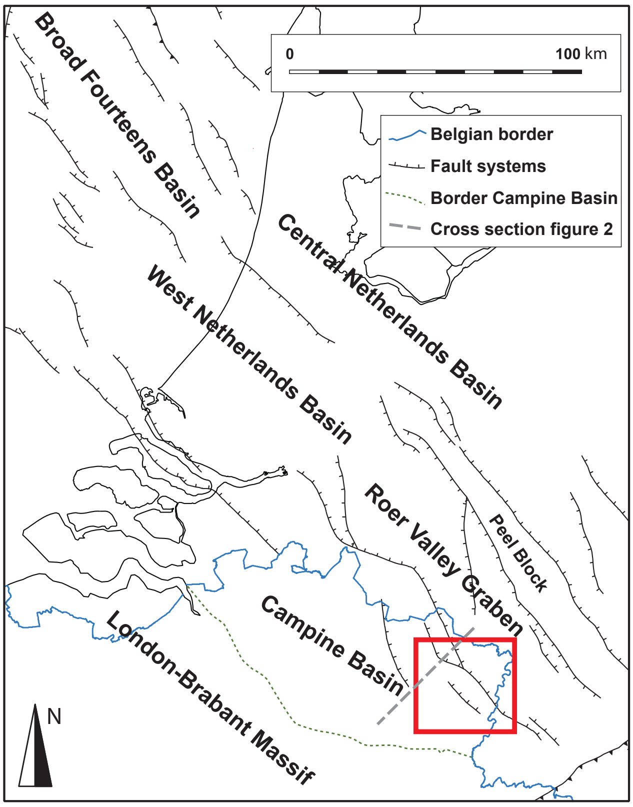


Figure 1. Structural elements map of the Netherlands and northern Belgium showing the Jurassic and Early-Cretaceous basins, highs and platforms (modified after De Jager, 2007). The study area is indicated by the red rectangle.

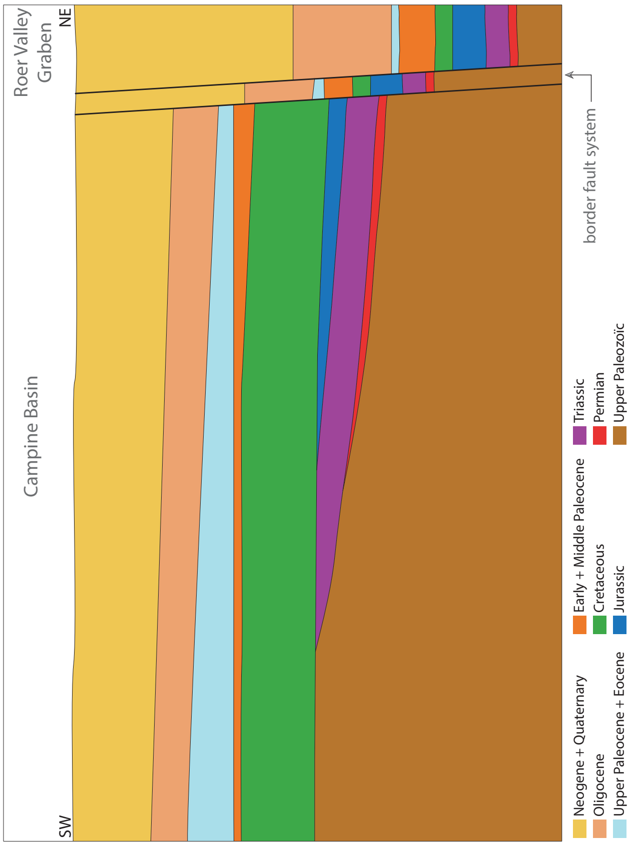


Figure 2. Schematic SW-NE cross section of the Campine Basin and Roer Valley Graben (see figure 1 for location).

1999; 2000), called the Bree Uplift (Bouckaert et al., 1981) (Fig. 3). The Bree Uplift is delimited to the south-west by the Bree fault and to the north-east by the Neeroeteren fault. As the Bree Uplift popped-up during the Sub-Hercynian inversion phase, its Cretaceous cover was strongly reduced by erosion.

The entire region was flooded again during the Maastrichtian and covered by carbonates until late in the Danian (Fig. 4).

Apart from a latest Maastrichtian episode of regional uplift and erosion (Dusar & Lagrou, 2007), no severe tectonic movements occurred in the SECB during carbonate deposition (Rossa, 1986). Carbonate sedimentation ended with a regional regression within the late Danian (correlatable to the late Danian Event or LDE, a globally recordable sedimentological and climatic event, Bornemann et al., 2009; Sprong et al., 2013), which, in NE Belgium, marked the switch to overall siliciclastic sedimentation. This switch coincides with a fundamental change in the intra-plate stress-field of Europe (Nielsen et al., 2005; 2007) which marked the onset of a differential subsidence of the Roer Valley Graben, a process that continued until the middle Selandian (Deckers et al., accepted). Simultaneously, the SECB experienced a tendency for normal faulting (Rossa, 1986). Only minor movements occurred during the Thanetian, which marked the start of a long tectonic quiet period (Demyttenaere, 1989).

In the Late Eocene, the entire region was progressively uplifted from north to south by the Pyrenean inversion phase (Geluk et al., 1994). This uplift caused major erosion of the older Paleogene strata in the SECB (Fig. 2). Subsidence resumed in the SECB during the Early Oligocene and increased during the Late Oligocene when it was incorporated in the Roer Valley Graben Rift System (Demyttenaere, 1989; Geluk, 1990). Most of the Paleozoic to Cenozoic fault systems in the SECB are oriented NW-SE, which is roughly parallel to the Roer Valley Graben border fault system.

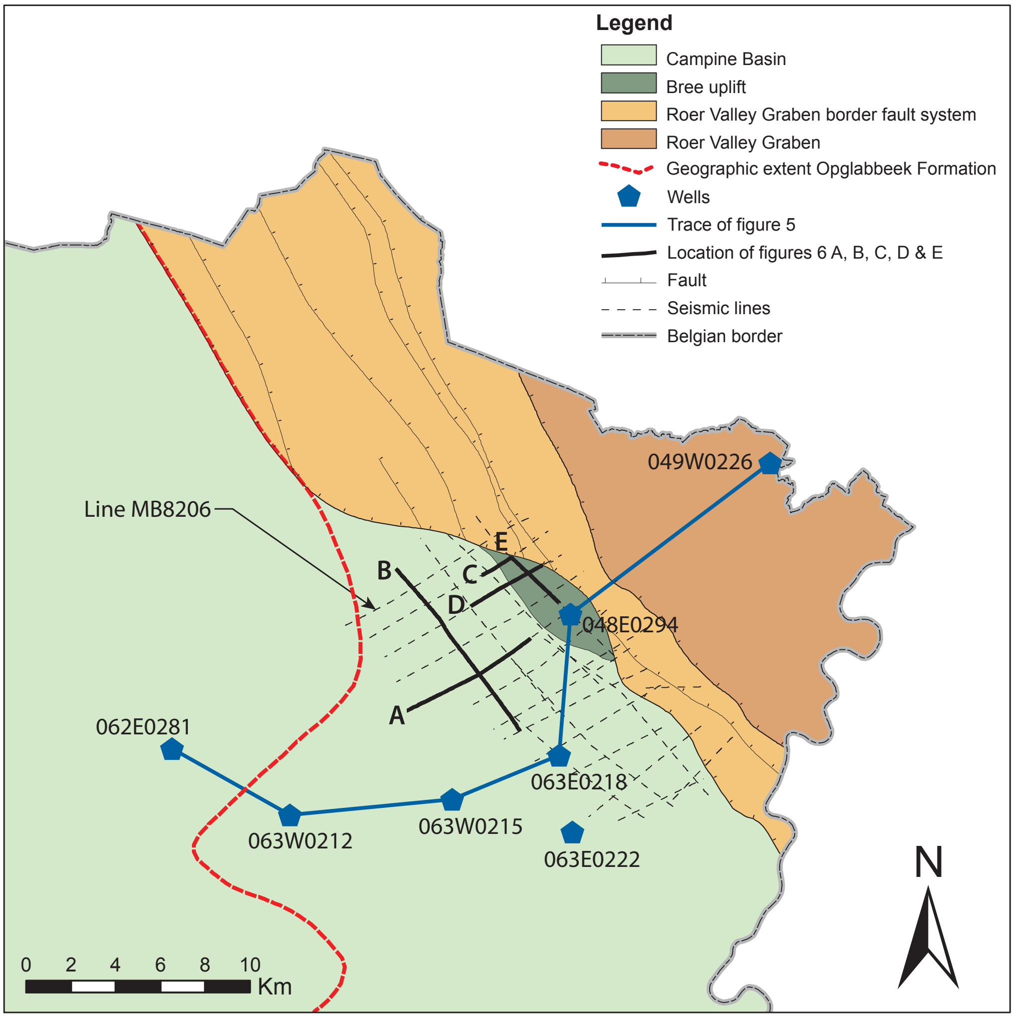


Figure 3. Overview of the south-eastern part of the Campine Basin and the Belgian sector of the Roer Valley Graben. The geographic extent of the Opglabbeek Formation was modified after the G3Dv2-model (Matthijs et al., 2013).

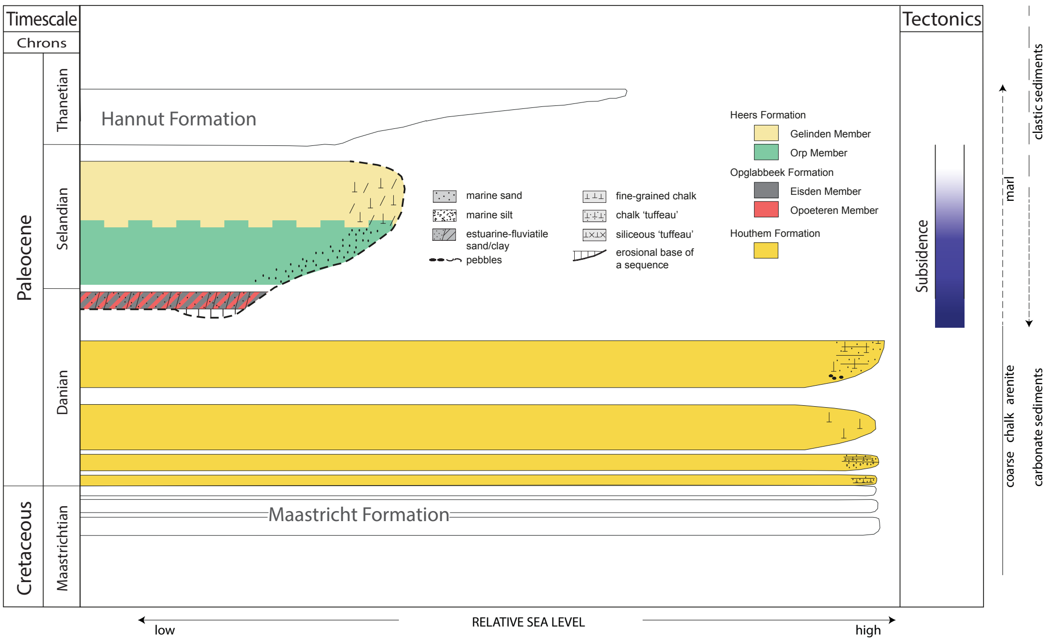


Figure 4. The sediment sequences and the relative sea-level at the time of their formation (modified after Vandenberghe et al., 2004).

3. Stratigraphy

During the Maastrichtian, the entire region was flooded and covered by the calcarenites of the Maastricht Formation. After a latest Maastrichtian hiatus (Dusar & Lagrou, 2007), the Maastricht Formation became covered by the early to middle Danian calcarenites of the Houthem Formation (Laga et al., 2001). The hiatus between the Maastricht and Houthem Formation is represented by a major karstified horizon (Bless et al., 1993). In the absence of biostratigraphic data, the high gamma-ray log values (or peak) in the interval around the karstified horizon are often used to distinguish these lithologically very similar formations (Slimani et al., 2011). The shallow marine calcarenites of the Houthem Formation covered north-eastern Belgium with a rather uniform thickness of 30-35 m (Fig. 5).

During the latest Danian, the Houthem Formation was locally overlain by the Opglabbeek Formation (Fig. 4; Steurbaut & Sztrákos, 2008). The lower part of the Opglabbeek Formation consists of the multi-coloured lignitic silty claystones with intercalated sandy levels of the Opoeteren Member and the upper part of the medium to coarse sand(stone)s of the Eisden Member (Steurbaut, 1998). In Belgium, the lateral continuous presence of the Opglabbeek Formation is restricted to the SECB and the Roer Valley Graben (Fig. 3). The Opglabbeek Formation reaches its maximum recorded thickness of 40 m in the south-western part of the Roer Valley Graben (De Koninck et al., 2011) (Fig. 5).

During the Selandian, the Heers Formation was deposited on top of the Opglabbeek and Houthem Formations (Fig. 4; Steurbaut, 1998; De Bast et al., 2013). The Heers Formation consists of a lower Orp Member and an upper Gelinden Member, respectively of early to middle Selandian and middle to late Selandian age (De Bast et al., 2013). The Orp Member represents a major transgression and consists of fine glauconitic marine sands, while the highstand Gelinden Member consists of shallow-water marls. The Heers Formation covers almost the entire Campine Basin and the Roer Valley Graben. Similar to the Opglabbeek Formation, the Heers Formation reaches its maximum recorded thickness of 55 m in the south-western part of the Roer Valley Graben (De Koninck et al., 2011) (Fig. 5). During the Thanetian, the Hannut Formation was deposited on top of the entire Heers Formation and in most parts of northern Belgium (Flanders) (Steurbaut, 1998; in press).

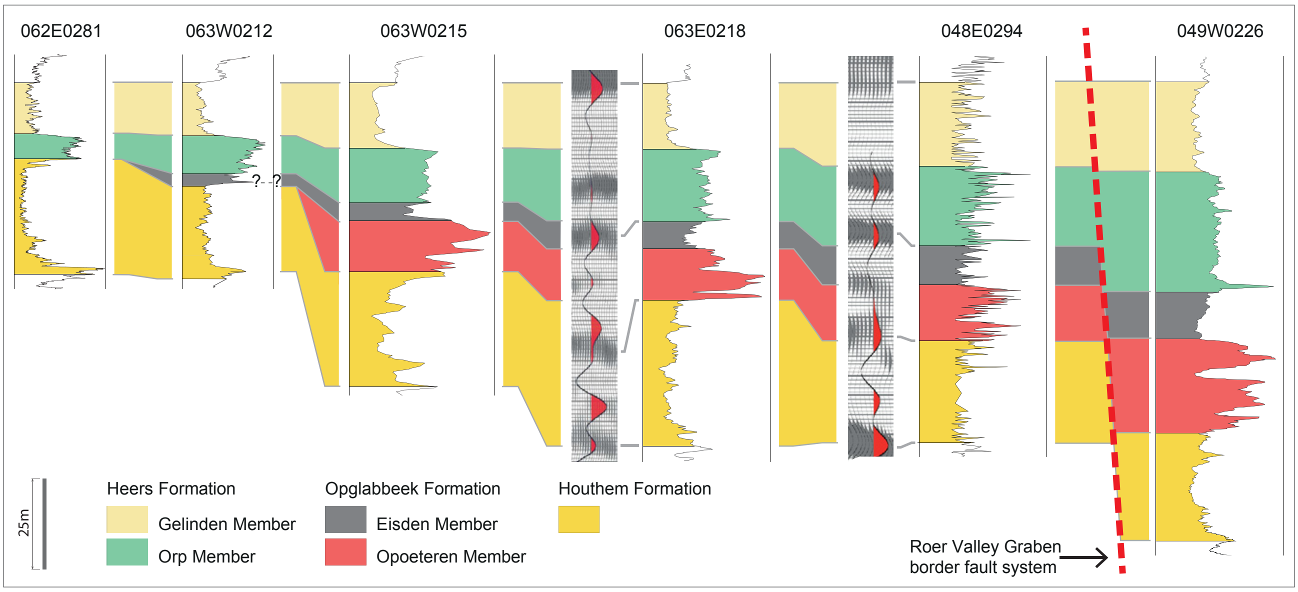


Figure 5. Well log and seismic interpretations from the Roer Valley Graben in the east towards the SECB in the west. The well log interpretations are extracted from De Koninck et al. (2011) and are presented on top of the gamma-ray logs. The black lines connect the well log interpretations to the corresponding red wiggles of the synthetic seismogram that are displayed on part of a reflection seismic line. The location of this trace is given in figure 3.

4. Dataset and methodology

4.1 Seismic data

The Neeroeteren-Rotem survey of 1980 and the Meeuwen-Bree survey of 1982 consist respectively of 83 and 90 km of 2D seismic reflection data within the SECB (see Figs 3 & 7). Both surveys consist of NW-SE and NE-SW directed seismic lines and were designed to image the Carboniferous basement, which is located a few hundred meters below the Paleocene strata. To enhance the resolution of the zone below the top Carboniferous, the seismic data was reprocessed in 2003. During the conventional prestack processing, special care was taken to suppress the high noise level in the prestack data. This allowed a more clear visualization of lineaments such as faults and fractures. A further increase of resolution was achieved by Common-Reflection-Surface processing. A strongly increased stacking fold and the local optimization of the stacking parameters lead to a strongly improved resolution and much better signal-to-noise ratio. The improved quality of the Common-Reflection-Surface processing sections allows for a more detailed interpretation of the seismic signal below the top Carboniferous. After reprocessing, the resolution of the seismic data was also improved in the upper part of the section, allowing for a study of the Paleocene interval. After reprocessing, the resolution of the seismic data was sufficient to allow a study of the Paleocene interval. All seismic data is displayed with normal (SEG) polarity so that a downward increase in acoustic impedance is represented by a peak (black and red on Fig. 5; red on Fig. 6) and a downward decrease in acoustic impedance by a trough (blue on Fig. 6). Thickness trends will be discussed in terms of two-way-travel time thickness and not in real thickness.

4.2 Seismic-to-well ties

Seismic interpretation was based on correlation with interpreted well log data. For three wells (two of which are given in Fig. 5) a synthetic seismogram was created from the sonic (and for one well also from the density) log data, which enabled ties for every formation boundary.

Dependent on the resolution of the seismic data, the Houthem Formation either lacks or contains one relatively weak internal reflector. The top and base reflectors of the Houthem Formation are laterally continuous and characterized by relatively high reflection amplitudes. The base reflector represents the transition from soft to hard carbonates, while the top reflector represents the downward transition from siliciclastics to carbonates.

A thick Opglabbeek Formation contains one rather irregular and laterally discontinuous internal reflector. The sandstone banks in the top of the Eisden Member form the laterally continuous top reflector of the Opglabbeek Formation.

A thick Heers Formation is characterized by two positive internal reflections (or peaks), while the transition from the marls of the Gelinden Member to the underlying sands of the Orp Member is represented by a through. The top reflector of the Heers Formation obtains a high reflection amplitude as it represents the transition from clayey to marly sediments.

5. Results

5.1 Houthem Formation (Danian)

The top and base reflectors of the Houthem Formation are nearly parallel (Fig. 6) and therefore suggest a rather uniform thickness throughout the SECB, which is consistent with well data (Fig. 5). Subtle two-way-travel time thickness variations may occur across (younger) faults, but these are most likely related to the resolution of the seismic data or fluctuations in interval velocities rather than to actual changes in thickness.

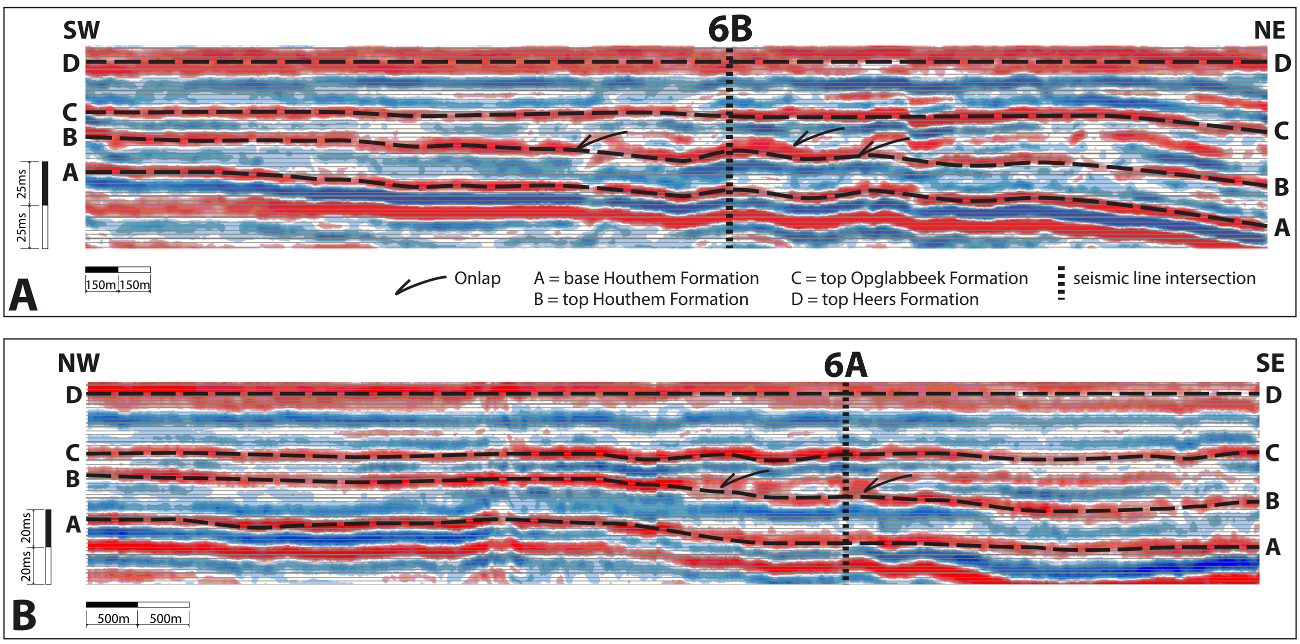
5.2 Opglabbeek Formation (latest Danian)

The Opglabbeek Formation unconformably overlies the Houthem Formation. The unconformity is expressed by onlap of the Opglabbeek Formation reflectors on the Houthem Formation (Figs 6 A & B). The Opglabbeek Formation reaches its greatest thicknesses in the immediate footwall to the Roer Valley Graben border fault system and starts thinning away from it (Fig. 7).

The westward thinning and restricted presence of the Opglabbeek Formation was in the past often interpreted as result of erosion right after its deposition (c.f. Vandenberghe, 1998). The onlap pattern now shows that the presence of (in particular the lower parts of) the Opglabbeek Formation was instead restricted to areas with sufficient subsidence during a relatively low sea-level. The thickness of the Opglabbeek Formation is therefore used as an indicator for differential subsidence during the latest Danian.

Based on the lateral variations in the magnitude of differential subsidence, the study area can be divided in a north-western (roughly the Meeuwen-Bree survey area) and a south-eastern sector (roughly the Neeroeteren-Rotem survey area).

In the north-western sector, the rate of subsidence strongly decreases in south-western direction (Fig. 7), as indicated by onlap of the intra-Opglabbeek Formation reflector on the Houthem Formation (Fig. 6 A). On top of this pattern, the rate of subsidence progressively decreases from the south-east to the north-west (Fig. 7). In the north-westernmost study area (i.e. seismic line MB8206) the Opglabbeek Formation eventually pinches out by south-westward onlap of its top reflector on the Houthem Formation. To the north of this line, the Opglabbeek Formation most likely becomes restricted to the Roer Valley



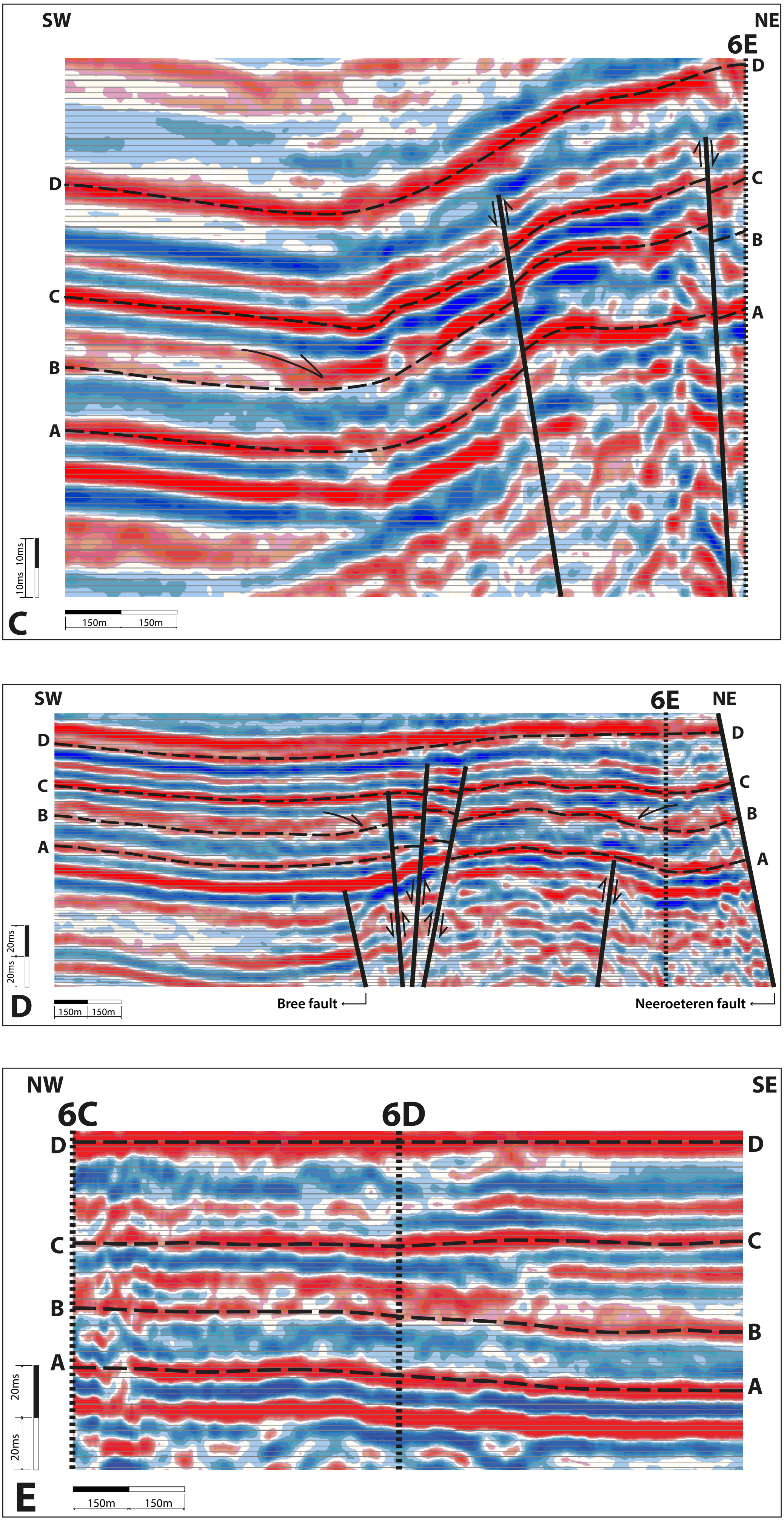


Figure 6. Seismic sections across the study area. Locations are given in figure 2. **A.** SW-NE section that shows the south-west directed thinning of the Opglabbeek and Heers Formations in the north-western sector. The top of the Heers Formation is flattened. **B.** NW-SE section that shows the north-west directed thinning of the Opglabbeek and Heers Formations in the north-western sector. The top of the Heers Formation is flattened. See figure 6A for the legend. **C & D.** SW-NE sections across the northern part of the Bree Uplift. These sections show that the Opglabbeek Formation thins on top of the forced folded Bree Uplift and that the Heers Formation thins only on fault blocks that pop-up in between oppositely dipping reverse faults. See figure 6A for the legend. **E.** NW-SE section along the northern part of the Bree Uplift and along the footwall to the north-easternmost fault of figure 6C. The Opglabbeek Formation thins towards the north-west as the northern part of the Bree Uplift was folded into an anticline during the latest Danian. The thickness of the Heers Formation hardly changes along this section since the hangingwall block and not the footwall block to the north-easternmost fault of figure 6C was uplifted. The top of the Heers Formation is flattened. See figure 6A for the legend

Graben, while all the seismic lines to its south are located within the geographic extent of this formation (Fig. 3).

In the south-eastern sector, the rate of subsidence decreases much more gradually in south-western direction (Fig. 7) as shown by convergence of the top and base Opglabbeek Formation reflectors. The south-eastern sector thus formed a low-lying area with a depositional slope that gradually went upwards in the north-western sector as shown by onlap of the intra-Opglabbeek Formation reflector on the Houthem Formation (Fig. 6 B). The same pattern is expressed by the geographic extent of the Opglabbeek Formation, which reaches far into the west in the SECB, but strongly retreats towards the east in the direction of the north-eastern part of the Campine Basin (Fig. 3).

On top of the Bree Uplift, the thickness of the Opglabbeek Formation subtly changes across several small normal and reverse faults (Figs 6 C & D). Vertical offsets along faults at the stratigraphic level of the Opglabbeek Formation were less than 10 m. The northern part of the Bree Uplift was folded into an anticline with reduced thickness of the Opglabbeek Formation on top (Figs 6 C, D, E & 7). Folding was induced by reverse reactivation of the Bree fault in the south-west and a fault to the west of the Neeroeteren fault in the north-east. As the northern part was uplifted, the southern part of the Bree Uplift experienced relatively strong subsidence.

5.3 Heers Formation (early to late Selandian)

The reflectors of the Heers Formation conformably overlie the Opglabbeek Formation. The Heers Formation reaches its greatest thicknesses in the immediate footwall to the Roer Valley Graben border fault system. Away from the border fault system, the Heers Formation thins (Fig. 6 A), which is interpreted to reflect a lateral decrease in the amount of early to late Selandian subsidence.

Similar as during the deposition of the Opglabbeek Formation, the south-western directed decrease in the amount of subsidence was more or less gradual in the low-lying south-eastern sector and much stronger in the north-western sector of the study area. This shows that differential subsidence of the SECB continued after the latest Danian with similar relative rates. This is consistent with well log interpretations of De Koninck et al. (2011) which showed that the presence of the Opglabbeek Formation is often associated with an increase in the thickness of the overlying lower Heers Formation or Orp Member. The percentage of the total thickness that decreases in south-western direction is however higher for the Opglabbeek Formation than for the Heers Formation. This is most likely due to the more gradually changing thickness of the upper Heers or Gelinden Member with respect to the underlying Orp Member and Opglabbeek Formation (De Koninck et al., 2011). The rates of subsidence thus decreased after the middle Selandian.

On top of the Bree Uplift, the expression of deformation locally changed after the Danian. Folding of the northern part of the Bree Uplift for example ended. Instead, oppositely dipping reverse faults breached the anticline and thereby popped-up small-sized fault blocks (Figs 6 C & D). Whereas folding had caused uplift on the entire northern part of the Bree Uplift, breaching restricted the uplift to the reverse fault hangingwalls. As a consequence, the footwalls to some of these reverse faults are characterized by a relatively thin Opglabbeek Formation and a relatively thick Heers Formation (Figs 6 C, D & E). Maximum vertical offsets along faults at the stratigraphic level of the Heers Formation were in the order of 5 m. All of the faults that had shown activity during the deposition of the Heers Formation on top of the Bree Uplift died out just underneath or within its top reflector, which is roughly within the Gelinden Member (Figs 6 C & D).

6. Discussion and conclusion

6.1 Early to middle Danian

During the early to middle Danian, the calcarenites of the Houthem Formation were deposited in several southern North

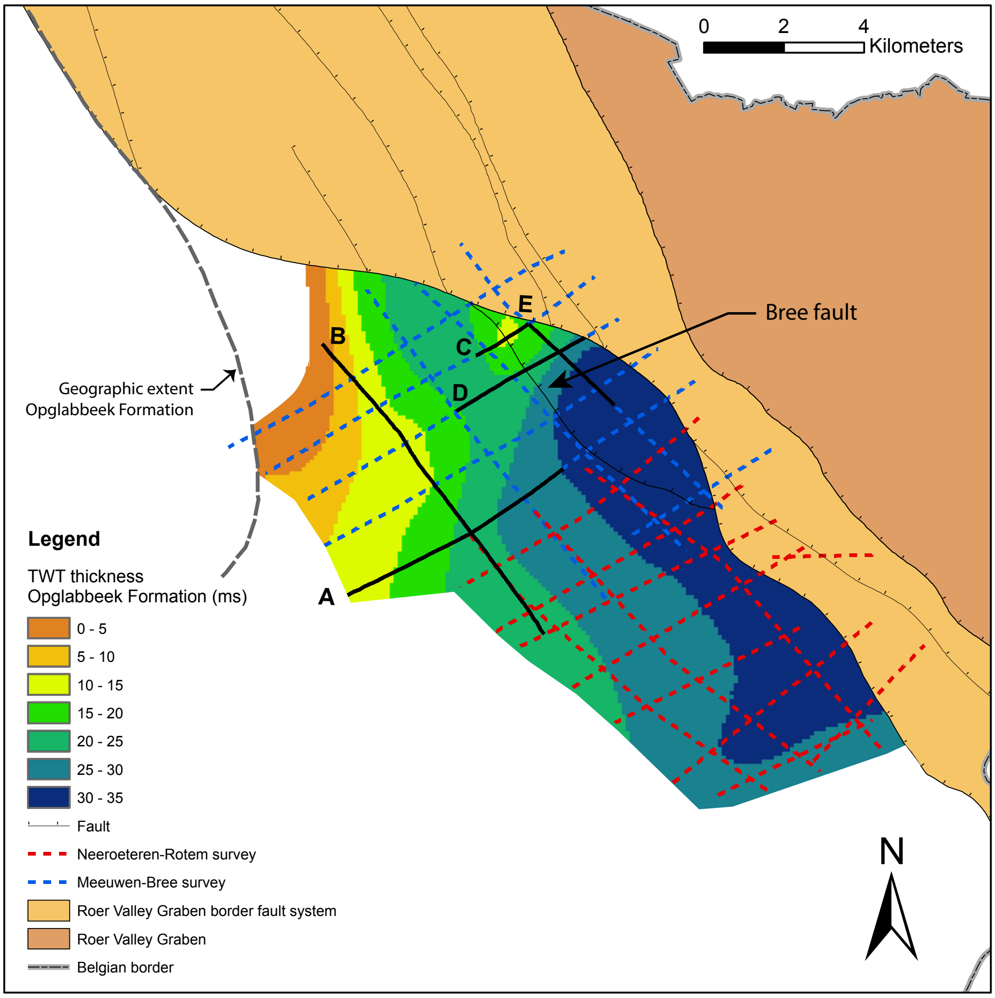


Figure 7. Schematic two-way-travel time thickness (isochronopach) map of the Opglabbeek Formation in the study area.

Sea basins, including the Campine Basin. The regularity in time span (Slimani et al., 2011) and thickness of the Houthem Formation throughout the eastern part of the Campine Basin shows that it was not affected by significant tectonic activity during the Danian.

6.2 Latest Danian and Selandian

During the late Danian, a fundamental change in the intra-plate stress-field of Europe marked the onset of low-amplitude stress-relaxation features in several North European basins (Nielsen et al., 2005; 2007). Deckers et al. (in press) showed that, under these new stress conditions, the southern part of the Roer Valley Graben became downthrown by flexural subsidence along its border zone. This study shows that the south-eastern part of the Campine Basin was simultaneously subjected to flexural subsidence with progressively increasing and laterally varying rates in the direction of the southern part of the Roer Valley Graben (Figs 6 A, B & 7).

The subsiding parts of the Roer Valley Graben and SECB formed a large (probably isolated) depocenter that (because of the latest Danian relative sea-level low) was outlined by the infill of the lowstand continental to shallow marine siliciclastics of the Opglabbeek Formation. In one well that penetrates this depocenter (Belgian Geological Survey file 63E0222, for location see figure 3), the contrast in bedding between the infilling siliciclatics and the underlying calcarenites is distinct (pers. comm. M. Dusar). In the south-eastern sector of the SECB, the subsidence rates remained high far into the south-west, which created a major pathway for further westward transgression and deposition of the Opglabbeek Formation. Stainier (1931) proclaimed that the Opglabbeek Formation attained lateral facies variations within this pathway. The strongest pulse of subsidence most likely occurred even before the deposition of the Opglabbeek Formation.

Seismic and well log data show that the relative rates of latest Danian subsidence continued during the early to middle Selandian deposition of the transgressive Orp Member (lower Heers Formation), which filled the depocenter and covered its former flanks. Well log data shows that the north-eastern part of the Campine Basin was not part of the depocenter, but formed a relative high without deposition of the Opglabbeek Formation and only limited coverage by the Orp Member (Fig. 5). Also in the Roer Valley Graben, subsidence was restricted to the southern part, while the northern part was probably uplifted (see figure 7 in Deckers et al., in press).

Well log data shows that the amplitude of differential subsidence in the SECB decreased when the Orp Member became covered by the middle to late Selandian Gelinden Member (upper Heers Formation). Also in the Roer Valley Graben, the intensity of stress-relaxation tectonics diminished after the middle Selandian (c.f. Deckers et al., in press).

The Bree Uplift, located in the easternmost SECB or footwall to the Roer Valley Graben border fault system, was also deformed during the late Danian to middle Selandian phase. The expression of deformation shares many similarities with positive flower structures that typically develop in wrench or transpressional strike-slip zones (e.g. Christie-Blick and Biddle, 1985; Naylor et al., 1986). Nevertheless, it remains difficult to reliably distinguish strike-slip faults (Harding, 1990), especially based on low resolution 2D seismic data. However, since the Bree Uplift itself is interpreted as a Late Cretaceous transpressional half positive flower structure (Dusar & Langenaeker, 1992; Langenaeker, 1999; 2000), it is likely that some of its strike-slip faults were in fact reactivated by a potentially oblique extensional stress-field (i.e. transtension). Also in other southern North Sea basins, like the Broad Fourteens Basin, stress conditions caused tensional reactivation of faults during the deposition of the Heers Formation (de Lugt et al., 2003). As stress-relaxation tectonics diminished after the middle Selandian, faults on top of the Bree Uplift die out in the Gelinden Member (Fig. 6 C & D).

7. Acknowledgements

The authors gratefully acknowledge financial support from the Environment, Nature and Energy Department of the Flemish government. Katleen Van Baelen is thanked for her excellent work on the figures. Sian Loveless was of great help by reviewing the early version of this manuscript. The manuscript has benefited significantly from the constructive comments of reviewers Dr E. Steurbaut and Prof M. De Batist.

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Manuscript received 05.11.2013, accepted in revised form 02.04.2014, available on line 01.05.2014