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A review on the structural styles of deformation during Late Cretaceous and Paleocene tectonic phases in the southern North Sea area

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ABSTRACT

The Mesozoic rifts in the southern North Sea area were affected by Late Cretaceous to Paleocene inversion. Two main inversion phases were traditionally identified in this interval: the Sub-Hercynian and the Laramide phases. The Sub-Hercynian phase started in the early Late Cretaceous, peaked during the Campanian and ended in the late Maastrichtian, while the Laramide phase started in the late Danian and ended in the Thanetian. The Late Cretaceous Sub-Hercynian phase was strong and occurred in several pulses. These pulses led to basin-scale uplift by large reverse movements along basin-bounding faults and resulted in large amounts of erosion (up to 2 km) of Mesozoic and older sediments. The middle Paleocene Laramide phase on the other hand resulted in mild, domal uplift of some Late Cretaceous inverted basins and subsidence (into depocenters) of others. The subsequent Cenozoic inversion phases displayed similar or lower amplitudes and wavelengths of vertical surface movements as the Laramide phase. The transition from the Sub-Hercynian to the Laramide phase in the southern North Sea area therefore coincides with the overall transition from fault-controlled inversion to broad domal vertical surface movements.

1. Introduction

During the Mesozoic, a series of N-S-, NW-SE- to WNW-ESE-oriented rift-basins developed in Western Europe (Fig. 1). A large number of these rift-basins were located in the current southern North Sea area (for locations see Fig. 2). Rifting ended in the Early Cretaceous and from the Late Cretaceous onwards, the rift-basins underwent several phases of uplift and erosion (basin inversion; Ziegler, 1990). There are notable differences in the effects of the different inversion phases on the rift-basins, in particular with respect to timing, magnitude of uplift and structural style (De Jager, 2003). The structural styles of inversions are extracted from seismic and stratigraphic records. Much of the stratigraphic records from inversion phases in the southern North Sea area were, however, removed by the uplift and erosion during the inversion phases themselves or by a subsequent inversion phase. It is consequently often very difficult to distinguish the structural style of individual inversion phases.

This is especially the case for the Paleocene Laramide phase, which took place after the strong Late Cretaceous Sub-Hercynian phase and before the mild latest Eocene Pyrenean inversion phase (c.f. De Jager, 2003). As a result, strongly different views exist on the structural style of the Laramide phase, namely that of strong, fault-controlled uplift (Huyghe and Mugnier, 1994; Nalpas et al., 1995; De Jager, 2003, 2007) or that of a mild domal uplift (Nielsen et al., 2005, 2007; Deckers, 2015; Deckers and Matthijs, 2016).

The aim of this study is to distinguish the structural styles of the Sub-Hercynian and Laramide phases based mainly on existing literature data, seismic profiles and well log correlations. First, we give an overview on the Late Cretaceous to Paleocene stratigraphic records in the southern North Sea area. Then, we discuss the indications that these stratigraphic records hold on the structural style of deformation as given by previous studies and this study. Finally, we discuss the consequences of the insights on the structural style of deformation upon existing regional tectonic models and concepts of Cenozoic basin evolution in the southern North Sea area.

2. Late Cretaceous to Late Paleocene stratigraphic framework

In northwest Europe, the Late Cretaceous to middle Danian (ca. 100-62 Ma) stratigraphic succession is developed as a uniform cover of predominantly friable, micritic limestones that are gathered into the Chalk Group (Van Adrichem Boogaert and Kouwe, 1997; Fig. 3). Locally, such as in the Dutch Central Graben (De Jager, 2003) or flanks of the Roer Valley Graben (Bless et al., 1986), the Chalk Group contains

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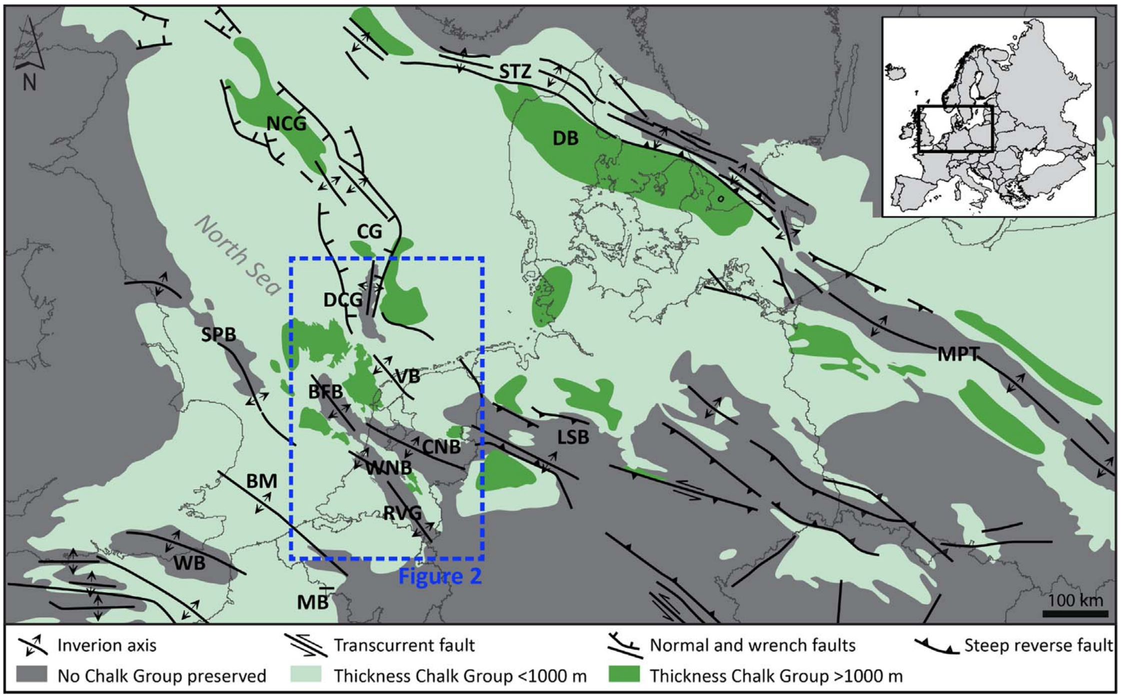

Fig. 1. Late Cretaceous structural setting in central Europe (modified after Ziegler, 1990; Nielsen et al., 2005; Deckers, 2015). The location of Fig. 2 is indicated. BFB = Broad-Fourteens Basin; BIH = Brabant Massif; CNB = Central Netherlands Basin; DB = Norwegian-Danish Basin; CG = Danish Central Graben; IOW = Island of Wight; LSB = Lower Saxony Basin; MB = Mons Basin; NGB = North German Basin; RVG = Roer Valley Graben; SPB = Sole Pit Basin; STZ = Sorgenfrei-Tornquist Zone; VB = Vlieland Basin; WB = Weald-Boulonnais Axis; WNB = West Netherlands Basin.

sandstone layers (Fig. 3). In the Netherlands, the Chalk Group is generally divided into Cenomanian Texel Formation, the Turonian to Maastrichtian Ommelanden Formation and the Danian Ekofisk Formation (Fig. 3). In the southern areas of the Netherlands and northern Belgium, a more detailed subdivision of the Chalk Group has been established (see Fig. 3).

Regional carbonate deposition came to an abrupt end during the late Danian. During the latest Danian relatively low sea-level, the Chalk Group was locally overlain by the continental deposits of the Opglabbeek Formation in the region around the Roer Valley Graben (Steurbaut and Sztrákos, 2008; Figs. 3 & 4). The Opglabbeek Formation consists of multi-coloured lignitic silty claystone with intercalated sandy levels, and medium to coarse sand(stone)s (Steurbaut, 1998). During the Selandian transgression, the Heers Formation was deposited on top of the Opglabbeek Formation and older strata Graben in and around the Roer Valley Graben (Steurbaut, 1998; Figs. 3 & 4), the Central Netherlands Basin (Deckers, 2015; Fig. 5) and south of the West Netherlands Basin (Worum and Michon, 2005; Fig. 6). The Heers Formation consists of fine glauconitic marine sands (Orp Sand Member) and shallow-water marls (Gelinden Marl Member; Steurbaut, 1998). These marls consist mainly of reworked Cretaceous nannofossils from the Chalk Group (Steurbaut, 1998; Vandenberghe et al., 1998). In the offshore areas of the Netherlands and the UK, the Maureen Formation respectively represents the time-equivalent of the Opglabbeek and Heers Formations (Figs. 3 & 7). In the central and northern parts of the North Sea area, the Maureen Formation generally represents deeper marine facies (deep shelf/bathyal) compared to the continental/shallow shelf deposits of the Opglabbeek and Heers Formations.

During the Thanetian, the southern North Sea area became covered by clayey deposits of the Hannut Formation (in Belgium) and the Lista Formation (offshore UK; Fig. 3). The Hannut and Lista Formations generally become coarser-grained towards the more proximal southern margin of the North Sea Basin, where the latter passes into the Thanet Sand Formation (Jolley, 1998). The transition from the Heers and Maureen Formations towards the Hannut and Lista Formation coincides with a strong decrease in carbonate-content throughout the North Sea Basin (Steurbaut and Sztrákos, 2008).

3. Late Cretaceous to Late Paleocene tectonics based on the stratigraphic records

3.1. Late Cretaceous: Sub-Hercynian phase (sections A1 and A2 in Fig. 9)

The effects of the Late Cretaceous Sub-Hercynian phase on the Mesozoic rifts in the southern North Sea area are discussed in detail in the studies of De Jager (2003, 2007). This (roughly N-S) compressional phase started in the Turonian and peaked during the Campanian (De Jager, 2003). Compression led to uplift and erosion of up to 2 km, but in most areas significantly less (De Jager, 2003), of the Mesozoic rifts and the simultaneous subsidence of their flanks into (asymmetric) marginal troughs. Uplift of the Roer Valley Graben might have started in the Turonian, but the sediment record indicate that the troughs in its flanks probably only started developing from the Santonian onwards (compare sections A1 and A2 of Fig. 9). The Santonian to Maastrichtian simultaneity of inversion of the Roer Valley Graben and subsidence of its flanks is evidenced by the progressive increase in clastic sediment input in the Chalk Group in these flanks in the direction of the Roer Valley Graben (Bless et al., 1986; Figs. 3, 4 and 9 section A2). The simultaneity of inversion of the Dutch Central Graben and subsidence of its flanks is then again evidenced by redeposited carbonates (slumps and/or slide sheets) in the Chalk Group that fills the latter (Van der Molen et al., 2005). Uplift of the Mesozoic rifts took place by generally large reverse movements along basin-bounding faults (see major faults in Fig. 2). Where there is a thick sequence of Zechstein (Late Permian) salt, the supra-salt faults are in most cases completely decoupled from the sub-salt faults. Inversion is then manifested only by broad uplift and erosion of the pre-inversion sequences. In areas with a thin Zechstein salt sequence, inversion faults may detach within the salt causing impressive thrusts (e.g. north-western flank of the Broad Fourteens Basin). In the areas without salt deposits, the inversion faults at shallow stratigraphic