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Comment

Cenozoic structures in the eastern North Sea Basin — A case for salt tectonics: Discussion

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ABSTRACT

Clausen et al. (2012) rule out that regional tectonism was important in the development of the eastern North Sea Basin during the Miocene. However, detailed study of outcrops, boreholes and high-resolution seismic data across the eastern North Sea reveals that regional tectonism was important in the development of the basin. Regional tectonism both resulted in inversion of former basins and in the triggering of salt movements. Reactivation of older fault system may also have occurred. The morphology of the basin created by these processes strongly controlled major displacements of the shoreline, in routing the fluvial systems, in shaping valleys and in transporting very coarse-grained sediments far into the basin. The role of salt tectonism as indicated by Clausen et al. (2012) is in agreement with earlier studies, but the significant salt movements during the Quaternary onshore Denmark must be clearly separated from only minor movements in the Miocene.

1. Introduction

Clausen et al.'s (2012) recent publication in Tectonophysics that excludes regional tectonism as a significant process in the Neogene development of the eastern North Sea Basin, seems to be in conflict with several previous studies (Hillis et al., 2008; Knox et al., 2010; Pharaoh et al., 2010; Rasmussen, 2009; Ziegler, 1982 and references therein). These studies indicate that crustal compression forces during the Miocene were transmitted into the plate interior and caused inversion of former basins in the central and eastern part of the North Sea area (Esmerode et al., 2008; Rasmussen, 2009), and in the southwestern part of the North Sea (Hillis et al., 2008; Knox et al., 2010; Ziegler, 1982). The remarkable correlation of unconformities across the North Sea and with the North Atlantic (Stoker et al., 2010) shows that tectonism played a significant role in the development of the Miocene North Sea Basin exactly as occurred in the Late Cretaceous and early Cenozoic (Mogensen and Korstgaard 1993; Ziegler, 1982).

In the present discussion the Tertiary lithostratigraphy of Rasmussen et al. (2008, 2010) is used (Fig. 1). The database, structural features and key boreholes are shown in Fig. 2. The discussion will concentrate on issues raised by Clausen et al. (2012) about Neogene tectonism in the North Sea Basin, i.e. inversion in the Central Graben, the role of the Ringkøbing-Fyn High, and Salt tectonism.

2. Inversion in the Central Graben

The main issue of Clausen et al.'s (2012) article is to rule out that inversion tectonism commenced in the Central Graben during the Early Miocene. In Fig. 3, two seismic sections show the development of the Cenozoic succession across the Ringkøbing-Fyn High and Central Graben. The northern seismic section shows that the base of the Cenozoic succession has a concave upward morphology within the Central Graben area (Fig. 3A) which was correctly interpreted to be associated with compaction-related subsidence within the graben area by Clausen and Korstgaard (1993). In contrast, the southern section shows a distinctly different shape with convex upward morphology in the Central Graben area (Fig. 3B). This convex upward structure includes the entire width of the southern Danish Central Graben (Fig. 3A). A detailed analysis of this structure (see Rasmussen, 2009) reveals that it forms a classic inversion structure. The inversion structure (Igor Ridge, Fig. 4) has long been known and was described by e.g. Vejbæk and Andersen (2002 and references therein). However, the Miocene evolution of the structure was not revealed in their study because they did not map the Cenozoic succession in detail. Similarly, Clausen et al. (2012) only mapped major Cenozoic surfaces; Upper Oligocene unconformity (UOU) and top Lark Formation (Middle Miocene) which is at a similar resolution as many other studies from the North Sea area (e.g. Anell et al., 2012; Gołędowski et al., 2012; Huuse et al., 2001). However, in order to reveal the Miocene evolution of the Igor Ridge more detailed subdivision is necessary, i.e. on the scale of sequences which reveals sedimentary architectures such as reflector terminations, hiatuses or gradually thinning of sequences around a structure (Fig. 5). The detailed study of the

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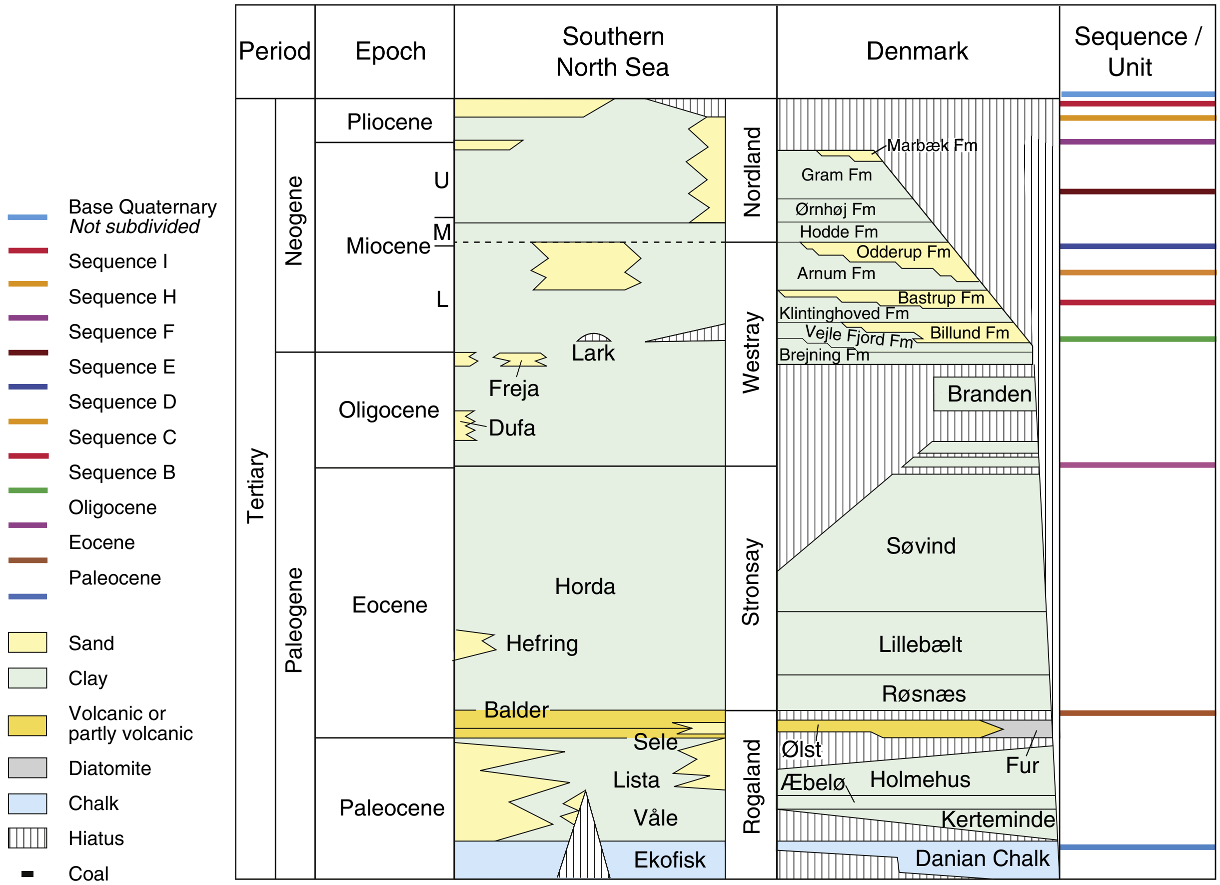

Fig. 1. Tertiary/Cenozoic lithostratigraphy of onshore Denmark and the southern North Sea. The boundary of the Nordland Group is based on Rasmussen et al. (2008) and Eidvin and Rundberg (2007). Seismic boundaries used in the present study are indicated to the right. Modified from Rasmussen et al. (2008, 2010).

Cretaceous succession by Vejbæk and Andersen (2002) clearly shows pinch-out of intra Cretaceous units on the growing inversion structure (Fig. 4C), but the main up-warping of the Igor structure commenced after the Cretaceous as seen from the flattened section and the post-Cretaceous section (Fig. 4B and C). The architecture of the Early Miocene succession around the inversion structure clearly shows that the structure was formed before deposition of Lower Miocene sediments, being characterised by reflector terminations and pinching out of the lowermost Miocene succession (Fig. 4A) — very similar to what occurred during the Cretaceous (Vejbæk and Andersen, 2002). So why should this not be applicable for the Miocene succession? The location of the inversion structure, mainly confined to the southern part of the Central Graben, was probably a consequence of the change in fault strike (dogleg) of the Coffee Soil fault (Fig. 2) where compressional forces were concentrated during the well known Alpine tectonic event, the Savian Phase of Late Oligocene–Early Miocene (e.g. Pharaoh et al., 2010; Ziegler, 1982). An earliest Early Miocene age of the structure is also consistent with the Oligocene–Miocene hiatus found in the marginal part of the inversion structure in the Alma-1 well (Schiøler 2005).

The compactional procedure provided in Clausen et al. (2012) is very selective and represents a narrow part across the Coffee Soil Fault and does not include the Cenozoic succession across the inverted Central Graben (Igor Ridge) and the Ringkøbing-Fyn High. The stratigraphic resolution of the study of Clausen et al. (2012) is very low and did not consider sedimentary architecture, e.g. pinching out of units within these major units. As demonstrated in Fig. 4 and the study of Rasmussen (2009) the stratigraphy is more complex than simple draping of marine clays across the entire basin. Consequently, the compactional procedure around narrow selected sections does not provide new insight into the development of the inversion structure and is certainly not a methodology to rule out a tectonic origin of the anticline found in the southern part of the Danish Central Graben. Especially not in this case as stated by Vejbæk and Andersen (2002); c.f. The early phases show that inversion movements are mainly confined to narrow zones and controlled by pre-existing faults, whereas the late phases are less directly fault controlled and are more expressed as gentle folding and upwarping of the basins.

That inversion commenced in the Central Graben during the Early Miocene is not a special phenomenon. The entire southwestern North Sea was subject to inversion tectonism at that time, i.e. the Artois Swell in Belgium (Knox et al., 2010; Van Vliet-Lanoë, 2002) and the Sole Pit area (Hillis et al., 2008; Knox et al., 2010). According to Blundell (2002) there is also evidence for uplift of the Weald Basin at the Late Oligocene–Early Miocene boundary which is actually coincident with the described inversion in the Central Graben (Rasmussen, 2009). The inversion structure in the Danish area is located c. 1000 km from the Alpine Deformation Front which is quite similar to the c. 850 km of the Sole Pit structure. Consequently, why should the Central Graben not have been influenced by compression during this period as it was during the Late Cretaceous and early Cenozoic?

3. The Ringkøbing-Fyn High and Norwegian–Danish Basin

Rasmussen (2009) did not interpret the Ringkøbing-Fyn High as an inversion structure, but demonstrated that reactivation occurred e.g. along the Brande Trough and perhaps the southern boundary fault. The topography of this trough and other structural elements on the high was very important in controlling the depositional system (distribution of reservoir rocks) during the Early Miocene (Rasmussen, 2009; Rasmussen and Dybkjær, 2005).