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Late Cretaceous to recent tectonic evolution of the North German Basin and the transition zone to the Baltic Shield/southwest Baltic Sea

M. Al Hseinat [a,b,*,1], C. Hübscher [a]

[a] Institute of Geophysics, Center for Earth System Research and Sustainability, University of Hamburg, Bundesstrasse 55, 20146 Hamburg, Germany
[b] Faculty of Marine Sciences, Department of Coastal Environment, the University of Jordan, PO Box 2595, Aqaba 77110, Jordan

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ABSTRACT

In this study we investigate the Late Cretaceous to recent tectonic evolution of the southwestern Baltic Sea based on a dense grid of seismic reflection profiles. This area covers the Baltic Sea sector of the salt influenced North German Basin and its transition to the salt free Baltic Shield across the Tornquist Zone. The Upper Cretaceous to recent structural evolution is discussed by means of individual seismic sections and derived high-resolution time-structure maps of the main horizons, i.e., the Upper Cretaceous, Tertiary and Pleistocene. The Upper Cretaceous and Tertiary layers reveal numerous significant faults throughout the study area. Several of these faults propagate upwards across the unconsolidated Pleistocene sediments and occasionally penetrate the surface. The salt influenced North German Basin reveals three major fault trends: NW-SE, N-S and NNE-SSW. Several of these faults are located directly above basement (sub-salt) faults and salt pillows. The majority of these faults are trending N-S to NNE-SSW and parallel the direction of the Glückstadt Graben faults. In the salt free Tornquist Zone, we identify two major shallow fault trends, which are NW-SE and NE-SW. The majority of these faults are located above basement faults, following the direction of the Tornquist Zone. We conclude that generally basement tectonics controls activation and trends of shallow faults. If salt is present, the ductile salt layer causes a lateral shift between the sub- and supra-salt faults. Major plate reorganisation related to the Africa-Iberia-Europe convergence and the subsequent Alpine Orogeny caused reactivation of pre-existing faults and vertical salt movement in the Late Cretaceous. The change of stress orientation from NE-SW to a NW-SE during Neogene caused another phase of fault and salt tectonic reactivation. We explain that the ice-sheet loading and/or present-day stress field may have acted in combination, causing the recent tectonics and upward extension of the faults.

1. Introduction

The study area is located in the southwest Baltic Sea, covering the North German Basin and the transition zone to the Baltic Shield (Figs. 1 and 2a). Several marine geophysical studies carried out in the past decades have documented multiple tectonic events throughout the geological history of the region, for example the BABEL (BABEL working group, 1991, 1993), DEKORP-BASIN (e.g., DEKORP-BASIN Research Group, 1999; Krawczyk et al., 1999; Meissner and Krawczyk, 1999), EUGENO-S (EUGENO-S working group, 1998) and POLONAISE '97 (e.g., Grad et al., 1999; Guterch et al., 1999) projects. These projects mainly aimed on a better understanding of the deep-crustal structures therein. The overall tectonic evolution of the study area included five main periods, which are collision events during the Paleozoic, Permian rifting, extension during much of the Mesozoic, inversion during Late Cretaceous-Paleogene times and NW-SE extension since the Neogene. Repeated glaciation/deglaciation processes during Pleistocene times further had a significant impact on the evolution of northern Germany and surrounding areas (Reicherter et al., 2005). The advance and retreat of large ice sheets causes lithospheric depression and rebound in areas beneath and marginal to the ice, as the lithosphere equilibrate with the changing ice load (e.g., Sirocko et al., 2008).

This so called glacial isostatic adjustment (GIA) describes the response of the solid Earth to mass redistribution during a glacial cycle (e.g., Bergsten, 1954; Cathles, 1975; Ekman, 1991a, 1991b; Ekman, 2009; Ekman and Mäkinen, 1996; Johansson et al., 2002; Kaufmann and Wolf, 1999; Kierulf et al., 2014; Klemann and Wolf, 2005; Lambeck et al., 1998a; Mitrovica, 1996; Mörner, 1979; Plag et al., 1998; Spada et al., 2011; Steffen et al., 2006; Steffen and Wu, 2011; Whitehouse, 2009; Wolf, 1993; Wu and van der Wal, 2003). The

* Corresponding author at: Institute of Geophysics, Center for Earth System Research and Sustainability, University of Hamburg, Bundesstrasse 55, 20146 Hamburg, Germany.
E-mail addresses: muayyad.al-hseinat@uni-hamburg.de, m.hseinat@ju.edu.jo (M. Al Hseinat).
[1] Current address: Faculty of Marine Sciences, Department of Coastal Environment, the University of Jordan, Aqaba Branch, Jordan, PO Box 2595, Aqaba 77110, Jordan.

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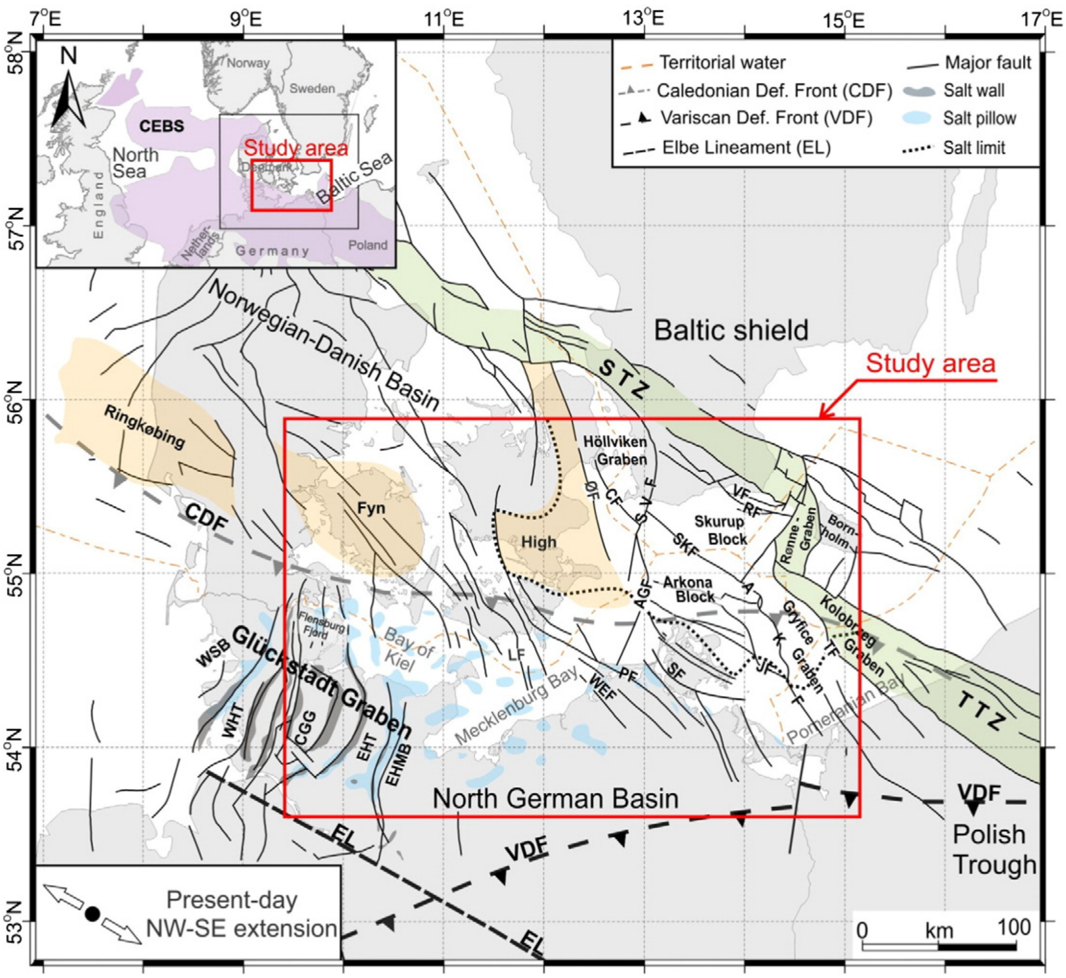

Fig. 1. Tectonic map of the Central European Basin System with the approximate location of the main structures within the study area (compiled from Baldschuhn et al., 1991; Bayer et al., 1999; Clausen and Pedersen, 1999; Krauss, 1994; Kossow et al., 2000; Lokhorst et al., 1998; Maystrenko et al., 2005a; NIA, 2000; Reicherter et al., 2008; Schlüter et al., 1997; Thomas et al., 1993; Vejbæk, 1997). The present-day stress field orientation is based on Kley et al. (2008) and Kley and Voigt (2008). AGF: Agricola Fault; AKF: Adler-Kamien Fault; CF: Carlsberg Fault; CGG: Central Glückstadt Graben; EHT: Eastholstein Trough; EHMB: Eastholstein Mecklenburg Trough; JF: Jasmund Fault; LF: Langeland Fault; ØF: Øresund Fault; PF: Prerow Fault; RF: Romeleasen Fault; SF: Samtens Fault; SKF: Skurup Fault; STZ: Sorgenfrei-Tornquist Zone; SVF: Svedala Fault; TF: Trzebiatow Fault; TTZ: Teisseyre-Tornquist Zone; VF: Vomb Fault; WEF: Werre Fault; WHT: Westholstein Trough; and WSB: Westschleswig Block.

rebound's influence of the last glacial advance is still happing and will continue for another few thousand years (e.g., Kumar and Sunil Singh, 2012; Le Meur, 1996; Steffen and Wu, 2011).

There is strong theoretical and empirical support for the idea that loading by major ice sheets does not only cause large-scale subsidence and lithospheric flexure, but also regional and local vertical and horizontal movements, which may be accommodated by faulting (e.g., Al Hseinat and Hübscher, 2014; Al Hseinat et al., 2016; Arvidsson, 1996; Brandes et al., 2012a, 2012b; Dyke et al., 1991; Fenton, 1994; Johnston, 1987; Kujansuu, 1964; Lagerbäck, 1978; Lagerbäck and Sundh, 2008; Lang et al., 2014; Muir-Wood, 2000; Munier and Fenton, 2004; Olesen, 1988; Quinlan, 1984; Sandersen and Jørgensen, 2015; Sauber and Molnia, 2004; Shilts et al., 1992; Steffen et al., 2014a, 2014b, 2014c, 2016; Stewart et al., 2000; Turpeinen et al., 2008; Wu et al., 1999). The effect of the ice loads on pre-existing faults and/or salt tectonics has been described in several studies (e.g., Al Hseinat and Hübscher, 2014; Al Hseinat et al., 2016; Brandes and Tanner, 2012; Lang et al., 2014; Lehné and Sirocko, 2007, 2010; Liszkowski, 1993; Sirocko et al., 2008; Stackebrandt, 2005). Reicherter et al. (2005) pointed out that the post-glacial landscape evolution in northern Germany shows significant fault reactivation.

Several geophysical studies in the western Baltic provided evidences for Tertiary tectonics, but the too low vertical resolution hampered studying shallow subsurface faulting and therewith recent tectonics (neotectonic) (e.g., Kossow and Krawczyk, 2002; Krawczyk et al., 2002; Krzywiec et al., 2003).

The availability of a large (~20.000 km) high-resolution, multi-channel seismic dataset collected between the Little Belt northwest of the Bay of Kiel and the Tornquist Zone provides the unique chance to close that gap (Fig. 2a). It adds valuable information to the understanding of the Late Cretaceous to recent structural evolution. The comparison of the Pleistocene faults map with deep-rooted faults will give a first idea about the driving forces, e.g., plate tectonics, salt tectonics or ice-load induced tectonics.

2. Tectonic evolution and main structural elements

Located along the northern margin of the Central European Basin System (CEBS) in the southwestern Baltic Sea, the study area has been long influenced by several major tectonic events from Paleozoic to present-day (Fig. 1). These include: the Caledonian and Variscan Orogenies (Late Cambrian-Late Carboniferous), rifting phases (Early Permian), subsidence during much of the Mesozoic, Late Cretaceous-Early Tertiary inversion and post-glacial isostatic adjustment since Late Pleistocene times.

During the Caledonian Orogen, the closure of the Tornquist Ocean was in the Ordovician-Silurian (Smit et al., 2016) resulting in accretion by oblique convergence and collision between Avalonia microcontinent