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RESEARCH ARTICLE

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Impact of Late Cretaceous inversion and Cenozoic extension on salt structure growth in the Baltic sector of the North German Basin

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Abstract

The Late Cretaceous to Cenozoic is known for its multiple inversion events, which affected Central Europe's intracontinental sedimentary basins. Based on a 2D seismic profile network imaging the basin fill without gaps from the base Zechstein to the seafloor, we investigate the nature and impact of these inversion events on Zechstein salt structures in the Baltic sector of the North German Basin. These insights improve the understanding of salt structure evolution in the region and are of interest for any type of subsurface usage. We link stratigraphic interpretation to previous studies and nearby wells and present key seismic depth sections and thickness maps with a new stratigraphic subdivision for the Upper Cretaceous and Cenozoic covering the eastern Glückstadt Graben and the Bays of Kiel and Mecklenburg. Time-depth conversion is based on velocity information derived from refraction travel-time tomography. Our results show that minor salt movement in the eastern Glückstadt Graben and in the Bay of Mecklenburg started contemporaneous with Late Cretaceous inversion in the Coniacian-Santonian. Minor salt movement continued until the end of the Late Cretaceous. Overlying upper Paleocene and lower Eocene deposits show constant thickness without indications for salt movement suggesting a phase of tectonic quiescence from the late Paleocene to middle Eocene. In the late Eocene to Oligocene, major salt movement recommenced in the eastern Glückstadt Graben. In the Bays of Kiel and Mecklenburg, late Neogene uplift removed much of the Eocene-Miocene succession. Preserved deposits indicate major post-middle Eocene salt movement, which likely occurred coeval with the revived activity in the Glückstadt Graben. Cenozoic salt structure growth critically exceeded salt flow during Late Cretaceous inversion. Cenozoic salt movement could have been triggered by Alpine/Pyrenean-controlled thin-skinned compression, but is more likely controlled by thin-skinned extension, possibly related to the beginning development of the European Cenozoic Rift System.

KEYWORDS
Baltic Sea, basin inversion, Mesozoic–Cenozoic structural evolution, North German Basin, salt tectonics, seismic imaging, thin-skinned salt movement

1 | INTRODUCTION

The inversion of the Permian intracontinental sedimentary basins in Central Europe and its controlling processes have been studied for about 100 years (e.g. Doornenbal & Stevenson, 2010; Kley, 2018; Kley & Voigt, 2008; Kockel, 2003; Lamplugh, 1919; Schuh, 1922a, 1922b, 1922c; Voigt, 1962; Ziegler, 1987). Intraplate compressional stress, often transmitted over large distance, can invert former extensional sedimentary basins by compressional reactivation of their fault systems and uplift and folding of the basin fill and basin floor (Brun & Nalpas, 1996; Krzywiec, 2006; Ziegler et al., 1995). The term "basin inversion" refers to a change from subsidence to uplift in a basin controlled by a fault system due to a change in the tectonic regime from extension to shortening (Cooper & Williams, 1989). A mobile salt layer present at the basin floor may decouple the suprasalt sedimentary overburden from subsalt basement deformation, which influences the structural style of both extensional and compressional deformation within the overburden (e.g. Letouzey et al., 1995; Withjack & Callaway, 2000). During basin inversion, preexisting salt structures are preferentially reactivated as halite is weaker than the other laterally adjacent sedimentary rocks. Thereby, even shortening exerted during the earliest stages of basin inversion can remobilize the salt by squeezing the salt structures and arching their roofs (Callot et al., 2012; Jackson & Hudec, 2017; Mohr et al., 2005; Rowan & Vendeville, 2006).

Multiphase uplift and inversion pulses affected the North German Basin (NGB) and other sub-basins of the large intracontinental Southern Permian Basin (Figure 1). After a long-lasting tectonic period of thermal subsidence and extensional deformation since the Carboniferous, shortening and inversion followed from Late Cretaceous times onwards (e.g. Maystrenko et al., 2008; Ziegler et al., 1995). Past publications often considered four major distinct inversion events throughout the history of the Southern Permian Basin. These uplift and inversion events are commonly associated to compressional intraplate stress transmitted within the European foreland during Africa-Iberia-Europe convergence and subsequent Alpine and Pyrenean orogenies (de Jager, 2003; Kley & Voigt, 2008; Kockel, 2003; Krzywiec, 2006; Vejbaek & Andersen, 2002; Ziegler et al., 1995). The first event in the Late Cretaceous (Subhercynian, between 90 and 70 Ma) is widely accepted and has been investigated in most parts of the Southern Permian Basin (e.g. Kley, 2018; Ziegler et al., 1995). Compressional stress during this event induced significant shortening of the basement and caused basin-scale uplift, erosion, large reverse movements along basin-bounding faults and thin-skinned folding of Mesozoic strata detached along the salt layers (de Jager, 2003; Kley, 2018; Kley & Voigt, 2008; Kockel, 2003; Ziegler et al., 1995). The second event occurred in the late Paleocene (Laramide, around 60 Ma) and acted strongest in most Dutch basins. This event is characterized by a widespread unconformity associated to large-scale domal uplift in Central Europe (Deckers & van der Voet, 2018; de Jager, 2003; Ziegler et al., 1995). However, recent studies doubt that far-field effects originating from Africa-Iberia-Adria-Europe convergence caused the unconformity. Instead, these studies suggested sea level fluctuations (Kockel, 2003) or thinning of the mantle lithosphere and dynamic topography driven by mantle plumes as a possible cause of the unconformity (Kley, 2018; von Eynatten et al., 2021). Following inversion pulses in the late Eocene to Oligocene (Pyrenean, 40–30 Ma) and late Oligocene to Miocene (Savian, 30–20 Ma) are documented for the southern North Sea and west of it (Kley, 2018; Ziegler et al., 1995). However, lacking timing constraints hamper a precise separation of the two events in many areas (Kley, 2018).

Highlights

- We present high-resolution seismic depth images from the Baltic sector of the North German Basin.
- Detailed thickness maps reveal the impact of Late Cretaceous–Cenozoic tectonics.
- Coniacian–Maastrichtian minor salt movement was coeval with uplift of the Grimmen High.
- Cenozoic salt movement outranked salt flow during Late Cretaceous inversion.
- We discuss the structural style of Cretaceous–Cenozoic events in the regional tectonic setting.

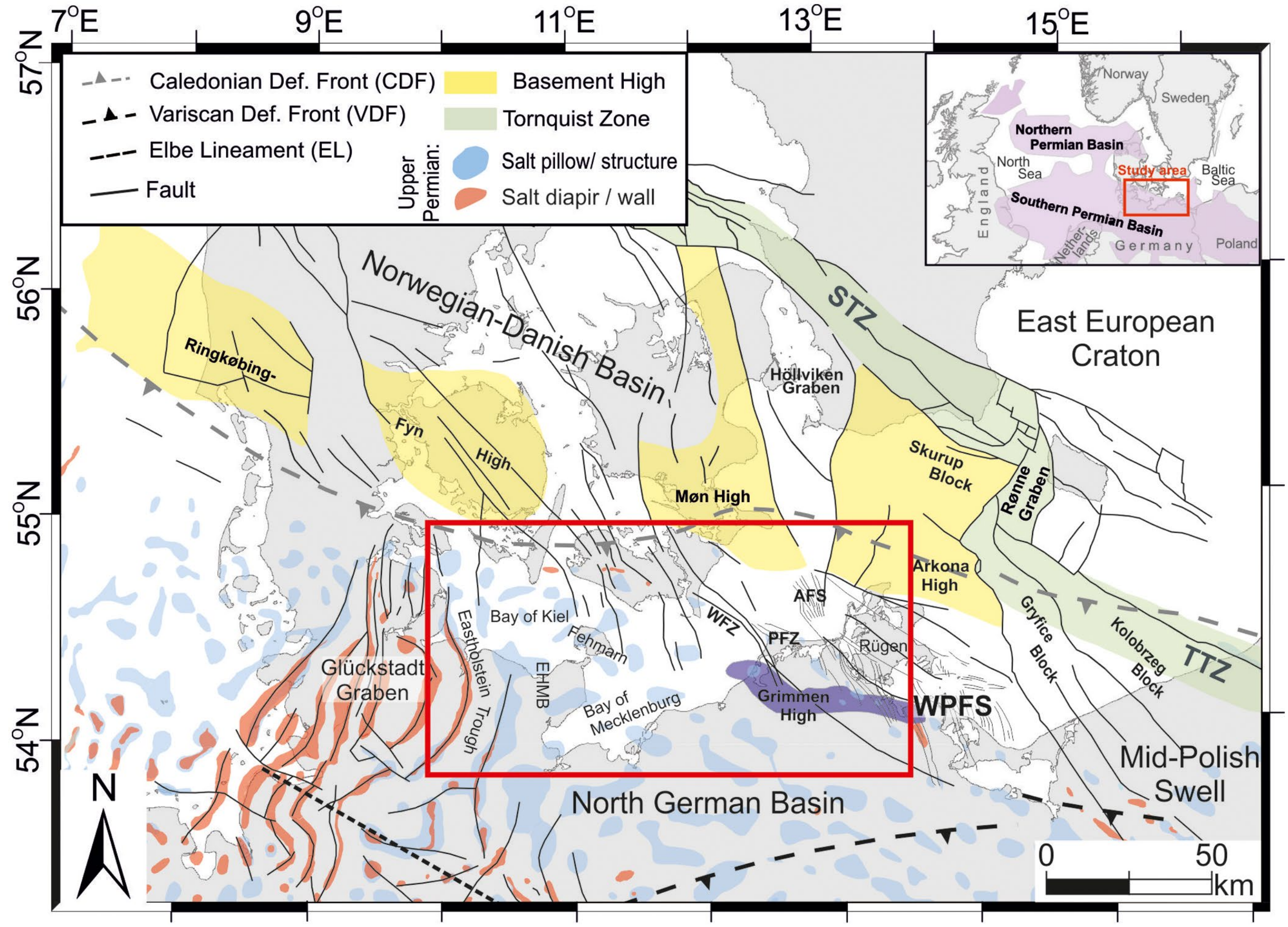


FIGURE 1 Structural elements of the northern North German Basin (modified after Ahlrichs et al., 2020). Inset shows approximate outline of the northern and southern Permian Basin. Red box marks the study area. Salt structures after Vejbaek (1997); Dadlez and Marek (1998); Reinhold et al. (2008); Warsitzka et al. (2019). AFS: Agricola Fault System; EHMB: Eastholstein-Mecklenburg Block; PFZ: Prerow Fault Zone; STZ: Sorgenfrei-Tornquist Zone; TTZ: Teisseyre-Tornquist Zone; WFZ: Werre Fault Zone; WPFS: Western Pomeranian Fault System

The terms to distinguish Late Cretaceous to Cenozoic inversion events ("Subhercynian", "Laramide", "Pyrenean", "Savian") are named after regions, whose context to inversion in Central Europe is partly misleading (e.g. Laramie mountains in North America, the river Save in Slovenia). However, these inversion events can also be temporally distinguished (e.g. Doornenbal & Stevenson, 2010; de Jager, 2003). Therefore, we refer to the individual inversion events ("Subhercynian", "Laramide", "Pyrenean", "Savian") discussed in the following based upon the geological time when they occurred (Late Cretaceous, late Paleocene, late Eocene- Oligocene, late Oligocene – Miocene).

The dating of basin inversion is challenging where corresponding uplift and following erosion partly removed the sedimentary record obliterating parts of its inversion history. According to Warsitzka et al. (2019), regions affected by mild inversion and thin-skinned shortening can be identified by the analysis of salt structures and the reactivation of salt flow. Krzywiec (2006) analysed peripheral salt structures in the Mid Polish Trough (MPT) and showed that peripheral salt structures respond readily to regional shortening by revived growth even during the early stages of basin inversion. In contrast with many other areas in the NGB, the Baltic sector of the NGB contains a relatively complete Cretaceous and Cenozoic sedimentary record. Our study area covers the peripheral region of the NGB and contains numerous salt structures, which formed prior to inversion (Figure 1; e.g. Hansen et al., 2007; Hübscher et al., 2010). Thus, the Baltic sector of the NGB is an ideal site to identify active phases of Late Cretaceous to Cenozoic inversion and analyse their impact on the sedimentary record.

Previous studies analysed salt structure evolution in the Baltic sector of the NGB as a function of the regional tectonic framework by means of seismic imaging and regional mapping (Al Hseinat & Hübscher, 2014, 2017; Al Hseinat et al., 2016; Hansen et al., 2005, 2007; Hübscher et al., 2010; Kossow & Krawczyk, 2002; Zöllner et al., 2008). These authors identified four major post-Permian tectonic phases affecting salt structure evolution: (1) Late Triassic–Early Jurassic extension triggered salt movement. (2) A phase of uplift and erosion related to the North Sea Doming event followed from Middle Jurassic to Early Cretaceous times. (3) Sedimentation resumed towards the end of the Early Cretaceous and the study area experienced a phase of relative tectonic quiescence without salt movement in the Late Cretaceous. (4) At the Late Cretaceous to Cenozoic transition, shortening induced by the onset of Africa-Iberia-Europe convergence lead to basin inversion and reactivated salt flow. However, these studies lack a detailed stratigraphic subdivision to date the onset of basin inversion and to identify individual inversion events. In a local study analysing a crestal graben above a salt wall of the eastern Glückstadt Graben, Huster et al. (2020) used a refined Cenozoic stratigraphy to identify Paleogene and Neogene fault reactivation, which the authors associated with compressional stress induced by the Alpine and Pyrenean orogenies. In the most recent study, Ahlrichs et al. (2020) used a regional seismic transect from the "BalTec" expedition (Hübscher et al., 2016). The acquisition parameters of the "BalTec" survey allowed to overcome problems of shallow water, low vertical resolution, stretch mute effects caused by large source to receiver distances and sparse well data. As a result, the authors presented a high-resolution gapless seismic image from the base of the Zechstein salt to the seafloor and derived a detailed seismostratigraphic concept for the northeastern NGB margin, which allowed specification of the onset of Late Cretaceous inversion to the Coniacian-Santonian.

In this study, we integrate the "BalTec" database with other 2D seismic surveys from the study area to refine the seismostratigraphy of the Upper Cretaceous and Cenozoic. We present a key two-way travel-time seismic section from the Eastholstein Trough and three key seismic depth sections with an unprecedented a level of vertical resolution for the study area. We focus on mapping of the Upper Cretaceous and Cenozoic reflectors to investigate salt movement during Late Cretaceous to Cenozoic basin inversion. By using refraction travel-time tomography for constraining the time-depth conversion, this results in thickness maps of Upper Cretaceous and Cenozoic units with an unprecedented detailed stratigraphic subdivision for the study area (Cenomanian-Turonian, Coniacian-Santonian, Campanian, Maastrichtian-Danian, upper Paleocene, Eocene-Miocene). The aim of this study is to identify and date phases of salt movement and explain their association with Late Cretaceous to Cenozoic tectonic events along the northern margin of the NGB. Based on our refined stratigraphic subdivision of the Upper Cretaceous and Cenozoic, we differentiate between individual episodes of increased tectonic activity during the Late Cretaceous to Cenozoic, which is novel for the Baltic sector of the NGB. Thereby, the results of this study contribute to a better understanding of the evolution of salt structures in relation to regional tectonics in the NGB, which is of great interest for the usage of the deeper subsurface (e.g. for CO_2 storage [CCS], geothermal energy or nuclear waste repository). Besides, our findings contribute to a prospective offshore extension of the recently published 3D geological overview model (TUNB Working Group, 2021) that has been developed according to increasing demands on subsurface use in Germany.

2 | GEOLOGICAL SETTING

The study area comprises the Baltic Sea sector of the NGB from the Bay of Kiel in the west to the Bay of Mecklenburg and Rügen Island in the east (Figure 1). The western Bay of Kiel covers the Eastholstein Trough marking the eastern part of the NNE–SSW trending Mesozoic–Cenozoic Glückstadt Graben, which formed a NGB depocenter with up to 11 km of post-Permian sediment thickness (Maystrenko et al., 2005b). In contrast, the central to eastern Bay of Kiel and the Bay of Mecklenburg cover the Eastholstein Mecklenburg Block, the peripheral region between Glückstadt Graben and the northeastern basin margin towards Rügen Island. Here, the post-Permian sediment thickness is decreased to 2–4 km and affected by the Western Pomeranian Fault System (Bachmann et al., 2010). An approximately E-W running set of basement highs (sensu Peacock & Banks, 2020), the Rinkøbing-Fyn High, Møn High and Arkona High, mark the northern basin margin. The Grimmen High is located at the northeastern basin margin and forms a west-northwest (WNW) striking uplifted zone where the Cretaceous cover is absent or strongly reduced. On a regional scale, the basin floor in the study area dips gently towards the south.

2.1 | Late Permian to Early Cretaceous evolution

Basin formation began in the Late Paleozoic with extensive volcanism, faulting, lithospheric thinning and subsequent thermal subsidence (Maystrenko et al., 2008; Ziegler, 1990). In late Permian times, repeated restricted seawater influx under arid conditions led to the deposition of the Zechstein layered evaporite sequence. In the study area, the Zechstein succession consists of seven cyclothems with varying amounts of clay, carbonates, anhydrite, halite and potash sequences (Peryt et al., 2010; Strohmenger et al., 1996). While the Werra (Z1) cyclothem contains mostly less mobile anhydrites and carbonates, mobile halite components are frequent in the Stassfurt (Z2), Leine (Z3), Aller (Z4) and Ohre (Z5) cyclothems. The Friesland (Z6) and Fulda (Z7) cyclothems consist of mostly lacustrine and continental sediments and are only present in the southern part of the study area (e.g. Best, 1989; Peryt et al., 2010). Throughout the complex, multiphase basin evolution, the presence of the thick Zechstein evaporite sequence led to the formation of numerous salt structures including salt pillows, salt diapirs and salt walls (Figure 1).

Thermal subsidence lasted until the Middle Triassic in the study area. During Early to Middle Triassic times, the Buntsandstein and Muschelkalk successions were deposited. These units consist of interlayered mudstones and carbonates (Figure 2; Kossow & Krawczyk, 2002; Van Wees et al., 2000). In Early to Middle Triassic times, thermal subsidence was locally interrupted by extension, which formed a narrow graben in the central Glückstadt Graben (Brink et al., 1992). In the Late Triassic, E–W directed extension widened the Glückstadt Graben and triggered intensive salt movement in the study area (Hansen et al., 2005, 2007; Hübscher et al., 2010; Maystrenko et al., 2005b). In the Bay of Mecklenburg, salt movement began contemporaneously to the formation of the NW–SE trending Western Pomeranian Fault System and was associated with dextral transtensional strike slip movements at the Tornquist Zone (Ahlrichs et al., 2020). From Middle Jurassic to Albian times, uplift induced by the central North Sea Doming event interrupted sedimentation in the study area and eroded much of the Jurassic and partly Upper Triassic deposits (Figure 2; Hansen et al., 2007; Hübscher et al., 2010; Schnabel et al., 2021; Underhill & Partington, 1993). Rising sea levels in the Lower Cretaceous led to resumed sedimentation in the Albian.

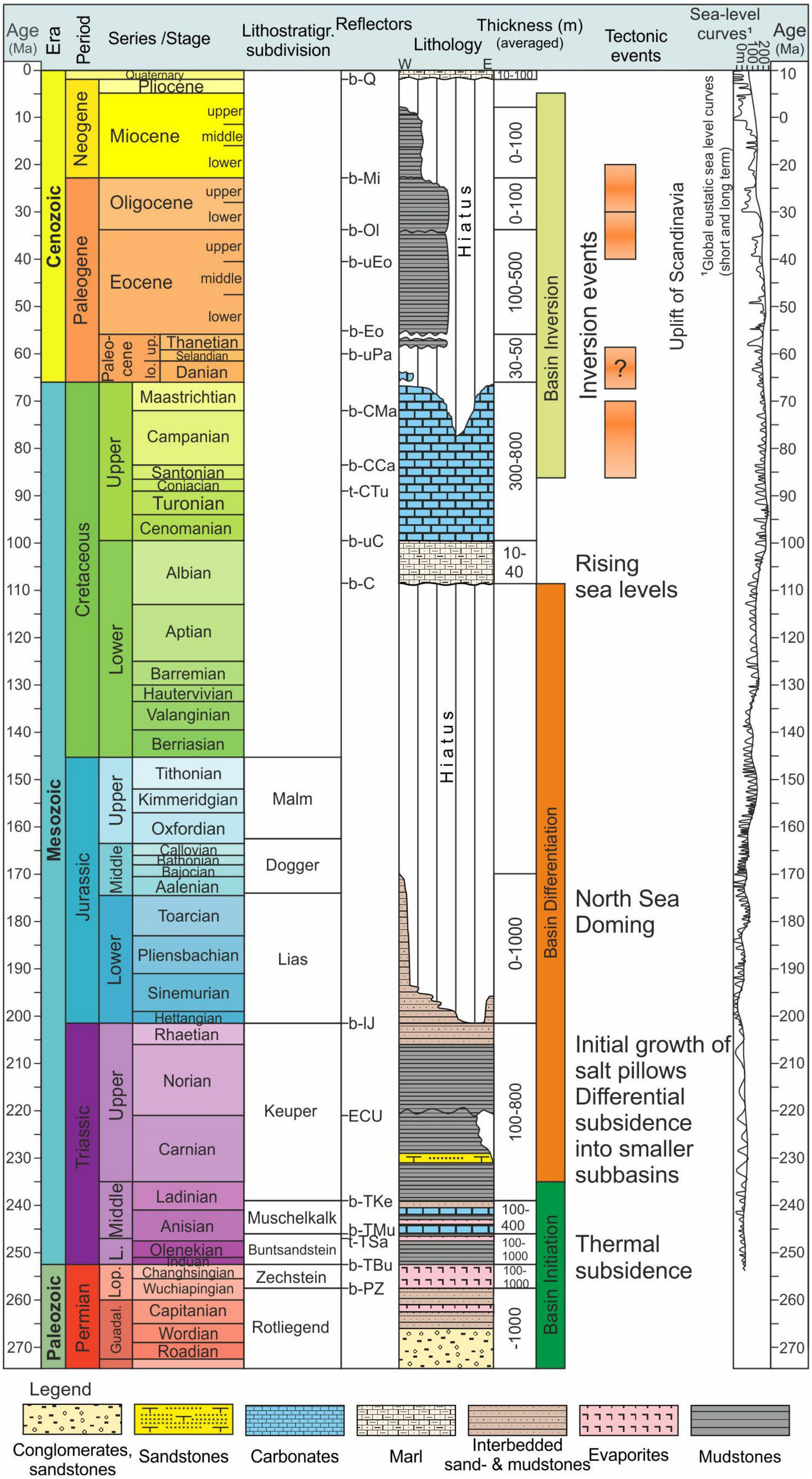
2.2 | Late Cretaceous to recent evolution

After the resumed sedimentation in the Albian, a relatively quiet tectonic phase with long lasting deposition of horizontally layered chalk units in shallow to deep marine conditions persisted from the Cenomanian until the Turonian (Kossow & Krawczyk, 2002; Vejbaek et al., 2010). In the late Turonian to Santonian, major plate reorganization and the onset of the Africa-Iberia-Europe convergence transmitted compressional stress into the European foreland (Kley & Voigt, 2008). Resulting horizontal shortening led to uplift and erosion and renewed salt movement at the northern NGB margin (Hansen et al., 2007; Hübscher et al., 2010; Kossow & Krawczyk, 2002). The uplift of the Grimmen High started in the Coniacian to Santonian and reached its peak in the Campanian-Maastrichtian (Ahlrichs et al., 2020; Kossow & Krawczyk, 2002). This was coeval with salt movement in the Bay of Mecklenburg and fault reactivation at the Werre Fault Zone and within the Western Pomeranian Fault System (Ahlrichs et al., 2020; Al Hseinat & Hübscher, 2017; Deutschmann et al., 2018; Seidel et al., 2018). At the Grimmen High, corresponding erosion removed almost the entire Cretaceous succession while only upper Maastrichtian deposits are missing in most other parts of the study area (Ahlrichs et al., 2020; Hoth et al., 1993; Katzung, 2004). Compressional stress caused only mild inversion of the Glückstadt Graben indicated by slight uplift of diapir roofs and minor salt movement in the marginal parts of the graben (Maystrenko et al., 2005b, 2006). Inversion-generated topographic highs along the Tornquist Zone influenced depositional patterns in the Chalk Sea through contour currents (Hübscher et al., 2019; and references therein).

Paleogene conditions remained shallow to deep marine with Scandinavia serving as a sediment source since its uplift in Paleocene to Oligocene times (Japsen et al., 2007; Nielsen et al., 2002). In the study area, Paleogene successions were deposited relatively far from the paleo coastline (Hinsch, 1986; Japsen et al., 2007). Paleocene deposits in the study area comprise Danian chalk and upper Paleocene (Thanetian) claystones (Figure 2; Hinsch, 1986; Katzung, 2004). Due to a large-scale domal uplift in the late Paleocene (Ziegler et al., 1995), Selandian sedimentary units are missing and Danian chalk is only preserved in the Eastholstein Trough in the western Bay of Kiel and in the northwestern, Danish part of the study area. Upper Paleocene claystones overlie the corresponding widespread unconformity and are largely preserved west of the Grimmen High (Vinken & International Geological Correlation Programme, 1988).

A phase of relative tectonic quiescence followed in the early to middle Eocene (Hinsch, 1986; Katzung, 2004). In late Eocene times, almost E–W directed extension restarted salt movement in the Glückstadt Graben with thickest sediment accumulation and salt withdrawal in the marginal parts (Maystrenko et al., 2005b). In the Eastholstein Trough in the western Bay of Kiel, salt flow was reactivated in the late Eocene to Oligocene; this was accompanied by faulting above the outer salt wall (Al Hseinat et al., 2016). Huster et al. (2020) noticed that this Eocene phase of salt tectonics started contemporaneous to resumed approx. N–S directed late Eocene to early Miocene intraplate compression related to the Alpine and Pyrenean orogenies (Kley, 2018).

Shallow marine conditions prevailed in the Oligocene to earliest Miocene with ongoing salt



movement in the eastern Glückstadt Graben and onshore eastern Germany (Hinsch, 1986; Katzung, 2004). In Miocene times, the principal horizontal stress regime in the study area changed to NW–SE extension (Al Hseinat & Hübscher, 2017; Kley et al., 2008). This change is associated with reactivation along preexisting

FIGURE 2 Lithostratigraphic chart showing the interpreted key seismic reflectors, dominant lithology and average thickness. Reflectors modified after Ahlrichs et al. (2020). The right columns illustrate important tectonic events of the North German Basin evolution (Kossow & Krawczyk, 2002; Bachmann et al., 2008; Kley, 2018) and the global long and short term eustatic sea level curves (Haq et al., 1987; Haq, 2014, 2017, 2018). b-Q: base Quaternary Unconformity; b-Mi: base Miocene; b-Ol: base Oligocene; b-uEo: base upper Eocene; b-Eo: base Eocene; b-uPa: base upper Paleocene; b-CMa: base Upper Cretaceous Maastrichtian; b-CCa: base Upper Cretaceous Campanian; t-CTu: top Upper Cretaceous Turonian; b-uC: base Upper Cretaceous;b-C: base Cretaceous; b-lJ: base Lower Jurassic; ECU: Early Cimmerian Unconformity; b-TKe: base Triassic Keuper; b-TMU: base Triassic Muschelkalk; t-TSa: top Triassic Salinarröt; b-TBu: base Triassic Buntsandstein; b-PZ: base Permian Zechstein

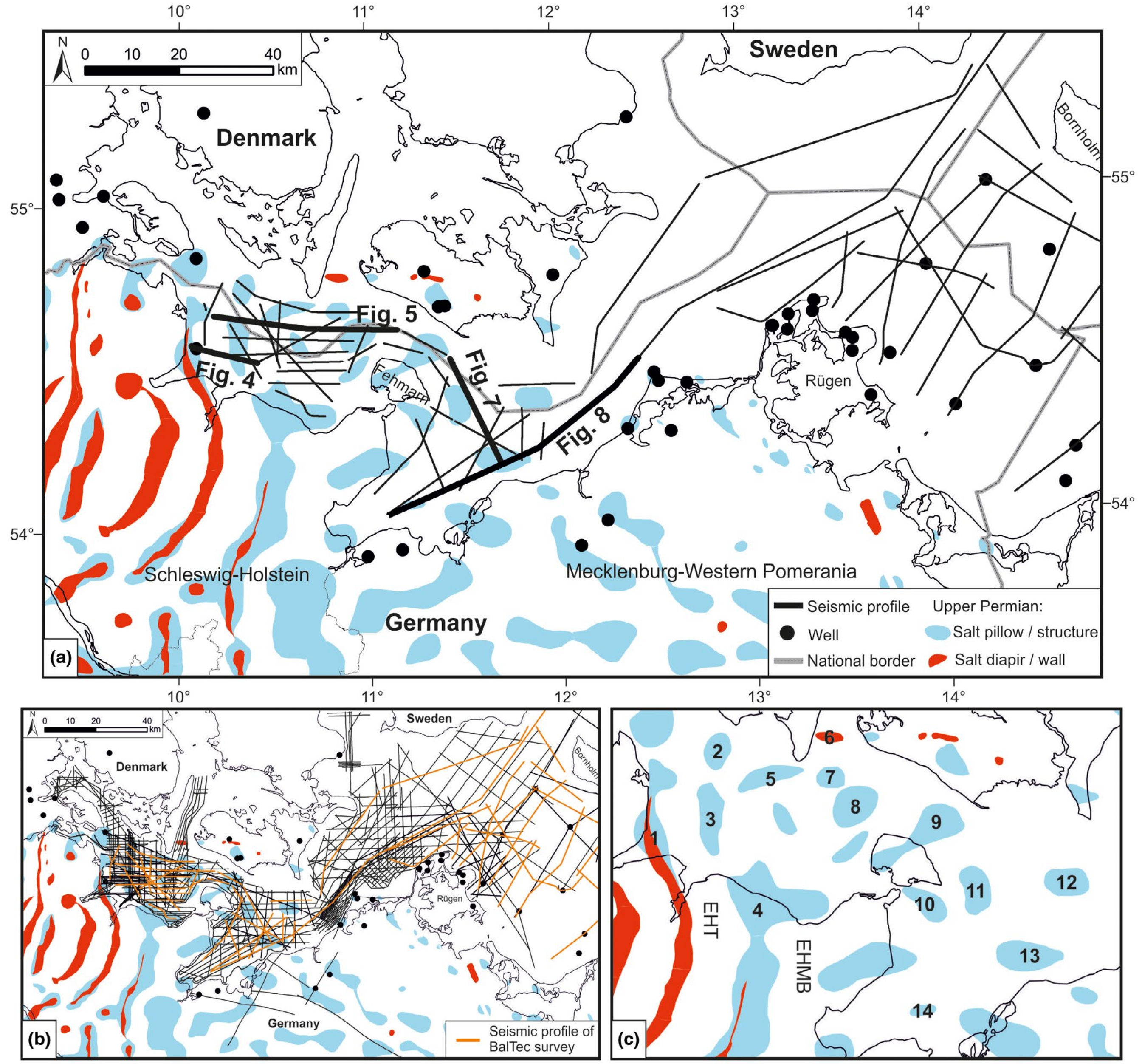


FIGURE 3 Maps showing the location of seismic profiles and wells used in this study. A: Seismic profiles from the BalTec survey and location of shown profiles in this study. B: Complete database with all available seismic profiles and wells used for mapping. Orange lines: seismic profiles of the BalTec survey. C: Names of salt structures in the Bays of Kiel and Mecklenburg. 1: Waabs; 2: Schleimünde; 3: Kieler Bucht; 4: Plön; 5: Langeland; 6: Kegnaes Diapir; 7: Langeland Ost; 8: Vinsgrav; 9: Fehmarn; 10: Fehmarnsund Ost; 11: Staberhuk Ost; 12: Neobaltic; 13: Trollegrund Nord; 14: Boltenhagen Nord. Salt structures after Vejbaek (1997); Dadlez and Marek (1998; Reinhold et al. (2008); Hübscher et al. (2010); Warsitzka et al. (2019). EHT: Eastholstein Trough (between salt structures 1 and 2-3-14); EHMB: Eastholstein Mecklenburg Block (east of salt structures 2-3-14)

structural elements as, for example, the Ringkøbing-Fyn High, and related to intraplate stress transmitted into the European foreland by the Alpine Orogeny (Rasmussen, 2009). At this time, the North Sea Basin was reshaped and the hinterland uplifted, which resulted in regional uplift of the Ringkøbing-Fyn High and adjacent areas by ca. 600 m (Japsen et al., 2015; Rasmussen, 2009). Corresponding erosion removed much of the Miocene, Oligocene and partly upper Eocene deposits in the study area. More complete stratigraphic sequences are only preserved in peripheral sinks adjacent to salt structures in the Glückstadt Graben and onshore Germany (Hinsch, 1986, 1987; Katzung, 2004). Pliocene sediments were not deposited (Hinsch, 1987; Japsen et al., 2015; Katzung, 2004). Quaternary glacial erosion removed further Neogene and Paleogene sedimentary units (e.g. Sirocko et al., 2008).

3 | DATABASE AND METHODS

3.1 | Seismic database

In this study, we use a 2D high-resolution seismic reflection dataset with a total profile length of more than 10,000 km acquired during several surveys in the past decades (Figure 3). The dataset consist of seismic profiles acquired between 1998 and 2004 by the Universities of Aarhus and Hamburg as part of the BaltSeis and NeoBaltic projects (Hübscher et al., 2004). Additional seismic data were acquired during multiple student field exercise cruises of the University of Hamburg between 2005 and 2019 (Al Hseinat & Hübscher, 2014, 2017; Al Hseinat et al., 2016; Hansen et al., 2005, 2007; Hübscher et al., 2010; Huster et al., 2020; Kammann et al., 2016). Furthermore, we use reprocessed seismic profiles of the Petrobaltic database (Rempel, 1992; Schlüter et al., 1997),

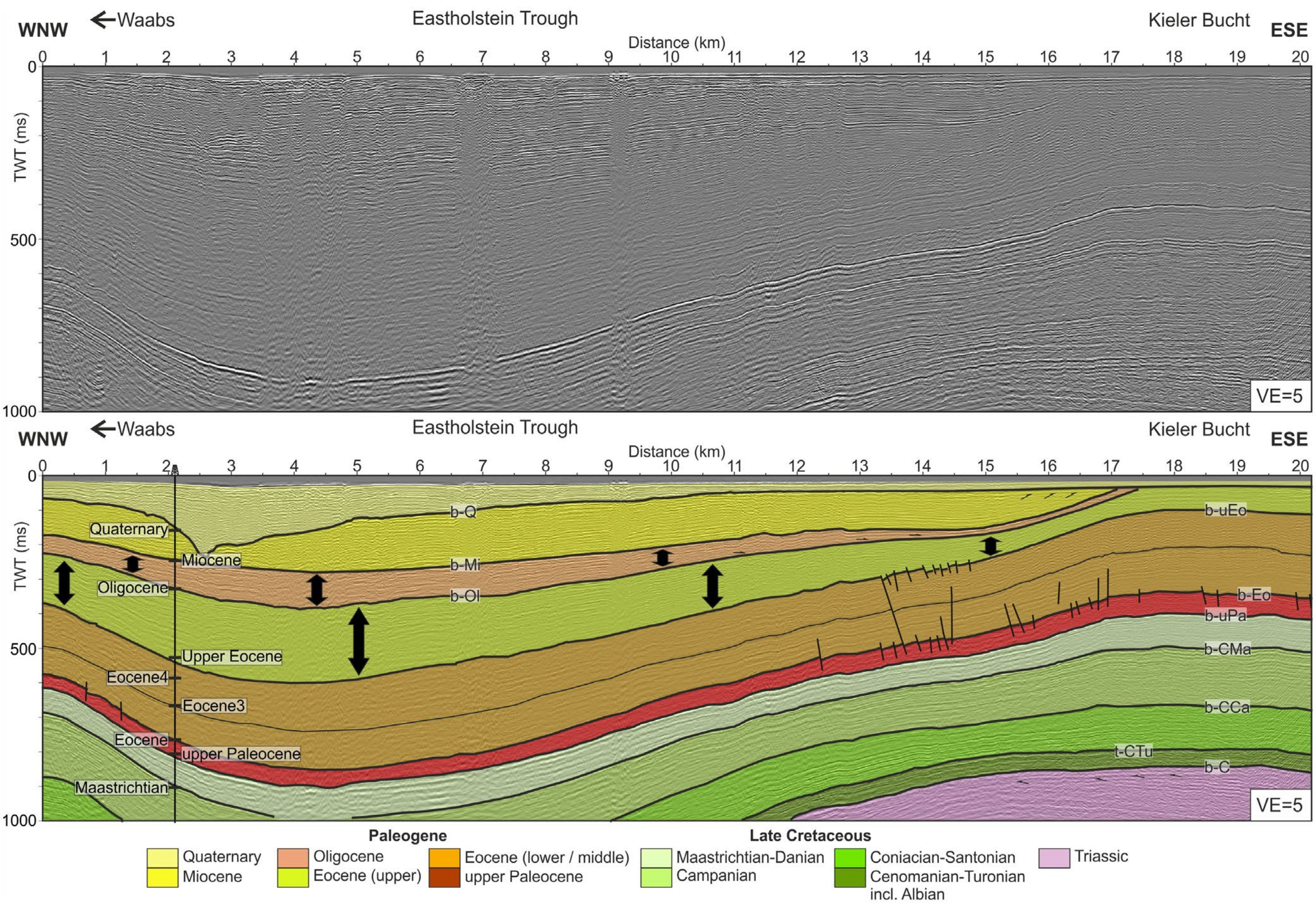


FIGURE 4 Profile AL526-20, covering the Eastholstein Trough in the western Bay of Kiel: Time migrated section with well tie to undisclosed industry well data. Well markers converted to time by check shot data. Note the black arrows pointing out the divergent upper Eocene and Oligocene units with increasing thickness towards the Eastholstein Trough. Note the Quaternary incision at profile distance 2.5 km. For profile location, see Fig. 3a. VE: vertical exaggeration. Reflectors (see also Figure 2): b-Q: base Quaternary Unconformity; b-Mi: base Miocene; b-Ol: base Oligocene; b-uEo: base upper Eocene; b-Eo: base Eocene; b-uPa: base upper Paleocene; b-CMa: base Upper Cretaceous Maastrichtian; b-CCa: base Upper Cretaceous Campanian; t-CTu: top Upper Cretaceous Turonian; b-uC: base Upper Cretaceous;b-C: base Cretaceous

profiles of the PQ2 cruise of the DEKORP-BASIN'96 campaign (DEKORP-BASIN Research Group, 1999) and lines of the GSI76B survey (kindly provided by ExxonMobil Production Deutschland GmbH, 1976). These individual and more local surveys were connected using the "BalTec" 2D seismic dataset collected during the MSM52 cruise by the University of Hamburg in cooperation with the Federal Institute for Geosciences and Natural Resources (BGR), University of Greifswald, Polish Academy of Sciences, Uppsala University and the German Research Centre for Geosciences Potsdam (BGR & UHH, 2016; Hübscher et al., 2016). The "BalTec" dataset consists of a network of high-resolution multichannel seismic data (dominant frequency of 80 Hz, vertical resolution of ca. 5–30 m) from the western Bay of Kiel up to Bornholm Island (Figure 3a). Acquisition parameters and seismic data processing, including elaborate multiple attenuation and denoizing, allowed continuous imaging from the Zechstein salt base up to the seafloor (see Ahlrichs et al., 2020 for a detailed description).

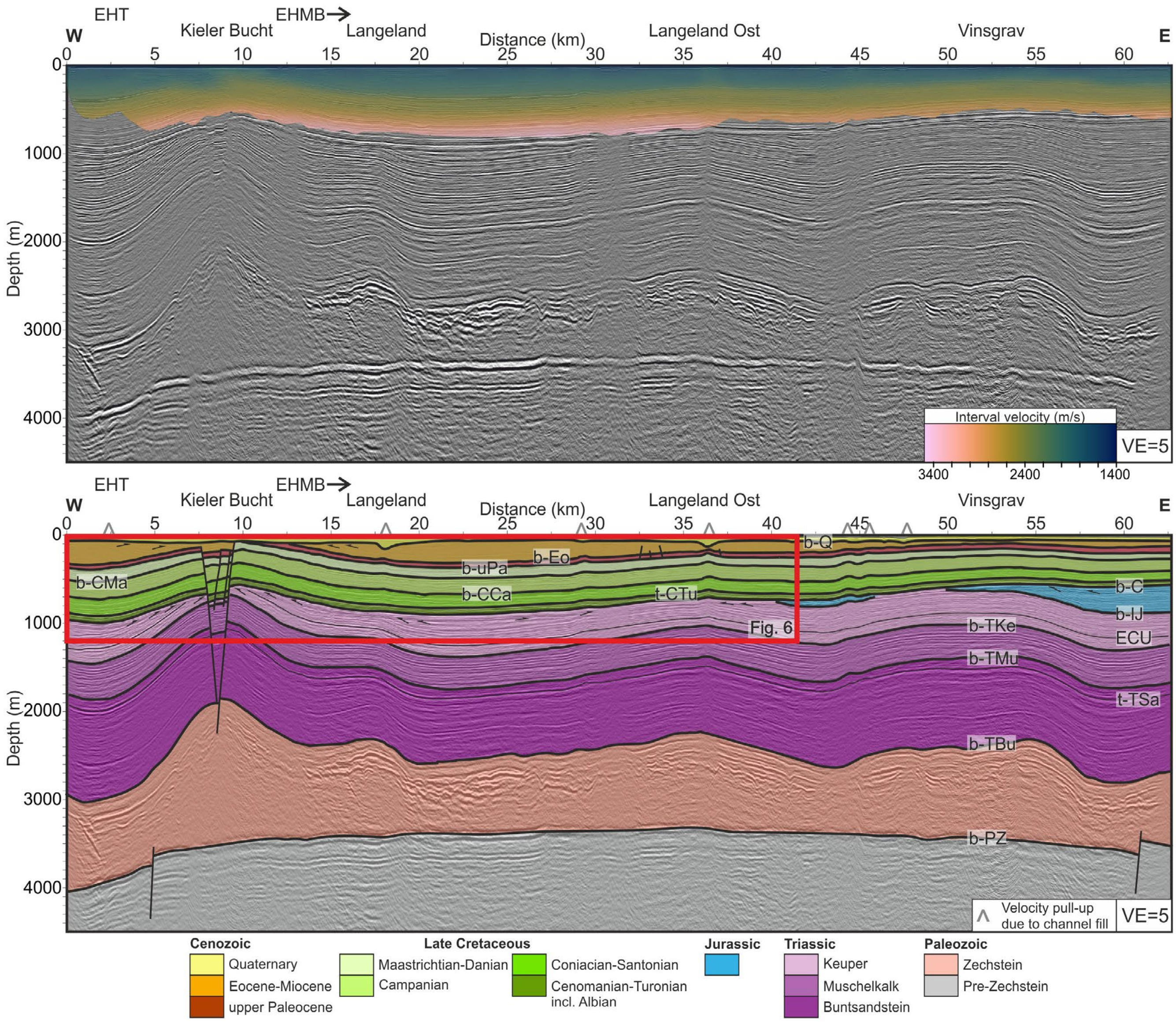


FIGURE 5 Profile BGR16-232, located in the Bay of Kiel: Uninterpreted prestack depth migrated section showing velocity results from the travel-time tomography (top) and intepreted section (bottom). For location, see Fig. 3a. Salt structures are marked on top of the section. Note the small velocity pull-ups due to high-velocity channel infill near the seafloor (marked with grey "^" symbols along the distance axis. See Frahm et al., 2020 for further details). VE: vertical exaggeration. EHT: Eastholstein Trough; EHMB: Eastholstein-Mecklenburg Block. Reflectors (see also Figure 2): b-Q: base Quaternary Unconformity; b-Eo: base Eocene; b-uPa: base upper Paleocene; b-CMa: base Upper Cretaceous Maastrichtian; b-CCa: base Upper Cretaceous Campanian; t-CTu: top Upper Cretaceous Turonian; b-C: base Cretaceous; b-lJ: base Lower Jurassic; ECU: Early Cimmerian Unconformity; b-TKe: base Triassic Keuper; b-TMU: base Triassic Muschelkalk; t-TSa: top Triassic Salinarröt; b-TBu: base Triassic Buntsandstein; b-PZ: base Permian Zechstein

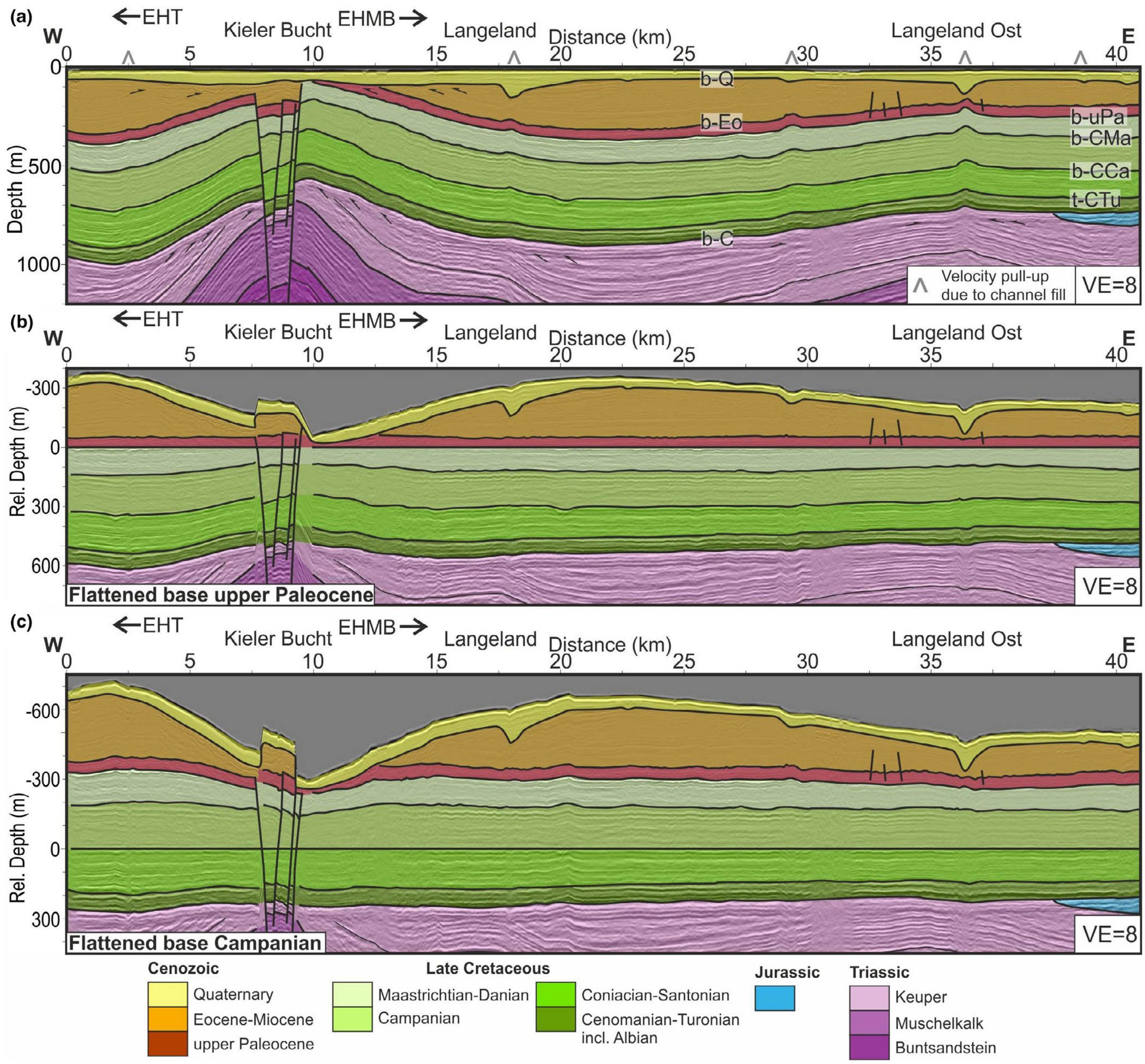


FIGURE 6 Zoom of profile BGR16-232 (Figure 5), located in the bay of Kiel. Note the increased vertical exaggeration. B and C show flattened section at base Campanian and base late Paleocene respectively. Note the small velocity pull-ups due to high-velocity channel infill near the seafloor (marked with grey "^" symbols along the distance axis. See Frahm et al., 2020 for further details). EHT: Eastholstein Trough; EHMB: Eastholstein-Mecklenburg Block. VE: vertical exaggeration. Reflectors labeled as in Figures 2 and 5

3.2 | Stratigraphy

Stratigraphic interpretation of seismic units in this study follows the extended stratigraphic framework described in detail in Ahlrichs et al. (2020). Seismic data were calibrated with well information of nearby deep research and hydrocarbon exploration wells (Figure 3; Hoth et al., 1993; Nielsen & Japsen, 1991; Schlüter et al., 1997). We linked the stratigraphic interpretation to previous studies in the area, both onshore and offshore (Baldschuhn et al., 2001; Deutschmann et al., 2018; Hansen et al., 2005, 2007; Hübscher et al., 2010; Huster et al., 2020; Lykke-Andersen & Surlyk, 2004; Zöllner et al., 2008). To further refine the seismo-stratigraphy, especially for the Cenozoic, we tied seismic profiles to undisclosed industry well data in the western Bay of Kiel (Figure 4). We interpreted 17 seismic horizons namely *base Quaternary Unconformity, base Miocene, base Oligocene, base upper Eocene, base Eocene, base*

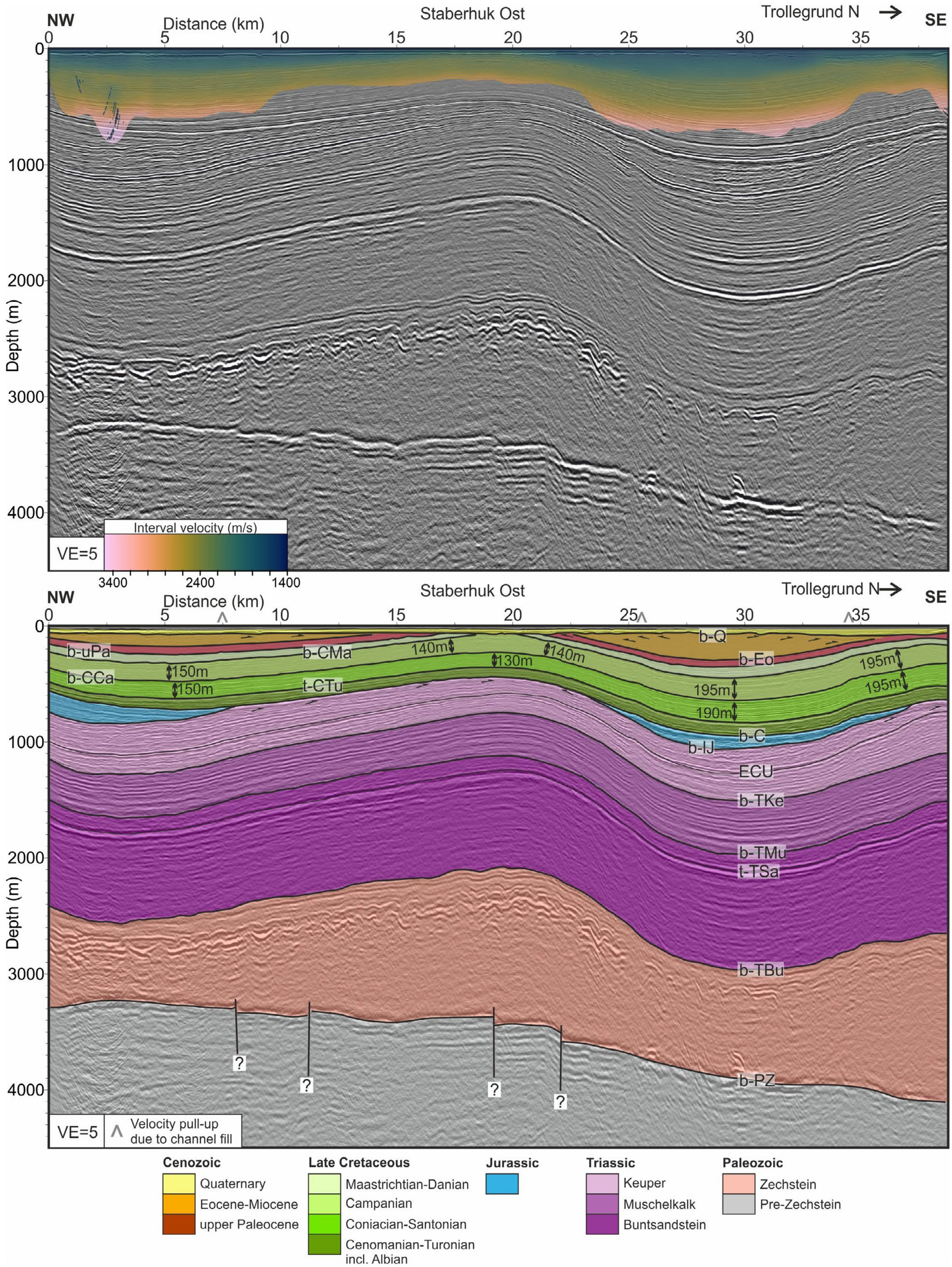


FIGURE 7 Profile BGR16-230, located in the Bay of Mecklenburg: Uninterpreted prestack depth migrated section showing velocity results from the travel-time tomography (top) and intepreted section (bottom). For location, see Fig. 3a. Salt structures are marked on top of the section. Values within Coniacian-Santonian and Campanian units denote approximate thickness at the black arrow location. Faults at the base Zechstein with question mark are uncertain as the small offsets could also be velocity artefacts. Note the small velocity pull-ups due to high-velocity channel infill near the seafloor (marked with grey "^" symbols along the distance axis. See Frahm et al., 2020 for further details). VE: vertical exaggeration. Reflectors labeled as in Figs. 2 and 5

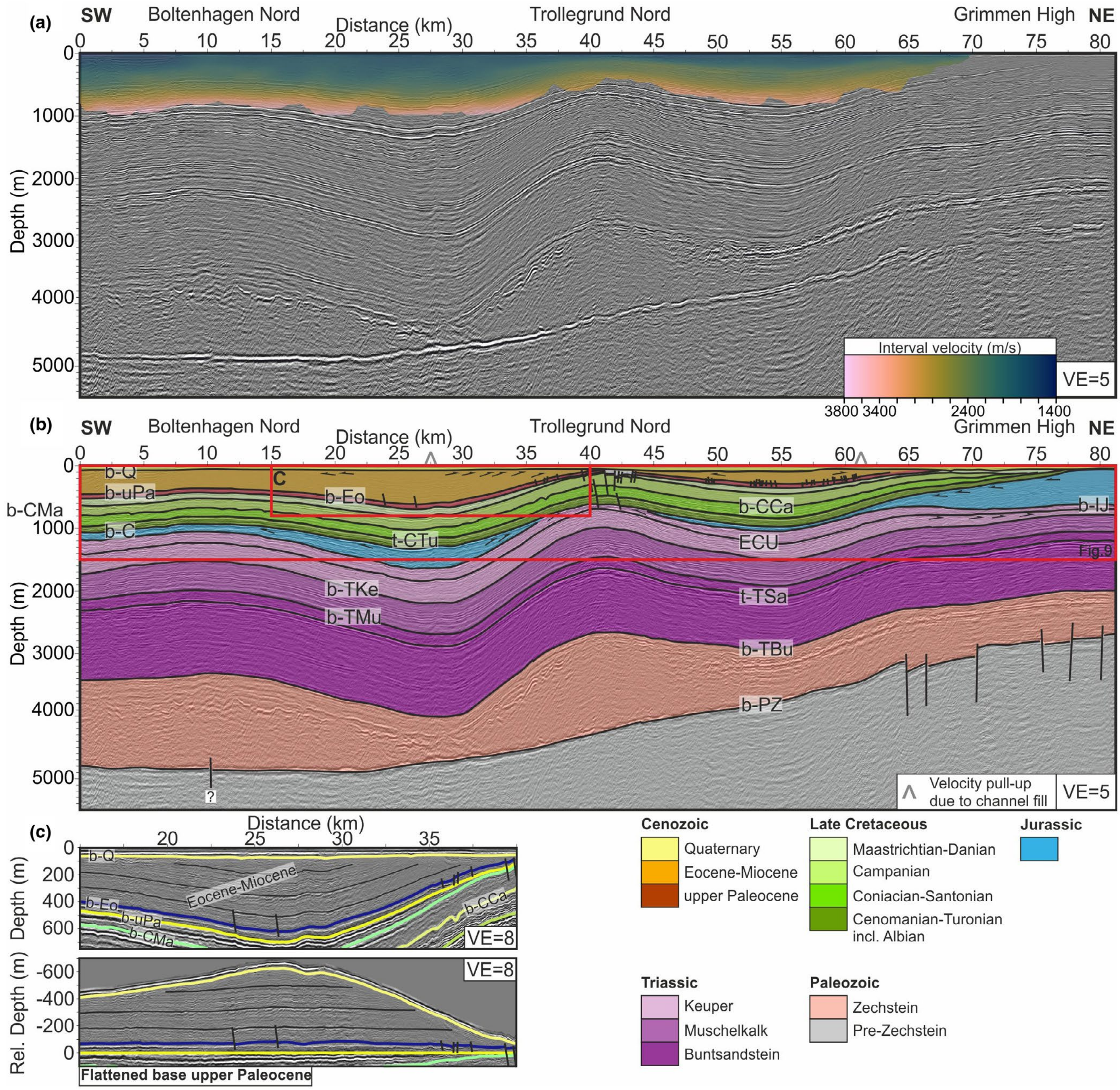


FIGURE 8 Profile BGR16-254, located in the Bay of Mecklenburg: A: Uninterpreted prestack depth migrated section showing velocity results from the travel-time tomography. B: Intepreted section. For location, see Fig. 3a. Salt structures are marked on top of the section. Fault at the base Zechstein with question mark is uncertain as the small offset could also be velocity artefacts. C: Zoomed in section of Eocene-Miocene unit. Note the concordant internal layering of the Eocene-Miocene unit and missing of diverging strata. Note the small velocity pull-ups due to high-velocity channel infill near the seafloor (marked with grey “^” symbols along the distance axis. See Frahm et al., 2020 for further details). VE: vertical exaggeration. Reflectors labeled as in Figures 2 and 5

upper Paleocene, base Maastrichtian, base Campanian, top Turonian, base Cretaceous, base lower Jurassic, Early Cimmerian Unconformity, base Keuper, base Muschelkalk, top Salinarröt, base Buntsandstein, base Zechstein (Figure 2). However, we could only trace the horizons base Miocene, base Oligocene and base upper Eocene within the Eastholstein Trough (Figure 1). The Albian unit is too thin to be resolved throughout the study area so that the base Upper Cretaceous and base Cretaceous reflectors cannot be differentiated.

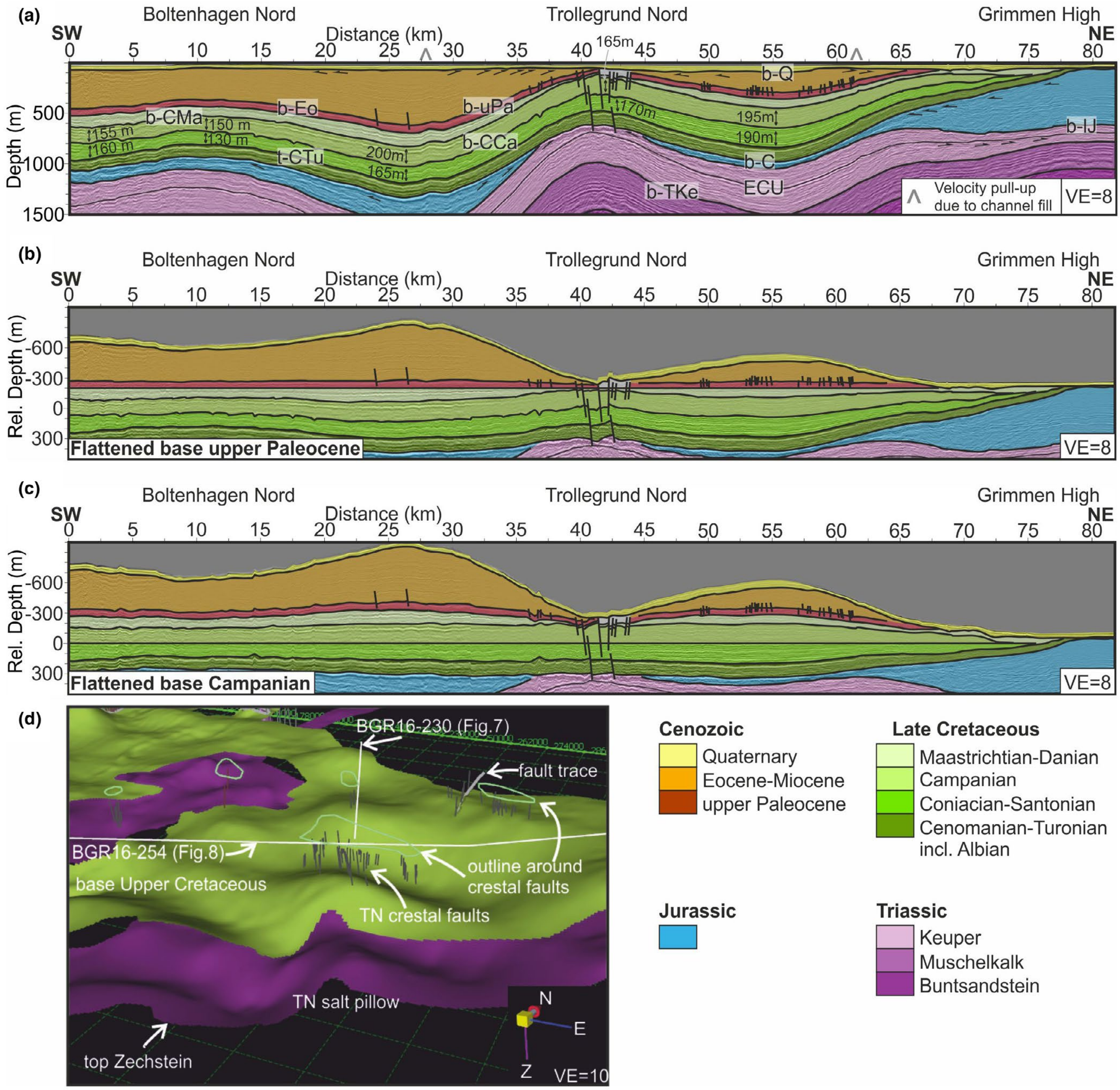


FIGURE 9 Zoom of profile BGR16-254 (Figure 8), located in the Bay of Mecklenburg. See Figure 3 for location. Note the increased vertical exaggeration. B and C show flattened section at base Campanian and base upper Paleocene respectively. D: 3D view from the southeast on the Trollegrund Nord (TN) salt pillow in the Bay of Mecklenburg in order to visualize small crestal faults above the pillow. Grey lines mark crestal faults piercing the Upper Cretaceous units. Mint-green line above the faults outlines the location of the crestal fault picks and is displayed accordingly in map view in Figures 11 and 12. Note the small velocity pull-ups due to high-velocity channel infill near the seafloor (marked with grey "^" symbols along the distance axis. See Frahm et al., 2020 for further details). VE: vertical exaggeration

3.3 | Depth imaging and refraction travel-time tomography

We focused our velocity analysis on three key profiles: one crossing the Bay of Kiel in E–W direction and two lines crossing the Bay of Mecklenburg in NW–SE and NE–SW direction, respectively (Figures 5, 7 and 8, see Figure 3 for location). For these profiles, we derived a spatially variant velocity field by migration velocity analysis (MVA). In the MVA procedure, common offset gathers are prestack depth migrated (Stork, 1992). In a top-down approach, the overlying velocity field of a selected horizon

TABLE 1 Interval velocity information from published literature (Hansen et al., 2007; Jaritz et al., 1991; Schlüter et al., 1997; Schnabel et al., 2021; van Dalfsen et al., 2006) and results of the refraction travel-time tomography and used velocity for conversion of the isochron maps.

Interval velocity information from published literature and of the refraction tomography in this study velocity values in (m/s)							
	Linear velocity relationship[a] k: gradient in (1/s); V_0: starting velocity in (m/s)			MVA	MVA	Refraction tomography	
Method	Jaritz et al. (1991)	Schlüter et al. (1997)	van Dalfsen et al. (2006)	Hansen et al. (2007)	Schnabel et al. (2021)	This study	Conversion interval velocity
Miocene-Eocene	V_0: 1,550–1,800		V_0: 1,700–1,875	2,000	1,765–2,580	1,600–2,420 ø: 1,920	1,900
Late Paleocene	k: 0.7		k: 0.288			1,790–2,600 ø: 2,170	2,200
Danian-Maastrichtian	V_0: 1,800–2,450	V_0: 1,800–3,200	V_0: 1,700–2,900	2,400	2,255–3,195	1,985–2,890 ø: 2,345	2,400
Campanian	k: 1.0	k: 1.2–0.9	k: 0.882			2,160–3,510 ø: 2,565	2,600
Santonian-Coniacian						2,410–3,710 ø: 2,925	2,900
Turonian-Cenomanian						2,740–3,465 ø: 3,000	3,000
Zechstein	4,500	4,100–5,100	4,050–5,550	4,800	4,200–4,900		4,500[b]

[a]These studies use a linear velocity relationship $V_Z = V_0 + kZ$. V_Z: Velocity at depth Z; V_0: starting velocity; k: velocity gradient; ø: average. Velocity values in m/s.

[b]Zechstein conversion interval velocity is based on the average of published velocities.

is stepwise adjusted until reflections in the common offset gathers are flat (see Schnabel et al., 2021). The derived velocity fields were used for prestack depth migration, which resulted in gapless depth images overcoming imaging artefacts like velocity pull-ups below salt structures (Figures 5–9).

For the three key seismic depth sections, we derived velocity information using refracted first arrival P-waves (recorded by 2,700 m long streamer cable) by performing a travel-time tomography (Figures 5, 7 and 8). The tomography uses the PStomo_eq algorithm developed and described by Tryggvason (1998). The forward problem is solved by finding a first order finite difference solution to the Eikonal equation resulting in a first arrival travel-time field (Podvin & Lecomte, 1991). The ray paths are found by back tracing the rays from the receivers to the source (Hole, 1992). The inversion uses the iterative LSQR conjugated gradient algorithm (Paige & Saunders, 1982) to minimize the objective function (eq. 13 in Tryggvason, 1998). Frahm et al. (2020) proved the applicability of this method to the "BalTec" data.

We analysed the derived velocity field to identify lateral velocity variations within the seismo-stratigraphic units. Beyond the expected velocity increase with depth, the tomography shows no significant lateral velocity variations for the Upper Cretaceous, Paleogene and Neogene successions (Figures 5, 7 and 8). Table 1 summarizes the results from published velocity information together with the velocity range and averaged interval velocities of individual units based on the results of the refraction tomography of all three profiles.

3.4 | Mapping

We mapped Upper Cretaceous and Cenozoic units to identify episodes of salt movement and their possible relationship to Late Cretaceous to Cenozoic tectonic inversion events. To correlate Late Cretaceous and Cenozoic thickness variations with salt structures, we also mapped the Zechstein succession. Base and top of the Zechstein unit are only imaged by the BalTec, Petrobaltic, DEKORP-BASIN'96 and GSI76B surveys and thus only these profiles contributed to the Zechstein mapping procedure. For mapping of the Upper Cretaceous (Cenomanian – Maastrichtian) and Cenozoic (Paleocene – Miocene) units, we used all available seismic profiles in the dataset (Figure 3b). Using the available horizon picks for each horizon, we created two-way traveltime-structure maps by minimum curvature spline interpolation with a grid cell size of 300 × 300 m. For the Quaternary, we used the base Quaternary Unconformity time-structure map from Al Hseinat and Hübscher (2017). We created isochron maps (vertical thickness in two-way time) for the Zechstein, Cenomanian-Turonian, Coniacian-Santonian, Campanian, Maastrichtian-Danian, upper Paleocene, Eocene-Miocene units (provided in the supporting information, Ahlrichs et al., 2021). We converted the isochron maps to isochore maps in meters by using constant interval velocities derived from averaging the results of the refraction travel-time tomography (Table 1). We chose this constant velocity conversion as a first approach because the tomography requires long streamer cables to record refracted waves and, thus, this was only possible for the BalTec data. Accordingly, velocity information is sparsely distributed and creating a sophisticated area-covering laterally variable velocity model is a challenging task of future work.

We interpreted thickness maps, seismic profiles and flattened sections to identify local and regional thickness variations. Besides vertical tectonic movements, differential compaction, water level and sedimentation processes influence the sediment thickness (e.g. Betram & Milton, 1989). For our study area, we assume that sediment thickness variations reflect differential sedimentation and erosion caused by vertical tectonic movements such as uplift/subsidence, faulting and salt movement. Based on the geological conditions during Cretaceous and Paleogene deposition (sedimentation in rather stable shallow to deep marine conditions after large-scale erosion caused by Mid-Jurassic North Sea Doming, see Section 2), we expect mainly horizontally layered deposition modified by post-depositional vertical tectonic movements and less dominant effects of differential compaction and sea level fluctuations. However, we cannot fully exclude effects of differential compaction and sea level fluctuations, especially for the Neogene since falling sea levels and uplift in early Miocene times likely changed the depositional environment in the study area (Hinsch, 1986, 1987; Rasmussen, 2009).

4 | OBSERVATIONS

Based on key seismic profiles and thickness maps of the Zechstein, Upper Cretaceous and Cenozoic successions, we analyse the local thickness variations in the Upper Cretaceous – Cenozoic overburden to identify phases of salt movement during inversion phases. In the following sections, we interpret the increased thickness of a unit in the overburden above the rim-syncline of a salt structure (peripheral sink, sensu Jackson & Hudec, 2017) and thinning of the overburden towards the crest of a salt structure, possibly affected by the development of crestal faults as evidence for syndepositional salt movement and salt structure growth. Accordingly, we interpret relatively uniform thickness across salt structures as an indication for no salt movement during this time. For location and names of discussed salt structures, see Figure 3c.

4.1 | Key seismic profiles

4.1.1 | Crestal faulting during Late Cretaceous and late Eocene salt movement in the eastern Glückstadt Graben

At the eastern Glückstadt Graben in the western Bay of Kiel, faults form a prominent crestal graben above the salt pillow "Kieler Bucht" at the transition from the Eastholstein Trough to the Eastholstein-Mecklenburg Block (Figure 5). The eastern bounding fault pierces the overburden from within the upper Zechstein up to the Quaternary successions. The profile shows further smaller salt pillows towards the east. The Buntsandstein and Muschelkalk units have uniform thickness throughout the profile. The Keuper unit thins and reflectors converge towards the pillow crests indicating the initiation of salt pillow formation. Jurassic deposits are only preserved in the eastern part of the profile above rim-synclines of salt structures. The Cenomanian-Turonian unit has a quite constant thickness characterized by concordant reflections, which indicates a phase of salt tectonic quiescence (Figure 6). The flattened section at base Campanian shows minor thickness variations in the Coniacian-Santonian and Campanian at the flanks of the salt pillow "Kieler Bucht" (Figure 6b). Thickness of the Maastrichtian-Danian unit slightly increases towards the Eastholstein Trough. The overlying upper Paleocene is concordant and with only ca. 50 m thickness quite thin. Apart from the crestal zone of the salt pillow "Kieler Bucht", the upper Paleocene has uniform thickness, which suggests ceased salt movement (Figure 6c). Above the crestal zone, the unit is missing, which we explain by post-depositional erosion. The Eocene-Miocene unit, bound at the top by the erosional base Quaternary Unconformity, shows increased thickness at the flanks of the salt pillow "Kieler Bucht", especially within the western peripheral sink (Eastholstein Trough, Figure 6c). Within the crestal graben, thicker Eocene-Miocene deposits are preserved indicating revived growth of the salt pillow "Kieler Bucht" and reactivation of the crestal faults at least during the Eocene-Miocene.

4.1.2 | Late Eocene – Oligocene salt movement in the Eastholstein Trough

The central part of the Eastholstein Trough, in the western Bay of Kiel, contains a relatively complete succession of Paleogene and Neogene sedimentary units (Figure 4). Upper Paleocene and lower Eocene units show rather uniform thickness characterized by concordant reflections, which indicates a phase of relatively tectonic quiescence without salt movement. The upper Paleocene and lower Eocene units contain numerous small-scale faults, which remind of polygonal faults. Upper Eocene and Oligocene units are divergent towards the centre of the Eastholstein Trough, which indicates recommencing salt movement in the late Eocene (Figure 4, compare black arrows). Towards the east, thickness of the upper Eocene unit decreases while Oligocene and Miocene units are truncated by the base Quaternary Unconformity.

4.1.3 | Late Cretaceous and Eocene–Miocene salt movement in the Bay of Mecklenburg

Figure 7 shows a NW–SE profile in the Bay of Mecklenburg imaging the salt pillow "Staberhuk Ost" and adjacent rim-synclines. Multiple faults with partly small offsets characterize the base Zechstein. The Buntsandstein and Muschelkalk units show uniform thickness throughout the profile, whereas convergence and crestal erosion of Keuper strata denote the initiation of salt pillow development. The Jurassic unit is only preserved above the rim-synclines. The Cenomanian-Turonian unit shows gradually increasing thickness from the NW to SE reflecting a thickness increase towards the basin centre as the profile is not exactly parallel to the basin margin. Local thickness variations within the Cenomanian-Turonian around the salt pillow as well as crestal faults are not visible. Thus, we interpret this as a phase of salt tectonic quiescence. Minor local thickness variations (50–60 m) in the Coniacian-Santonian and Campanian between the pillow crest and above the adjacent rim-synclines indicate the development of small peripheral sinks and revived salt movement (Figure 7). Minor salt pillow growth continued in the Maastrichtian-Danian represented by increased thickness of the unit above the rim-synclines and thinning and erosion towards the crest of the salt pillow "Staberhuk Ost". The upper Paleocene unit shows uniform thickness suggesting ceased salt movement during this time. Preserved Eocene-Miocene deposits above the rim-synclines show concordant internal reflections, which are truncated by the base Quaternary Unconformity above the pillow crest. Assuming a locally constant amount of Neogene and Quaternary erosion, increased thickness of the Eocene-Miocene unit above the rim-synclines indicates salt withdrawal from the rim-synclines during the Cenozoic, where the observed remnants of the Eocene-Miocene unit are prekinematic.

4.1.4 | Late Cretaceous and Eocene-Miocene salt movement in the Bay of Mecklenburg at the transition to the Grimmen High

The SW–NE profile shown in Figure 8 crosses two salt pillows in the Bay of Mecklenburg. Multiple faults offset the base Zechstein in the northeastern part of the profile. The thickness of the Buntsandstein and Muschelkalk increases gradually towards the southwest, in the direction of the basin centre. The Keuper unit shows local thickness variations around the salt pillows, especially in the upper part, indicating the initiation of salt movement and pillow growth, which is in accordance to the observations from Figure 7. In the SW part of the profile, preserved Jurassic strata have slightly increased thickness while the unit terminates in a toplap towards the crest of the salt pillow "Trollegrund Nord". Towards the Grimmen High, the Jurassic unit shows increased thickness. The Cenomanian-Turonian unit has uniform thickness and relatively concordant layering (Figure 9). Coniacian-Santonian units thin and reflectors converge towards the Grimmen High, whereas thinning becomes more prominent in the Campanian and Maastrichtian-Danian (Figure 9b). Above the crest of the salt pillows, the Coniacian-Santonian and more prominent the Campanian and Maastrichtian-Danian units show reduced thickness compared to the flanking peripheral sinks, which evidences salt pillow rise by salt withdrawal from the rim-synclines. At the salt pillow "Trollegrund Nord", numerous crestal faults with relatively small throw dissect the Upper Cretaceous units. They likely developed in response to the rising salt. The upper Paleocene unit shows relatively uniform thickness. Numerous small-scale faults pierce this unit (Figure 9c). Thickness of the Eocene to Miocene unit is increased in peripheral sinks while reduced thickness is visible towards the salt structures. However, the Eocene-Miocene unit lacks internal diverging reflectors (Figure 8c).

4.2 | Thickness maps

4.2.1 | Zechstein

Due to the basin configuration, Zechstein thickness shows a general trend of increasing thickness from the basin margin in the north towards the south (Figure 10). Areas of locally increased thickness coincide well with the published locations of Zechstein salt structures (Hübscher et al., 2010; Reinhold et al., 2008; Vejbaek, 1997; Warsitzka et al., 2019). However, for

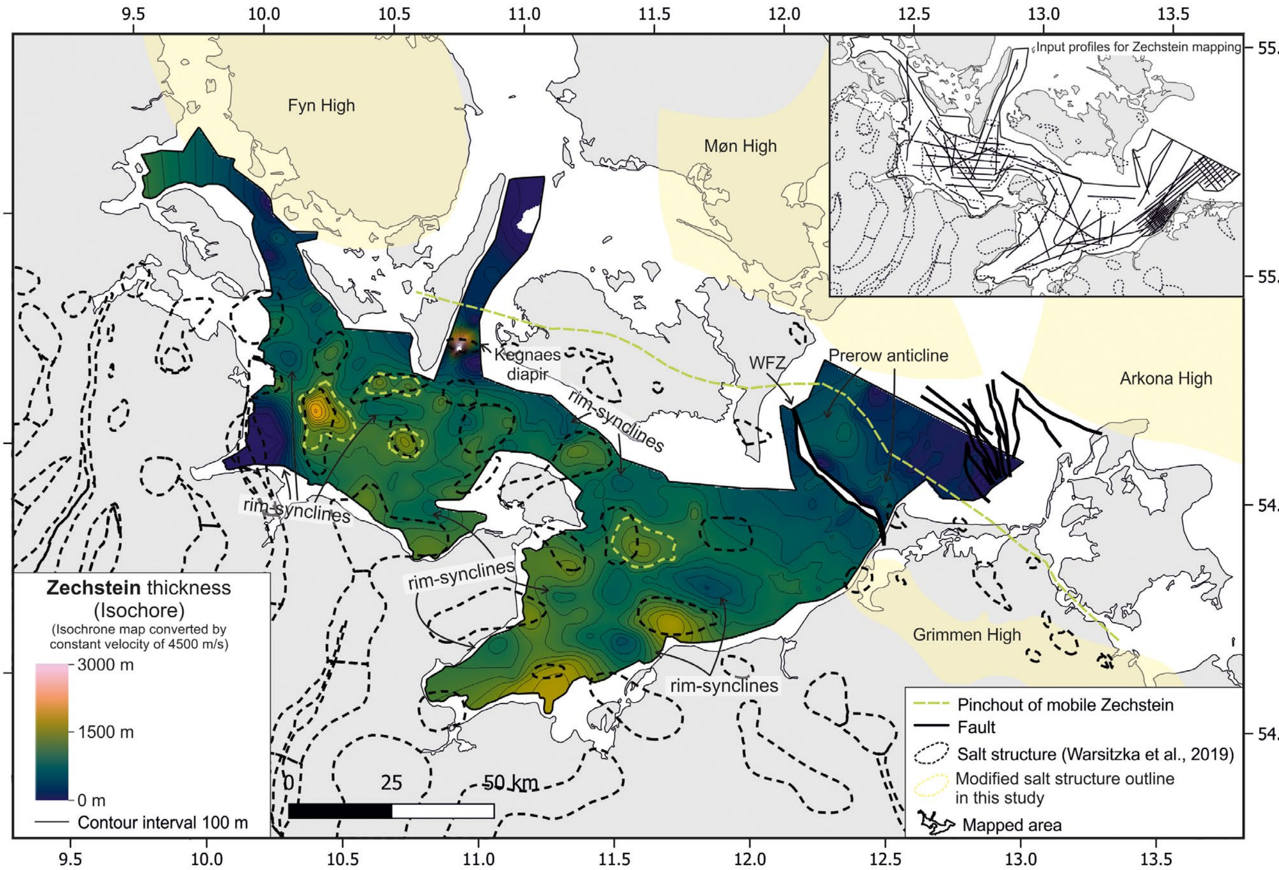


FIGURE 10 Zechstein isochore map (isochrone map converted using a constant interval velocity of 4500 m/s. Yellow dashed lines mark modified outline of salt structures based on mapped thickness in this study. Pinchout of mobile Zechstein after Katzung (2004); Pharaoh et al. (2010). Inset shows input profiles for Zechstein mapping (top and base Zechstein are only imaged by subset of the database). WFZ: Werre Fault Zone

three structures in the Bay of Kiel and one in the Bay of Mecklenburg, our new mapping reveals a slightly different location and shape. The better coverage of the subsurface by the new BalTec data imaging the deeper subsurface leads to a more circular outline of the salt structures "Kieler Bucht", "Langeland", "Langeland Süd" and "Staberhuk Ost" (compare dashed yellow and adjacent dashed black lines in Figure 10). We did not modify the shape for salt structures that were not well-covered by seismic profiles, as only a subset of the database imaged top and base Zechstein (inset of Figure 10, e.g. salt pillow "Neobaltic"), or where the thickness map does not show a distinctively different shape. Northeast of the Werre Fault Zone, a zone of increased Zechstein thickness trending parallel to the fault is visible (Prerow anticline in Figure 10).

4.2.2 | Upper Cretaceous

The Cenomanian-Turonian isochore map (Figure 11a) shows relatively uniform thickness throughout the study area. While the mean thickness of the unit is approx. 80 m within the Bay of Kiel, mean thickness in the Bay of Mecklenburg is with approx. 100 m slightly higher. Thickness variations do not correlate with the location of salt structures. The variations are small and occur across large distances.

The mean thickness of the Coniacian-Santonian unit is approx. 150 m, both in the Bay of Kiel and Bay of Mecklenburg (Figure 11b). The NE–SW trend of increasing thickness resembles the basin configuration. Minor local thickness variations are observed in the Eastholstein Trough, whereas no local thickness variations are observed in the eastern Bay of Kiel. In the Bay of Mecklenburg, we observe minor local thickness variations around salt structures. From the Bay of Mecklenburg towards the Grimmen High, the Coniacian-Santonian unit thins out (Figure 11b). We interpret the thinning as a result of syndepositional uplift of the Grimmen High in response to the onset of basin inversion.

The Campanian has a mean thickness of approx. 180 m in the Bay of Kiel and 160 m in the Bay of Mecklenburg (Figure 11c). Increased thickness of the Campanian unit within the Eastholstein Trough and south of the salt pillow "Kieler Bucht" indicate the development of peripheral sinks and revived salt movement in the Glückstadt Graben. However, thickness variations are only in the range of several tens of meters, thus, representing only minor salt movement. The eastern Bay of Kiel shows the typical NNE–SSW trend of increased thickness reflecting the basin configuration. Above the crests of salt pillows in the Bay of Mecklenburg, thickness of the Campanian is reduced. Adjacent areas of slightly increased thickness suggest the development of minor peripheral sinks, which indicates at least minor salt movement (Figure 11c). Thinning towards the Grimmen High is evident from both the southwest and northeast.

An approx. 25 km wide zone of eroded Campanian forms the northwestern flank of the Grimmen High, which suggest ongoing uplift of the Grimmen High during the Campanian.

The Maastrichtian-Danian unit has a mean thickness of 105 m in the Bay of Kiel and approx. 70 m in the Bay of Mecklenburg (Figure 11d). Danian chalk is only preserved in the Eastholstein Trough in the western Bay of Kiel and in the northwestern study area (note blue dashed line in Figure 11d). Thus, the mapped thickness represents mainly Maastrichtian deposits in most parts of the study area. The isochore map shows local thickness variations in the Eastholstein Trough and adjacent areas with slightly increased thickness adjacent to the salt structures. These areas coincide with increased thickness visible in the Campanian. In the eastern Bay of Kiel, the depositional trend seems to have changed from previously NNE–SSW increasing thickness as, for example, visible for the Campanian to NW–SE in the Maastrichtian-Danian. However, the thickness variations are minor over a large distance. Note the NNE–SSW striking contour line west of Fehmarn. In the Bay of Mecklenburg, areas of locally increased thickness adjacent to salt structures coincide with those in the Campanian. The Maastrichtian-Danian unit is thinned or partly eroded above salt pillow crests, which indicates ongoing salt movement accompanied by the development of peripheral sinks.

4.2.3 | Cenozoic

The upper Paleocene unit is relatively thin and uniform in thickness throughout the study area (Figure 12a). The mean thickness is approx. 70 m. The NW–SE thickness trend of the Maastrichtian-Danian unit prevails in the upper Paleocene. Above many salt pillows, the upper Paleocene thickness is reduced due to crestal erosion. Where the top Paleocene is preserved, the unit shows relatively constant thickness. Deepening of peripheral sinks is not visible. Thus, the crestal erosion must have been post-depositional and salt movement ceased during the late Paleocene.

The Eocene-Miocene unit shows comparable large thicknesses (Figure 12b, note the higher contour interval of 50 m). Within the Eastholstein Trough, more than 700 m of Eocene to Miocene deposits were accumulated, whereas thickness of the unit ranges between 0 and 100–200 m above the adjacent salt structures. In the northeastern Bay of Kiel, thickness variations are small and do not clearly correlate with the salt structures “Langeland Ost” and “Vinsgrav”. In the southeastern Bay of Kiel and within the Bay of Mecklenburg, we observe increased thickness adjacent to salt structure, while the unit shows reduced thickness above the crests. Although, overall thickness within the peripheral sinks is smaller than in the Eastholstein Trough. Throughout the study area, local thickness variations clearly correlate with the salt structures and indicate salt withdrawal from rim-synclines due to revived salt movement during the Eocene to Miocene in the Eastholstein Trough, southern Bay of Kiel and Bay of Mecklenburg.

4.3 | Faults

Multiple faults cut the Upper Cretaceous and Cenozoic units (Figures 11 and 12). At the western boundary of the Eastholstein Trough, a crestal graben formed above the salt wall “Waabs”. At the eastern border of the Eastholstein Trough, two prominent N–S striking faults cut the Upper Cretaceous and Cenozoic units and form a crestal graben above the salt structures “Schleimünde”" and “Kieler Bucht” (Figure 11). At least the eastern boundary fault is detached in the Zechstein (Figure 5). The thickness of the Upper Cretaceous and Paleocene units within the crestal graben is relatively similar to the graben shoulders. The top part of the crestal graben is filled with Eocene-Miocene deposits, which leads to a locally increased thickness within the graben comparing the adjacent area (Figures 5 and 12b). This indicates a reactivation of the crestal faults within the Eocene to Miocene.

Above the salt structures “Langeland” (Bay of Kiel), “Staberhuk Ost”, “Neobaltic”, Fehmarnsund Ost” and “Trollegrund Nord” (all Bay of Mecklenburg), many small faults pierce the Upper Cretaceous and Cenozoic units. We outlined the area where these small-scale crestal faults are visible (Figure 9d and mint line in Figures 11 and 12). They are restricted to the crest of salt pillows, which suggests they developed during the growth of the salt structures.

5 | INTERPRETATION AND DISCUSSION

In this section, we interpret and discuss our observations derived from seismic imaging and mapping of the Zechstein, Upper Cretaceous and Cenozoic units in the context of the structural evolution and tectonic framework of the NGB and adjacent areas. Special emphasis is put on identification and characterization of basin inversion phases. Common criteria of inversion tectonics include the reactivation of normal faults as reverse faults as well as folding and uplift of sedimentary units. Furthermore, inversion induced compression can reactivate salt movement including squeezing, arching of the roofs and growth of salt structures. This leads to the development of peripheral sinks and thinned overburden above the crest of the salt structure (e.g. Cooper & Williams, 1989; Jackson & Hudec, 2017; Letouzey et al., 1995). In the following, we interpret and discuss phases of salt movement and their relation to phases of Late Cretaceous to Cenozoic inversion. Thereby, we use the terminology explained in the introduction to refer to the individual inversion events (“Subhercynian”, “Laramide”, “Pyrenean”, “Savian”) based upon the geological time when they occurred (Late Cretaceous, late Paleocene, late Eocene- Oligocene, late Oligocene – Miocene).

We presented thickness (isochore) maps of the Zechstein, Upper Cretaceous and Cenozoic units, which represent isochrone maps converted by a constant interval velocity (Table 1). As the velocity of sedimentary units in the overburden generally increases with depth due to higher compaction, the converted maps underestimate the thickness of the Upper Cretaceous and Cenozoic units in an area, which experienced higher burial depth, e.g. above the rim-syncline of salt structures. Similarly, for areas which experienced less burial, for example above the crest of a salt structure, the thickness is overestimated. Therefore, we can expect that the true local thickness variations around salt structures are slightly more pronounced than shown by Figures 11 and 12. Zechstein interval velocity varies by composition based on the relative content of halite. Interval velocity increases in rim-synclines, where halite is depleted and mechanically stronger portions of the Zechstein succession dominate (mostly anhydrite and non-evaporite rocks). In salt structures, where halite accumulated, the Zechstein interval velocity converges to the interval velocity of pure halite (4,500 m/s) (Schnabel et al., 2021). Thus, we underestimate Zechstein thickness for areas with major salt depletion (Figure 10).

During the mapping procedure, we analysed and traced visible faults in the Upper Cretaceous and Cenozoic units (Figures 11 and 12). Thereby, the extended seismic dataset allowed a reevaluation of previously published fault traces in the study area (Al Hseinat & Hübscher, 2017).

5.1 | Late Cretaceous: From tectonic quiescence to inversion

The study area wide relatively uniform thickness and concordant layering of the Cenomanian-Turonian unit resulted from the relatively quiet tectonic conditions persisting until the Coniacian to Santonian. This is in good accordance with the results of previous studies (Baltic sector of the NGB: e.g. Hansen et al., 2007; Hübscher et al., 2010; onshore Mecklenburg-Western Pomerania: e.g. Kossow

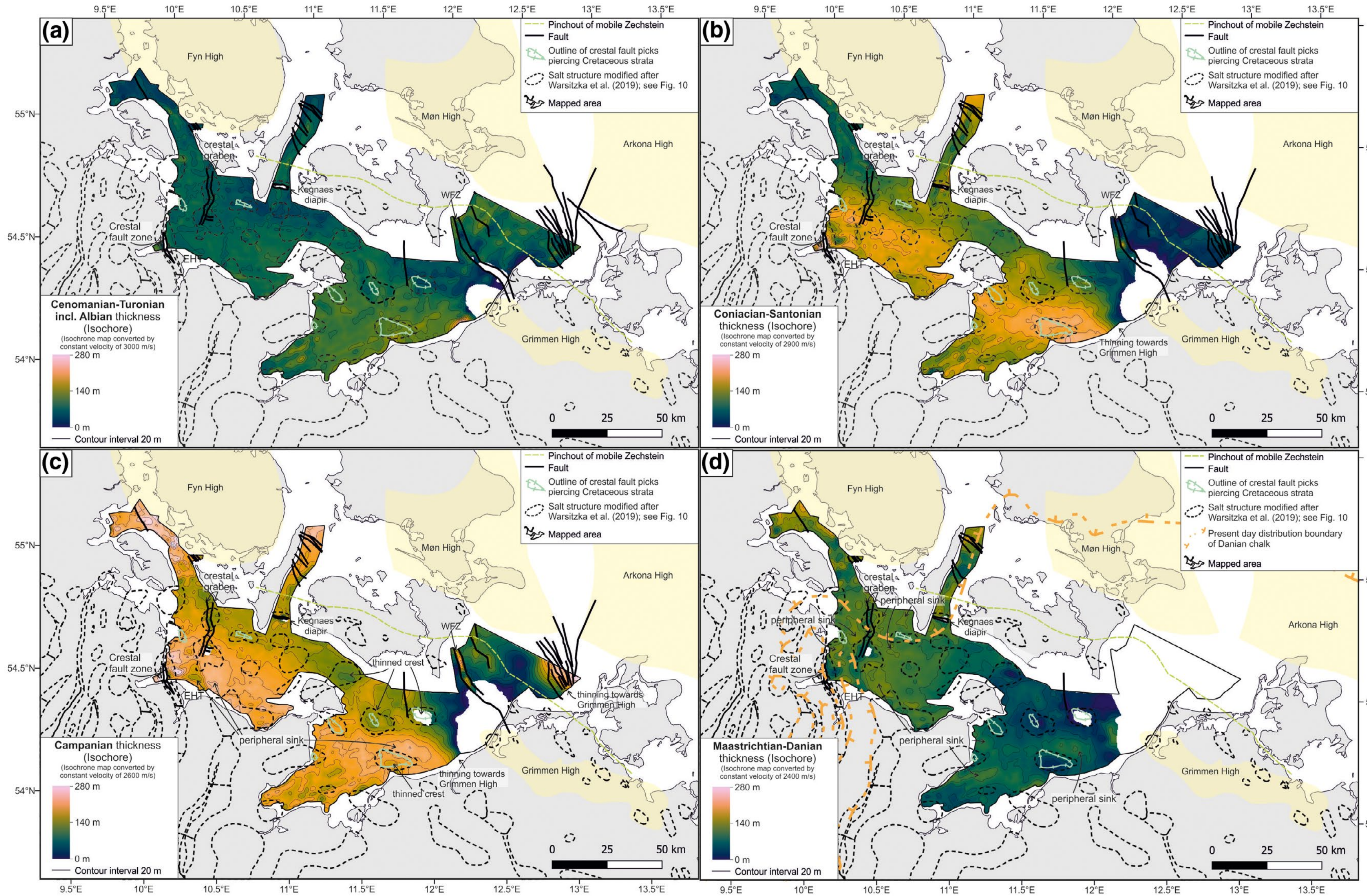


FIGURE 11 Structural elements of the northern North German Basin (modified after Ahlrichs et al., 2020). Inset shows approximate outline of the northern and southern Permian Basin. Red box marks the study area. Salt structures after Vejbaek (1997); Dadlez and Marek (1998); Reinhold et al. (2008); Warsitzka et al. (2019). AFS: Agricola Fault System; EHMB: Eastholstein-Mecklenburg Block; PFZ: Prerow Fault Zone; STZ: Sorgenfrei-Tornquist Zone; TTZ: Teisseyre-Tornquist Zone; WFZ: Werre Fault Zone; WPFS: Western Pomeranian Fault System

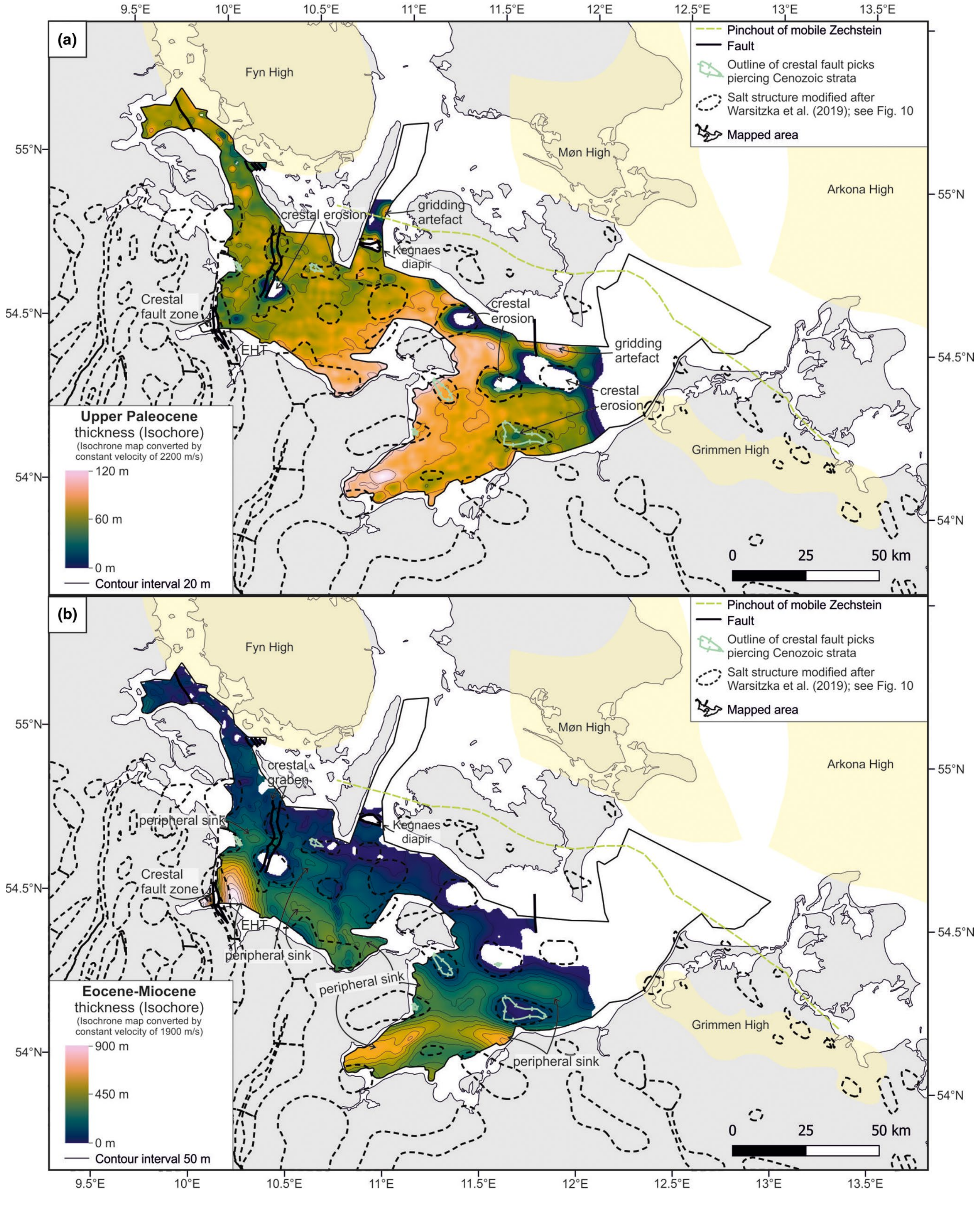


FIGURE 12 Isochore maps of Paleogene and Neogene units (isochrone maps converted using a constant interval velocity). A: upper Paleocene, B: Eocene-Miocene. EHT: Eastholstein Trough. Pinchout of mobile Zechstein after Katzung (2004); Pharaoh et al. (2010)

& Krawczyk, 2002; Glückstadt Graben: e.g. Maystrenko et al., 2006).

At the northeastern basin margin, mapping of the Upper Cretaceous units with a detailed stratigraphic subdivision allowed to date the uplift of the Grimmen High and define its northwestern, offshore, spatial extent (Figure 11). The uplift started in the Coniacian-Santonian and persisted in the Campanian. Thus, the uplift occurred contemporaneous to the onset (90–70 Ma) of the Africa-Iberia-Europe convergence and the corresponding inversion in adjacent sub-basins of the Southern Permian Basin (Kley, 2018; Kley & Voigt, 2008; Ziegler et al., 1995; Harz mountains: Voigt et al., 2004; Lower Saxony: Kockel, 2003; Netherlands: de Jager, 2003; Poland: Krzywiec, 2006; Denmark: Vejbaek & Andersen, 2002). The direction of shortening during this Late Cretaceous inversion event was rather uniformly in NNE–SSW direction (Kley & Voigt, 2008). The Grimmen High strikes NW–SE, which is almost perpendicular to the direction of shortening, which further supports a causative relation (Kossow & Krawczyk, 2002).

In the Eastholstein Trough and in the Bay of Mecklenburg, minor local thickness variations of the Coniacian-Santonian when comparing the overburden above salt structures and their vicinity suggest revived salt movement coeval with uplift of the Grimmen High and the onset of basin inversion (Figures 6, 7, 9 and 11). Thickness variations become more prominent in the Campanian and Maastrichtian, which suggests increased salt movement. In the eastern Bay of Kiel, local thickness variations of Upper Cretaceous units are smaller suggesting less salt movement in the transition between Glückstadt Graben and the northeastern basin margin.

Because of the observed uniform thickness of the Cenomanian-Turonian, we can exclude that differential loading caused the reactivation of salt movement in the Baltic sector of the NGB. The horizontal layering and tectonic quiescence in the Cenomanian-Turonian requires a tectonic trigger for salt movement in the Coniacian-Santonian. The coeval onset of basin inversion makes a thin-skinned reactivation of salt structures driven by compressional intraplate stress related to the Africa-Iberia-Europe convergence reasonable. Minor basement shortening and corresponding reverse movements at inverted basement faults could be sufficient to induce thin-skinned shortening and minor reactivation of preexisting salt structures. Kossow and Krawczyk (2002) estimated about 1 km of subsalt and 3 km of suprasalt shortening for the area north of the Gardelegen Fault up to the northeastern basin margin with progressively decreasing deformation intensity towards the NE (see figure 3 in Kossow & Krawczyk, 2002). The expected minor deformation intensity is in accordance to minor salt movement in the Baltic sector of the NGB. At the northeastern basin margin, uplift of the Grimmen High and fault reactivation of the thin-skinned Werre Fault Zone (Ahlrichs et al., 2020) evidence compressional deformation. Onshore Mecklenburg-Western Pomerania, at the southwestern flank of the Western Pomeranian Fault System (WPFS, Figure 1), a recently published 3D geological overview model shows numerous NW–SE striking faults at the base Zechstein (TUNB Working Group, 2021). These faults are decoupled from the overburden and reach at least partly from the onshore mainland up to the eastern coast of the Bay of Mecklenburg. Faults dissecting the base Zechstein in the northeastern part of Figure 8 might represent the offshore prolongation of these onshore faults. The NW–SE orientation of the base Zechstein faults is favourable for a reactivation during Late Cretaceous shortening and similar to the reactivated faults of the WPFS further north, where mobile Zechstein units are absent (Deutschmann et al., 2018; Seidel et al., 2018). Further visible offsets of the base Zechstein imaged by seismic data in the Bay of Mecklenburg could represent additional basement faults (Figures 7 and 8). However, the partly small offsets might also represent velocity artefacts, which needs further investigations to verify this assumption.

In the outer Glückstadt Graben, a thin-skinned compressional reactivation of salt movement due to Late Cretaceous inversion was already interpreted by Maystrenko et al. (2006). These authors observed squeezed salt diapirs with arched roofs. However, indications for Late Cretaceous basement shortening in the Glückstadt Graben are lacking and the link of thin- and thick-skinned deformation needs further investigation (Warsitzka et al., 2016). Our interpretation of minor salt movement caused by thin-skinned compression in the Eastholstein Trough and Bay of Kiel is in agreement with Maystrenko et al. (2006). In contrast with the faults of the WPFS, Late Cretaceous contraction acted almost parallel to the approx. NNE–SSW trending salt structures and underlying basement faults of the Glückstadt Graben (Figure 1), which explains the small intensity of salt flow in the Eastholstein Trough (Figure 11). Thereby, the eastern Bay of Kiel and the area around Fehmarn Island represents a transition zone from the influence of the Glückstadt Graben in the west to higher influence of the basin margin faults of the WPFS in the east.

5.2 | Late Paleocene: Large-scale uplift

The upper Paleocene thickness map shows only small variations with large wavelengths in the study area (Figure 12a). In comparison with the NNE–SSW to NE–SW trend of increasing thickness of the Upper Cretaceous units (Figure 11), the upper Paleocene trend is rather

NW–SE with a NE–SW elongated zone of increased thickness around Fehmarn Island. However, thickness variations are small and the mapped area might not display the true regional pattern. Thickness variations do not correlate with salt structures in the Bays of Kiel and Mecklenburg. Missing peripheral sinks and concordant layering (see flattened sections in Figures 6 and 9) approve that post-depositional erosion caused the thinned overburden above salt structure crests (Figure 12a). Furthermore, lower and middle Eocene deposits imaged in the Eastholstein Trough are likewise relatively uniform in thickness, which indicates ceased salt movement and relative tectonic quiescence during the late Paleocene to middle Eocene (Figure 4).

There are different views in the literature concerning a late Paleocene inversion phase within the Southern Permian Basin. While some authors considered a fault-controlled uplift (e.g. de Jager, 2003; Nalpas et al., 1995) or proposed a domal uplift mechanism by lithospheric folding (e.g. Deckers & van der Voet, 2018; Nielsen et al., 2005), others questioned the existence of late Paleocene inversion and suggested that sea-level fluctuations caused the unconformity (Kockel, 2003). Recent studies explain the unconformity by large-scale domal uplift caused by thinning of the mantle lithosphere and dynamic topography driven by mantle plumes (Kley, 2018; von Eynatten et al., 2021). For the study area, well information and paleogeographic maps prove a stratigraphic gap between Danian chalk and preserved upper Paleocene claystones (Thanetian) (Hoth et al., 1993; Vinken & International Geological Correlation Programme, 1988). Assuming that fault-controlled uplift caused the stratigraphic gap, we would expect local thickness variations and thin-skinned compressional reactivation of salt movement similar to the Late Cretaceous inversion event. However, the structural style of deformation of the Paleocene is quite different to the Late Cretaceous inversion. The lack of salt movement and the regional unconformity overlain by upper Paleocene deposits of relatively uniform thickness are in better accordance with a large-scale domal uplift. The structural style in the Paleocene is similar to the Mid Jurassic North Sea Doming event, where large-scale uplift and erosion in the Jurassic was followed by a period of relative tectonic quiescence in the Albian to Turonian (Hansen et al., 2007; Hübscher et al., 2010). The temporal correlation of the stratigraphic gap in the study area (ca. 66–59 Ma) with the late Paleocene domal uplift in other parts of the Southern Permian Basin suggests a causative relation (Central Europe, 75–55 Ma: von Eynatten et al., 2021; southern North Sea, ca. 62–59 Ma: Deckers & van der Voet, 2018; British Isles, 65–55 Ma: Holford et al., 2009). Thereby, the Baltic sector of the NGB could mark the northeastern prolongation of the domal uplift in central Germany (von Eynatten et al., 2021).

5.3 | Cenozoic salt movement

Diverging upper Eocene strata and development of a large peripheral sink in the Eastholstein Trough evidence the reactivation of salt movement and renewed activity in the outer Glückstadt Graben (Figures 4 and 12). Salt movement persisted during the late Eocene to Miocene indicated by the development of peripheral sinks and crestal faulting above the salt structures “Schleimünde” and “Kieler Bucht” with increased infill of the crestal graben with Eocene-Miocene deposits. This is in accordance to previous studies investigating the eastern Glückstadt Graben (onshore: Baldschuhn et al., 2001; Maystrenko et al., 2005a; offshore: Al Hseinat et al., 2016; Hansen et al., 2005; Huster et al., 2020).

Outside of the Eastholstein Trough, we observe eroded or thinned Eocene-Miocene strata above salt structure crests, whereas the unit shows increased thickness above rim-synclines (Figure 12b). These local thickness variations clearly correlate with the salt structures in the Bays of Kiel and Mecklenburg. This suggests salt withdrawal from rim-synclines and subsidence of the overlying overburden, while corresponding growth of salt structures subjects the crestal overburden to a higher degree of erosion. However, the preserved Eocene-Miocene unit lacks divergent strata, even above rim-synclines, that would directly date the salt movement (Figures 7–9). Neogene uplift and erosion and subsequent Quaternary glacial erosion (Rasmussen, 2009; Sirocko et al., 2008) removed much of the Eocene-Miocene deposits in the Baltic sector of the NGB. Well information and pre-Quaternary maps of the study area and adjacent onshore regions indicate that preserved sedimentary units are mostly of early to middle Eocene and partly late Eocene, Oligocene and early Miocene age (wells onshore Mecklenburg Western Pomerania: Hoth et al., 1993; Pre-Quaternary maps of Schleswig Holstein and Mecklenburg – Western Pomerania: Hinsch, 1991; Schulze, 1995). The latter occur mostly above rim-synclines of salt structures. Therefore, we can assume that outside of the Eastholstein Trough, our mapped Eocene-Miocene unit comprises mostly lower to middle Eocene deposits. Based on a conceptual model (Figure 13), we propose that the reactivation of salt movement took place in post-middle Eocene times due to the following considerations:

The Albian and Upper Cretaceous units were deposited above a major erosional unconformity (Figure 2). During deposition, relative tectonic quiescence persisted with uniform thickness distribution and horizontal layering. During Late Cretaceous inversion, minor salt movement led to minor local thickness variations. Thus, we can still consider layering as approx. horizontal at the

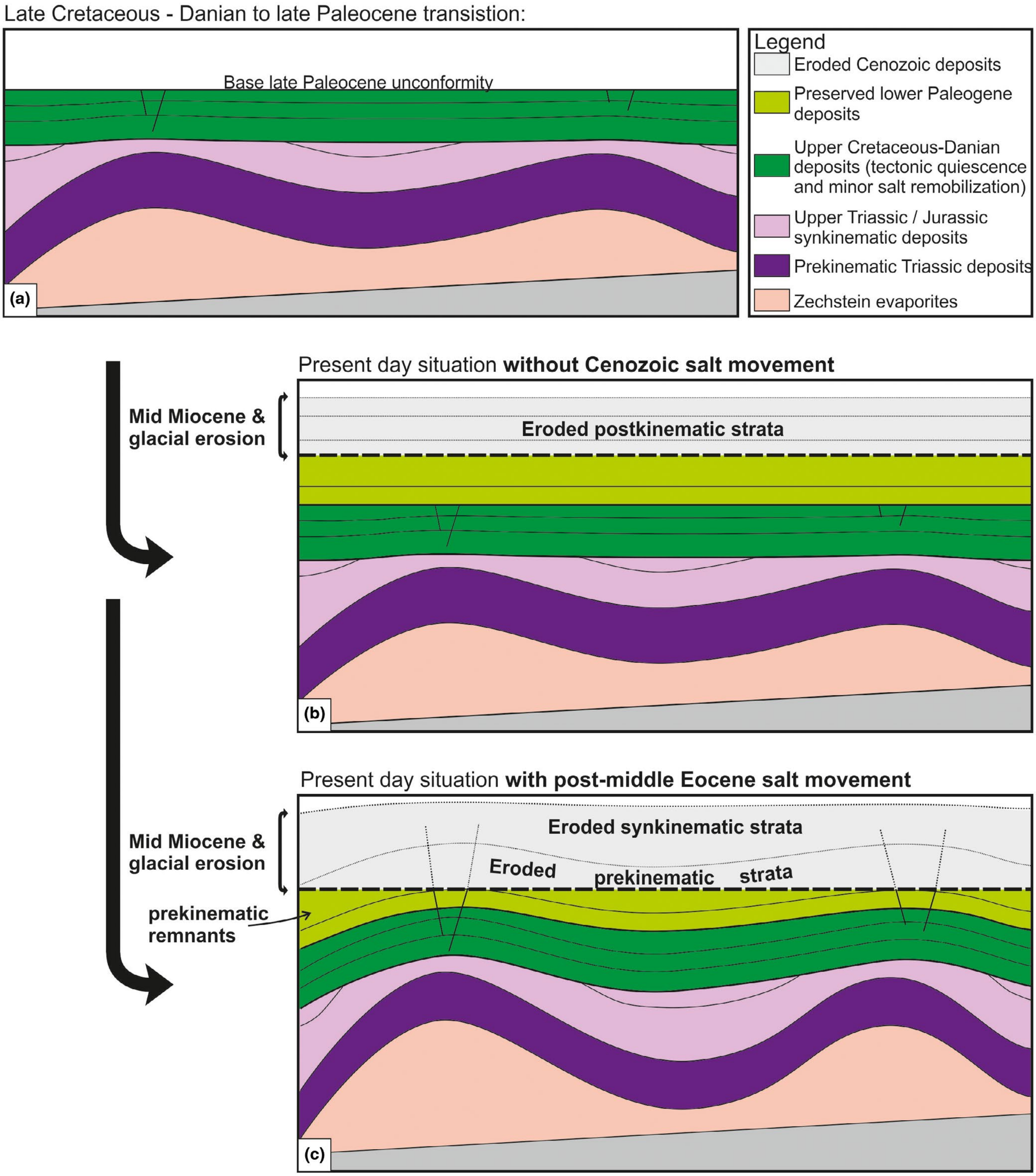


FIGURE 13 Conceptual model visualizing the necessity of a Cenozoic phase of salt movement. A: Initial situation at Late Cretaceous-Danian to late Paleocene transition. B: Present-day situation without Cenozoic salt movement. Note that only postkinematic strata is eroded. C: Present-day situation with post-middle Eocene salt movement. Note the eroded prekinematic strata, prekinematic remnants and the eroded synkinematic (divergent) strata

Late Cretaceous-Danian to late Paleocene transition, especially as large-scale late Paleocene erosion presumably re-flattened the paleo-relief (Figure 13a). Assuming no salt movement occurred during the Cenozoic, we would expect horizontally layered sedimentary units deposited in Eocene to early Miocene shallow to deep marine conditions. Neogene and Quaternary erosion removed sedimentary units but a more or less horizontal layering would remain (Figure 13b). However, seismic images show that the Eocene-Miocene unit is folded across the salt structures (Figures 5, 7 and 8), which requires a post-middle Eocene phase of salt movement that overprinted prior horizontal layering of upper Paleocene to middle Eocene deposits (Figure 13c). Neogene and Quaternary erosion then removed synkinematic divergent strata (Figure 8c), leaving behind mostly the prekinematic lower to middle Eocene (Figure 13c). We cannot fully exclude that the reactivation of salt movement in the Cenozoic was during the Neogene. However, the observed renewed salt movement in the eastern Glückstadt Graben during the late Eocene to Oligocene makes a coeval reactivation of the salt structures of the Eastholstein Mecklenburg Block likely. Local thickness variations of the Eocene-Miocene units exceed those of Upper Cretaceous units by far (Figures 4, 11 and 12b). Hence, after the initial growth of salt structures in the Triassic and Jurassic, the second major phase of salt movement and growth of salt structures was likely in the late Eocene to early Miocene.

5.4 | Cause of Cenozoic reactivation of salt movement

The uniform thickness of the upper Paleocene unit suggests a phase of salt tectonic quiescence that ended in the late Eocene. In the following, we discuss potential trigger mechanism for the late Eocene salt remobilization.

The late Eocene to Oligocene reactivation of salt movement was contemporaneous to recommencing northward movement of Iberia and increasing rates of Africa-Iberia-Adria-Europe convergence associated to the Pyrenean and Alpine orogenies (e.g. Handy et al., 2010). This resulted in approx. N–S directed shortening in the European foreland and a further phase of inversion in the Southern Permian Basin (e.g. Kley, 2018). The direction of compression is similar to the Late Cretaceous inversion event and almost parallel to the NNE–SSW striking Glückstadt Graben. As discussed before, this makes the structures unfavourable for compressional reactivation. At the northeastern basin margin, shortening during the late Eocene-Oligocene inversion event acted oblique to the NW–SE striking faults of the WPFS (Figure 1) and further SW located base Zechstein faults (shown in a 3D geological overview model, see TUNB Working Group, 2021). Here, we cannot exclude a contribution to salt movement driven by compression. However, salt movement in post-middle Eocene times exceeded the salt flow during the Late Cretaceous. It is therefore questionable why similar directed compressional stress would result in a quite different response of the salt structures in the study area, especially in the Glückstadt Graben (minor Late Cretaceous vs. major late Eocene movement), in particular as shortening during the Late Cretaceous event was stronger than during the Paleogene (e.g. Vejbaek et al., 2010).

Coeval with the late Eocene-Oligocene revived activity in the Glückstadt Graben, Central Europe experienced rifting and the development of the European Cenozoic Rift System (ECRIS, Figure 14; Dèzes et al., 2004). Development of the northern part of the ECRIS, namely the Upper Rhine Graben, the Roer Graben and the Hessian grabens, began during the late Eocene (Dèzes et al., 2004). The authors attributed opening of the rifts to transtensional reactivation of older crustal discontinuities controlled by orthogonal N to NE directed compressional stress originating in the Alpine and Pyrenean collision zones. However, missing strike-slip deformation of upper Eocene-Oligocene deposits, as well as poorly constrained dating of compressional deformation, in the Upper Rhine Graben and the Massif Central grabens led Michon and Merle (2005) to question an Alpine control. They interpreted the late Eocene-Oligocene development in terms of passive rifting due to E–W to ESE–WNW extension (Figure 14).

The Glückstadt Graben is located approx. 500 km north of the Upper Rhine Graben (Figure 14). In contrast with the Rhine Rift System, it is floored by thick Zechstein salt. Maystrenko et al. (2005a) noted that the rapid subsidence in the Glückstadt Graben during the Paleogene to Neogene coincided with subsidence of the North Sea and was likely related to E-W extension. An E-W extensional event acted almost perpendicular to the graben axis, thus making a reactivation favourable. This is in agreement with a higher degree of salt movement compared to the Late Cretaceous and the observed reactivation of the N–S striking crestal graben in the western Bay of Kiel (Figure 12b). Moreover, the development of a N–S striking normal fault, which pierces from the basement into the Paleogene successions, proves E–W extension (Scheck-Wenderoth et al., 2008). This fault is located at the eastern border of the Eastholstein Trough, below the onshore part of the salt structure “Plön” (Figures 1 and 3). In the Bay of Kiel, a thick-skinned fault like this is not visible and thin-skinned faulting predominates. The coeval activity of the ECRIS and similar favourable orientation makes an extensional trigger for Cenozoic salt movement in the southwestern Baltic sector of the NGB plausible and suggests a causative relationship to the development of the ECRIS (Figure 14). At the northeastern basin margin, an extensional reactivation of the approx. NNW–SSE striking basement faults, south to southeast of the Bay of Mecklenburg, could also induce a reactivation of salt movement by thin-skinned extension. However, whether these faults were reactivated during the Cenozoic is unclear. To validate this, further research, including improved images of the subsalt, is needed.

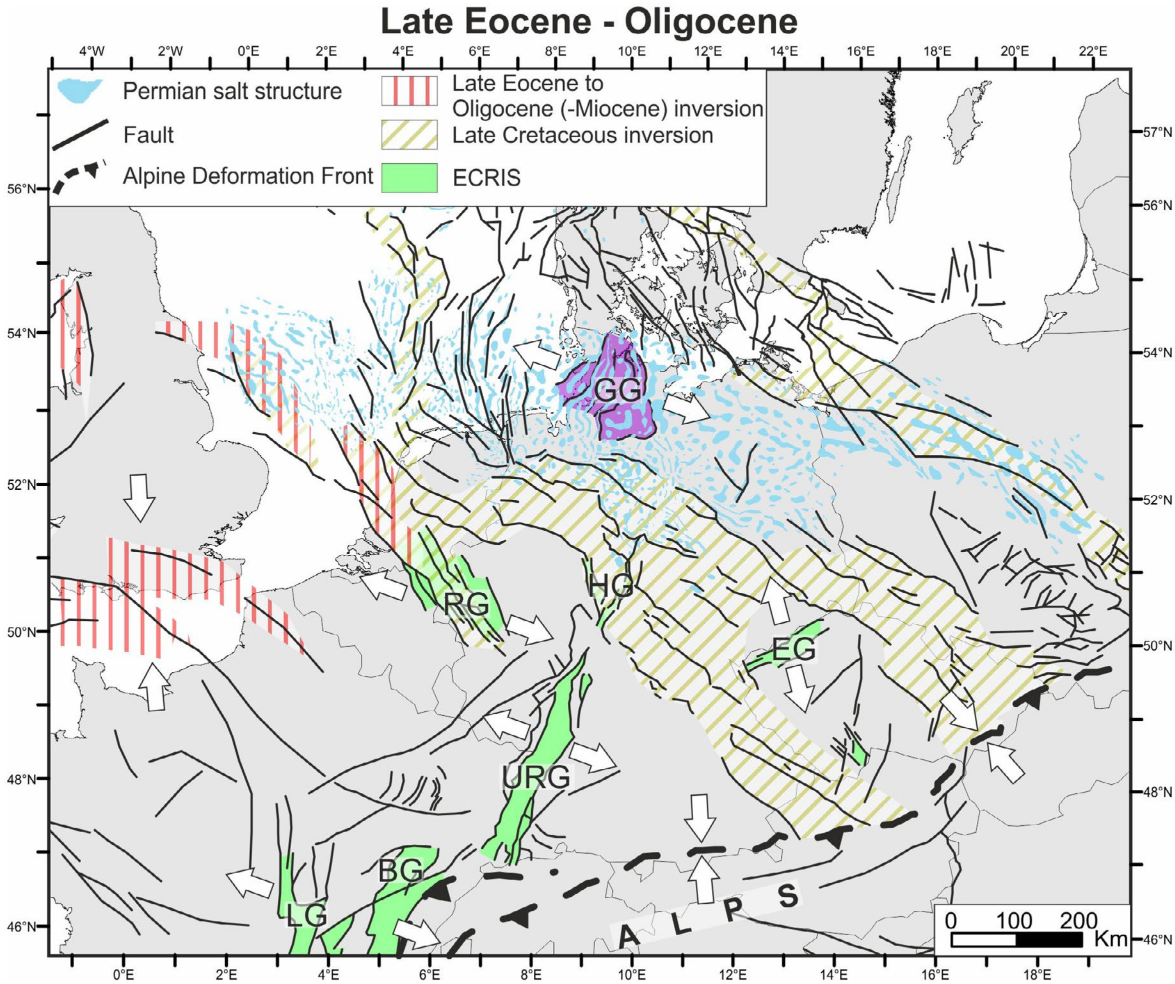


FIGURE 14 Regional sketch map showing late Eocene to Oligocene stage of structural evolution of the European Cenozoic Rift System (ECRIS) in relation to the Glückstadt Graben and salt structures in the study area. Arrows indicate kinematics. Areas affected by Late Cretaceous and late Eocene to Oligocene (-Miocene) inversion are also shown. Compiled after Michon et al. (2003); Dèzes et al. (2004); Mazur et al. (2005); Kley et al. (2008); Kley (2018). Fault pattern simplified and without claim to completeness. BG: Bresse Graben; EG: Eger Graben; HG: Hessian grabens; LG: Limagne Graben; GG: Glückstadt Graben; Roer Graben; URG: Upper Rhine Graben

6 | CONCLUSIONS

We analysed the Late Cretaceous and Paleogene evolution in the Baltic sector of the North German Basin margin using a dense network of high-resolution 2D seismic data. Stratigraphic interpretation was linked to previous studies and nearby wells. We presented key prestack depth migrated seismic profiles and thickness maps of the Zechstein, Upper Cretaceous and Cenozoic units with refined stratigraphic subdivisions that are novel for the study area. We used a refraction travel-time tomography to estimate an averaged interval velocity for key Upper Cretaceous and Cenozoic units, which we used to constrain constant velocities for time-depth conversion. The Zechstein thickness map allowed redefining the geometry of four salt structures in the Bays of Kiel and Mecklenburg. The refined stratigraphic subdivision allows differentiating between episodes of increased tectonic activity during the Late Cretaceous and Cenozoic. The main conclusions are:

- Late Cretaceous basin inversion in the Baltic sector of the North German Basin started coevally with neighbouring sub-basins in the Coniacian-Santonian with increased activity in the Campanian. Shortening induced by Africa-Iberia-Europe convergence caused uplift of the Grimmen High and contemporaneous minor movement of Zechstein salt in the outer Glückstadt Graben and Bay of Mecklenburg. However, salt movement leading to growth of salt structures and the development of peripheral sinks was relatively small compared to later Cenozoic movements.
- Upper Paleocene thickness variations are minor and have large wavelengths in the study area. Salt

movement ceased during the Paleocene without further growth until the middle Eocene. The regional unconformity at the base of the upper Paleocene unit is in accordance with a large-scale domal uplift in the late Paleocene. The structural style is similar to the Jurassic/early Cretaceous, where large-scale erosion due to the North Sea doming event was followed by a phase of tectonic quiescence.

- Upper Eocene and Neogene successions in the eastern Glückstadt Graben proof salt movement by increased sediment accumulation and diverging reflectors within peripheral sinks. The reactivation of salt movement began in the late Eocene and lasted to early Miocene times.
- Outside the Glückstadt Graben, eroded Paleogene deposits hamper direct evidence for late Eocene salt movement in the Bays of Kiel and Mecklenburg. However, thickness variations of preserved strata and missing synkinematic strata indicate significant salt movement in post-middle Eocene times. We propose that this phase of intensified salt movement was coeval and causally related to the salt flow in the eastern Glückstadt Graben during the late Eocene to Oligocene. However, we cannot fully exclude a phase of Neogene salt movement. Salt structure growth during the Cenozoic exceeded growth during Late Cretaceous inversion and represents the phase of major growth since the Late Triassic to Jurassic initial salt structure growth.
- Cenozoic salt movement in the study area is coeval with renewed compressional stress in Central Europe induced by the Pyrenean and Alpine orogenies. Thin-skinned compressional salt movement induced by a reactivation of basement faults at the northeastern basin margin could explain the reactivation of salt movement in the Cenozoic in the Bay of Mecklenburg. For the Glückstadt Graben, a compressional reactivation seems unlikely. The different structural style of minor Late Cretaceous and major Cenozoic movement suggests that compression is not the best explanation for the reactivation of salt flow during the Cenozoic, especially for the Glückstadt Graben. An E-W directed extensional event possibly related to the development of the European Cenozoic Rift System is more suitable as a driver of Cenozoic salt movement in the southwestern Baltic sector of the North German Basin. Whether salt movement at the northeastern basin margin might also be induced by an extensional reactivation of basement fault at the basin margin needs further analysis.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization of this work was done by NA, CH and VN. NA is the corresponding author and carried out the seismic processing, seismic interpretation and mapping in this study. NA created the figures and was the primarily writer of the manuscript. Structural interpretation and the discussion of the results in the context of the regional framework were done by NA, VN, CH and ES. AW applied the refraction travel-time tomography, extracted the velocity information and mainly wrote the paragraph describing the tomography method in Section 3.3. JK provided further input in the discussion of the results and their association with inversion events in Central Europe. All authors contributed to editing of the manuscript.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/bre.12617.

DATA AVAILABILITY STATEMENT

Seismic profiles, isochore maps (in TWT and meters) shown in this study and time-structure maps used to create the isochore maps are available in the supplementary material of this article (see Ahlrichs et al., 2021). Further seismic data used for mapping, are available from the authors and the Federal Institute for Geosciences and Natural Resources (BGR) upon reasonable request. The authors thank ExxonMobil Production Deutschland GmbH for providing the seismic profiles of the GSI76B survey.

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