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Salt tectonics in intracontinental sedimentary basins: Triassic–Jurassic salt movement in the Baltic sector of the North German Basin and its relation to post-Permian regional tectonics

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Abstract
The formation and structural evolution of complex intracontinental basins, like the North German Basin, mark fundamental earth processes. Understanding these is not only essential to basic research but also of socioeconomic importance because of the multitude of resources, potential hazards, and subsurface use capability in such basins. As part of the Central European Basin System, major subsidence and structural differentiation affected the Baltic sector of the North German Basin in Permian-to-Jurassic times. A dense network of high-resolution 2D seismic data together with nearby wells allow the creation of regional maps with refined stratigraphic subdivision of unprecedented spatial resolution covering the bays of Kiel and Mecklenburg (Baltic Sea). Cross sections along the basin margin allow reconstruction of the structural evolution of the Zechstein salt and its overburden. At the northern basin margin, near the Kegnaes Diapir, thinning of the Buntsandstein and divergent reflectors indicate Early Triassic faulting and salt movement. In the Late Triassic, tectonic activity increased as expressed by the onset of salt movement in the north-eastern Glückstadt Graben, major growth of the Kegnaes Diapir and faulting at the north-eastern basin margin during deposition of the Keuper (Erfurt, Grabfeld, Stuttgart and Weser formations). At the north-eastern basin margin, we interpret the accumulation of Keuper and Jurassic deposits as an infill of a local sub-basin bordered by the Werre Fault Zone and Agricola Fault System. Between the Glückstadt Graben and the north-eastern basin margin, the Eastholstein–Mecklenburg Block formed a more stable area, where salt movement first began during the latest Triassic. In the peripheral part of the basin, salt movement was triggered by thin-skinned extension associated with thick-skinned faulting within the axial parts of major graben systems. Indications for gravity gliding are absent. Reactive diapirism is restricted to the basin margin, where reduced overburden thickness and Late Triassic erosion allowed diapiric breakthrough.

1 | INTRODUCTION

The North German Basin forms part of the intracontinental Southern Permian Basin and has a complex and long history of basin evolution from the Carboniferous to Quaternary (Figure 1) (see, e.g. overviews: Maystrenko et al., 2008; Pharaoh et al., 2010; Ziegler, 1990a). Even though the overall basin evolution is well understood, the link among regional tectonics, salt movement and inherited deep-rooted structures at a regional scale and the temporal resolution of geological stages remain partly elusive. In times of growing interest in the usage of the deeper subsurface, e.g. for geoengineering projects like Carbon Capture and Storage (CCS), geothermal energy utilization, storage of renewable energy or the search for a nuclear repository, a profound understanding of the evolution of the basin and its deep-rooted fault systems is very important (Gill, 2017).

The Baltic sector of the North German Basin (NGB) covers the northern basin margin including a part of the north-eastern Glückstadt Graben, which experienced intensive extension and salt movement during the Triassic, and the Western Pomeranian Fault System at the north-eastern basin margin, which developed due to Triassic transtensional tectonics (Figure 1) (Krauss & Mayer, 2004; Maystrenko et al., 2005a, 2005b). The presence of evaporite sequences, including mobile salt units (high halite content), played a major role in the area's structural development due to their weakness and ability to flow like a viscous fluid. This allowed the formation of many salt structures across the Baltic sector of the NGB, making this region an ideal study area to investigate the impact of regional tectonics on salt movement (Reinhold et al., 2008; Vejbæk, 1997). Among the salt structures are a WNW–ESE

Highlights

- High quality seismic data depict the basin structure of the Baltic sector of the North German Basin.
- Seismic imaging and mapping show Triassic–Jurassic salt movement in the bays of Kiel and Mecklenburg.
- Basin margin restricted reactive diapirism by reduced overburden thickness and Late Triassic erosion.
- Thin-skinned extension by thick-skinned faulting in the axial graben systems triggered salt movement.
- Fault analysis of the northeastern basin margin—Late Triassic reactivation of Paleozoic structures.

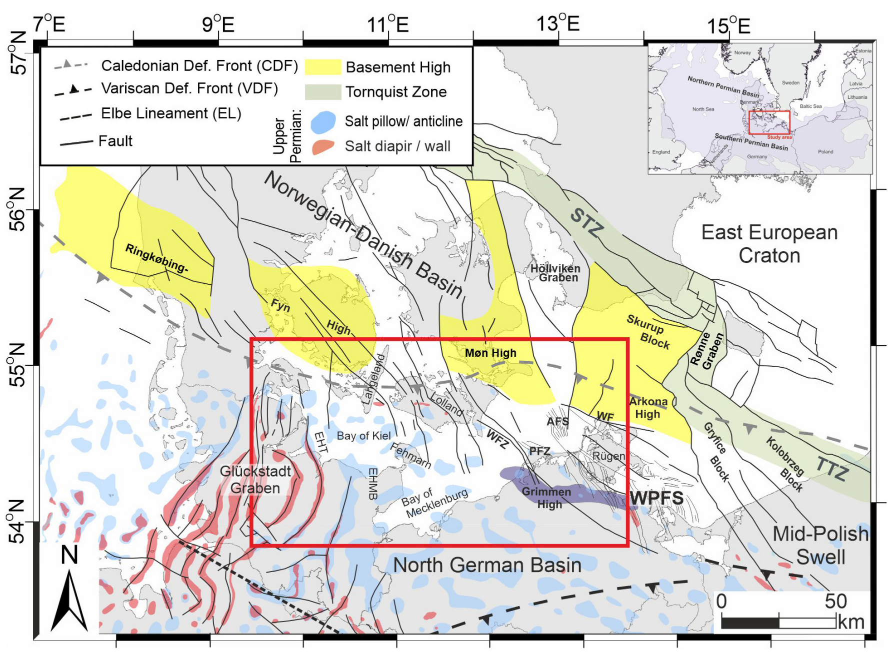


FIGURE 1 Structural overview of the northern North German Basin (modified after Ahlrichs et al., 2020, 2021). Inset shows approximate outline of the northern and southern Permian Basin (present-day limit of Permian deposits after Maystrenko & Scheck-Wenderoth, 2013). Salt structures were compiled after Vejbæk (1997), Dadlez and Marek (1998), Reinhold et al. (2008), Warsitzka et al. (2019), Ahlrichs et al. (2021). AFS, Agricola Fault System; EHT, Eastholstein Trough; EHMB, Eastholstein–Mecklenburg Block; PFZ, Prerow Fault Zone; STZ, Sorgenfrei-Tornquist Zone; TTZ, Teisseyre-Tornquist Zone; WF, Wiek Fault; WFZ, Werre Fault Zone; WPFS, Western Pomeranian Fault System.

striking set of four salt diapirs at the northern basin margin, spreading across the island of Lolland towards Langeland (Figure 1). Their isolated location at the basin margin, surrounded by salt pillows, is unique within the NGB. The causative relation of salt tectonics, basin configuration and regional tectonics, which led to the formation of these diapirs, remains unclear.

In the past, much research analysing the post-Permian sedimentary record has been done in the Baltic sector of the NGB (Al Hseinat et al., 2016; Al Hseinat & Hübscher, 2014, 2017; Deutschmann et al., 2018; Frahm et al., 2020; Hansen et al., 2005, 2007; Hübscher et al., 2004, 2010, 2019; Huster et al., 2020; Kammann et al., 2016; Maystrenko et al., 2005a, 2005b; Schnabel et al., 2021; Zöllner et al., 2008). These studies used seismic imaging and mapping of post-Permian units with a lithostratigraphic subdivision in the order of geological series to analyse the regional structural evolution. In a recent study, Ahlrichs et al. (2021) presented regional maps of the Baltic sector of the NGB with a refined stratigraphic subdivision of Late Cretaceous and Cenozoic units specifying the onset of Late Cretaceous inversion and Palaeogene salt movement. For the Triassic, such regional maps resolving the stratigraphic subdivision beyond the level of the main lithostratigraphic units of the Germanic Triassic are lacking in the Baltic sector of the North German Basin. Studies carried out in the adjacent onshore areas (Denmark: Clausen & Pedersen, 1999; Glückstadt Graben and Lower Saxony: Baldschuhn et al., 2001; Frisch & Kockel, 1999; Kockel, 2002; Warsitzka et al., 2016; Mecklenburg-Western Pomerania: Beutler et al., 2012) show a refined stratigraphic subdivision of the Triassic units.

In this study, we focus on the Triassic–Jurassic phase of basin evolution to enhance both the understanding of regional tectonics and the initial development of salt structures prior to Late Cretaceous inversion. We use a dense network of high-resolution 2D seismic data in combination with onshore and offshore wells to refine the stratigraphic subdivision and create regional maps of the Triassic–Jurassic units, which close the gap to adjacent onshore areas (Figures 2 and 3). We present key seismic profiles and regional time–structure and isochron maps of the Zechstein, Buntsandstein, Muschelkalk, Keuper II (Erfurt, Grabfeld, Stuttgart and Weser formations), Keuper I (Arnstadt and Exeter formations) and Jurassic units (mostly Liassic) to analyse the Triassic-to-Jurassic structural evolution of the region (Figure 2). Thereby, we strive for a detailed structural analysis of the basin margin and its fault systems and propose an explanation for the development of salt diapirs at the northern basin margin. Together with previous studies setting up the stratigraphic framework (Ahlrichs et al., 2020) and investigating the Late Cretaceous and Cenozoic development (Ahlrichs et al., 2021), this study completes the analysis of the impact of regional post-Permian tectonics on salt structure evolution in the Baltic sector of the NGB. Additionally, our results contribute to a planned offshore extension of the recently published 3D geological overview model of the onshore part of the NGB, which was developed to meet the increasing demands on subsurface use in Germany (TUNB Working Group, 2021).

2 | GEOLOGICAL SETTING

The study area is located at the northern margin of the North German Basin (NGB) and extends from the Bay of Kiel in the west to the Bay of Mecklenburg and Rügen Island in the east (Figure 1). The crust below the Baltic sector of the North German Basin consists of an assemblage of Caledonian and Variscan consolidated terranes and its transition to the Precambrian East European Craton (Figure 1) (e.g. Guterch et al., 2010). This transition zone is termed the Trans-European Suture Zone and extends from the Caledonian Deformation Front in the north to the Elbe Lineament in the south (Figure 1) (Berthelsen, 1992; Guterch et al., 2010). The Ringkøbing-Fyn High, Møn High and Arkona High are a WNW–ESE-trending series of basement highs (sensu Peacock & Banks, 2020), which separate the NGB and the Norwegian–Danish Basin (Figure 1). In the western part of the study area, the NNE–SSW-trending Mesozoic-Cenozoic Glückstadt Graben formed a NGB depocentre with up to 11 km of post-Permian sediment thickness strongly influenced by salt tectonics (e.g. Maystrenko et al., 2005a) (Figure 1). The Eastholstein Trough (EHT) marks the eastern part of the Glückstadt Graben and partly extends into the western Bay of Kiel. The central and eastern Bay of Kiel together with the Bay of Mecklenburg form the peripheral region between the axial part of the Glückstadt Graben and the north-eastern basin margin (Eastholstein–Mecklenburg Block (EHMB)), where the sedimentary infill of the basin amounts to 2–4 km (Figure 1) (Maystrenko et al., 2005b). The eastern part of the study area is characterized by the Western Pomeranian Fault System, a series of NW–SE- to NNW–SSE-striking faults often bordering Y-shaped grabens (e.g. were Fault Zone, Prerow Fault Zone and Agricola Fault System, see Figure 1) (Krauss & Mayer, 2004).

Figure 2 briefly summarizes the development of the NGB showing the main tectonic events together with the dominant lithology. In the late Carboniferous–early Permian, basin formation began with wrench faulting, volcanism and lithospheric thinning followed by thermal subsidence (Ziegler, 1990b). During the late Permian, repeated restricted seawater influx under arid conditions led to extensive evaporation and the deposition of the layered

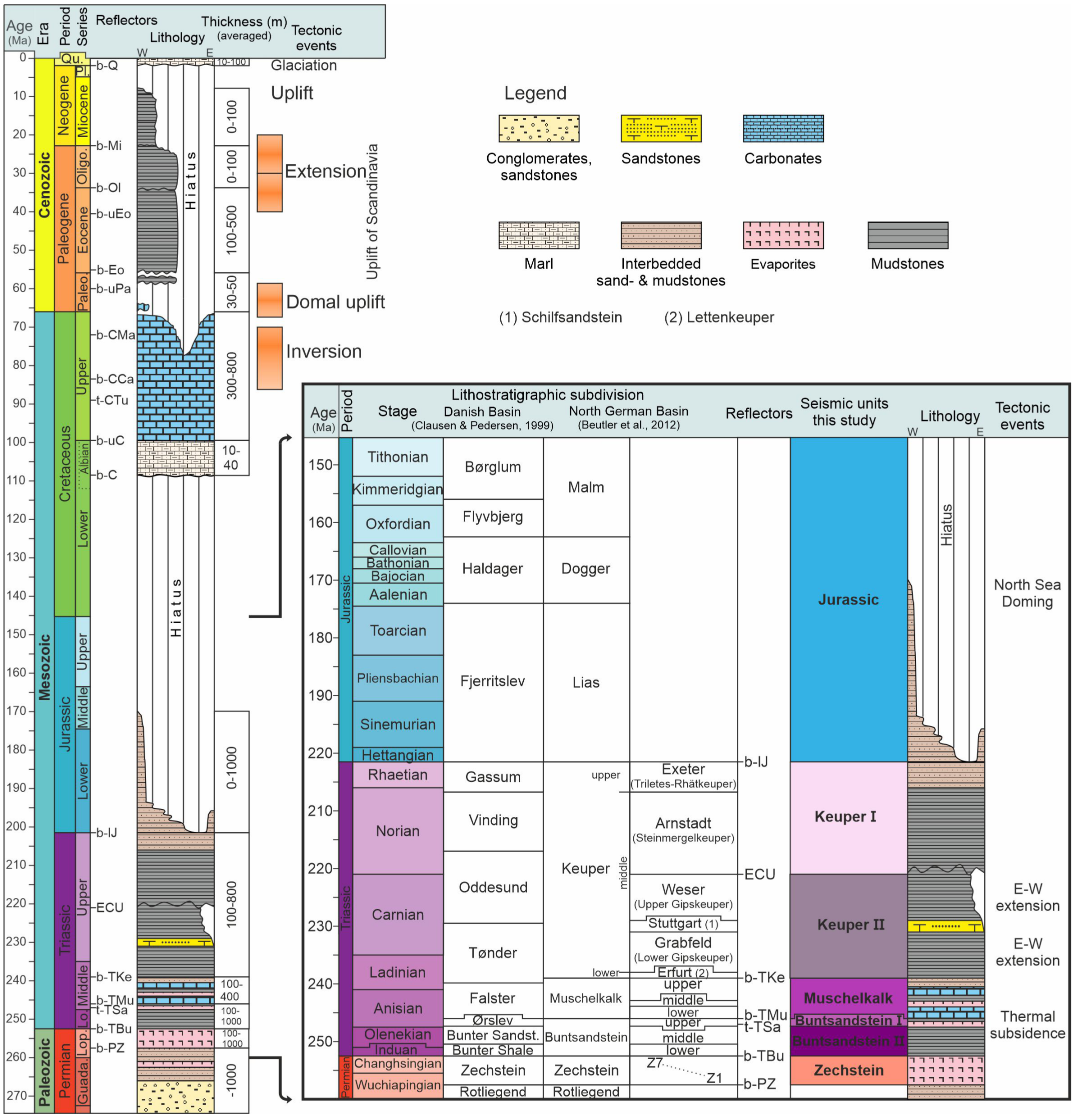


FIGURE 2 Lithostratigraphic chart of the North German Basin showing dominant lithology, main tectonic events, average thickness and lithostratigraphic subdivision of the Triassic and Jurassic (Compiled from Ahlrichs et al., 2021; Bachmann et al., 2008; Beutler et al., 2012; Clausen & Pedersen, 1999; Kossow & Krawczyk, 2002; STD, 2016). Reflectors modified after Ahlrichs et al. (2020). Reflectors: 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 Palaeocene; 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. Other abbreviations: Bunter Sand.: Bunter Sandstone; Guada.: Guadalupian; Lo.: Lower; Lop.: Lopingian; Oligo.: Oligocene; Paleo.: Palaeocene; Pl.: Pleistocene; Qu.: Quaternary.

Zechstein evaporite succession within the basin (Figure 2) (Peryt et al., 2010; Strohmenger et al., 1996). The Zechstein succession consists of seven cyclothems with varying amounts of clay, carbonates, anhydrite, halite and potash sequences. Due to the highest amount of mobile halite and relatively small amount of immobile anhydrite, the Stassfurt cyclothem is the most important for salt tectonics in our study area (e.g. Kossow et al., 2000). Thermal subsidence lasted until the Middle Triassic throughout the deposition of the Buntsandstein and Muschelkalk successions (Figure 2) (Van Wees et al., 2000). Locally, subsidence was enhanced by extension forming a narrow graben in the central Glückstadt Graben during the Early and Middle Triassic (Brink et al., 1992).

An eustatic sea-level drop established terrestrial conditions in the Late Triassic during deposition of the Keuper units (Nöldecke & Schwab, 1976). During the Late Triassic, E–W-directed extension widened the Glückstadt Graben and caused intensive salt movement including reactive diapirism (Brink et al., 1992; Maystrenko et al., 2005b).

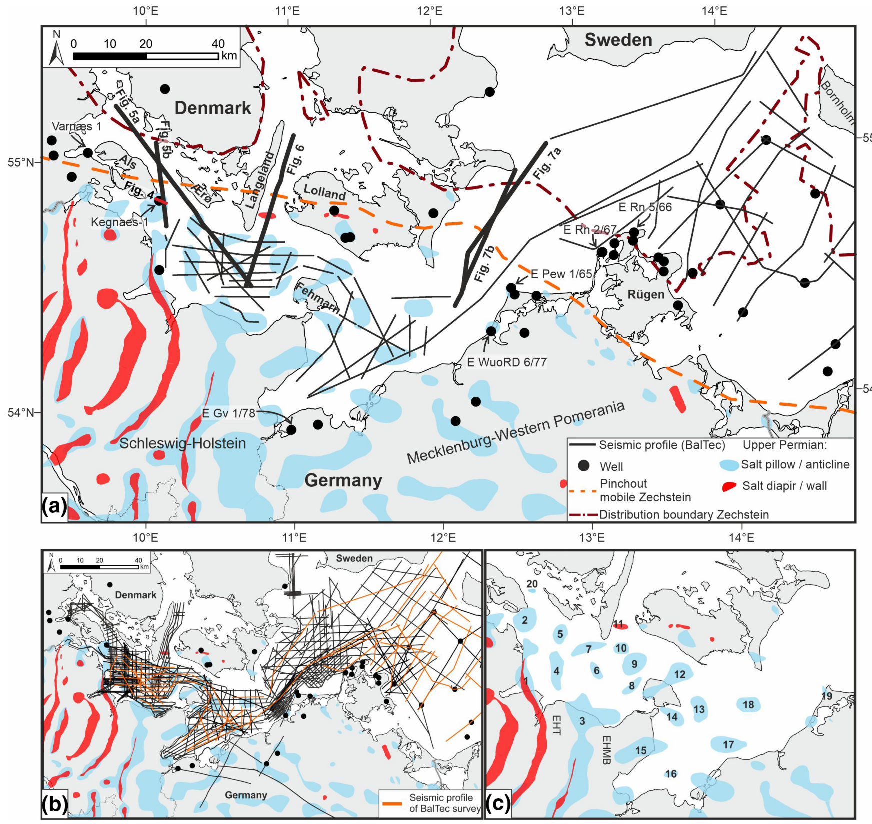


FIGURE 3 Seismic and well database (modified after Ahlrichs et al., 2021). (a) Seismic profiles of the BalTec survey and locations of presented profiles together with wells in the study area. Key wells for the stratigraphic correlations are labelled. Distribution boundary of the Zechstein unit and pinch out of mobile Zechstein units (low halite content does not allow salt movement) simplified after (Katzung, 2004; Peryt et al., 2010; Seidel, 2019). (b) Complete database with all available seismic profiles and wells used for mapping. (c) Names of salt structures (after Reinhold et al., 2008; Vejbæk, 1997): 1: Waabs; 2: Bredgrund; 3: Plön; 4: Kieler Bucht; 5: Schleimünde; 6: Langeland Süd; 7: Langeland; 8: Flüggesand; 9: Vinsgrav; 10: Langeland Ost; 11: Kegnaes; 12: Fehmarn; 13: Staberhuk Ost; 14: Fehmarnsund Ost; 15: Cismar; 16: Boltenhagen Nord; 17: Trollegrund Nord; 18: Neobaltic; 19: Prerow and 20: Als Øst (discovered in this study).

Contemporaneously, the Zechstein salt started moving within the EHMB (Hansen et al., 2005, 2007; Hübscher et al., 2010). At the north-eastern basin margin, Late Triassic transtension caused the development of the Western Pomeranian Fault System (WPFS) by reactivation of pre-existing NW–SE-oriented Palaeozoic faults (Krauss & Mayer, 2004; Seidel et al., 2018). Contemporaneously to the faulting in the WPFS, salt movement started in the Bay of Mecklenburg (Ahlrichs et al., 2020). A major erosional unconformity, termed the Early Cimmerian Unconformity, characterizes the Keuper succession in the study area (Beutler & Schüler, 1978). The unconformity is especially prominent around Rügen Island, where in some areas, the entire lower Keuper deposits are missing (Beutler & Schüler, 1978). From Middle Jurassic times until the Albian, the North Sea Doming event caused uplift and a phase of non-deposition during which widespread erosion removed much of the Jurassic and partly Upper Triassic deposits in the study area (Figure 2) (Hübscher et al., 2010; Japsen et al., 2007; Underhill & Partington, 1993; Ziegler, 1990b). Jurassic deposits are almost exclusively preserved in peripheral sinks of salt structures and are mostly of Early Jurassic age (Baldschuhn et al., 2001; Hansen et al., 2005; Hoth et al., 1993; Hübscher et al., 2010; Zöllner et al., 2008). Assuming a locally similar degree of erosion, the correlation of thicker remnants of Jurassic deposits with the peripheral sinks could suggest ongoing salt movement during the Early Jurassic (Ahlrichs et al., 2020; Hansen et al., 2005). Sedimentation resumed in the Albian (Figure 2). The Cenomanian-to-Turonian succession was deposited in a period of relative tectonic quiescence (Vejbaek et al., 2010). In the late Turonian to Santonian, a major plate reorganization and the onset of the Africa–Iberia–Europe convergence subjected the study area to compressional stress leading to inversion at the northern NGB margin (Figure 2) (Kley & Voigt, 2008). Resulting horizontal shortening caused uplift, erosion and fault reactivation and contemporaneous minor salt movement (Ahlrichs et al., 2020; Al Hseinat & Hübscher, 2017; Hübscher et al., 2010). Following a phase of tectonic quiescence, salt movement restarted during the late Eocene to Oligocene in the Glückstadt Graben and likely also in the rest of the study area (Ahlrichs et al., 2021). In Miocene times, regional uplift led to erosion of much of the Miocene, Oligocene and partly upper Eocene deposits (Hinsch, 1987; Japsen et al., 2015; Rasmussen, 2009). Quaternary glaciation eroded further Neogene and Palaeogene sediments (e.g. Sirocko et al., 2008).

3 | DATABASE AND METHODS

3.1 | Seismic database

The seismic database consists of high-resolution 2D seismic reflection data with a total profile length of more than 10,000 km acquired during multiple surveys (Figure 3). The database includes seismic profiles of the BaltSeis and NeoBaltic projects (Hübscher et al., 2004, see Al Hseinat & Hübscher, 2017, for a detailed description), reprocessed profiles of the Petrobaltic database (Rempel, 1992; Schlüter et al., 1997), profiles of the DEKORP-BASIN'96 survey (DEKORP-BASIN Research Group, 1999) and four industry profiles. The more local surveys were connected by the BalTec data (Hübscher et al., 2016), a regional network of high-resolution 2D seismic data imaging the subsurface continuously from the Zechstein salt base up to the seafloor (see Ahlrichs et al., 2020, for a more detailed description).

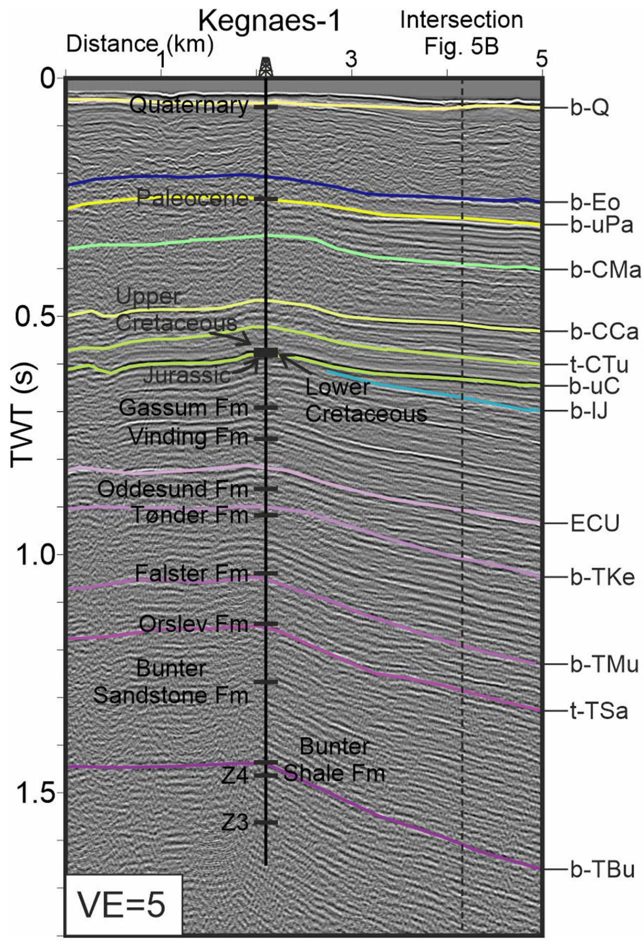


FIGURE 4 Well-to-seismic tie for the Kegnaeas-1 well. Markers show the base of the units (Nielsen & Japsen, 1991). For location, see Figure 3. See Figure 2 for reflector abbreviations and juxtaposition of German and Danish lithostratigraphic units. Fm, formation; VE, vertical exaggeration.

3.2 | Stratigraphy

Stratigraphic interpretation is based on the stratigraphic framework described by previous studies within the *StrucFlow* project (Ahlrichs et al., 2020, 2021). In this framework, 18 seismic horizons were identified: *base Quaternary Unconformity, base Miocene, base Oligocene, base upper Eocene, base Eocene, base upper Palaeocene, base Maastrichtian, base Campanian, top Turonian, base Upper Cretaceous, base Cretaceous, base lower Jurassic, Early Cimmerian Unconformity, base Keuper, base Muschelkalk, top Salinarröt, base Buntsandstein* and *base Zechstein* (Figure 2). Here, we focus on the Permian-to-Jurassic horizons to shed light on the impact of extensional tectonics on salt movement during the early stages of basin development. In combination with Ahlrichs et al. (2021), who focused on the Cretaceous–Cenozoic, this analysis complements the investigation of post-Permian salt movement in the Baltic sector of the NGB. The calibration of the seismic data with well information from deep research and hydrocarbon exploration wells was set up for the Bay of Mecklenburg and the area west of Rügen Island (Hoth et al., 1993; Nielsen & Japsen, 1991; Schlüter et al., 1997). Here, Ahlrichs et al. (2020) presented the most recent and comprehensive description of seismic–well ties for nearby onshore wells. We traced these horizons across the study area using all available seismic data (Figure 3). Additional control on the well-to-seismic tie was provided by the Kegnaes-1 well in the Bay of Kiel and Danish wells west of the Island of Als (Figures 3 and 4) (Nielsen & Japsen, 1991). We linked the stratigraphic interpretation to previous onshore and offshore studies in the area (Al Hseinat et al., 2016; Baldschuhn et al., 2001; Clausen & Pedersen, 1999; Deutschmann et al., 2018; Hansen et al., 2005, 2007; Hübscher et al., 2010; Maystrenko et al., 2005a, 2005b; Michelsen, 1978; Zöllner et al., 2008).

3.3 | Mapping

The mapping procedure uses all available picks for each horizon to create two-way travel time (TWT) structure maps by minimum curvature spline interpolation with a grid cell size of 300 × 300 m. Only faults, which could be traced across multiple seismic profiles, have been included in the maps. For time–depth conversion, a precise velocity model covering the entire study area is necessary. This is a challenging aspect of future work as velocity information is sparsely distributed due to the lack of offshore wells and seismic depth data. To give an idea of the depth range imaged by the presented seismic profiles, the right profile axis shows an approximated depth calculated using a constant velocity of 3 km/s. This velocity represents the average velocity of the subsurface in the study area based on published velocity information (Schnabel et al., 2021, see their table 1). We estimated the thickness of each mapped unit by calculating isochron maps (vertical thickness in TWT) (see Figure 2 for age constrains). Thickness was converted from TWT to metre by using a constant velocity selected for each unit based on previous studies (Hansen et al., 2007; Schlüter et al., 1997; Schnabel et al., 2021).

3.4 | Identification of salt movement

We analyse seismic profiles and isochron maps to identify local and regional thickness variations in the Triassic–Jurassic units. Regional and local thickness variations are interpreted as an expression of differential sedimentation and erosion caused by vertical tectonic movements, differential compaction and sedimentation processes (Bertram & Milton, 1989). During synkinematic sedimentation, the timing of the growth of a salt structure can be deduced from the surrounding sediments by analysing the geometric relationship between overburden strata and the salt structure (e.g. Jackson & Hudec, 2017). Over geological time scales, salt can flow like a viscous fluid if the salt body experiences differential loading by, e.g. a varying gravitational load (e.g. by differential sedimentation) or displacement loading (e.g. by extension or shortening) (Jackson & Hudec, 2017). When salt flows from the surrounding area into the salt structure, the top of salt subsides in the area of withdrawal, which creates additional accommodation space for more sediments. These processes lead to increased thickness of the synkinematic unit if compared to adjacent areas without salt movement (e.g. Jackson & Hudec, 2017). Likewise, the accumulation of salt decreases accommodation space resulting in a thinner synkinematic unit above the salt structure. When the regional sedimentation rate exceeds the rate of rise of the salt structure, the locally thickened synkinematic strata in the peripheral sink (sensu Jackson & Hudec, 2017) are characterized by converging and diverging layering (Sørensen, 1986). In the case of a regional sedimentation rate smaller than the rise rate of the salt, angular unconformities between the layering of the peripheral sink and the prekinematic overburden develop (Sørensen, 1986). Therefore, we interpret local thickness variations across salt structures, characterized by thinning of the overburden towards the crest and thickening of the overburden above the flanks of a salt structure (peripheral sink) as evidence for syndepositional salt movement and salt structure growth. This includes a converging and diverging reflector pattern respectively. Accordingly, locally uniform thickness across salt structures indicates the absence of salt movement.

4 | OBSERVATIONS

We use key seismic profiles, time-structure and isochron maps of the Zechstein, Triassic and Jurassic units to analyse the basin configuration, regional depositional patterns and local thickness variations in order to identify active phases of salt movement during the Triassic–Jurassic.

4.1 | North-western basin configuration

In the north-western part of the study area, two profiles, which run from the basin margin southwards into the Bay of Kiel, image numerous salt pillows (Figure 5) (Reinhold et al., 2008; Vejbæk, 1997). Faults pierce the base Zechstein at the basin margin (Figure 5a, profile km 13). South of the island of Ærø (Figure 3), a prominent fault, offsets the base Zechstein by ca. 300 ms TWT (Figure 5a, profile km 50). Between the islands of Als and Ærø, the profiles show a previously undescribed salt structure, here named 'Als Øst', which is characterized by numerous faults in the Triassic–Jurassic overburden (Figure 5a,b). Thickness of the Buntsandstein and Muschelkalk units gradually increases towards the south and basin centre, without any distinct local thickness variations, and thus, no signs of active salt movement (Figure 5a,b).

The Keuper II unit is thin but uniform in thickness in the northern part of the profiles (Figure 5). At the SE flank of the Als Øst salt pillow, this unit is characterized by increased thickness, which indicates the onset of salt movement (Figure 5a). Towards the south-east, the ECU reflector erosionally truncates the Keuper II unit (Figure 5a, profile km 50–55). Across the salt pillows 'Schleimünde' and 'Langeland', the Keuper II unit shows varying thickness by thinning towards the crest of the structures indicating the initiation of salt structure growth during deposition of the Keuper II (Figure 5a). In the hanging wall of the listric fault north of the Als Øst salt pillow (F1 in Figure 5b), the Keuper II unit shows thickness variations. Additionally, the Keuper II unit has increased thickness at the southern flank of

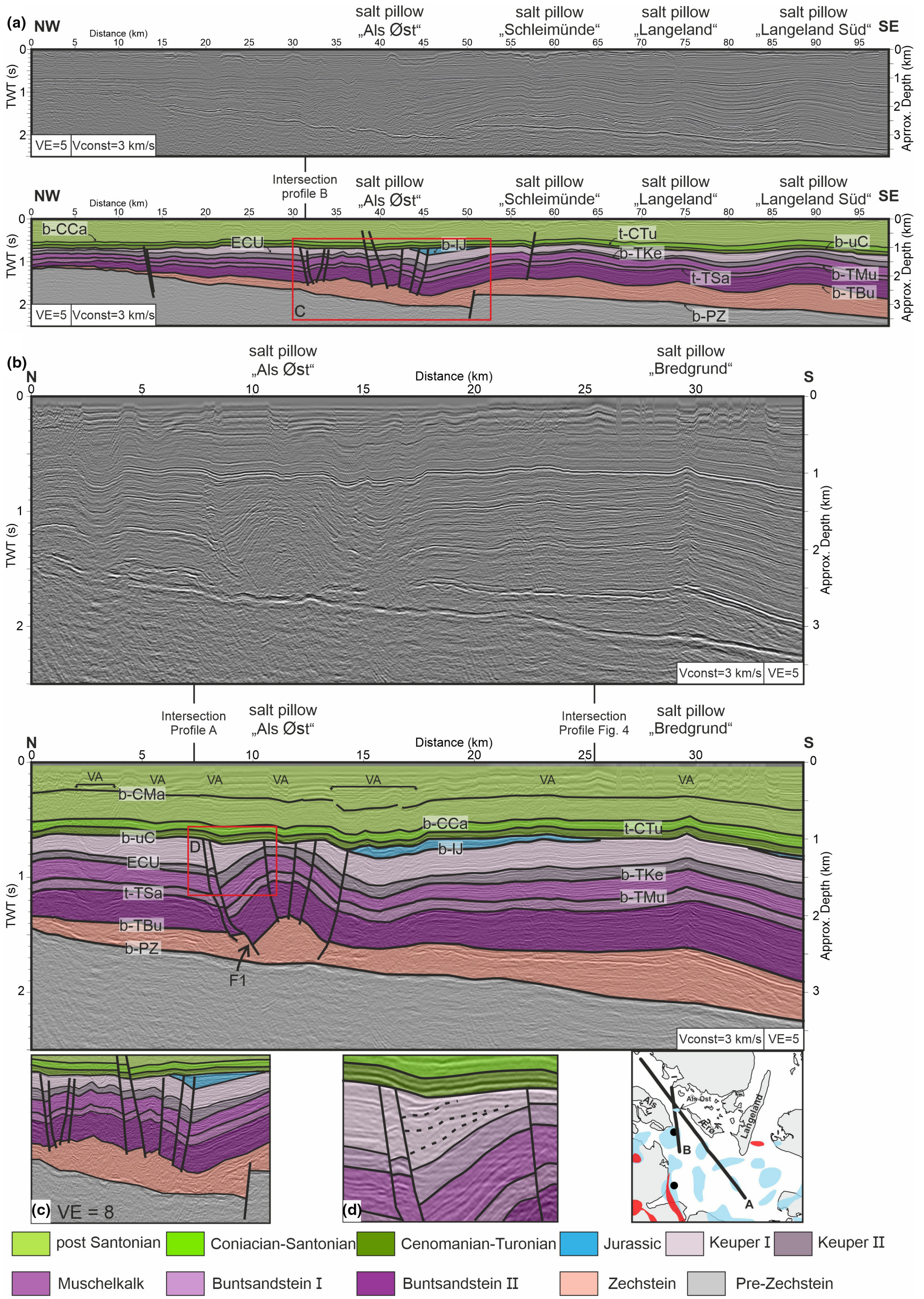

(a)
NW
SE
salt pillow „Als Øst“
salt pillow „Schleimünde“
salt pillow „Langeland“
salt pillow „Langeland Süd“
Distance (km)
TWT (s)
Aprrox. Depth (km)
VE=5
Vconst=3 km/s
Intersection profile B
b-CCa
ECU
b-IJ
t-CTu
b-TKe
b-uC
t-TSa
b-TMu
b-TBu
b-PZ
C
(b)
N
S
salt pillow „Als Øst“
salt pillow „Bredgrund“
Distance (km)
Approx. Depth (km)
Vconst=3 km/s
VE=5
Intersection Profile A
Intersection Profile Fig. 4
VA
b-CMa
b-CCa
t-CTu
b-uC
b-IJ
D
ECU
b-TKe
b-TMu
t-TSa
b-TBu
b-PZ
F1
(c) VE = 8
(d)
Als Øst
Als
Ærø
Langeland
B
A
post Santonian
Coniacian-Santonian
Cenomanian-Turonian
Jurassic
Keuper I
Keuper II
Muschelkalk
Buntsandstein I
Buntsandstein II
Zechstein
Pre-Zechstein

FIGURE 5 Time-migrated profiles a and b, located at the north-western basin margin (see Figure 3). An approximated depth is shown at the right axis of the profile (calculated using a constant velocity of 3 km/s). (c) Enlargement of the Als Øst salt pillow. (d) Enlargement of the Keuper I at the northern flank of the Als Øst salt pillow; note the divergent reflector pattern denoted by the dashed lines. VA, velocity artefact; VE, vertical exaggeration.

the structure and slightly thins towards the crest of the Als Øst salt pillow, which would suggest salt movement (Figure 5b).

Throughout most of the profile, the Keuper I unit is capped at the top by the Mid-Jurassic Unconformity, expressed by the b-uC reflector (Figure 5). At the northern flank of the Als Øst salt pillow, the reflection pattern of the Keuper I unit is divergent towards the listric fault (F1 in Figure 5b, close up in Figure 5c; note divergence between dashed lines and onlap). This suggests syndepositional faulting and salt movement during the deposition of the Keuper I unit. Jurassic deposits are only preserved in the peripheral sinks at the southern flank of the Als Øst salt pillow (Figure 5).

4.2 | Northern basin configuration and the Kegnaes diapir

In the central part of the study area, a N–S-striking profile runs from the basin margin into the Bay of Kiel imaging the salt diapir 'Kegnaes' (Figure 6) (Vejbæk, 1997). The width of the diapir is ca. 1 km at its top and 3 km at its root. The narrow stem suggests that the diapir was mildly squeezed. In the southern part of the profile, ca. 1.5-km-wide zone with highly disturbed reflection pattern and uncertain stratigraphy is visible (Figure 6a, profile km 8). North of the Kegnaes Diapir (KD), the Triassic overburden above the strongly reduced Zechstein salt shows increased thickness and is intensely faulted (Figure 6a,b). Beneath, two basement step faults pierce the base Zechstein. While the northern fault does not propagate further into the suprasalt overburden, the southern fault dissects the Zechstein and Triassic successions.

Overall, the Buntsandstein unit shows a general trend of gradually increasing thickness towards the south-directed basin centre. The exception to this trend is a zone, where the Buntsandstein locally thins towards the south until reaching the northwards dipping fault F2 (Figure 6a,b, profile km 23–28). Noteworthy, this zone is located about a kilometre north and above the footwall of the basement step faults (Figure 6a,b). Above the northern flank of the diapir, the Buntsandstein unit within the hanging wall of the F3-labelled fault shows divergent reflectors towards the fault (Figure 6c), which indicate an early phase of faulting. Towards the diapir, the Buntsandstein slightly thins suggesting salt movement coeval to the faulting (Figure 6b,c). The Muschelkalk concordantly overlies the Buntsandstein and shows relatively constant thickness across the profile (Figure 6a). The Keuper II unit has a relative uniform thickness in the northern part of the profile. Between profile km 23 and 28, the Keuper II unit dips towards the south and gradually thins. In this area, multiple conflicting dips cross the Keuper unit. These conflicting dips are probably caused by out-of-plane reflections originating from the sides of the 2D profile (see, e.g. Drummon et al., 2004). In the fault zone north of the diapir, the Keuper II unit has increased thickness (Figure 6b). This zone represents the primary peripheral sink and indicates salt movement and normal faulting (Figure 6b). At both flanks of the diapir, the Keuper II toplaps against the ECU reflector. Salt movement and faulting continued during deposition of the Keuper I indicated by increased thickness within the faulted zone and at the southern flank of the diapir (Figure 6b). Right there, Jurassic deposits were preserved from erosion. The Cenomanian–Turonian and Coniacian–Santonian units overlie the Triassic–Jurassic deposits without visible thickness variations. (Figure 6a,b). At the flanks, these units are slightly folded and terminated against the diapir. The Cretaceous directly above the crest of the diapir is unclear as the seismic image does not resolve the shallow strata in the uppermost part of the profile (Figure 6b).

4.3 | North-eastern basin configuration

In the north-eastern part of the study area, two profiles image the basin margin and the pinch out of the Zechstein unit (Figure 7). In the north-eastern part of the profiles, multiple basement faults pierce the southwards dipping base Zechstein (Agricola Fault System, Figure 7). The Falster Fault in Figure 7a only pierces the Mesozoic overburden, while in the profile located further east, the fault reaches into the pre-Zechstein (Figure 7b). In the south-western part, faults of the Werre Fault Zone (Werre FZ) only pierce the Mesozoic overburden (Figure 7). The Buntsandstein and Muschelkalk units gradually increase in thickness towards the basin centre further south without local thickness variations, and thus, no signs of syndepositional faulting.

The Keuper II unit in the hanging wall of the Falster Fault has increased thickness, which suggests initial syndepositional faulting (Figure 7). The north-eastern border fault of the WFZ is SW-dipping slightly listric fault where

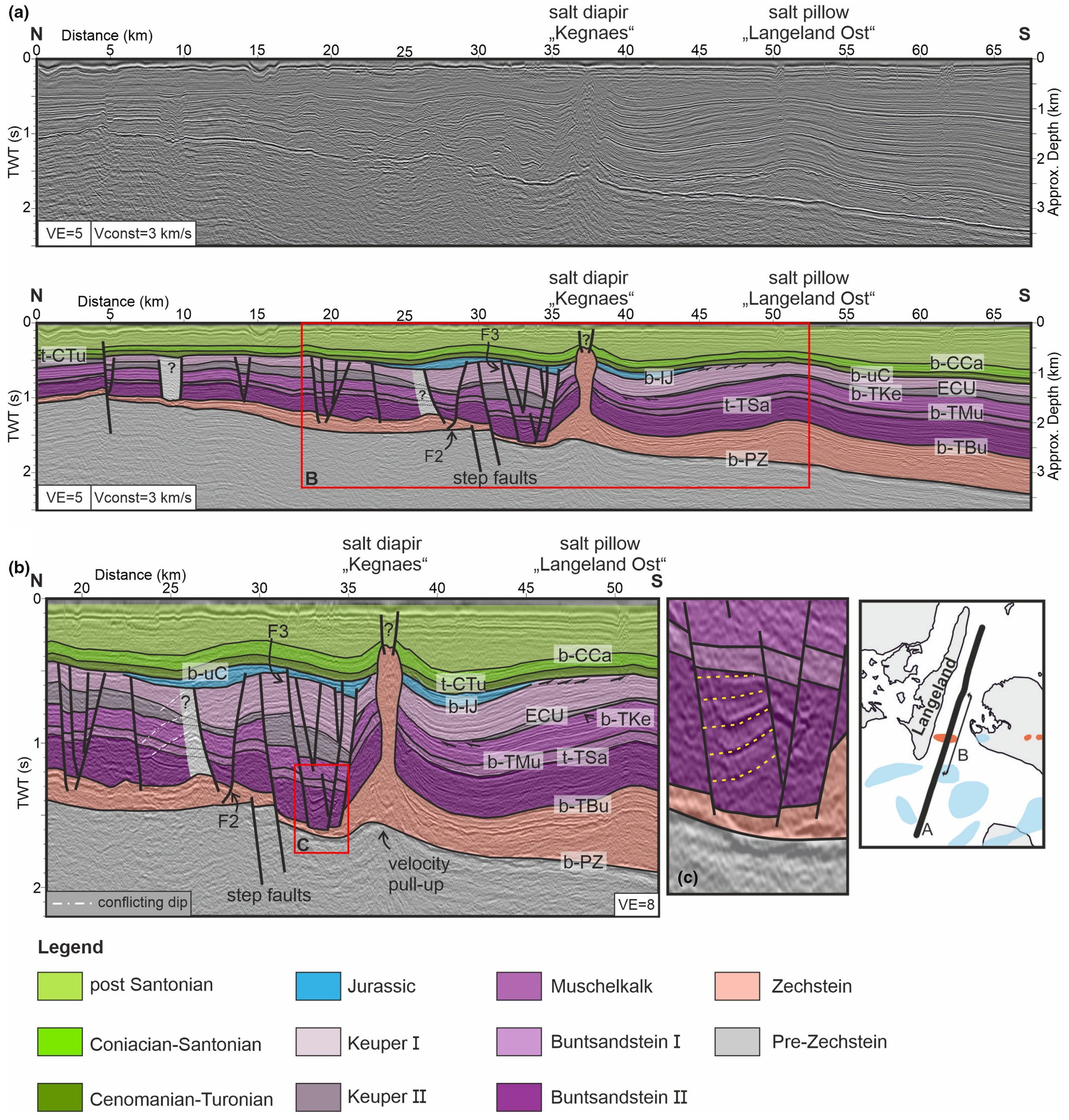


FIGURE 6 Time-migrated profile crossing the northern basin margin (see Figure 3). An approximated depth is shown at the right axis of the profile (calculated using a constant velocity of 3 km/s). Stratigraphy in the light grey areas marked with '?' (ca. profile km 58 and 25) is unknown due to highly disturbed reflection patterns. Exact extend of the roof and cover of the diapir are unsure. Salt structures are marked on top of the section. Reflectors labelled as in Figure 2. (b) Enlargement as shown in a (with higher vertical exaggeration). Note the erosional termination of the Keuper II unit at the flanks of the diapir. (c) Enlargement of b showing divergent reflections within the Buntsandstein north of the Kegnaes Diapir. VE, vertical exaggeration.

the Keuper II unit shows increasing thickness towards the fault (Figure 7b). In between the WFZ and Agricola Fault System (Agricola FS), the thickness of the Keuper I unit is approximately doubled, which suggests increased subsidence in this area (Figure 7). Increased thickness of the Keuper I unit in the hanging wall of the Falster Fault suggests ongoing normal faulting (Figure 7b). The Keuper I unit within the WFZ shows increased thickness compared to south-west of the Werre Fault, however, the unit shows an almost horizontal orientation (Figure 7b).

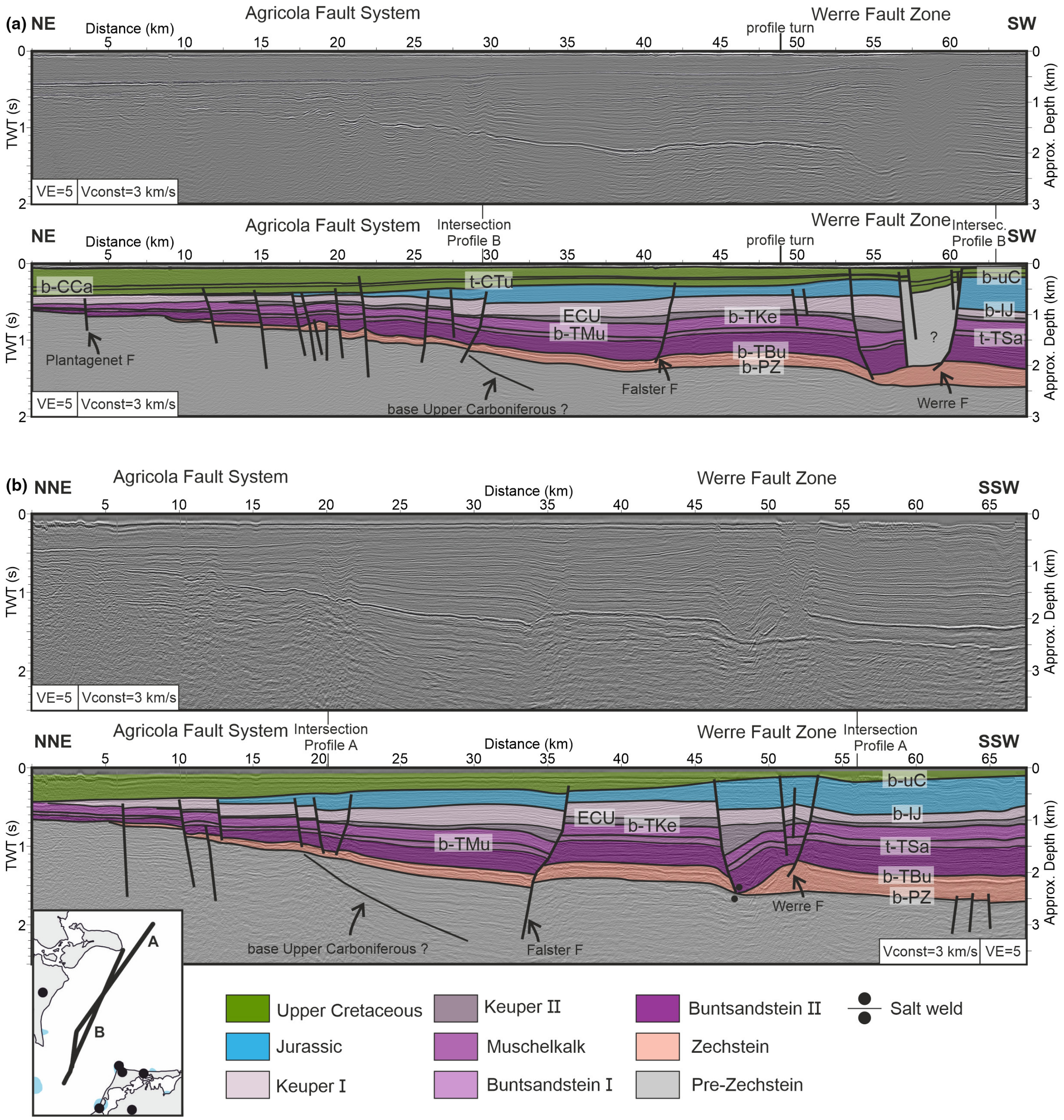


FIGURE 7 Time-migrated profiles a (BGR16-221) and b imaging the north-eastern basin margin. See Figure 3 for location. Fault systems are marked at the top of the sections. An approximated depth is shown at the right axis of the profile (calculated using a constant velocity of 3 km/s). Note the profile turn and thus different profile orientation of a and b and resulting different appearance of structures, especially of the Werre Fault Zone. F, fault; VE, vertical exaggeration. Reflectors labelled as in Figure 2. See Ahlrichs et al. (2020) for an additional profile imaging of this area.

4.4 | Mapping of stratigraphic units

4.4.1 | Zechstein

The base Zechstein shallows from 2900 ms TWT, representing the central part of the basin, towards its pinch out at the north-eastern basin margin at ca. 500 ms TWT (Figure 8a). West of Rügen Island, the NE–SW trend is locally interrupted by ca. 20-km-wide depression (Figure 8a). Across the basin margin, multiple faults pierce the base Zechstein (Figure 8a, faults marked with AFS, PF, WF, PaF and AVF and faults near the islands

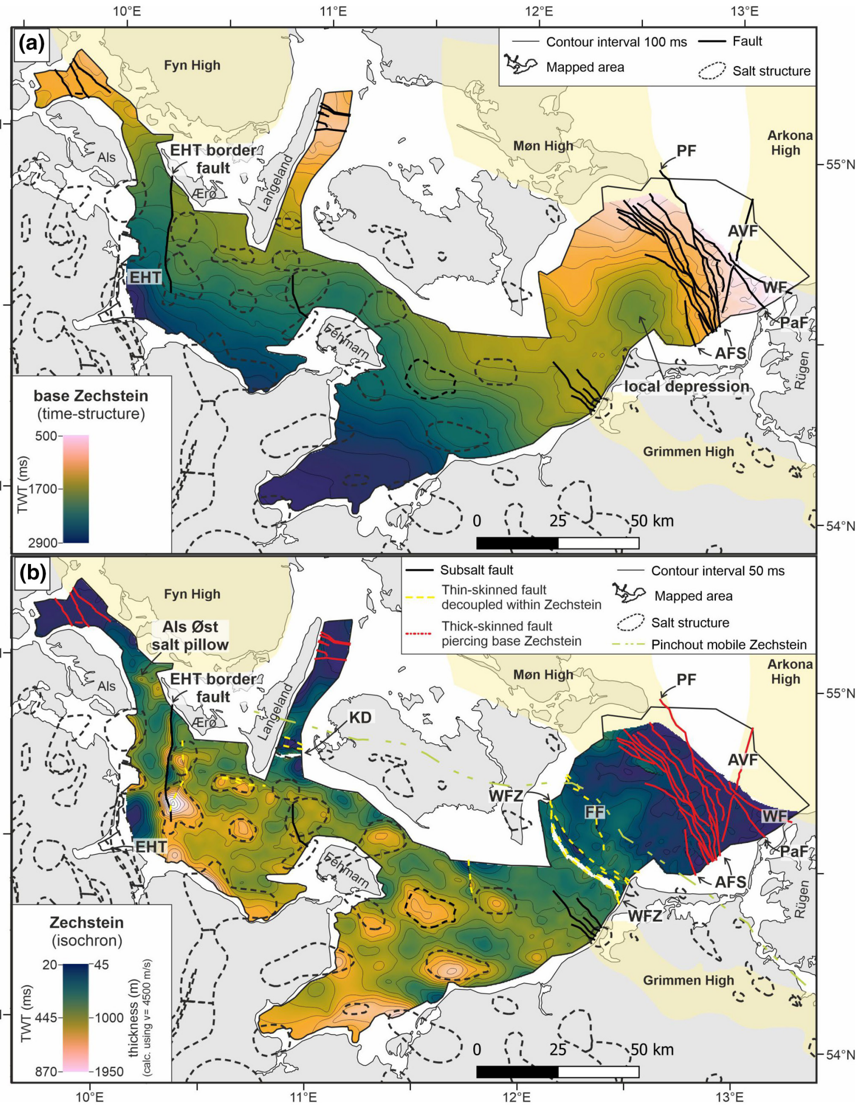


FIGURE 8 Zechstein. (a) Base Zechstein time-structure map in TWT. (b) Zechstein isochron map in TWT. AFS, Agricola Fault System; AVF, Agricola–Svedala Fault; EHT, Eastholstein Trough; FF, Falster Fault; KD, Kegnaes Diapir; PaF, Parchim Fault; PF, Plantagenet Fault; WF, Wiek Fault; WFZ, Werre Fault Zone.

of Langeland and Als). Additional faults with partly small offsets are visible north-west of Grimmen High and north-west of Fehmarn Island. In the western Bay of Kiel, a prominent fault showing a large offset of the base Zechstein (as imaged by Figure 5a) strikes N–S, parallel to the salt structures Schönberg–Kieler Bucht (Figure 8a). This fault marks the eastern border of the EHT. Thickness of the Zechstein unit correlates well with the known locations of salt structures (Figures 1 and 8b). Mapping reveals a new small salt pillow named 'Als Øst' (Figure 5 and 8b).

4.4.2 | Buntsandstein and Muschelkalk

The base Buntsandstein and base Muschelkalk time-structure maps show the general N–S to NE–SW trend from the shallow margin towards the deeper basin locally modified by the presence of Zechstein salt structures (Figures 9a and 10a). Thickness of the Buntsandstein and Muschelkalk units gradually increases towards the basin centre due to the higher degree of subsidence away from the basin margins (Figures 9b and 10b). Thickness variations are close to seismic resolution (ca. 50 ms TWT, ca. 75 m, 3 km/s) and do not correlate with the salt structures. Between the Werre FZ and Agricola FS, the isochron map of the Buntsandstein unit reveals a zone of locally increased thickness (Figure 9b). In the Muschelkalk, this zone is not visible (Figure 10b).

4.4.3 | Keuper

The base Keuper time-structure map shows a similar pattern as the base Muschelkalk (Figure 11a). The isochron map of the Keuper II unit reveals the general thickening trend towards the south (Figure 11b). At the north-eastern basin margin, south of the Island of Ærø and south of the KD, the Keuper II unit is eroded (Figure 11a,b). Further modifications to the general thickness trend are visible between the Werre FZ and Agricola FS, where the

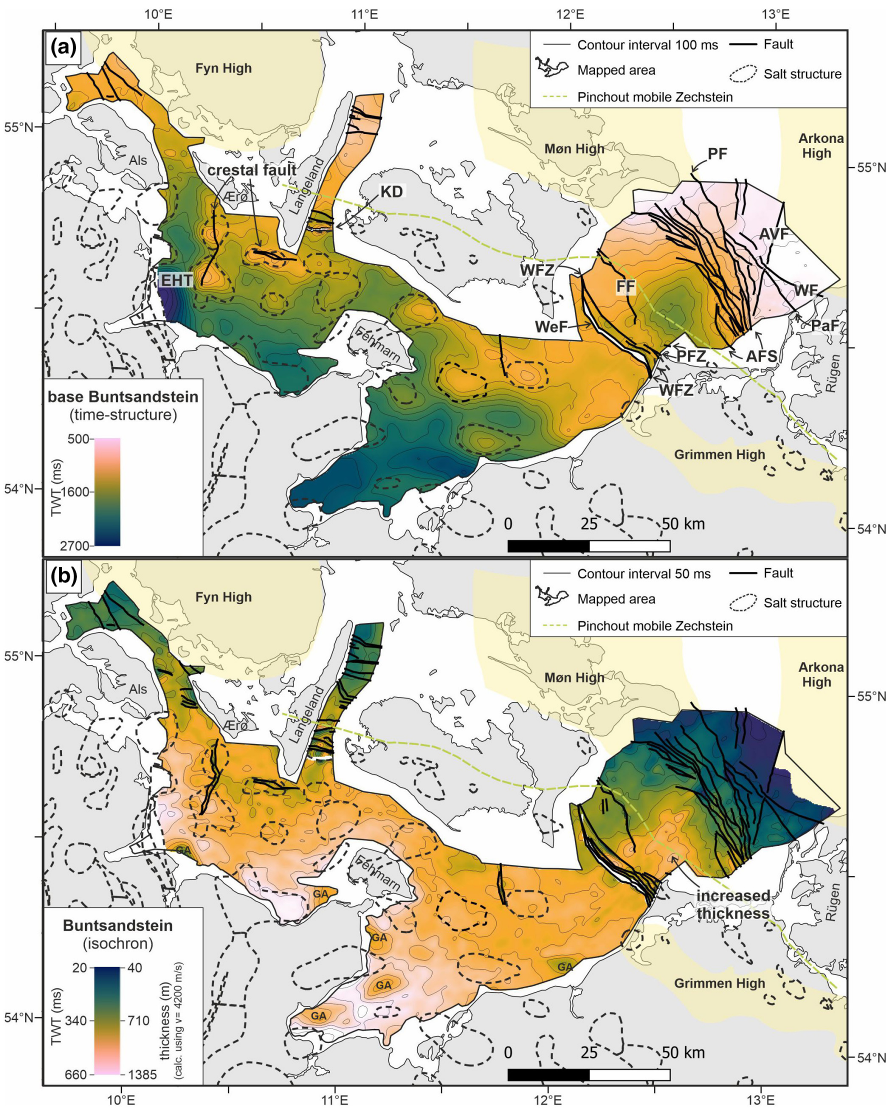


FIGURE 9 Buntsandstein. (a) Base Buntsandstein (top Zechstein) time-structure map in TWT. (b) Buntsandstein isochron map in TWT. AFS, Agricola Fault System; AVF, Agricola–Svedala Fault; EHT, Eastholstein Trough; FF, Falster Fault; KD, Kegnaes Diapir; PaF, Parchim Fault; PF, Plantagenet Fault; PFZ, Prerow Fault Zone; WF, Wiek Fault; WeF, Werre Fault; WFZ, Werre Fault Zone. GA: Gridding artefact caused by either lack of seismic data in the area or velocity artefacts by, e.g. shallow gas.

thickness of the Keuper II is locally more than doubled (Figure 11b, PD: Prerow Depression). The graben within the Werre FZ shows increased infill with Keuper II sediments (Figure 11b). Furthermore, the Keuper II isochron map shows local thickness variations across salt structures such as the thinned crest of the Fehmarn salt pillow and the development of the northern peripheral sink of the KD, which is also intensely faulted (Figure 11b). In the EHT, thickness of the Keuper II is increased. In the Bay of Mecklenburg, the Keuper II isochron map shows a zone of locally increased thickness at the southern border of the gridded area expanding across the crest of the Trollegrund Nord salt pillow, which is unexpected in terms of salt movement. Due to the connection to the edge of the mapped area, this zone possibly represents a gridding artefact.

In many parts of the study area, the Keuper I is affected by erosion related to the Mid-Jurassic Doming. Thus, when interpreting thickness variations in the Keuper I, one needs to consider that in areas where the Jurassic is missing, the top of the Keuper I unit is eroded and the present thickness represents the thickness preserved from erosion (Figure 12b, white line and Figure 13). Between the Werre FZ and Agricola FS, thickness of the Keuper I is increased (Figure 12b). Compared to the Keuper II unit, the zone of increased thickness widened and the local depocentre shifted north-west (compare area marked with PD in Figures 11b and 12b). North-west of Grimmen High, the Keuper I is thinned and shows a local E–W trend (Figure 12b). North-east of the salt pillow 'Trollegrund Nord' in the Bay of Mecklenburg, north of the KD, and in the EHT, thickness of the Keuper I is locally increased (Figure 12b).

4.4.4 | Jurassic

The base Jurassic time-structure map shows the strongly disrupted character of the unit (Figure 13a). Maximum thickness is visible in the Prerow Depression (Figure 13b). Compared to the Keuper I unit, this zone of increased thickness further widened and includes the area south-west of the

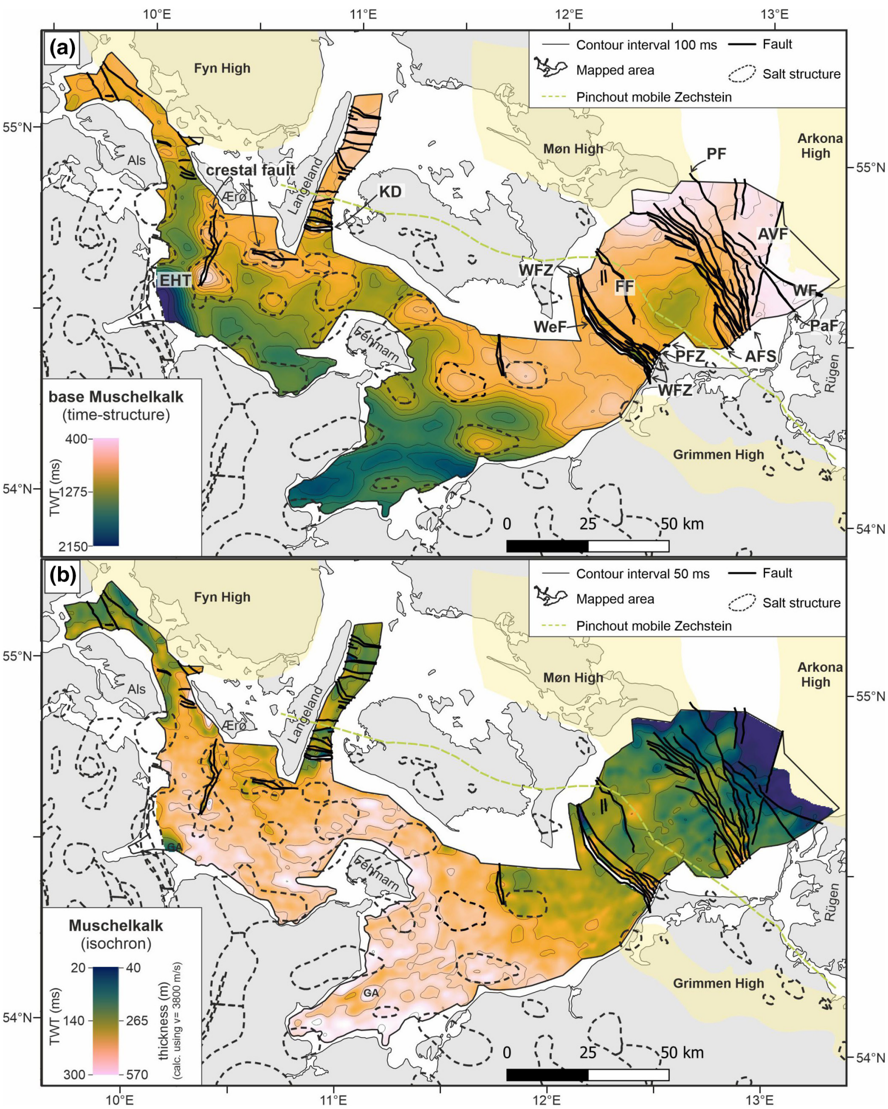


FIGURE 10 Muschelkalk. (a) base Muschelkalk time-structure map in TWT. (b) Muschelkalk isochron map in TWT. See Figure 9 for abbreviations.

Werre FZ. In the Bay of Mecklenburg, the preserved Jurassic unit is thin and completely eroded above the crest of salt structures (Figure 13b). In the Bay of Kiel, almost the entire Jurassic unit is missing. Generally, the Jurassic unit is thin or reduced above the crest of salt structures while thicker Jurassic remnants are located above the flanks (Figure 13b).

5 | INTERPRETATION AND DISCUSSION

In the following, we will interpret and discuss our observations in the context of the existing literature covering the timing of salt movement and faulting.

5.1 | Comparison with previous work

The south-to-south-west dip of the base Zechstein, pinch out of the Zechstein unit at the north-eastern basin margin and location of salt structures within the study area (Figures 5–8) are in agreement with the overall known basin configuration (Peryt et al., 2010). The trend of increasing thickness of the Buntsandstein and Muschelkalk towards the south-directed basin centre (Figures 9 and 10) is in accordance with previous studies and explained by thermal subsidence from late Permian-to-Middle Triassic times (Baldschuhn et al., 2001; Hansen et al., 2005; Hübscher et al., 2010; Kossow & Krawczyk, 2002; Zöllner et al., 2008). Thereby, subsidence was highest in the basin centre leading to increased sedimentary infill with Buntsandstein and Muschelkalk deposits (Scheck & Bayer, 1999; Van Wees et al., 2000). Local modifications of this trend could result from differential compaction, sea level fluctuations and sedimentation processes, which might have caused, e.g. the visible thickness variations in the Buntsandstein in the central Bay of Mecklenburg or of the Muschelkalk north-west of Fehmarn Island (Figures 9 and 10) (Bertram & Milton, 1989).

The inferred Late Triassic erosion causing the ECU (Figures 11 and 12) is in accordance with previous studies

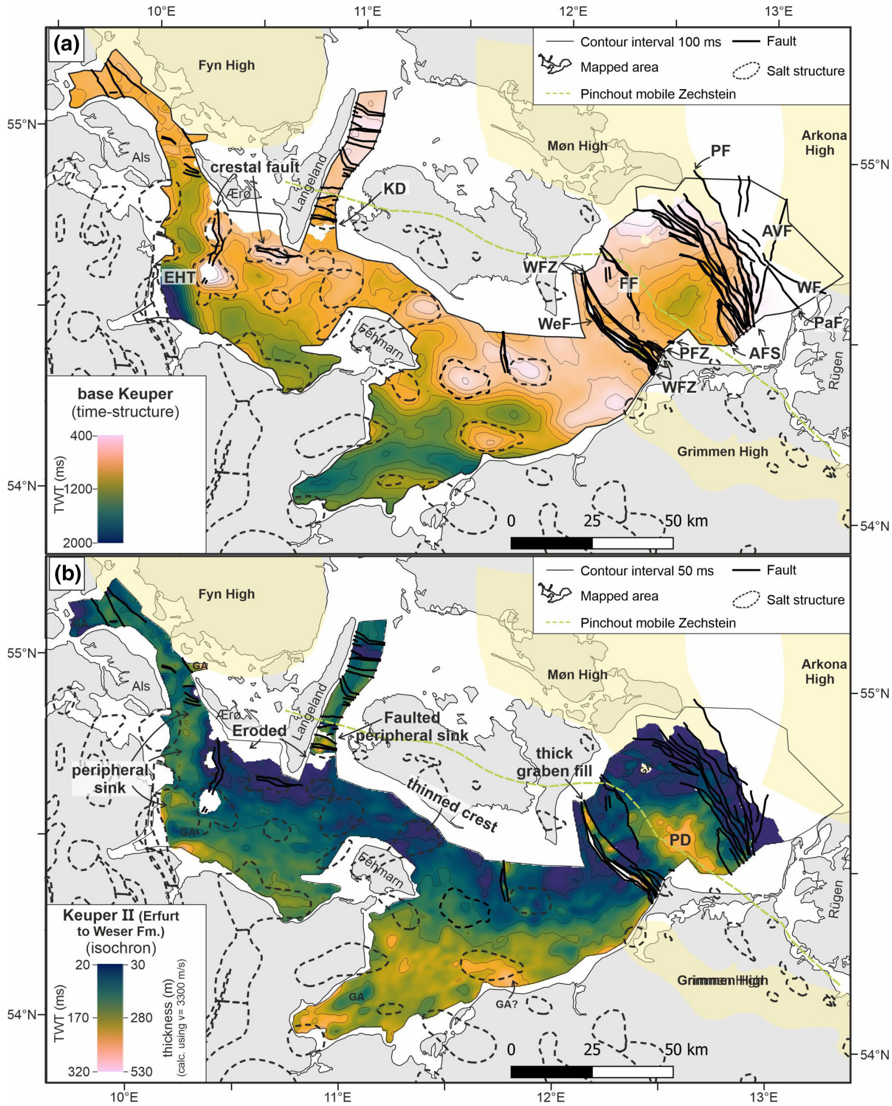


FIGURE 11 Keuper II. (a) base Keuper time-structure map in TWT. (b) Keuper II isochron map in TWT. Note the absence of Keuper II deposits adjacent to the islands of Ærø and Langeland and north-west of Rügen due to erosion causing the Early Cimmerian Unconformity (ECU). PD: Prerow Depression. See Figure 9 for further abbreviations.

(Bachmann et al., 2010; Beutler & Schüler, 1978). Adding to the existing maps (e.g. subcrop map of the ECU in Bachmann et al., 2010), we observe erosion of the entire lower and middle Keuper unit underlying the ECU south of Ærø island, west of Langeland and south of the KD (Figure 11). Hence, the area affected by Late Triassic erosion seems to stretch across the entire southern margin of the Ringkøbing-Fyn, Møn and Arkona highs, which fits the observations of Clausen and Pedersen (1999), based on onshore seismic profiles and well data.

This study provides an update to the published fault pattern and differentiates between subsalt and suprasalt faults (Figures 8–13). Northwest of the Grimmen High, we identified subsalt faults solely dissecting the pre-Zechstein, which likely form the offshore prolongation of faults visible in the TUNB model onshore Mecklenburg–Western Pomerania (TUNB Working Group, 2021). A bit further north-east, the Werre FZ marks a thin-skinned fault zone only affecting the Zechstein and suprasalt overburden. These faults show the decoupling effect of the Zechstein salt and accordingly, thickness of the Zechstein in this part of the basin and further south is sufficient to effectively decouple the suprasalt cover from the basement (e.g. Stewart et al., 1996; Withjack & Callaway, 2000). Furthermore, our mapping shows a prominent basement fault in the western Bay of Kiel, which we interpret as the eastern border fault of the EHT (Figures 5 and 8). The fault trace coincides with maps of Vejbæk (1997) and was imaged by Ahlrichs et al. (2021) (their Figure 5). The salt structures 'Kieler Bucht' and 'Schönberg' strike parallel to the fault and are located directly adjacent to it. The development of these salt structures is likely controlled by the underlying basement fault decoupled by the thick Zechstein salt (Stewart et al., 1996; Warren, 2008; Withjack & Callaway, 2000). This is in agreement with many salt structures, which are underlain by basement faults in other parts of the Glückstadt Graben (e.g. Baldschuhn et al., 2001; Maystrenko et al., 2005b).

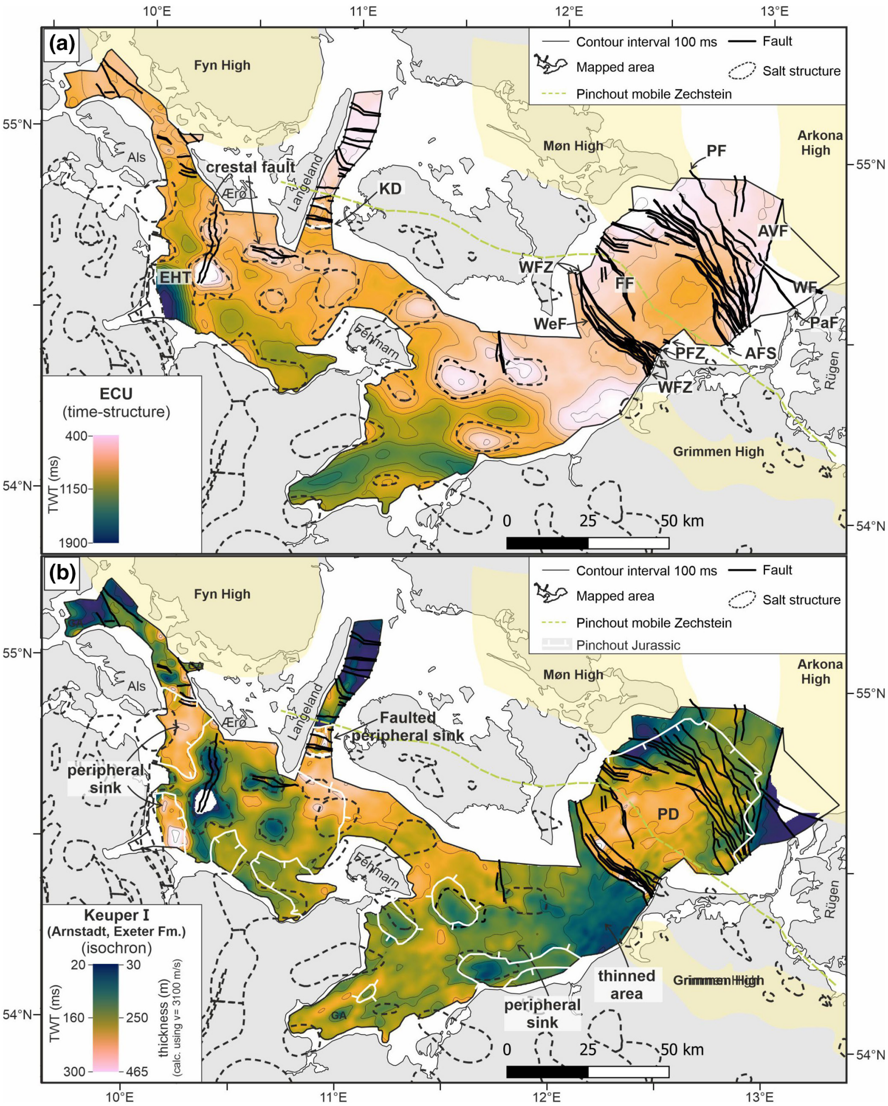


FIGURE 12 Keuper I. (a) Early Cimmerian Unconformity (ECU) time-structure map in TWT. (b) Keuper I isochron map in TWT. White line shows area of preserved Jurassic deposits, hence, where the Keuper I was spared from Mid-Jurassic erosion. PD: Prerow Depression; see Figure 9 for further abbreviations.

5.2 | Timing of salt movement

The triggering of salt movement in the Baltic sector of the North German Basin driven by extension during the Late Triassic is well established (Al Hseinat et al., 2016; Clausen & Pedersen, 1999; Hansen et al., 2005, 2007; Hübscher et al., 2010; Zöllner et al., 2008). Using a single seismic profile located in the Bay of Mecklenburg, Ahlrichs et al. (2020) established a refined stratigraphic subdivision of the Triassic, which revealed initial salt movement during deposition of the Keuper II unit. This study provides regional maps of the Buntsandstein, Muschelkalk, Keuper and Jurassic units with the refined stratigraphic subdivision established by Ahlrichs et al. (2020) to analyse the spatial character of salt movement in the Baltic sector of the North German Basin.

The Buntsandstein and Muschelkalk units do not show local thickness variations and thus, were deposited prior to the development of the salt structures (Figures 9 and 10). This pre-kinematic phase during the Early and Middle Triassic in the eastern Glückstadt Graben and EHMB agrees with previous onshore and offshore studies (Al Hseinat et al., 2016; Hansen et al., 2005; Hübscher et al., 2010; Maystrenko et al., 2005b; Warsitzka et al., 2016; Zöllner et al., 2008). Notably, the increasing thickness of the Buntsandstein and Muschelkalk units towards the basin centre, which represents a differential load acting on the Zechstein salt, did not trigger salt movement in the Baltic sector of the North German Basin. A possible explanation would be that the gradually increasing thickness of the Buntsandstein and Muschelkalk represents only subtle thickness variations for the scale of salt structures. Thus, forces driving salt flow by this kind of differential loading might not be sufficient to overcome resisting forces of salt flow (like boundary friction and strength of the overburden) (Hudec & Jackson, 2007; Warsitzka et al., 2013).

5.2.1 | Eastholstein Trough

Local thickness variations in the Keuper II unit indicate initial salt movement in the Eastholstein Trough

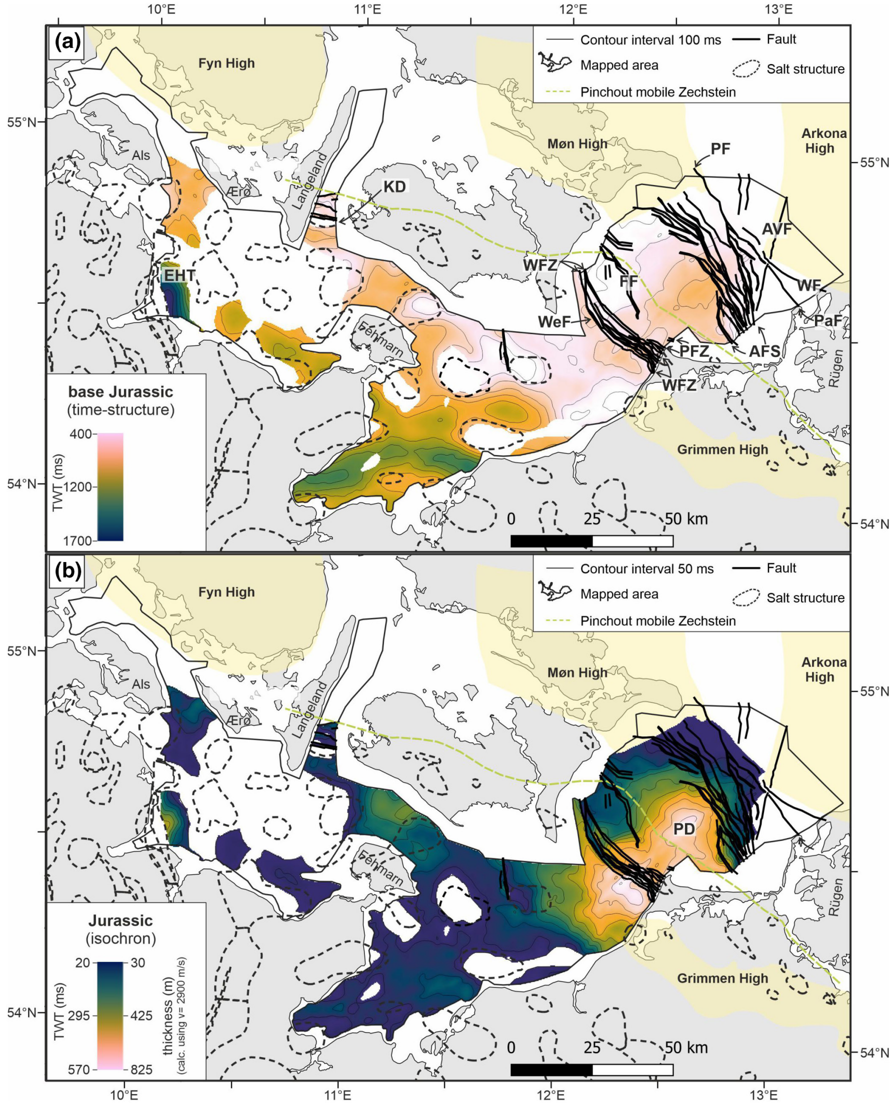


FIGURE 13 Jurassic. (a) Base Jurassic time-structure map in TWT. (b) Jurassic isochron map in TWT (calculated using the base Upper Cretaceous time-structure map of Ahlrichs et al., 2021). The entire Jurassic unit was affected by strong Mid-Jurassic erosion and thus, mapped thickness only represents preserved remnants. PD: Prerow Depression; see Figure 9 for further abbreviations.

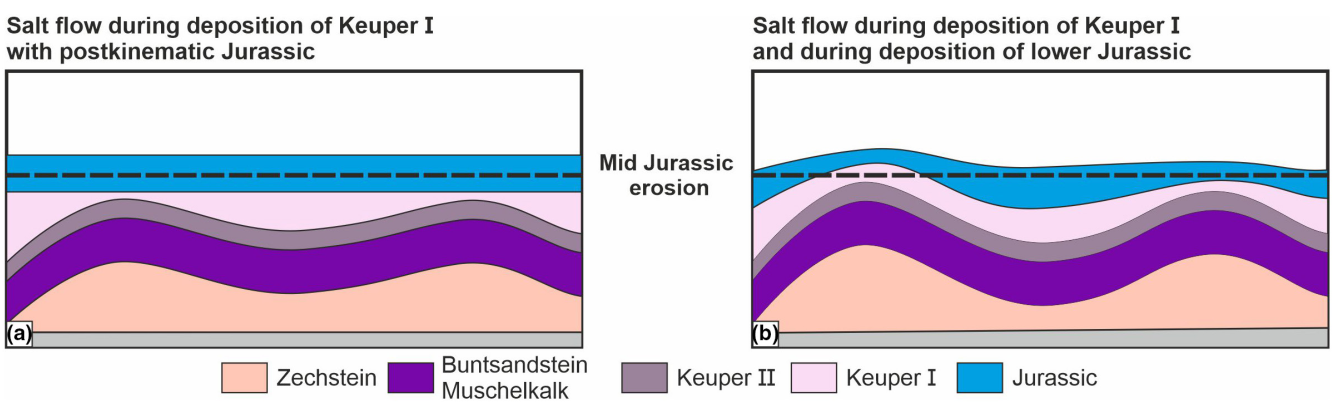


FIGURE 14 Conceptual model assuming high sedimentation rate and syndepositional salt flow during deposition of the Keuper I followed by post-kinematic deposition of the Lower Jurassic (a) and with ongoing salt movement in the Early Jurassic (b). Model is based on the assumption that a high sedimentation rate during deposition of the Keuper I exceeded salt rise and thus, the peripheral sinks are completely filled with Keuper sediments. Black dashed line represents erosional surface due to the Mid-Jurassic North Sea Doming event.

(EHT) (Figure 11). This is in agreement with previous studies covering the Glückstadt Graben and north-west Germany, where discrete pulses of extension and salt movement were observed in the early Late Triassic during deposition of the Grabfeld and Weser formations (Al Hseinat et al., 2016; Frisch & Kockel, 1999; Kockel, 2002;

Maystrenko et al., 2005b). Salt movement continued during deposition of the Keuper I unit in the EHT (Figure 12), even though extension abated (Frisch & Kockel, 1999). We explain the ongoing salt structure growth by differential loading induced by the foregone extensionally triggered salt flow (Hudec & Jackson, 2007; Kehle, 1988). Jurassic sediments were strongly affected by erosion related to the Mid-Jurassic Doming event. Thus, the present-day thickness represents the thickness of the remnants preserved from erosion and cannot be used directly to infer active salt flow. Preserved Jurassic deposits have increased thickness within the EHT (Figure 13). Maystrenko et al. (2005b) interpreted a Jurassic pulse of salt movement, which temporally correlated with extension in the Lower Saxony Basin. Sedimentation in the Glückstadt Graben during the Late Triassic was relatively high (Bachmann et al., 2008), so assuming that sedimentation during deposition of the Keuper in the EHT exceeded or matched the accommodation space created by subsiding salt, we can expect that the peripheral sinks of the Keuper unit were completely synkinematically filled (Figure 14a). Jurassic deposition without salt movement would then yield parallel to subparallel layered strata affected by later erosion. Then, we would expect that the present-day remnants show no major local thickness variations (Figure 14a). Therefore, the preserved Jurassic depositional pattern indicates ongoing salt movement in the Early Jurassic prior to erosion (Figure 14b).

5.2.2 | Eastholstein–Mecklenburg Block

Within the Eastholstein–Mecklenburg Block (EHMB), the Keuper II thickness within shows the general thickening trend towards the south and local thickness variations unit hardly correlate with the salt structures (Figure 11). During this time, salt movement seems to be restricted to the Eastholstein Trough, Kegnaes Diapir and Werre FZ, whereas the salt structures of the EHMB remained mostly inactive. Only the crest of the 'Fehmarn' salt pillow is slightly thinned, which could indicate the onset of minor salt movement. In large parts of the Bay of Kiel and above the crests of most salt structures, the top of the Keuper I unit is eroded. Thus, thickness variations in the Keuper I unit cannot be directly attributed to salt movement where the overlying Jurassic is completely missing (white line in Figure 12). North-east of the salt pillow 'Trollegrund Nord', increased thickness of the Keuper I unit and a slightly divergent reflector suggest the beginning of salt movement and development of a small peripheral sink (Figure 12) (Ahlrichs et al., 2020). The Jurassic in the EHMB is strongly affected by erosion and thicker remnants are only preserved at the flanks of salt structures (Figure 13). In the absence of salt movement, we would expect Jurassic and Keuper I deposits to be horizontally layered without local thickness variations (Figure 14a). Therefore, the pattern of Jurassic erosion and higher preservation in rim synclines indicates salt movement prior to erosion (Figure 14b). Based on the only minor indications for Triassic salt in the Bay of Mecklenburg, we suppose that the Early Jurassic salt movement dominated in the EHMB. Hence, the onset of salt movement in the EHMB was considerably later than in the surrounding areas (Glückstadt Graben and north-eastern basin margin). We interpret this as an indication for the EHMB acting as a more stable transition zone between the Glückstadt Graben and the WPFS at the north-eastern basin margin, whose development is controlled by tectonic movements along the Tornquist Zone (Krauss & Mayer, 2004; Seidel et al., 2018).

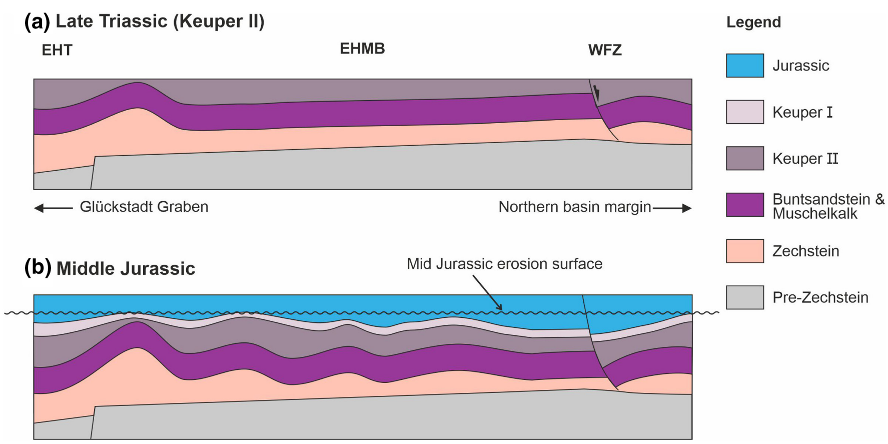


FIGURE 15 Conceptual model showing the development of salt structure within the Eastholstein–Mecklenburg Block (EHMB) during the Triassic–Jurassic. Within the Late Triassic, deformation was confined to the Eastholstein Trough (EHT) and fault zones at the northern basin margin (such as Werre Fault Zone, WFZ) (a). The EHMB in between acted as a stable transition zone, where salt movement began only in latest Triassic-to-Jurassic times (b).

5.2.3 | Kegnaes Diapir

The proposed development of the Kegnaes Diapir (KD) is sketched in Figure 16. Our observations suggest first tectonic activity and salt movement already during deposition of the Buntsandstein (Figure 6). Above the northern flank of the KD, the Buntsandstein shows divergent reflectors within the hanging wall of the fault F3, suggesting initial suprasalt faulting accompanied by salt movement (Figure 16b). This forms the initial development of the KD by reactive diapirism (Vendeville & Jackson, 1992). Increased thickness of the Lower Triassic above the northern flank of the KD shown by Bialas et al. (1990) further supports our observations of salt movement during the deposition of the Buntsandstein. Additionally, the reduced thickness of the Buntsandstein above the footwall of the basement faults suggests active tectonics during this time (Figures 6b). Uplift of the footwall by a flexural cantilever model could explain the locally reduced thickness of the Buntsandstein (Figure 16b) (Kusznir & Ziegler, 1992). The location of the basement step faults north of the KD coincides with two NW–SE-striking top pre-Zechstein faults visible in fault maps of Vejbæk (1997), which formed during Late Carboniferous–early Permian transtension (Figure 1) (Thybo, 1997). Pre-Quaternary maps of Denmark show WNW–ESE-striking faults crossing Lolland Island (Hakansson & Pedersen, 1992). These faults appear roughly parallel to the basin margin. During deposition of the Buntsandstein, the central parts of the basin experienced higher subsidence, while the basin margins, where the KD is located, suffered less subsidence. Stress, induced by this differential subsidence, could explain a reactivation of the Late Carboniferous–early Permian faults at the basin margin during the early Triassic. The velocity pull-up directly below the diapir masks the base Zechstein in this area and thus, a basement fault directly below the diapir as interpreted by Bialas et al. (1990) cannot be confirmed (Figure 6). Commonly, thermal subsidence and a phase of relatively minor tectonic activity without significant salt movement outside the Glückstadt Graben was thought to prevail within the northern NGB during the Early and Middle Triassic (e.g. Brink et al., 1992; Hansen et al., 2007; Hübscher et al., 2010; Maystrenko et al., 2005b; Warsitzka et al., 2016). The documented Early Triassic salt movement and faulting at the KD mark a newly discovered early stage of salt movement and faulting within the NGB, which contradicts the common perception of relatively quiet tectonic conditions during deposition of the Buntsandstein (e.g. Pharaoh et al., 2010).

The Muschelkalk deposits show a relatively constant thickness, which suggests that the tectonic activity abated and salt flow decreased (Figures 6b and 16c). During deposition of the Keuper II unit, salt structure growth increased again, indicated by the thick accumulation of Keuper II sediments north of the diapir (Figures 6b and 16d). This time marks the major phase of salt structure growth during the pillow stage of the KD, which occurred under ca. E–W regional extension (Maystrenko et al., 2005b; Sørensen, 1998). Extension likely thinned the overburden of the salt structure (Figure 16d). At the flanks of the diapir, the Keuper II terminates in a toplap against the ECU, suggesting that Late Triassic erosion further affected the roof of the KD (Figures 6b and 16e). Thus, we interpret the ECU as unroofing unconformity (Sørensen, 1998). Salt movement continued during deposition of the Keuper I unit with passive diapirism (sensu Vendeville & Jackson, 1992) and faulting within the overburden of the northern flank of the diapir (Figure 16f). Preserved Jurassic deposits are restricted to the overburden above both flanks of the diapir (Figure 6). Following the same argumentation for the Jurassic as described in Section 5.2.1, we interpret the preservation of Jurassic deposits in the peripheral sinks of the KD as a sign of ongoing salt movement during the Early Jurassic at least prior to Mid-Jurassic erosion (Figures 14 and 16g). The Cenomanian-to-Santonian units do not show hints of syndepositional salt movement, which is in accordance with findings from other salt structures in the study area (Ahlrichs et al., 2021). The narrow stem of the KD suggests that the diapir was mildly squeezed (e.g. Figure 16h). This likely occurred during Late Cretaceous inversion and is known from many other salt structures in the NGB (e.g. Kockel, 2003).

Based on the proposed structural evolution of the KD, the development of salt diapirs at the northern basin margin was accomplished by reactive diapirism in combination with a reduced overburden thickness by significant Late Triassic erosion. This allowed diapiric breakthrough by extension and erosion and explains the isolated location of the KD and possibly of the other three diapirs onshore Lolland at the northern basin margin. The absence of major Late Triassic erosion and increased overburden thickness of the salt structures located within the Bays of Kiel, and Mecklenburg did not allow diapirism. Such initiation of diapirism is known from parts of the Northern Permian Basin, such as the Danish North Sea (Sørensen, 1998).

5.3 | Faulting at the north-eastern basin margin

Between the Werre FZ and Agricola FS, mapping of the Zechstein unit shows a local depression of the base Zechstein, whose location coincides with a zone of increased thickness of the Buntsandstein, Keuper and

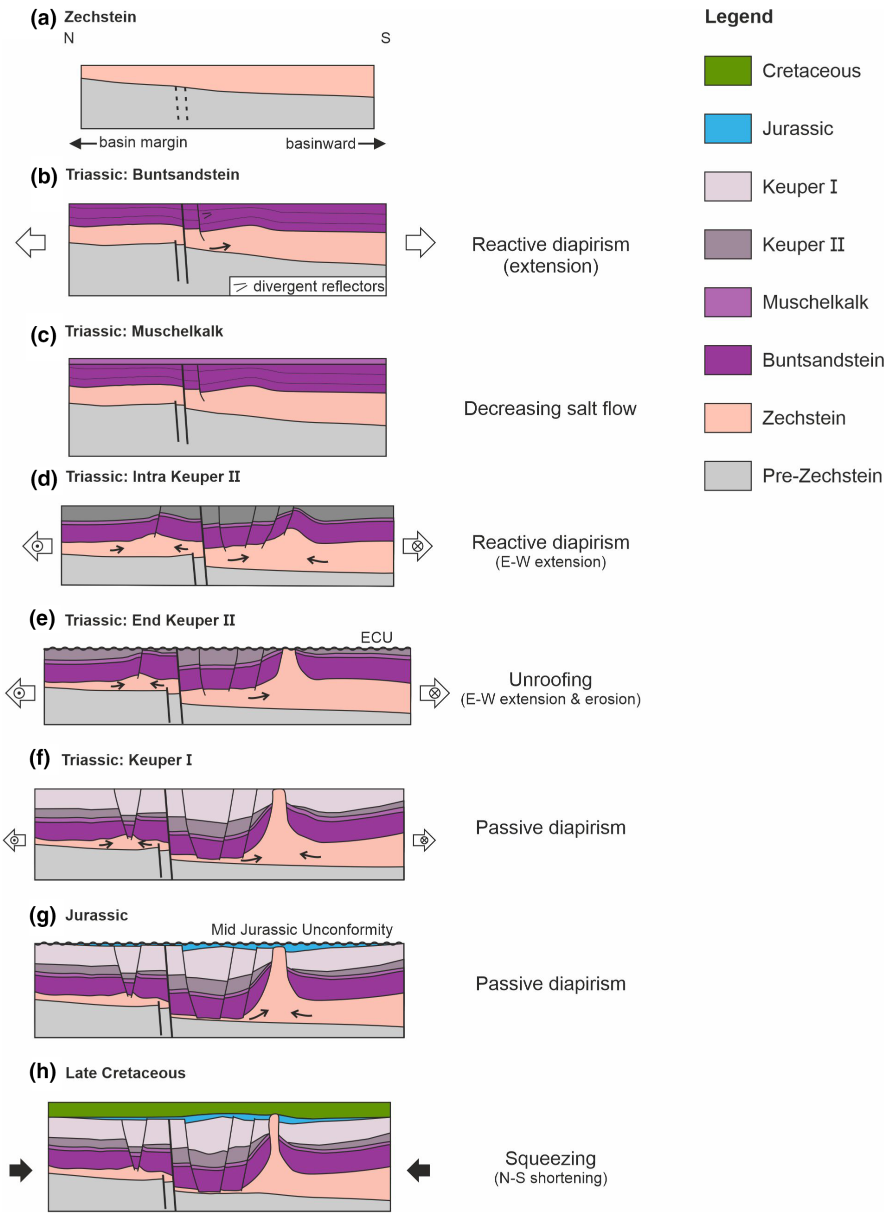
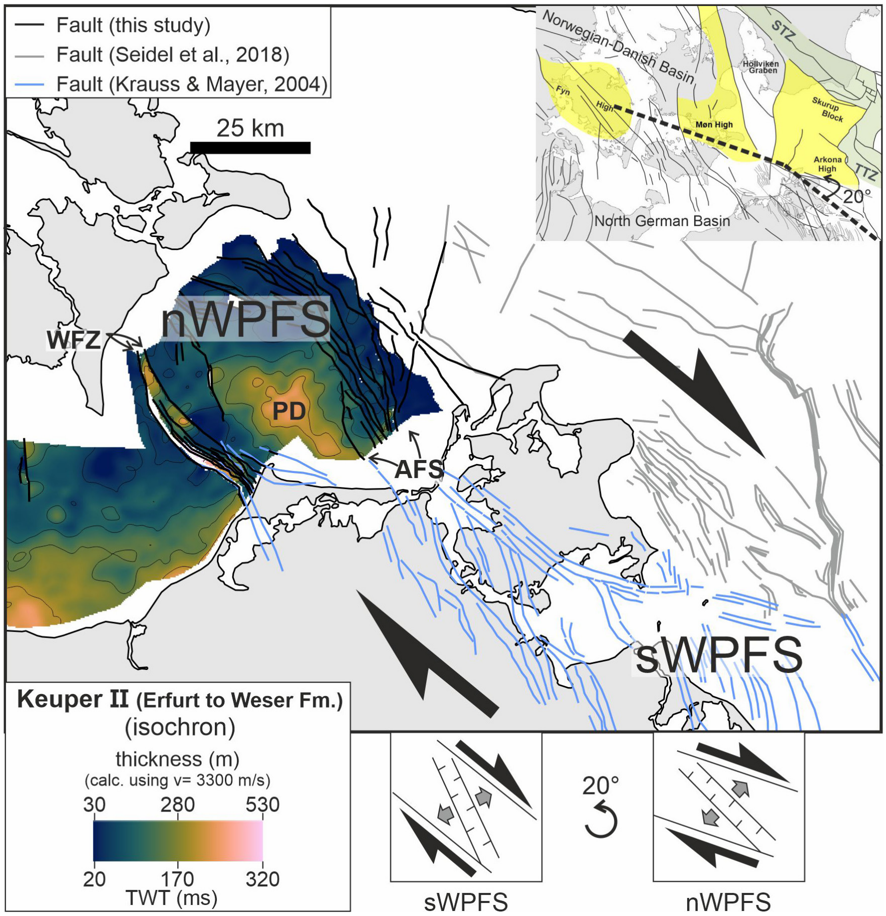


FIGURE 16 Conceptual model visualizing the proposed development of the Kegnaes Diapir alongside important diapiric stages and associated regional tectonics. Diapiric breakthrough was accomplished by Late Triassic extension and erosion allowing piercement across the reduced overburden thickness at the basin margin.

Jurassic successions (Figures 8, 9 and 11–13). The presence of this zone is well known in the literature (Buntsandstein: Scheck & Bayer, 1999; Keuper and Jurassic: Deutschmann et al., 2018; Hansen et al., 2007; Hübscher et al., 2010, the latter named this zone 'Prerow Depression' (PD)). The PD is part of NW–SE-oriented transtensional shear zone centred around Rügen Island (Deutschmann et al., 2018; Seidel et al., 2018). During the Triassic–Early Cretaceous, this area was affected by NW–SE dextral transtension along the Tornquist Zone, which led to the development of the Western Pomeranian Fault System (WPFS, Figure 17) (Krauss & Mayer, 2004). Faulting during deposition of the Keuper II unit in the Werre FZ and Agricola FS temporally correlates with faulting in other regions of the WPFS during deposition of the Grabfeld Formation (Beutler et al., 2012; Krauss & Mayer, 2004), and with E–W extension in the Glückstadt Graben (Figures 7 and 11) (Maystrenko et al., 2005b). During deposition of the Keuper I unit, faulting in the Werre FZ and Agricola FS persisted (Figure 12) (Ahlrichs et al., 2020). In this unit, the PD is more pronounced and includes the entire area between the Werre FZ and Agricola FS, suggesting ongoing subsidence (Figure 12). Faults of the Werre FZ and Agricola FS remained active in the Jurassic (Ahlrichs et al., 2020; Hübscher et al., 2010). The Jurassic deposits show a different pattern with a NE–SW elongated zone of increased thickness, which further broadened and additionally included the area south-west of the Werre FZ (Figure 13).

In the south-eastern part of the WPFS, the transtensional shear zone is characterized by en echelon faults and NW–SE-striking grabens, which were formed in between

FIGURE 17 Late Triassic reactivation of faults of the Western Pomeranian Fault System due to transtensional stress. Faults mapped in this study are shown together with faults from Krauss and Mayer (2004); Seidel et al. (2018). The southern part of the Western Pomeranian Fault System (sWPFS) is characterized by en echelon fault and NW–SE-striking grabens (Seidel et al., 2018). In the northern part of the Western Pomeranian Fault System (nWPFS), thickness of the Keuper II unit indicates a 20° counter-clockwise rotation of graben orientation correlating with a change in the orientation of the basin margin (dashed line in inset).



the major fault zones (Figure 17) (Seidel et al., 2018). Contrarily, en echelon faults are absent in the north-western part of the WPFS and shearing seems restricted to the faults of the bordering fault systems, while the area in between subsided without being further faulted (Figures 17 and 11–13). Notably, the thickness distribution of the Keuper II unit suggests a 20° counter-clockwise rotation of graben orientation compared to the south-eastern WPFS analysed by Seidel et al. (2018) (Figure 17). This rotation correlates with a change in orientation of the basin margin from NW–SE south-east of Rügen Island towards a more WNW–ESE trend along the Ringkøbing-Fyn High (dashed lines in the inset of Figure 17). This suggests that the development of the PD is influenced by the overall basin configuration and inherited Palaeozoic structures.

A possible explanation for the development of the PD would be rotational block faulting along deep-seated Palaeozoic faults, which were reactivated in the Triassic and Early Jurassic. These faults have listric character and are detached near the top of the Palaeozoic basement (Krawczyk et al., 2002). During fault reactivation, the subsiding hanging walls possibly rotated creating locally increased subsidence at the basin margin (Ahlrichs et al., 2020). However, the depositional pattern of the Buntsandstein and Keuper II units contradicts this explanation. Although the elongated zone of increased thickness of the Buntsandstein and Keuper II is located parallel to the basin margin, the local depocentre occurs in the centre between the Werre FZ and Agricola FS. Thus, the depocentre is not directly adjacent to the basin marginal faults of the Agricola FS, where we would expect the maximum subsidence of the hanging walls (Figure 11). The depositional pattern fits better to the development of a local sub-basin, bordered by the Agricola FS and Werre FZ (Figure 17). Interestingly, the location of the Keuper II depocentre within the PD correlates with the pinch out of mobile Zechstein units (Figure 11). This could indicate that extensional stress was localized here as it could no longer be transferred within the detachment horizon, similar to the model suggested by Krawczyk et al. (2002). A connection of the PD bordering faults to deeper Palaeozoic structures is indicated by the Late Triassic reactivation of the northern thick-skinned faults of the Agricola FS. The south-western border has a different character, as the Werre FZ is a thin-skinned fault system decoupled by the Zechstein. An influence from deep-rooted structures seems likely but needs further investigations by improved subsalt imaging. Accordingly, this area marks the transition zone between thick-skinned faulting at the basin margin and thin-skinned faulting decoupled by the Zechstein.

5.4 | Comparison with adjacent sub-basins of the Southern Permian Basin

Generally, immature salt pillows dominate the peripheral part of the basin within our study area (Figures 1 and 8). Salt welds are mostly absent. Mature salt walls and diapirs are almost exclusively located in the Glückstadt Graben apart from a few diapirs at the northern basin margin (Figure 1). The distribution of salt pillows and more complex salt structures in adjacent basins is comparable (e.g. Polish Basin: Krzywiec, 2012; Dutch Basins: ten Veen et al., 2012; German North Sea: Kockel et al., 1995). In the Polish Basin, salt pillows dominate the peripheral region (Krzywiec, 2012). Similar to the Baltic sector of the NGB, sub-Zechstein faulting played a minor role in the development of these structures (Krzywiec, 2012). In the Dutch North Sea, major salt movement concentrates above basement faults in the basin centre causing the development of salt diapirs and walls (ten Veen et al., 2012). Towards the peripheral region, minor salt movement occurred and only salt pillows are present (ten Veen et al., 2012). This is explained by less extension affecting the basin margin and platform highs during the Jurassic rifting (ten Veen et al., 2012). The development of the EHMB with its minor suprasalt deformation is very similar and likewise indicates that it experienced comparable less Triassic extension than the Glückstadt Graben. Interestingly, some salt diapirs developed along the platform edges within the Dutch North Sea basins, which were affected by Late Jurassic erosion (ten Veen et al., 2012). This could suggest a similar structural development as the Kegnaes Diapir in the Baltic Sea.

The Late Triassic initiation of salt structures within the Baltic sector of the NGB occurred coeval with the initial formation of many salt structures in the peripheral parts of adjacent basins (e.g. West Schleswig Block, onshore south-eastern NGB, Terschelling Basin, Silver Pit Basin and Polish Basin, see Figure 5 of Warsitzka et al., 2019). While the triggering of salt movement in the central part of major graben systems is mostly attributed to thick-skinned extension (e.g. Glückstadt Graben: Maystrenko et al., 2005b, Horn Graben: Best et al., 1983, axial part of Polish Basin: Krzywiec, 2012), a thin-skinned trigger mechanism by either extension or gravity gliding is mostly discussed for the peripheral regions (e.g. Cleaverbank Platform & Terschelling Basin: ten Veen et al., 2012, peripheral Polish Basin: Krzywiec, 2012, see also overview map in Warsitzka et al., 2019). The Triassic initial salt pillow growth in the Baltic sector of the North German Basin by thin-skinned extension was related to thick-skinned faulting within the central Glückstadt Graben. Therefore, initial salt tectonics had similar causes as in other peripheral parts of the Southern Permian Basin. The base Zechstein in the study area is tilted by ca. 1° and has a thick overburden (Figures 8–13) (Ahlrichs et al., 2020). Clear indications for up-dip gravity-driven extension by basinward dipping thin-skinned faults are absent, suggesting that gravity gliding played only a minor role, if at all (Figure 8) (see Ahlrichs et al., 2020 for a detailed discussion). Quantifying the true contribution of gravity gliding to salt movement in less extended basins, e.g. analogue modelling studies, is an aspect of future work (Warsitzka et al., 2021). Overall, the formation of salt structures by thin-skinned extension in the Baltic sector of the NGB can be well integrated with the transregional framework of Triassic extensional tectonics in the Southern Permian Basin (e.g. Pharaoh et al., 2010). The West Schleswig Block, which forms the western peripheral region of the Glückstadt Graben, and thus, the counterpart of the EHMB represent an exception. Here, no tectonic trigger for salt movement has been observed, which suggests salt tectonics due to differential loading (Warsitzka et al., 2019). Future work comparing the development of the Glückstadt Graben and its marginal areas could provide new insights into the triggering of salt movement in the West Schleswig Block.

6 | CONCLUSIONS

We analyse the Triassic-to-Jurassic structural evolution of the Baltic sector of the North German Basin using a dense network of high-resolution 2D seismic data tied to hydrocarbon and research wells. Presented profiles and time-structure and isochron maps of the Zechstein, Buntsandstein, Muschelkalk, Keuper II (Erfurt, Grabfeld, Stuttgart and Weser Formations), Keuper I (Arnstadt and Exeter Formations) and Jurassic units elucidate the Triassic–Jurassic structural evolution and salt movement of the region. Mapping of the Zechstein unit revealed a previously unknown salt structure east of Als Island ('Als Øst'). The fault pattern of the study area is updated including a differentiation among purely subsalt, thick-skinned and thin-skinned faults (Figure 8b). Thereby, the timing of salt movement and the transition from thick-skinned faulting at the basin margin to deformation decoupled by the presence of thick Zechstein salt towards the basin centre is shown. This elucidates the development of salt structures in the context of regional tectonics within an intracontinental sedimentary basin. Thick salt effectively decoupled basement deformation from the suprasalt cover. Comparable minor regional extension caused the development of mostly immature salt structures. The main conclusions are as follows:

- At the northern basin margin, our observations indicate earliest salt movement and faulting at the Kegnaes Diapir during deposition of the Buntsandstein. This early stage of faulting and salt movement is in contrast with the common perception of quiet tectonic conditions characterized by thermal subsidence based on the observations from other salt structures in the study area, where the Buntsandstein and Muschelkalk were deposited prior to salt movement (Figures 6, 9, and 10).
- Tectonic activity strongly increased in the Late Triassic during deposition of the Keuper II unit, including the onset of salt movement in the north-eastern Glückstadt Graben, major salt movement at the Kegnaes Diapir (reactive diapirism) and faulting at the north-eastern basin margin (Figure 11).
- During deposition of the Keuper I and Lower Jurassic units, salt movement continued in the north-eastern Glückstadt Graben and at the Kegnaes Diapir (Figures 12 and 13).
- We explain the development of salt diapirs at the northern basin margin based on the development of the Kegnaes Diapir by reactive diapirism in combination with a reduced overburden thickness by significant Late Triassic erosion (Figures 6 and 16).
- In the Triassic, the Eastholstein–Mecklenburg Block formed a more stable area at the transition between the Glückstadt Graben and the fault systems of the north-eastern basin margin. Major faulting is absent and salt movement started only in the latest Triassic with its dominant phase presumably in the Early Jurassic (Figure 15).
- The thick accumulation of Keuper and Jurassic deposits west of Rügen (Prerow Depression) represents a local sub-basin, bordered by the Agricola Fault System and the Werre Fault Zone. In this area, NW–SE-directed dextral strike-slip faulting along the Tornquist Zone induced transtension along inherited deep-seated Palaeozoic faults at the north-eastern basin margin. This caused increased subsidence of the Prerow Depression and corresponding accumulation of Keuper and Jurassic deposits (Figure 17).
- Triassic–Jurassic salt movement within the peripheral part of the North German Basin (Baltic Sea sector) was triggered by thin-skinned extension, which was decoupled from thick-skinned faulting within the central part of major graben systems like the Glückstadt Graben. Clear indications for gravity gliding contributing to Triassic–Jurassic salt movement are absent. Overall, salt structure development caused by thin-skinned extension in the Baltic sector of the North German Basin is in accordance with other peripheral regions of the intracontinental Southern Permian Basin.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The seismic profile BGR16-221 of Figure 7a, isochrone and time-structure maps shown in this study are available in the supplementary material of this article. Further seismic data used for mapping are available from the authors and the Federal Institute for Geosciences and Natural Resources (BGR) upon reasonable request. Industry seismic data are available upon request at ExxonMobil Production Deutschland GmbH.

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