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Salt movements within the Central European Basin System based on the results of the DFG-SPP 1135 “Dynamics of complex sedimentary basins under varying stress conditions by example of the Central European Basin System”

Salzbewegungen im Zentraleuropäischen Beckensystems auf Basis der Ergebnisse des DFG-SPP1135 "Dynamik sedimentärer Systeme unter wechselnden Spannungsregimen am Beispiel des zentraleuropäischen Beckensystems"

Yuriy Maystrenko*, Ulf Bayer*, Magdalena Scheck-Wenderoth*, Ralf Littke**

* - Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum GFZ;

** - Lehrstuhl für Geologie, Geochemie und Lagerstätten des Erdöls und der Kohle, RWTH Aachen.

Erdöl Erdgas und Kohle

Corresponding author: Yuriy Maystrenko

Helmholtz-Zentrum Potsdam

Deutsches GeoForschungsZentrum - GFZ

Telegrafenberg, B420

14473 Potsdam

Germany

yuram@gfz-potsdam.de

Phone: +49 331 288 1779

FAX: +49 331 288 1782

Abstract

Evolution of salt structures in relation to tectonic events within central part of the Central European Basin System is described by summarizing results which have been obtained and published in frame of the DFG-SPP 1135. These results illustrate main phases of salt tectonics within the basin system from the Triassic to present day. During the Buntsandstein and Muschelkalk, extension triggered raft tectonics and the salt movements within the Ems Trough, the Glückstadt and the Horn Grabens. The next phase of salt movements occurred in response to a Middle-Late Keuper regional extensional event which was strongest within the Triassic depocenters of the Central European Basin System, such as the Horn Graben, the Glückstadt Grabens, the Ems and the Rheinsberg Troughs. Regional erosion truncated the study area during the Late Jurassic-Early Cretaceous time. The magnitude of Late Jurassic-Early Cretaceous erosion is declining towards southern margin of the basin system where a dextral transtensional regime was established in the Lower Saxony Basin and neighboring areas during the Late Jurassic-Early Cretaceous. The late Early Cretaceous-early Late Cretaceous is characterized by a relative tectonic quiescence without strong salt movements. The Late Cretaceous-Early Cenozoic inversion provokated renewed salt movements, causing the thick-skinned salt tectonics along the Elbe Fault System and the thin-skinned character of salt movements towards the north from the area of strain localization. Post-inversion Cenozoic subsidence was accompanied by salt movements, related either to diapiric rise due to regional shortening and/or to local almost E–W directed extension.

Zusammenfassung

Basierend auf publizierte Ergebnisse im Rahmen des DFG-SPP 1135 wird die Entwicklung von Salzstrukturen in Bezug zu tektonischen Ereignissen im Zentraleuropäischen Beckensystem untersucht. Dabei werden die Hauptphasen der Salztektonik im Beckensystem von der Trias bis heute deutlich. Im Muschelkalk und Buntsandstein herrschte extensionsbezogenes ‚Rafting‘ im Emstrog, Glückstadtgraben und Horn Graben vor. Die nexte Phase verstärkter Salzbewegungen fand als Rektion auf eine beckenweites Dehnungsereignis im Mittleren bis Späten Keuper statt, das insbesondere die Depozentren des FHorn Grabens, Glückstadt Grabens, Elms und Rheinsberg Trogs betraf. Während des oberen Jura und der unteren Kreide wurde der gesamte Beckenbereich großflächig erodiert. Dabei klingt die Erosionsintensität von Norden nach Süden ab da der südliche Teil gleichzeitig von einem dextral-transtensionalen Regime betroffen war, insbesondere im Niedersächsischen Beckenbereich und benachbarten Gebieten. Der Zeitraum von der späten Unterkreide bis zur frühen Oberkreide ist in weiten Teilen des Beckensystems ist durch vorwiegend geringe tektonische Aktivität und schwache Salzbewegungen bestimmt. Eine Oberkretazische Cenozoische Inversion löste erneut intensive Salzbewegungen aus, die entlang des Elbe Vewerfungssystems ‚thick-skinned‘ ist und nach Norden mit zunehmender Entfernung von der stärksten Verformungszone einen ‚thin-skinned‘ Charakter annimmt. Die darauf folgend Subsidenz wurde von Salzbewegungen begleitet, die lokalem Diapir-Wachstum entsprachen und/oder durch lokalisierte Einengung bzw. lokal fast E-W gerichteter Dehnung bedingt wurden.

Introduction

The Central European Basin System covers the area of the Southern and Northern Permian basins. The Permian basins together with the superimposed post-Permian sub-basins (e.g. the North German Basin, the Norwegian-Danish Basin, the Polish Basin and the graben structures of the North Sea) form a complex basin system [1]. At the deep crustal level, the Central European Basin System is bounded by two regional fault zones, the Tornquist Zone in the northeast and the Elbe Fault System in the southwest (Fig. 1). The central part of the Central European Basin System corresponds to the Northern German Basin and is characterized by a very thick Meso-Cenozoic sedimentary succession. Meso-Cenozoic sediments are strongly deformed due to postdepositional movements of the Permian salt which pierced the sedimentary cover, forming huge salt walls and diapirs (Fig. 1).

The sedimentary cover of the Central European Basin System has been intensively studied since the end of 19th century mainly due to hydrocarbon exploration within the area. Thereby, many details have been published, including the structure and development of a variety of salt structures. One of the first systematic studies of salt structures in northern Germany was by Trusheim [13] who introduced the term “halokinesis”. In addition, Trusheim [14] proposed a kinematic concept for the relation between the growth history and the character of sedimentation close to active salt structures. Based on early seismic data from NW Germany, Sannemann [15] has shown that salt diapirs of the Glückstadt Graben developed successively in space and time, becoming younger with increasing distance from the central part towards the graben flanks. He called this phenomenon “salt-stock families”. Later on, Best et al. [16] focussed at the regional structure of the Glückstadt and Horn Grabens indicating similarities in the evolution of salt structures within both regions. Major aspects of the evolution and structure of northwest Germany were described by Brink et al. [17] observing “flower structures” in places where previously salt walls were assumed. The evolution of the Lower Saxony Basin has been discussed by Betz et al. [18]. A further step in understanding of the structure and evolution of northwest Germany was achieved by Baldschuhn et al. [4] providing the detailed structure of the region based on seismic lines and well data. Major phases of salt movements within the Northern German Basin have been described by Kockel [19]. Finally, since the beginning of this century until 2008, the Central European Basin System was intensively studied in DFG-projects after geophysical and geological data were provided by the oil and gas industry through the German Society for Petroleum and Coal Science and Technology (DGMK) in the frames of the DFG-SPP 1135 and DGMK 577 “Dynamics of complex sedimentary basins under varying stress conditions by example of the Central European Basin System”. Here, evolution of salt structures in relation to tectonic events is described by summarizing results which have been obtained and published in the context of the DFG-SPP 1135 with intensive summaries provided in the book “Dynamics of Complex Sedimentary Basins - The Example of the Central European Basin System” [20] and in the DGMK-Research Report 577-2/1 [21].

Structure and evolution of the central part of the Central European Basin System based on seismic reflection lines

Salt tectonics is one of the main deformation mechanisms within the sedimentary cover of the Central European Basin System. Various salt structures and styles of sedimentation are described in relation to tectonic sub-units of the Central European Basin System based on the results of seismic interpretation and 2D backward modelling.

The Glückstadt Graben

The Glückstadt Graben is one of the deepest post-Permian structures within the Central European Basin System and extends from the Ringkoebing–Fyn High to the Lower Saxony

Basin (Fig. 1). The reflection seismic profile, given in Fig. 2a, provides a regional overview of the region [8]. Along the line, the thick salt-rich Rotliegend and Zechstein strata are very thin between the salt structures, indicating depletion of the salt-rich layers within the Central Glückstadt Graben and the Eastholstein Trough. The overlying Buntsandstein and Muschelkalk have a constant thickness at the graben flank and variable thickness towards the axial part of the graben, indicating initial salt movements already in the Buntsandstein-Muschelkalk within the central part. The Keuper strata are represented by extreme thickness variations and complex seismic pattern (Fig. 2). This succession shows syn-depositional thickening towards the graben centre, and baselapping strata of the thickened Keuper indicate rapid subsidence due to salt movements during the downbuilding of the salt structures [8, 22, 23]. The thick Keuper succession shows typical concave and sigmoid reflections (Fig. 2a; base- and top-lapping) which are represented by alternations of clay and salt layers. Jurassic sediments are only preserved within the rim synclines along the edges of elongated salt walls. The presence of Jurassic sequence on the south-eastern flank of the Glückstadt Graben indicates that the Jurassic covered a wider area prior to Late Jurassic-Early Cretaceous erosion. The Cretaceous is characterized by an almost constant thickness and slightly thins from the Eastholstein Trough towards the south-eastern flank. The Cenozoic is characterised by thickened sequences between the salt structures and partial erosion within the crest of the salt structures. The thickest Cenozoic is observed within the deep marginal Eastholstein Trough (Fig. 2). Internal reflectivity of the thickened Cenozoic succession demonstrates the rim syncline character of deposition. This marginal trough is separated from the south-eastern flank of the graben by a steep westward-dipping normal fault beneath and above the salt wall. The seismic pattern indicates that the last reactivation of this fault occurred in the Late Cenozoic [8]. The subsidence centers shifted in time and in space as indicated by sediment thickening (Fig. 2a, white arrows). For instance, the central part of the profile with thick

Keuper is bounded by thick Jurassic sediments within the Eastholstein Trough. This Jurassic depression is overlapped by a thick Cenozoic sequence but without vertical alignment of the axes of maximum thicknesses. This indicates that the salt decoupled the deformation of the salt cover from the strata below and that the observed thickening of the sediments was a result of simultaneous salt movements.

Flattening of particular seismic reflections at selected time intervals provides structural snapshots of graben evolution [8]. Fig. 2b provides clear evidences for a regional unconformity as result of the Late Jurassic–Early Cretaceous erosional event, and Fig. 2c points towards normal faults below salt structures related to extension. Therefore, Keuper extension and associated normal faulting could have been a main trigger for the development of salt pillows and diapirs at that time. Thus, the evaluation of the seismic pattern of the Glückstadt Graben indicates that NNE–SSW trending salt structures might have been formed along basement faults and they could control abrupt changes of sediment thicknesses between salt structures.

Based on seismic data, initial salt movements were triggered already in the Buntsandstein-Muschelkalk and the main phase of salt tectonics took place during the Keuper within the Central Glückstadt Graben, when this region was affected by extension. Salt movements then continued during Jurassic times. The Jurassic was partly eroded during the Late Jurassic-Early Cretaceous as indicated by an unconformity. The Upper Cretaceous has an almost constant thickness and the internal parallel reflection pattern indicates a quiet tectonic setting with very minor salt movements. Salt movements resumed in the latest Late Cretaceous and continued during the Cenozoic at the margins of the Central Glückstadt Graben.

The Ems Trough

The Ems Trough is located south-west of the Glückstadt Graben (Fig. 1). A west-east running seismic line (Fig. 3) illustrates the influence of tectonic events on salt movements within the Ems Trough according to Mohr et al. [10, 24]. Along this line, base Zechstein is complicated by a sub-salt graben beneath the central salt structure (Fig. 3a). The lower part of the Buntsandstein succession is complicated by normal faults. The Keuper strata are characterized by a complex seismic pattern. The Lower Cretaceous erosional truncation affected the Triassic sequences down to Muschelkalk in the west and down to the Jurassic in the east. Cretaceous and Cenozoic strata dip and thicken slightly to the west with westward dipping normal faults (Fig. 3a).

Based on a combination of seismic interpretation and balanced retro-deformation, a model of salt tectonic deformation of the southern Ems Trough has been presented in [10] (Figs. 3b-g). The original thickness of the Zechstein salt is in the range of 820-940 m, increasing to the east (Fig. 3g). Before the Late Buntsandstein, the study area was affected by extension. At that time, the overburden has undergone faulting and rafting, whereas the base Zechstein remained unfaulted. The first extensional event and rafting triggered reactive salt diapirism, followed by active piercement of thinned overburden (Fig. 3f). A second extensional event occurred during the Late Muschelkalk (Fig. 3e), causing rafting and diapirism. During early Keuper times, differential loading, sedimentary progradation and lateral salt movements resulted in the formation of the primary rim-syncline in the eastern part of the profile. In the Middle Keuper, salt tectonics was activated in response to sub-salt extension, triggering normal faulting in the overburden and following reactive diapirism of the central salt structure. Afterwards, normal faulting of the base Zechstein resulted in reactive diapirism and subsequent downbuilding of the eastern salt structure as well (Fig. 3d). The termination of downbuilding is supposed during the Middle and Late Jurassic, when salt movements ceased and the salt diapirs were covered by sediments. During the Late Jurassic-Early Cretaceous the area was affected by regional erosion and tilting (Fig. 3c). The Late Cretaceous-Early Tertiary phase of salt movement is interpreted as a result of episodic horizontal shortening of salt structures. Two phases of shortening were identified in the latest Cretaceous and in the Paleogene [10]. In addition, subsurface salt dissolution above areas of subcroping salt structures caused westward dipping normal faults at the lowest Cenozoic-Cretaceous level (Fig. 3b).

The Pompeckj Block and Lower Saxony Basin

Salt tectonics within the Pompeckj Block and the Lower Saxony Basin is illustrated by a SSW-NNE running transect (profile 3 in Fig. 1), which crosses the WNW-ESE trending Aller Lineament (Fig. 4). The description of structure and evolution of the Pompeckj Block and the Lower Saxony Basin are based on an interpretation by Mazur and Scheck-Wenderoth [9]. Along the profile, the Zechstein sequence is characterized by rapid changes in thickness as a result of salt movements. The thicknesses of the Buntsandstein and Muschelkalk are almost constant along the interpreted seismic line (Fig. 4). Some variations in thickness are observed near the Solling High which corresponds to the SW margin of the Central European Basin System. The thickness of the Keuper varies along the transect. These changes of thickness can be attributed to syndepositional thickening of sediments in rim synclines associated with growth of salt structures (Fig. 4). The Jurassic is partly preserved and is represented by rapid thickness changes which are caused by both erosional truncation and variable rates of deposition within the rim synclines around the diapirs and salt pillows. The Lower Cretaceous is very thin in the northern part of the transect and partly absent in the southern part of the line (Fig. 4). On the other hand, the Lower Cretaceous sequence is very thick within the Lower Saxony Basin. The Upper Cretaceous is completely missing at the southern margin of the basin system. Thickening of the Upper Cretaceous occurs in salt rim synclines. This is especially pronounced near the Aller Lineament which is represented by two reverse faults (Fig. 4). The Cenozoic sequence is completely eroded within the Solling High and the southern part of the Lower Saxony Basin. Thickness variations of the Cenozoic above salt diapirs are most likely caused by salt movements. The structural and thermal evolution of the boundary zone between Pompeckj Block and Lower Saxony Basin was also discussed in the context of petroleum generation and basin modelling in [25].

The almost constant thickness of the Buntsandstein and the Muschelkalk along the interpreted transect implies a period of tectonic quiescence. The Keuper interval was associated with syndepositional salt movements which were probably triggered by normal faults at the pre-Zechstein level. The Jurassic was a period of rapid subsidence, especially within the Lower Saxony Basin. The depositional thickening of the Jurassic near some salt structures implies that salt movement occurred locally. The Late Jurassic-Early Cretaceous erosional event is recognised in terms of a regional unconformity which is traceable along the cross-section. The Early Cretaceous was a period of accelerated subsidence within the Lower Saxony Basin. During the Late Cretaceous to Early Paleogene, the study area has undergone an inversion. Inversion-related erosion caused uplift by up to 4 km in the Wiehengebirge area [26] and up to 6 km in the Osnabrück-Bramsche area [27]. A very pronounced inverted structure corresponds to the Aller Lineament where two overturned anticlines are cored by salt (Fig. 4). Therefore, the Late Cretaceous compressional deformations triggered salt movements responsible for some local thickening of the Upper Cretaceous in rim synclines [9]. The Late Cretaceous-Early Tertiary inversion was followed by subsidence during the Cenozoic when a thick cover of Cenozoic sediments was deposited in the areas of the Pompeckj Block and in the western part of the Lower Saxony Basin. Locally, seismic data indicate growth of salt diapirs simultaneous with overall subsidence in the Cenozoic [9].

The Bay of Kiel of the Baltic Sea

The next seismic line (Fig. 5a) is from the south-western part of the Bay of Kiel which corresponds to the northern part of the North German Basin. This line crosses a salt pillow showing an example provided by Hansen et al. [11]. The thicknesses of Buntsandstein and Muschelkalk strata are uniform without remarkable changes along the seismic line (Fig. 5a). In contrast, the Keuper sequence is missing above the crest of the salt anticline and thickens within the adjacent rim synclines. This profile shows that Jurassic sediments are missing along this line (Fig. 5a). The preserved Jurassic sediments were drilled by few deep wells in the study area and are all of Early Jurassic age according to [28]. The preservation of the Lower Jurassic within the rim synclines between the salt structures suggests that this sequence was deposited under the influence of halokinesis. Absence of the Middle and Upper Jurassic and the lowest Lower Cretaceous indicate that the Bay of Kiel was an area of non-deposition during Late Jurassic-Early Cretaceous time. Cretaceous strata have a constant thickness and are postdepositionally faulted in the crest of the salt anticline. The Cenozoic succession is thinning towards the salt anticline indicating a syndepositional growth of the salt pillow.

A model of tectonic development is shown in Figs. 5b-d [11]. Figure 5d indicates that Buntsandstein and Muschelkalk sequences do not show strong thinning or thickening anomalies implying a period of relative tectonic quiescence in the Bay of Kiel. The thickness variations of the Keuper (Fig. 5c) show that the sequence was deposited under the influence of salt movement. It is obvious from the restored section (Fig. 5b) that the uniform thickness of the Cretaceous succession indicates a period of tectonic quiescence. This situation continued until the latest Late Cretaceous when several salt structures were reactivated in the study area [11]. The reactivated salt movements were initiated in a compressional stress field due to the onset of the Alpine Orogenesis. This partly explains development of the depocenters between the salt structures during the deposition of the Cenozoic succession (Fig. 5a).

The Northeast German Basin (The Rheinsberg Trough)

The first complete seismic image across the Northeast German Basin (Fig. 6) was provided by the DEKORP BASIN'96 experiment [29, 7]. The major phases of salt tectonics in the Northeast German Basin are described based on the interpretation by Scheck et al. [7, 23]. This interpretation demonstrates that brittle deformations of the pre-Zechstein are most intense along the fault which bounds the Flechtingen High, where displacement is 2 s TWT at the level of the base Zechstein (Fig. 6). The rest of the profile is characterised by unfaulted basement or by presence of small basement faults. Above the Zechstein salt, the Mesozoic sequence is strongly folded with salt cored anticlines and salt-related synclines. The Buntsandstein-Muschelkalk succession has uniform thickness with some modifications at the top of salt structures. The Keuper–Jurassic package is thickening near salt structures in the central part of the profile which corresponds to the Rheinsberg Trough (Fig. 6). Salt-related thickening and associated syndepositional normal faults indicate rim syncline subsidence and extension during Keuper–Jurassic times. The Cretaceous covers the truncated surface of the Keuper–Jurassic sequence (Fig. 6), implying an influence of the major regional erosion during the Late Jurassic-Early Cretaceous. Late Cretaceous rim synclines between salt diapirs and pillows indicate syndepositional salt movement (Fig. 6). In this case the overlying deposits were folded due to the Late Cretaceous-Early Tertiary compression which triggered propagation of the horizontal stresses in the salt cover from the area of strain localization at the southern margin of the Northeast German Basin (see Flechtingen High in Fig. 6) [7]. This was followed by a phase of salt diapirism causing differential subsidence during the Cenozoic which is reflected by the presence of Cenozoic rim synclines along the profile.

The Mecklenburg Bay of the Baltic Sea

Structural and geological evolution of the northern part of the Northeast German Basin is revealed by use of a composed seismic section (Fig. 7a) from the Mecklenburg Bay (Fig. 1). A published interpretation of this line by Zöllner et al. [12] has been used for this paragraph. The base Zechstein is complicated by small-scale faults in the north-eastern part of the section (Fig. 7a). There are no significant variations in thickness of the Buntsandstein and the Muschelkalk. The Keuper sequence is characterized by thinning towards the north-east and by several internal unconformities in the northeast (Fig. 7a). The most pronounced unconformity separates Middle and Upper Keuper. The preserved Jurassic sediments have Early Jurassic age, while the Middle-Upper Jurassic is not present in any well of the region, pointing to a non-depositional time or deep erosion during the end of the Jurassic and at the beginning of the Cretaceous. Cretaceous sediments show only locally varying thickness. The latter implies the absence of salt movements during the large period of Cretaceous time. The Cenozoic is characterised by local thinning above salt pillows and by thickening between salt anticlines.

The geological evolution is illustrated by flattening of the seismic section to predefined horizons (Figs. 7b-g) [12], including a lateral migration of the salt to its original position. During the Zechstein, the study area was affected by subsidence with the depocenter in the south-east (Fig. 7g). Buntsandstein sedimentation also shows slightly increasing thickness in the south-east direction without evidences of salt movements (Fig. 7f). The Muschelkalk subsidence was rather uniform during a period of tectonic quiescence (Fig. 7e). The deposition of Keuper (Fig. 7d) was complicated by several unconformities, implying tectonic influences. During the Jurassic, a local depocenters developed along the section (Fig. 7c). The first phase of salt pillows formation occurred during the deposition of the Jurassic or simultaneously with erosion of Jurassic and Keuper sediments at the top of the pillows. In the Cretaceous, the region was inverted (Fig. 7b). Late Cretaceous-early Tertiary inversion triggered strongest salt movements along the interpreted section, causing the formation of relatively deep rim synclines during the Cenozoic (Fig. 7a)

Discussion

The results gathered in the DFG-SPP 1135 imply an interrelation between main phases of tectonic activity and the mobilization and movements of the Permian salt within the Central European Basin System. This means that tectonic evolution plays a key role in understanding the features of salt tectonics within this basin system.

According to the results presented here, the initiation of salt movements in the central segment of the Central European Basin System occurred already in the Buntsandstein [10, 22]. Thickening of the Buntsandstein within the axial part of the Glückstadt Graben clearly indicates the impact of salt movements on deposition (Fig. 2a). Within the Ems Trough, the interpretation of the high-quality prestack depth-migrated 3D seismic cube and a recent network of depth-migrated 2D seismic lines allow to investigate the Buntsandstein phase of salt tectonics in detail. There, Middle Buntsandstein faulting at the base salt resulted in decoupled faulting in the overburden and gravity gliding, initiating salt flow and raft tectonics [10]. This phase of salt tectonics was responsible for differential sedimentation of Buntsandstein strata in the Ems Trough (Fig. 3f). The extensional event is recognized in the Muschelkalk and also triggered raft tectonics and salt movements [10]. The internal seismic pattern of the Muschelkalk package within the Glückstadt Graben (Fig. 2a) strongly implies salt-related deposition, as well. These results are in agreement with previous studies which also identified an initial stretching events in Buntsandstein and Muschelkalk times for the Ems Trough, the Glückstadt and the Horn Grabens [30, 4, 31, 19]. On the other hand, the rest of the North German Basin is characterized by uniform thickness of the Buntsandstein and Muschelkalk without evidences of salt movements as illustrated by Figs. 4-7. This means that Buntsandstein and Muschelkalk extensional events and related salt movements were localized within the Ems Trough, the Glückstadt and the Horn Grabens, and a period of relative tectonic quiescence dominated within other sub-basins, such as the Lower Saxony Basin and the Northeast German Basin [7, 11, 9, 12].

During the Keuper time, the major phase of growth of salt structures occurred within the entire Central European Basin System [16, 30, 32, 17, 4, 19, 33]. This phase of salt tectonics was triggered by almost E-W directed Triassic extension culminating during the Middle Keuper [7, 22, 10, 34]. The Keuper interval is characterized by strong thickening of the strata, especially pronounced within the Glückstadt Graben (Fig. 2a), the Ems Trough (Fig. 3) and the Horn Graben. This thickening is directly related to syndepositional salt movements which were possibly triggered by normal faulting of the salt base [22, 10]. Strongly varying thickness of Keuper sequence has been also observed in the Northeast German Basin [7, 12]. The regional stretching event was accompanied by sub-salt normal faulting and may have triggered reactive diapirism which initiated the formation of the deep primary rim synclines during the Middle-Late Keuper. Therefore, the deposition of the Keuper was associated with rapid growth of discordant salt structures as indicated by the formation of major rim synclines (Figs. 2a, 3, 6). At that time, some of the salt domes reached the paleosurface on which the Permian salt locally extruded and partly redeposited due to superficial dissolution [8, 22, 34]. This is supported by the internal seismic pattern of the Keuper, lithostratigraphic data and the results of palynological investigations [14]. In addition, this phenomenon of halotectonics has been also documented in other salt-containing basins of the world [35]. For example, the present-day active salt glaciers are observed in the Zagros Mountains of Iran [36]. Therefore, the Middle-Late Keuper phase of salt tectonics was characterized by a regional character of salt movements with localization of strongest salt movements within the Horn Graben, the Glückstadt Graben, the Ems and the Rheinsberg Troughs.

Late Triassic salt movements continued during the Early Jurassic time within the Glückstadt Graben where Jurassic salt movements resulted in the formation of secondary rim synclines adjacent to the primary depocentres (Fig. 2a). Unfortunately within the other sub-basins of the basin system, Early Jurassic salt-related structures are poorly preserved due to the Late Jurassic-Early Cretaceous erosion. This event is well documented as the major erosional unconformity within the central segment of the Central European Basin System [37, 17, 11, 22, 10, 12] and can be easily recognised on seismic data (Figs. 2, 3, 5 and 7). The magnitude of Late Jurassic-Early Cretaceous erosion is declining towards the southern margin of the basin system in the Lower Saxony Basin and neighbouring areas where a dextral transtensional regime was established in the Late Jurassic-Early Cretaceous [18, 9]. The Late Jurassic-Early Cretaceous tectonic event caused growth of solitary salt structures as a response to changes in tectonic stresses within the Glückstadt Graben, the Pompeckj Block and the Lower Saxony Basin [4, 19, 22].

Post-erosional sedimentation resumed at the end of the Early Cretaceous, when almost all discordant salt structures (diapirs and walls) were covered by Hauterivian or younger sediments within the entire region [37, 17, 4, 11, 22, 12]. The thickness of the uppermost Lower Cretaceous and most of the Upper Cretaceous is very uniform through the Glückstadt Graben (Fig. 2a), the Ems Trough (Fig. 3), the Pompeckj Block (Fig. 4), the south-western Baltic Sea (Fig. 5) and northern part of the Northeast German Basin (Fig. 7). This regional feature indicates a tectonic quiescence during the late Early Cretaceous-early Late Cretaceous. At that time strong salt movements were interrupted within the mentioned areas. One possible reason for the absence of salt movements is a tectonically silent regime at this time. This is supported by other studies [38, 39] which demonstrated that tectonically induced salt movements can be interrupted during the absence of tectonic forces.

Salt movements were renewed during the Late Cretaceous-Early Cenozoic when the Central European Basin System was affected by compression. The strongest compressional deformations were localized along the Elbe Fault System, causing inversion and subsequent erosion of sediments in this region. Two major reverse faults are clearly visible within the Aller Lineament (Fig. 4). The Aller Lineaments is characterized by the absence of Upper Cretaceous sediments above the crests of two salt structures forming the core of the inverted uplifts (Fig. 4). The rim syncline character of deposition of the Upper Cretaceous around these salt structures indicates syndepositional salt movement due to the thick-skinned deformations at the Aller Lineament [9, 40].

A reverse fault bounds the Flechtingen High from the north-east (Fig. 6), indicating significant inversion-related uplift within the south-eastern part of the Northeast German Basin. Compressional stresses, localized in that area, caused folding of the salt overburden within the Northeast German Basin, while the base salt remained unfolded. The Permian salt followed the shape of the folded salt cover, moving from the fold troughs to the fold crests (Fig. 6). In this case, Permian salt decoupled the deformation of the salt cover from its base, indicating thin-skinned salt tectonics during the Late Cretaceous-Early Tertiary compression towards the north-east from the area of thick-skinned deformations [7, 41]. A similar situation is observed within the Ems Trough and the Glückstadt Graben where compressional stresses were transmitted from the southern margin of the basin system northward into the overburden, causing salt movements without involving the salt base into the deformations [10, 22].

Finally, post-inversion Cenozoic subsidence was accompanied by salt movements as reflected in the formation of Cenozoic rim synclines between salt structures and thinning or even erosion of sediments above the crests (Figs. 2a, 4, 5, 6, 7). The normal faults are only observed within crests of salt structures which were active during the Cenozoic within the Glückstadt Graben, the Ems Trough, the Pompeckj Block and the south-eastern Baltic Sea (Figs. 2a, 3, 5). The formation of these faults is possibly related to diapiric rise due to regional shortening [e.g. 10, 9]. On the other hand, Cenozoic post-inversion salt movements correlate temporally with normal faulting in the salt base, as well [8]. This thick-skinned extension is especially pronounced within the Eastholstein Trough of the Glückstadt Graben where a steep Cenozoic normal fault cuts overburden and base of the Permian salt (Fig. 2a). Formation of this normal fault is most likely related to almost E–W directed extension and coincides with the extensional events within the Rhine, the Leine and the Eger Grabens. Moreover, Lehne and Sirocko [42] observed recent vertical movements in the Glückstadt Graben which possibly are caused by rising salt structures, indicating present-day salt movements within the basin system. The latter can be related to Quaternary glacial loading/unloading which decreases the stability of salt structures compared to the pre-glacial state [43].

In the framework of DFG-SPP 1135 further detailed studies of the internal structure of salt walls and domes and of the influence of salt domes on temperature fields and fluid migration have been performed. These studies can only be mentioned here. According to well data and studies in the mines, the salt structures are not homogenous internally and contain folded and faulted salt layers composed of alternation of evaporates and carbonates [44]. Furthermore, the discordant salt structures (walls and diapirs) comprise a mixture of the Zechstein and the salt-rich Rotliegend in the Glückstadt Graben and surrounding areas [4, 22]. Locally, strong regular reflectivity is observed within the salt structures of the Glückstadt Graben, representing displaced clastic rocks of the salt-rich Rotliegend in the upper part of the salt walls or diapirs [22]. Based on reprocessing of seismic data, Baykulov et al. [45] have shown that some salt walls could also include displaced Triassic-Jurassic rocks. According to

[10], disconnected blocks of Buntsandstein are present locally within salt diapirs of the Ems Trough.

The physical and structural properties of the salt structures influence the temperature field of the Central European Basin System. Studies of conductive heat transfer show that the contrast between the thermal conductivity of the salt and the neighboring sediments produces thermal anomalies in vicinity of salt diapirs [46]. Furthermore, thermal differences around the salt structures control groundwater transport processes, providing the coupling between hydraulic and thermally-driven forces. This mechanism was reproduced by numerical modeling of thermally-driven brine flow within the North German Basin [47]. Therefore, the presence of huge salt structures has an impact on the temperature distribution within the sedimentary strata and therefore, it has a great influence on hydrocarbon generation within the basin system.

Summary

The Buntsandstein and Muschelkalk extension triggered raft tectonics and salt movements within the Ems Trough, the Glückstadt and the Horn Grabens, and a period of relative tectonic quiescence dominated within other sub-basins, such as the Lower Saxony Basin and the Northeast German Basin.

The Middle-Late Keuper regional extensional event initiated a phase of salt movements which were strongest within the Triassic depocenters of the Central European Basin System, such as the Horn Graben, the Glückstadt Grabens, the Ems and the Rheinsberg Troughs.

During the Late Jurassic-Early Cretaceous, major erosion regionally truncated the study area. The magnitude of Late Jurassic-Early Cretaceous erosion is declining towards the southern margin of the basin system in the Lower Saxony Basin and neighboring areas where dextral transtensional regime was established in the Late Jurassic-Early Cretaceous.

The late Early Cretaceous-early Late Cretaceous is characterized by a tectonic quiescence without strong salt movements.

Salt movements were renewed during the Late Cretaceous-Early Cenozoic compression. At that time, thick-skinned salt tectonics is observed along the Elbe Fault System where compressional deformations are localized. The thin-skinned character of salt movements is prevailing towards the north from the areas of strain localization.

Post-inversion Cenozoic subsidence was accompanied by salt movements, related either to diapiric rise due to regional shortening and/or to local almost E–W directed extension.

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Figures

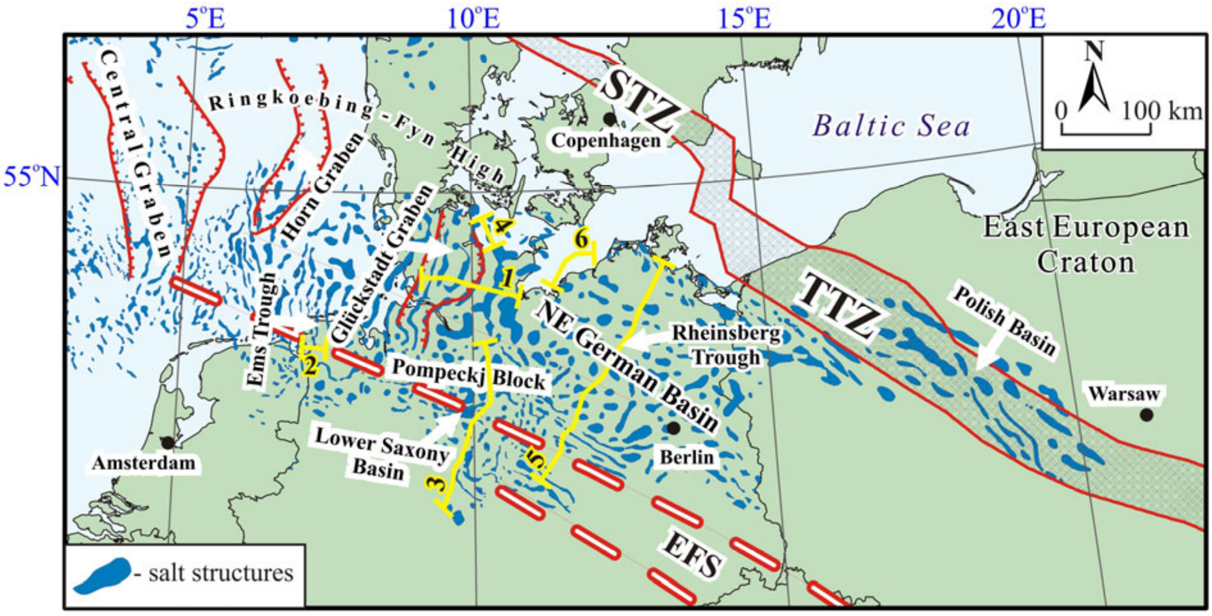

Figure 1. Structural map of the Central European Basin System with location of salt structures (compiled after [2, 3, 4, 5, 6]). Yellow lines are reflection seismic profiles [7, 8, 9, 10, 11, 12]. Structural elements: EFS - Elbe Fault System; STZ - Sorgenfrei-Tornquist Zone; TTZ - Teysseyre-Tornquist Zone.

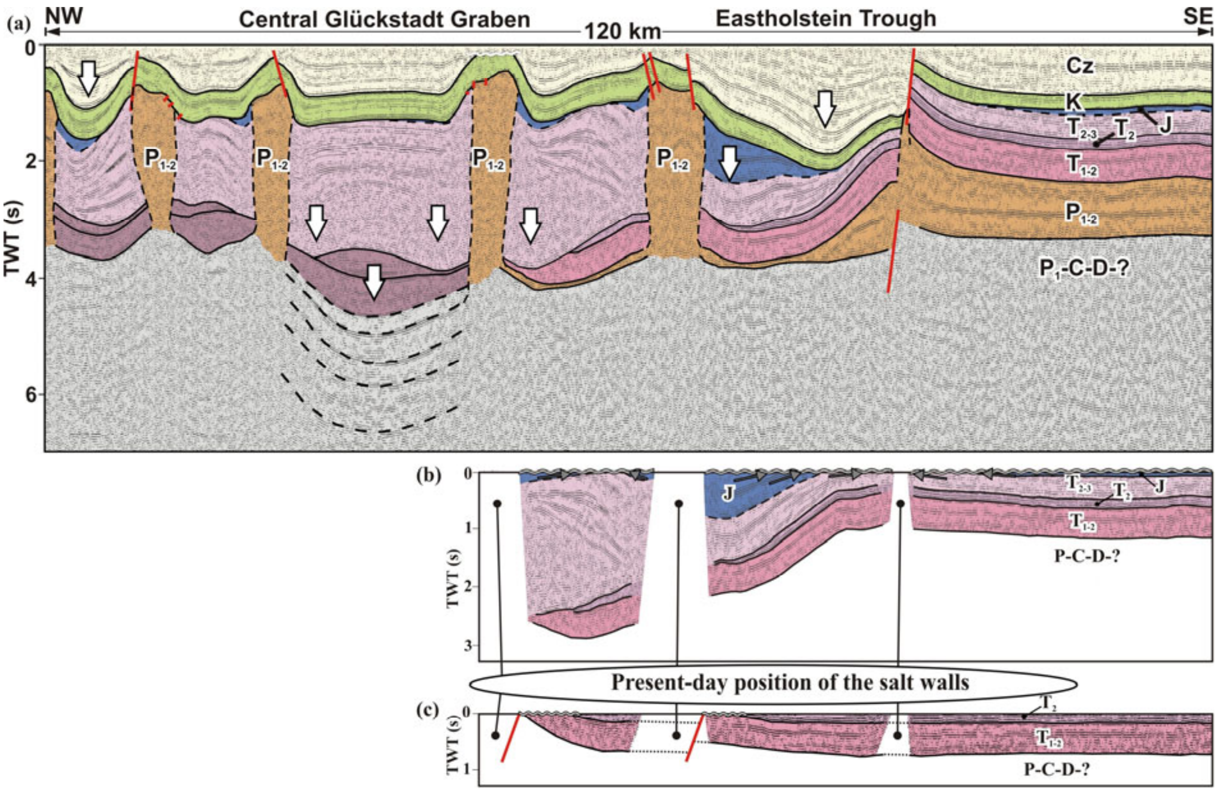

Figure 2. (a) Interpreted northwest–southeast transect across the Glückstadt Graben (profile 1 in Fig. 1; modified after [8]). Development of the Glückstadt Graben along the south-eastern part of profile 1 as visualized by flattening to selected stratigraphic levels: (b) reconstruction to the base of Cretaceous. Pre-Cretaceous regional erosion surface is shown and (c) reconstruction to the base of Keuper. Possible syn-rift faults and erosion are shown. Stratigraphic key: P_1-C-D - undivided Rotliegend, Carboniferous and Devonian deposits; $P_{1\text{-}2}$ - undivided salt-rich Rotliegend and Zechstein; $T_{1\text{-}2}$ –Buntsandstein; T_2 - Muschelkalk; $T_{2\text{-}3}$ - Keuper; J - Jurassic; K - Cretaceous; Cz - Cenozoic.

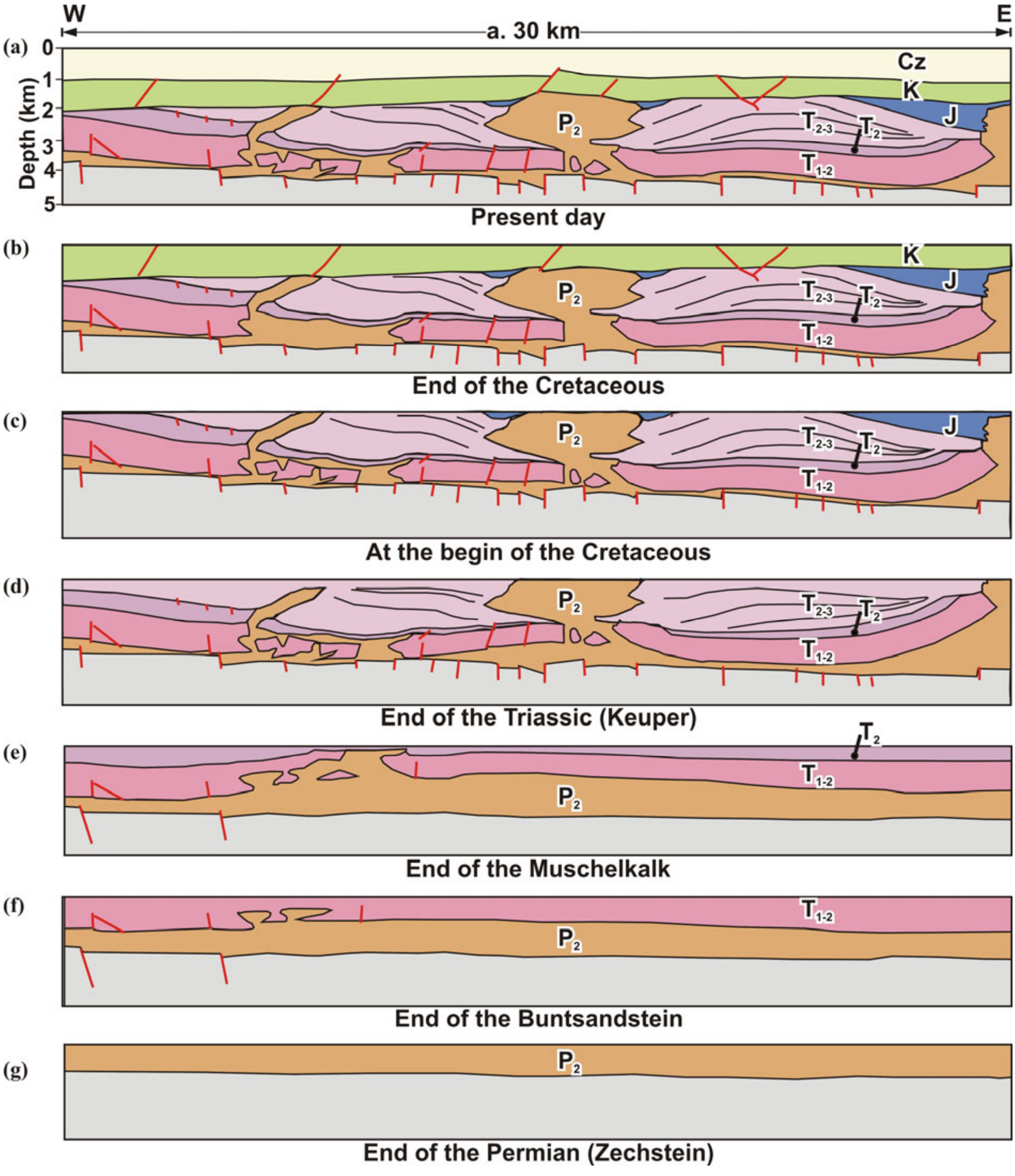

Figure 3. Sequential retro-deformation of the interpreted W-E seismic section (profile 2 in fig. 1) from the end of the Permian (Zechstein) (g) to the present-day geometry (a) (modified and simplified after [10]). Stratigraphic key: P_2 -Zechstein; $T_{1\text{-}2}$ –Buntsandstein; T_2 - Muschelkalk; $T_{2\text{-}3}$ - Keuper; J - Jurassic; K – Cretaceous; Cz - Cenozoic.

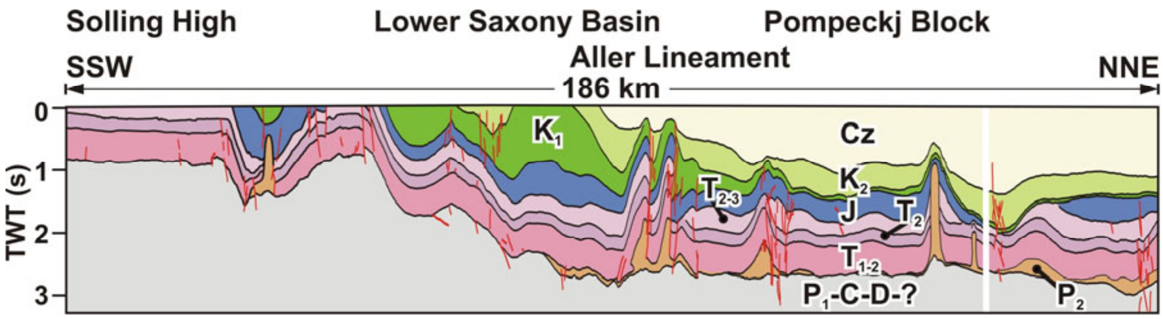

Figure 4. Interpreted seismic line (profile 3 in Fig. 1), running from the central North German Basin to the southern basin margin across the inverted Lower Saxony Basin (modified after [9]). Stratigraphic key: P_1-C-D - undivided Rotliegend, Carboniferous and Devonian deposits; P_2 -Zechstein; T_{1-2} –Buntsandstein; T_2 - Muschelkalk; T_{2-3} - Keuper; J - Jurassic; K_1 – Lower Cretaceous; K_2 – Upper Cretaceous; Cz - Cenozoic.

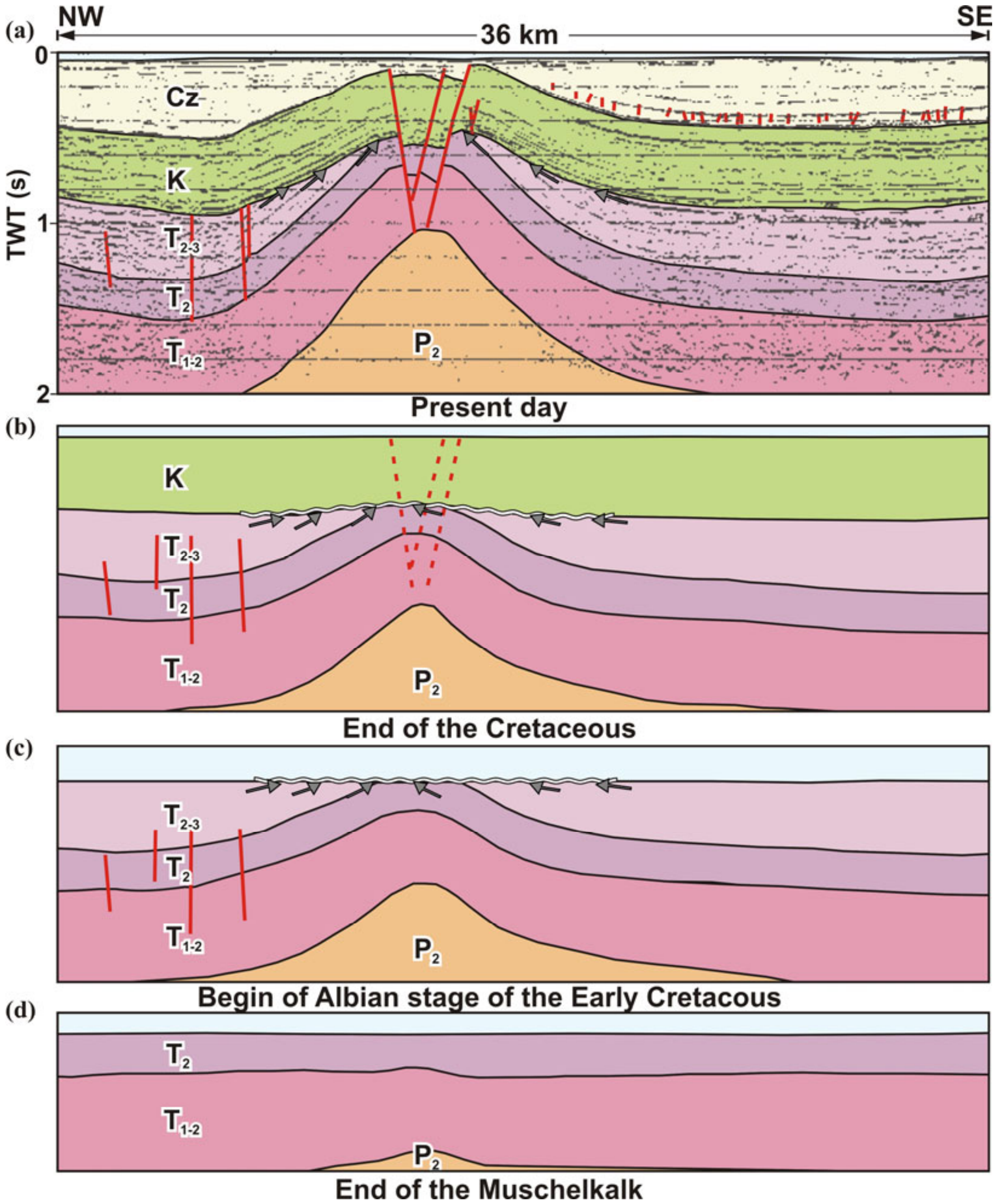

Figure 5. (a) Representative seismic section (profile 4 in Fig. 1), crossing salt pillow in the south-western part of the Bay of Kiel. (b)-(d) Structural reconstruction of the seismic line 6 from of the Permian (Zechstein) to present day (modified after [11]). For stratigraphic key see Fig. 4.

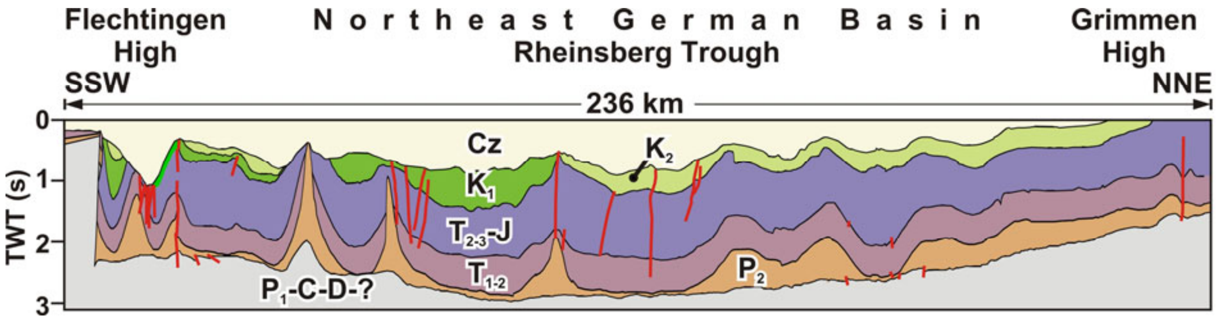

Figure 6. Interpreted reflection seismic line DEKORP BASIN9601 (profile 5 in Fig. 1), crossing the Northeast German Basin from the Grimmen High to the southern margin of the Central European Basin System (modified after [7, 23]. Stratigraphic key: P_1-C-D - undivided Rotliegend, Carboniferous and Devonian deposits; P_2 -Zechstein; $T_{1\text{-}2}$ – Buntsandstein-Muschelkalk; $T_{2\text{-}3}$-J –Keuper and Jurassic; K_1 – Lower Cretaceous; K_2 – Upper Cretaceous; Cz - Cenozoic.

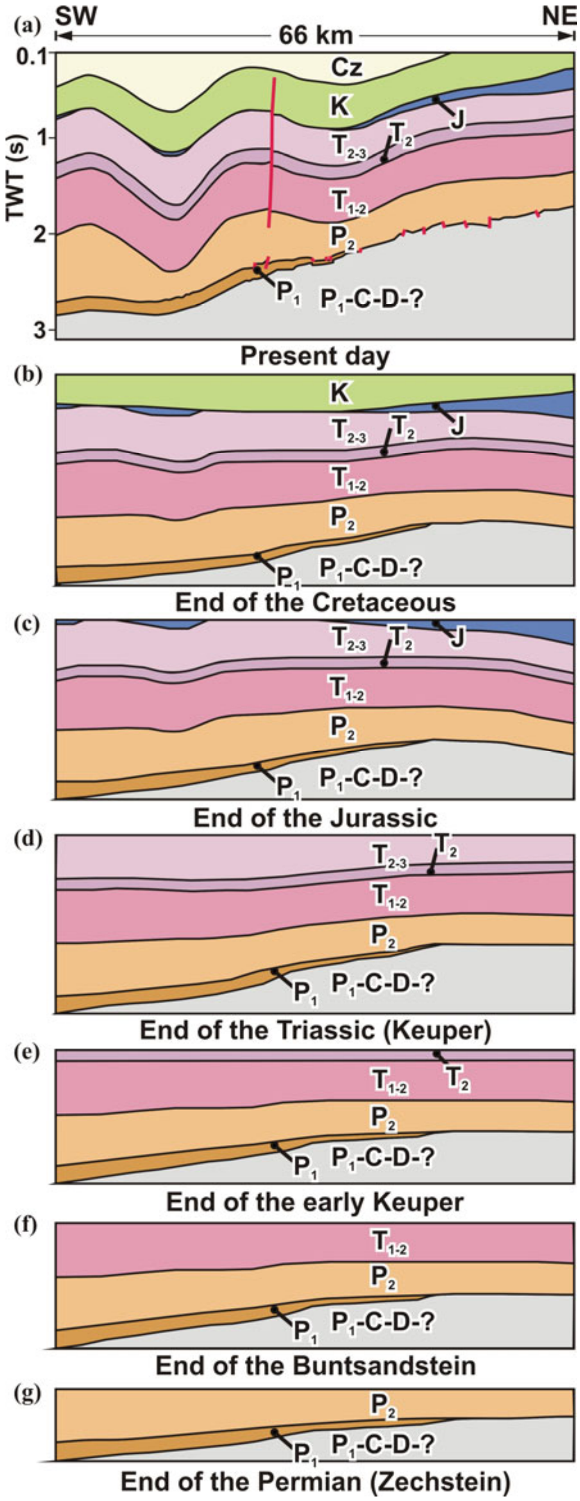

Figure 7. (a) Composed and interpreted seismic section from the RERIK area in the Mecklenburg Bay of the Baltic Sea (profile 6 in Fig. 1). (b)-(g) Geological model of evolution along the seismic line 5 from of the end of the Permian (Zechstein) to recent, using backstripped seismic data (modified and simplified after [12]). For stratigraphic key see Fig. 4.