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Ice-load induced tectonics controlled tunnel valley evolution – instances from the southwestern Baltic Sea

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A B S T R A C T

Advancing ice sheets have a strong impact on the earth's topography. For example, they leave behind an erosional unconformity, bulldozer the underlying strata and form tunnel valleys, primarily by subglacial melt-water erosion and secondarily by direct glacial erosion. The conceptual models of the reactivation of faults within the upper crust, due to the ice sheets' load, are also established. However, this phenomenon is also rather under-explored. Here, we propose a causal link between ice-load induced tectonics, the generation of near-vertical faults in the upper crust above an inherited deep-rooted fault and the evolution of tunnel valleys. The Kossau tunnel valley in the southeastern Bay of Kiel has been surveyed by means of high-resolution multi-channel seismic and echosounder data. It strikes almost south to north and can be mapped over a distance of ca 50 km. It is 1200–8000 m wide with a valley of up to 200 m deep. Quaternary deposits fill the valley and cover the adjacent glaciogenic unconformity. A near-vertical fault system with an apparent dip angle of >80°, which reaches from the top Zechstein upwards into the Quaternary, underlies the valley. The fault partially pierces the seafloor and growth is observed within the uppermost Quaternary strata only. Consequently, the fault evolved in the Late Quaternary. The fault is associated with an anticline that is between 700 and 3000 m wide and about 20–40 m high. The fault–anticline assemblage neither resembles any typical extensional, compressional or strike-slip deformation pattern, nor is it related to salt tectonics. Based on the observed position and deformation pattern of the fault–anticline assemblage, we suggest that these structures formed as a consequence of the differential ice-load induced tectonics above an inherited deep-rooted sub-salt fault related to the Glückstadt Graben. Lateral variations in the ice-load during the ice sheet's advance caused differential subsidence, thus rejuvenating the deep-rooted fault. As a result, the inherited fault propagated upwards across the Zechstein and post-Permian overburden and further grew during the ice sheet's retreat. The developing fault and anticline system under the ice sheet created a weakness zone that facilitated erosion by pressurized glacial and subglacial melt-water, as well as by the glaciers themselves. Near-vertical faults cutting through the post-Permian are abundant in the southwestern Baltic realm, which implies that the ice-load induced tectonic activity described above was not an isolated incident.

1. Introduction

Three major ice advances affected northern and northwestern Europe during the Late Pleistocene period: the Elsterian, Saalian and Weichselian advances (Liedtke, 1981; Ehlers, 1996). Tunnel valleys originated as subglacial channels and are defined as deep channel-form features incised into the Pleistocene at glaciated sites all over the world, but particularly in the Northern Hemisphere. These erosional valleys were intensively studied over the past two decades (Cofaigh, 1996; van Dijke and Veldkamp, 1996; Huuse and Lykke-Andersen, 2000; Praeg, 2003; Jørgensen and Sandersen, 2004; BurVal Working Group, 2006; Rattas, 2007), since they hold significant amounts of groundwater or, rarely, economic shallow gas. They may also contain aggregate for construction.

The valleys' formation is primarily attributed to subglacial melt-water erosion, and secondarily to direct glacial erosion, incising the underlying Tertiary strata during the glacial coverage (for a critical discussion see, e.g., Huuse and Lykke-Andersen, 2000). In addition, several authors mentioned the spatial correlation between the tunnel valleys and the faults beneath (Bruun-Petersen, 1987; Lykke-Andersen et al., 1993; Salomonsen, 1993, 1995; Schwarz,

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1996; Huuse and Lykke-Andersen, 2000; Sandersen and Jørgensen, 2002; BurVal Working Group, 2006). However, a causative inter-relation was never established.

The tunnel valleys were investigated in the western Baltic realm over the course of several studies. Huuse and Lykke-Andersen (2000) mapped the onshore distribution of these valleys in Denmark and northern Germany (Fig. 1). Stackebrandt et al. (2001) showed a spatial correlation between the tunnel valleys and the fault systems related to the major tectonic elements in the region that had not previously been discussed. Based on some very high-resolution single-channel seismic data, Atzler (1995) mapped the offshore prolongation of the Kossau valley into the Bay of Kiel by means of Boomer data of 0.5–11 kHz (−6 db interval) with up to 30 ms two-way travel time (TWT) signal penetration (Figs. 2 and 3). The full width of the valley is not resolved in the bathymetry; however, a narrow channel is presented (Fig. 4).

In this study, we examine the interplay between ice sheet loading/unloading and the resulting vertical movement of an inherited fault system related to the southeastern segment of the Glückstadt Graben (GG) in controlling the formation and evolution of the Kossau tunnel valley. The Universities of Aarhus and Hamburg collected the information for the dataset that we used within the framework of the BaltSeis and NeoBaltic projects (Hübscher et al., 2004; Hansen et al., 2005; Hübscher et al., 2010). It is also supplemented by information from four surrounding exploration wells (Fig. 3).

2. Setting and previous work

The study area – the Bay of Kiel in the southwest Baltic Sea – is part of the Northeast German Basin (NEGB) and represents the NE part of the South Permian Basin (Fig. 2). The NEGB belongs to a series of Carboniferous-Permian intercontinental basins extending from the North Sea to northern Poland, such as the GG, which is located in the southern corner of the study area (Fig. 2). The GG represents an NNE–SSW trending post-Permian sub-basin of the Central European Basin System (Maystrenko et al., 2005). The GG is one of the sedimentary basins where the sedimentary cover has been strongly affected by salt tectonics. The GG can be subdivided into three main domains (Fig. 2): (i) the Central GG; (ii) the marginal Eastholstein, Westholstein and Hamburg Troughs; and (iii) the outer Eastholstein, Westholstein and Mecklenburg blocks at the western GG flanks (Maystrenko et al., 2008). The onset of the regional E–W directed extension at the transition between the Middle and Late Triassic created N–S trending depocentres, as well as the associated salt structures, such as the GG. The eastern SW–NE trending marginal Eastholstein Trough evolved during the Jurassic period (Maystrenko et al., 2011).

Hansen et al. (2005) extensively studied the stratigraphy and structural evolution of the Bay of Kiel. According to these authors, the E–W directed regional extension during the Late Triassic and Early Jurassic, which created the GG, corresponds with the E–W striking fault system on top of a salt pillow in the Bay of Kiel. The development of the Central North Sea Dome, due to plutonic activity (Ziegler, 1990; Underhill, 1998), caused a period of uplift and erosion in the Middle Jurassic to Early Cretaceous, which removed parts of the Lower Jurassic and Upper Triassic successions. Sedimentation resumed towards the end of the Early Cretaceous and the subsidence continued without major tectonic activity.

On the Cretaceous to Cenozoic transition, the Alpine Orogenesis started and the regional stress field changed from extensional to compressional (Ziegler, 1990), causing a reactivation of vertical salt tectonics. Hansen et al. (2005, 2007) and Hübscher et al. (2010) stated that the post-Palaeozoic stratigraphic boundaries generally follow along the top of the Zechstein salt throughout the southwest Baltic realm.

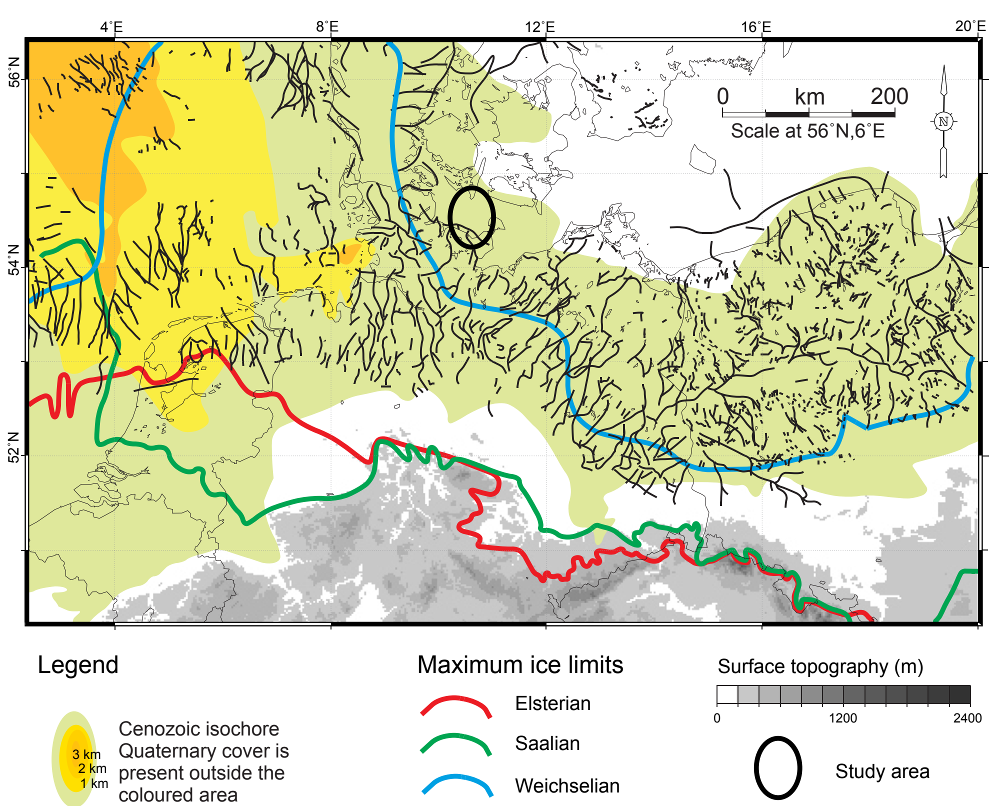

Fig. 1. Overview of Quaternary tunnel valleys in northwest Europe (modified after Huuse and Lykke-Andersen, 2000).

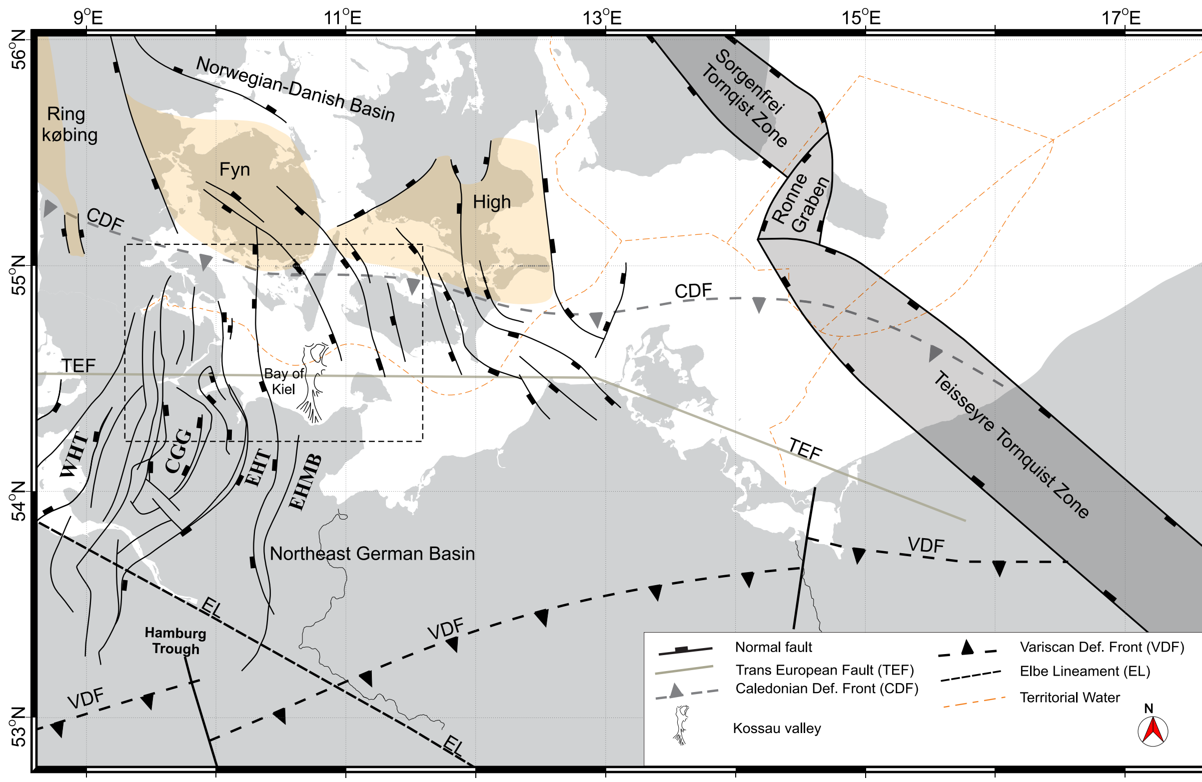

Fig. 2. Tectonic map of Northeastern German Basin with main structural elements (compiled from Baldschuhn et al., 1991; Krauss, 1994; Vejbæk, 1997; Bayer et al., 1999; Clausen and Pedersen, 1999; Kossow et al., 2000). The location of the Kossau tunnel valley is based on Atzler (1995). Dashed rectangle shows the study area. EHMB, Eastholstein Mecklenburg Block; EHT, Eastholstein Trough; CGG, Central Glückstadt Graben; and WHT, Westholstein Trough.

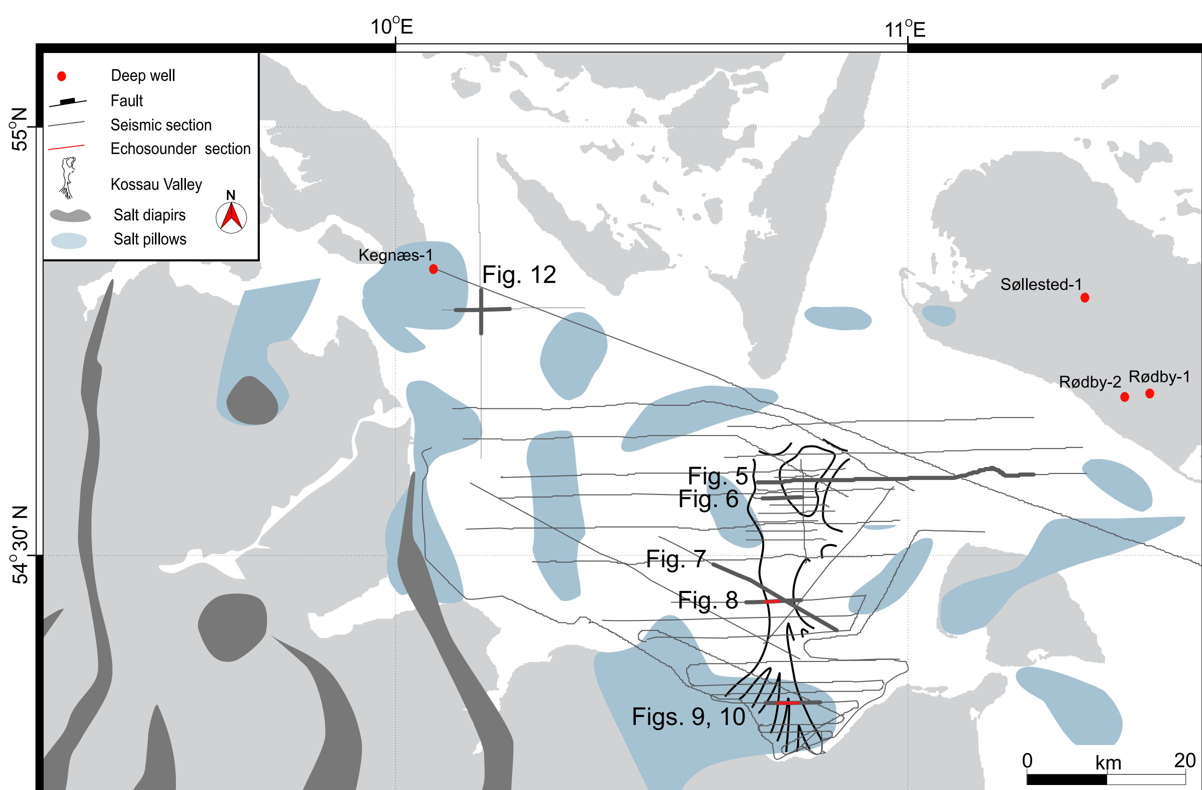

Fig. 3. Map of the study area, showing the positions of the seismic and echosounder sections as well as deep exploration wells. The location of the Kossau tunnel valley is based on Atzler (1995), the distribution of salt diapirs and pillows on Lokhorst et al. (1998).

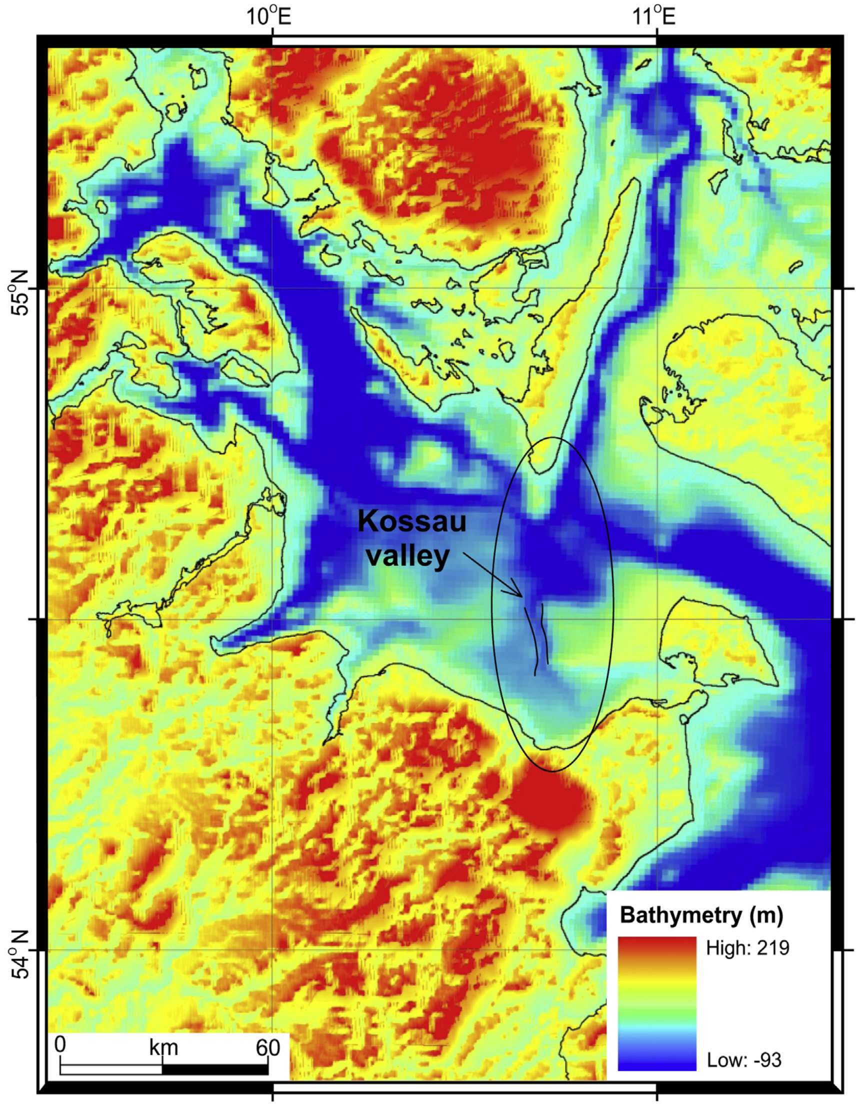

Fig. 4. Bathymetry of the study area (based on Seifert et al., 2001).

Since the mid-Quaternary times, the study area and adjacent areas have experienced at least three extensive glaciations: the Elsterian, Saalian and Weichselian ice sheets. These ice sheets covered most of the area presently known as Denmark, as well as northeastern and northwestern Germany and Poland (Liedtke, 1981; Ehlers, 1996). Characteristic features for these glaciations include tunnel valleys (Fig. 1), which were first recognized by Gottsche (1897) and were described as channels by Wolff (1907, 1909). Most of the valleys south of the study area are located in Schleswig–Holstein, have a depth of between 200 and 300 m and are up to 4 km wide (for an overview see, e.g. Piotrowski, 1994).

This author found that the tunnel valleys in the region are often filled with Lauenburg Clay, consisting of glaciolacustrine silts and clays deposited during the Elsterian ice sheet retreat. The maximum Saalian ice extent reached the low mountain range in central Germany, while the maximum Elsterian ice extent only reached the river Elbe (Fig. 1; Ehlers et al., 2004). Some 20,000 years ago, the Weichselian ice sheet covered eastern and northern Denmark, northeastern Germany, northern Poland and northern Britain (Fig. 1; Pasierbski, 1979; Bowen et al., 1986; Cameron et al., 1987; Long et al., 1988; Ehlers and Wingfield, 1991). The ice movement direction was approximately perpendicular to the present shoreline of the Baltic Sea Basin (Fig. 1; Piotrowski, 1994, 1997; Piotrowski and Tulaczyk, 1999).

The load of the inland glaciers pressed the lithosphere (including the earth's crust) into the asthenospheric mantle, which, after the ice retreat, was unloaded and uplifted over several thousand years, attaining an isostatic equilibrium (see Thorson, 2000; Sirocko et al., 2008 and the references therein). For example, the isostatic rebound after the last ice advance is still happening and will continue for another few thousand years (e.g. Le Meuer, 1996). Accordingly, the prevailing regional tectonic stress caused by plate convergence in the Alps or spreading in the Central Atlantic is overprinted by glacial stresses (Roth and Fleckenstein, 2001). Elastic crustal flexure resulted in a circular depression below the centre, caused a radial outward flow of the asthenosphere (Daly, 1934). The decay of the ice sheets is likely to have changed the equilibrium situation in the crust and upper mantle (Sirocko et al., 2008). The elastic response to the temporal and spatial varying ice-loads is considered to be instantaneous, whereas the viscoelastic response of the mantle is much slower and is active even thousands of years after the ice retreat (Stewart et al., 2000). These authors showed how the ice sheet loading/unloading may modulate not only the deep-seated viscoelastic response of the Earth, but also the nature and incidence of upper-crustal faulting, in addition to earthquake generation.

Sirocko et al. (2008) introduced several conceptual models for the interaction between ice-loading/unloading and salt tectonics. For example, one of these models describes how diapir rise is hindered during glaciation and how faults are blocked. After the ice sheets retreat, the faults are reactivated. Lehné and Sirocko (2010) observed a recent surface deformation of several millimetres per year along lineaments in northern Germany. Some of these lineaments coincide with the normal faults of the GG, which are covered by salt walls or diapirs. According to these authors, the deformation is most likely caused by an ongoing isostatic adjustment since time of the Weichselian maximum. Based on seismic data, Brandes et al. (2011) developed a tectonic model showing the reactivation of basement faults as a consequence of ice sheet loading. Brandes et al. (2011) also pointed out that the advancing ice sheet caused far field extensions within northwestern Germany, which might have reactivated the pre-existing normal faults.

Ice-load induced tectonics in the upper crust has been described several times in the literature. However, until now and to the best of our knowledge, there is no seismic dataset that elucidated this process in the upper crust from the surface down to the Mesozoic strata without any gap.

3. Database

The Universities of Aarhus and Hamburg collected a high-resolution multi-channel seismic dataset under the umbrella of the research projects BaltSeis and NeoBaltic (Fig. 3; Hübscher et al., 2004).

For the airgun seismics, either a 100 bar sleeve gun cluster (4 guns with 1.1 l total volume) or a single GI-Gun with a 0.7 l Generator or a 1.7 l Injector chamber volume were used (Table 1). The active length of the seismic cable was 200–300 m. The achieved penetration varied between 1.5 and 2.0 s TWT. All data were post-stack time migrated. Amplitude losses were compensated by a power function, which gradually enhanced reflection amplitudes with travel time. Hence, abrupt vertical or horizontal variations in reflection amplitudes were considered to be a hint for lithological variations.

Several profiles were measured with a Sparker source. Three electrode pairs with distances of ca 1.2 m were fired with 1800 kJ. The main signal frequency was about 250 Hz and the sample rate was 0.5 ms. The post-stack time migrated airgun and Sparker seismic data were uploaded to the HIS "KINGDOM" interpretation system for structural interpretation. Additional information was gathered with a hull-mounted echosounder operated with a parametric 6–8 kHz signal.

To facilitate and verify the seismic interpretations, four exploration wells were used to provide the stratigraphic constraints necessary for correlating the various interpreted horizons on the seismic profiles (Fig. 3). These wells include the following: the onshore Søllested-1, Rødby-1 and Rødby-2 (Nielsen and Japsen, 1991) and the offshore Kegnæs-1 exploration wells (Gearhart Geo Consultants, 1985).

Table 1
Seismic and hydroacoustic equipment used for acquiring all profiles shown in this study (see text for details).

Figure number	Survey name/year	Source	Streamer
5	DA99/1999	Sleeve Gun Array	300 m, 48 channels
6	DA99/1999	Sleeve Gun Array	300 m, 48 channels
7	HE172/2002	Sleeve Gun Array	300 m, 48 channels
8a	AL380/2011	Sparker	200 m, 64 channels
8b	AL380/2011	SES-2000	
9	AL380/2011	GI-Gun	200 m, 64 channels
10	AL380/2011	SES-2000	

4. Observations

4.1. Stratigraphic framework

The seismo-stratigraphic scheme used in this study is based on Hansen et al. (2005). These authors identified seven major post-Permian horizons across the entire study area (Fig. 5). These include: Base Middle Triassic, Base Upper Triassic, Base Jurassic, Mid Jurassic Unconformity (MJU), Base Upper Cretaceous (Base Chalk Group), Base Cenozoic and the Base Quaternary Unconformity (here: Base Glaciogenic Unconformity; BGU). Other internal reflections are present within the Upper Triassic, Jurassic, Upper Cretaceous and the Cenozoic successions. All of the horizons can be traced over the entire study area, except for the Jurassic sediments, which only exists in the eastern part (Hansen et al., 2005). The reduced signal-noise ratio of the lowermost 1.5–2 s TWT limits the interpretation of the top Zechstein surface. However, according to Hansen et al. (2005, 2007), the stratigraphic boundaries are sub-parallel to the top of the Zechstein salt.

4.2. Fault and anticline system

In Fig. 5a, the entire post-Permian succession reveals a slightly asymmetric triangular anticline between shots 2927 and 2995. Its apparent width is 1240 m and the height is ca 30 ms TWT (Fig. 5b). A near-vertical fault dissects the anticline. The Upper Cenozoic strata terminate against an erosional valley that is ca 2700 m wide and approximatley 160 ms TWT deep. The valley is filled and covered by Quaternary sediments (Fig. 5c). The valley's axis is offset to the anticline crest. The Cenozoic strata adjacent to the west of the valley are folded.

Further south, the triangular anticline converts into a narrow anticline with a width of ca 620 m (Fig. 6). The height decreases slightly with depth. A vertical set of listric and plane blind faults dip towards two near-vertical faults that cut through the anticline. One of them reaches at least from Muschelkalk into the infilled erosional valley. The contact between the infilling and the adjacent strata is seen as a continuous reflection. Cenozoic strata west of the valley are folded.

Towards the south, the anticline widens to approximately 3000 m. Here, it is ca 50 ms TWT high (Fig. 7). Pockmarks are present in the Upper Cretaceous from 510 ms TWT above IUC2 down to 690 ms TWT below IUC1. The Cretaceous and Cenozoic internal reflections are overprinted; the reflection pattern vertically turns from sub-parallel within the Triassic to chaotic above. Blind faults are abundant within the Cenozoic, but also occur in the Cretaceous and Triassic. Several near-vertical faults cut through the post-Permian succession and concentrate in the central anticline. Two of them reach up and pierce the seafloor. The seafloor rises by about 10 m southeast of the piercing point. The northwestern flank of the anticline is faulted with an outwards decreasing dip angle. Above the anticline, a 190 ms TWT deep and 5200 km wide valley that is covered by Quaternary deposits, cuts into the Cenozoic. The valley fill deposits consist of a lower seismically chaotic unit, followed by sub-parallel and northwestward diverging internal reflections disrupted by the near-vertical faults. Truncated strata mark the erosional valley. Again, only the Cenozoic strata west of the valley reveal folds.

The combined interpretation of the Sparker and echosounder data elucidates how seismic resolution influences near-vertical fault images (Fig. 8). Only the piercing point at the seafloor is

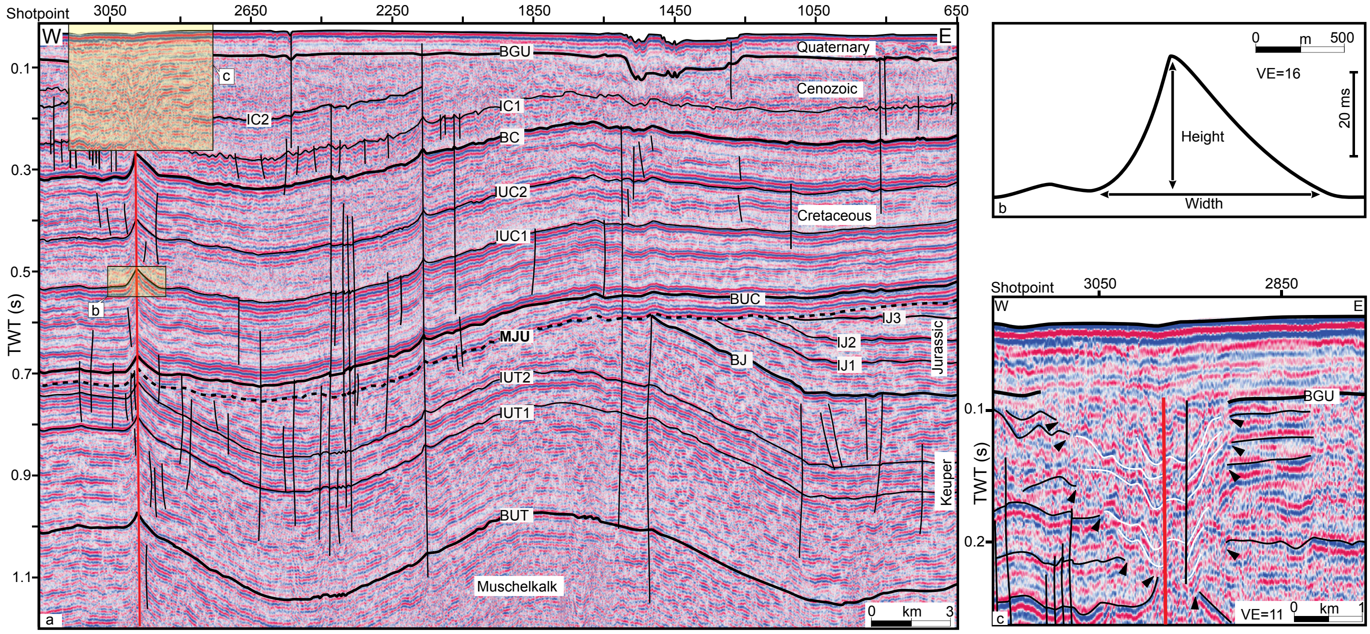

Fig. 5. Interpreted seismic cross-section from eastern Bay of Kiel (for location, see Fig. 3). (a) The section shows the entire post-Permian stratigraphy within the study area, revealing how the angular MJU separates the Triassic and Jurassic strata from the Cretaceous and Cenozoic sediments. Note the absence of the Jurassic sediment to the west, allowing the Upper Triassic sediments to truncate at the MJU surface. The entire post-Permian succession reveals anticline. A deep erosional valley is observed above the anticline. (b) Interpretation of the anticline. (c) Close-up view of the erosional valley (the valley boundaries are marked by black arrows). BUT, Base Upper Triassic; IUT 1 and 2, Internal Upper Triassic 1, 2 and 3; BJ, Base Jurassic; IJ 1, 2 and 3, Internal Jurassic 1, 2 and 3; MJU, Mid Jurassic Unconformity; BUC: Base Upper Cretaceous; IUC 1 and 2, Internal Upper Cretaceous 1 and 2; BC, Base Cenozoic; IC 1, 2 and 3, Internal Cenozoic 1, 2 and 3; and BGU, Base Glaciogenic Unconformity.

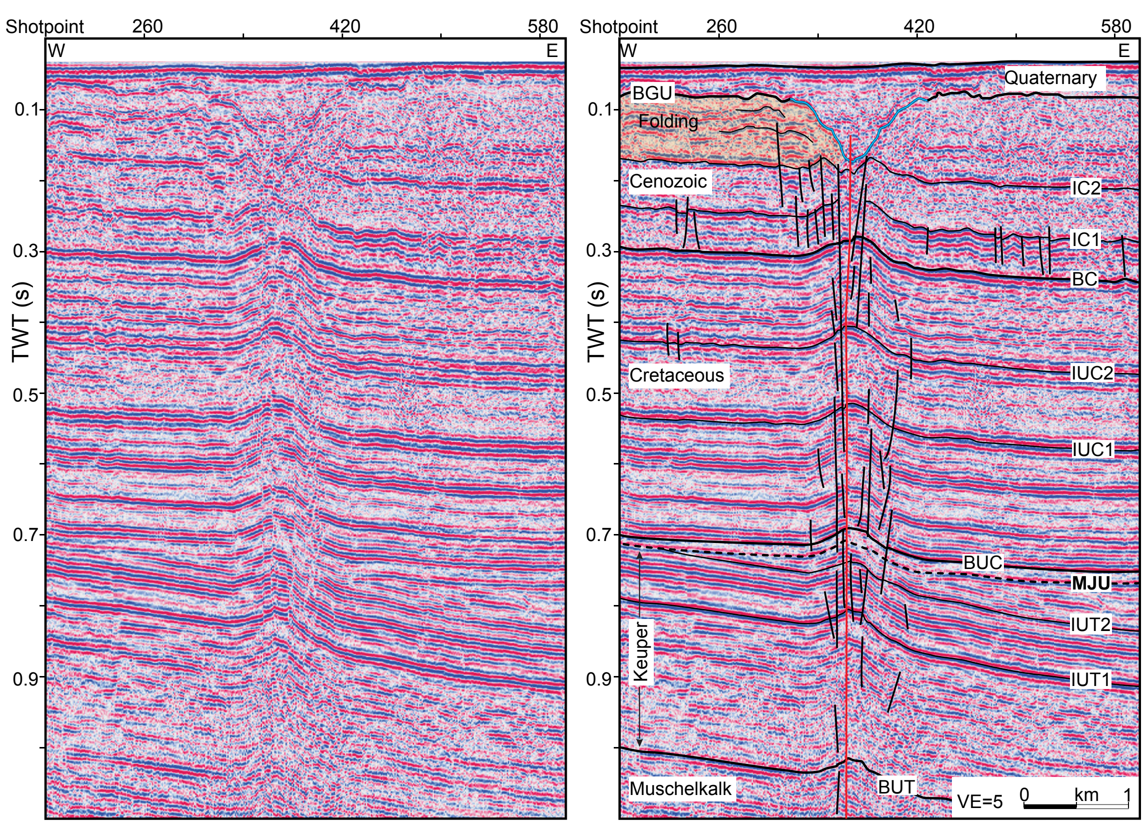

Fig. 6. W–E cross-section from northern Kossau valley (for location, see Fig. 3). A distinct reflection marks the erosional valley that cuts into the Cenozoic succession. Directly beneath, the entire post-Permian succession is folded. Upwards diverging faults characterize the anticline and adjacent strata. Cenozoic deposits are folded west of the valley. BUT; Base Upper Triassic; IUT1 and 2: Internal Upper Triassic 1 and 2; MJU: Mid Jurassic Unconformity; BUC: Base Upper Cretaceous; IUC 1 and 2: Internal Upper Cretaceous 1 and 2; BC: Base Cenozoic; IC 1 and 2: Internal Cenozoic 1 and 2; and BGU, Base Glaciogenic Unconformity.

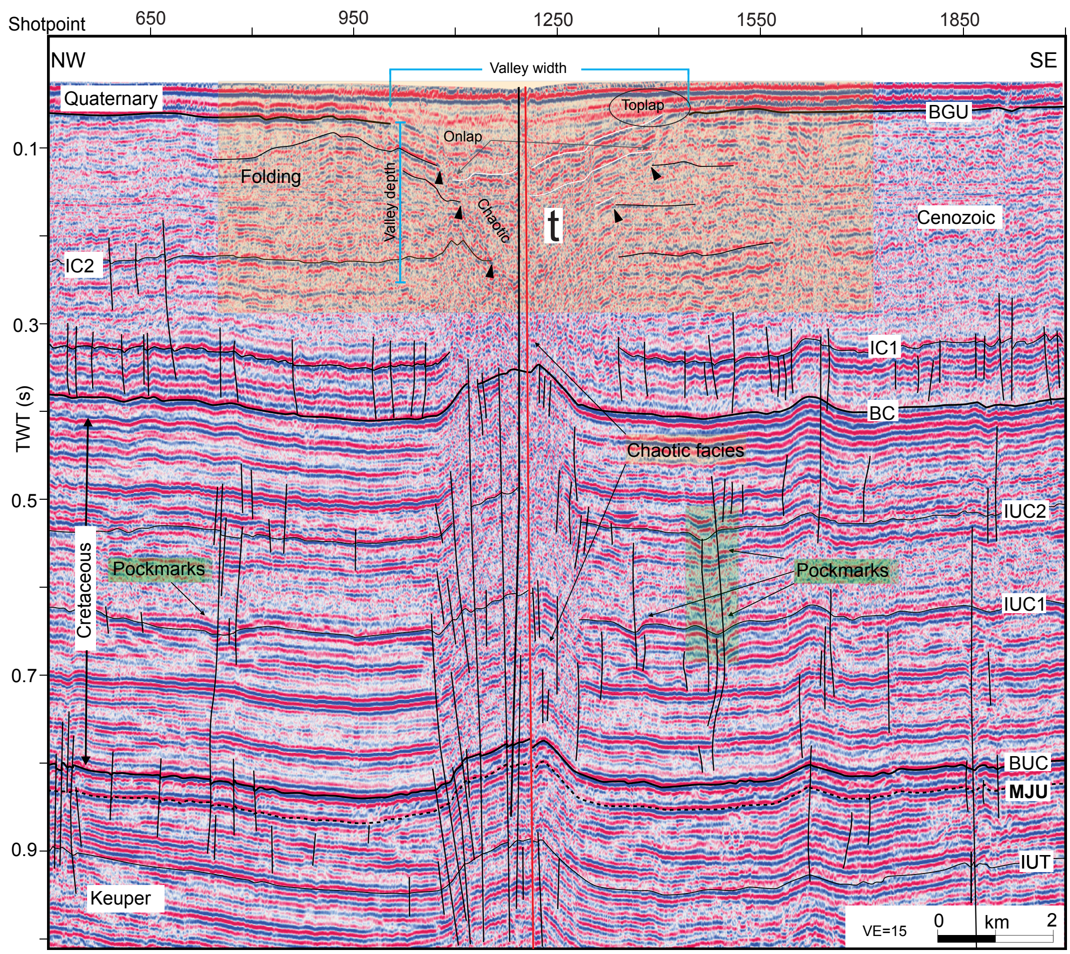

Fig. 7. NW–SE cross-section from middle Kossau valley (for location, see Fig. 3). The section shows entire post-Permian stratigraphy, reveals an erosional valley cutting into the Cenozoic. Valley boundaries are marked by black arrows. The westward dipping lower valley fill deposits may represent till (t). An anticline between shots 1100 and 1275 is located beneath the valley. Anticline reflections from the Triassic are well resolved but blurred within the Cretaceous and Cenozoic. Several vertical faults cut through the entire successions and two of them appear pierce the seafloor. Cenozoic deposits are folded northwest of the valley. Pockmarks are present within Upper Cretaceous. IUT: Internal Upper Triassic; MJU: Mid Jurassic Unconformity; BUC: Base Upper Cretaceous; IUC 1 and 2: Internal Upper Cretaceous 1 and 2; BC: Base Cenozoic; IC 1 and 2: Internal Cenozoic 1 and 2; and BGU, Base Glaciogenic Unconformity; t: till.

visible in the Sparker data. The 6 kHz parametric echosounder data, with a wavelength of ca 0.30 m in shallow sediments, resolve the complex valley fill pattern in greater detail. The presence of shallow gas hinders deeper signal penetration. The data show an upwards-concave valley fill with chaotic and disrupted facies, followed by inwards diverging reflections (onlap and toplap facies). The substrata west of the valley are folded.

The seismic profile in Fig. 9 strikes W–E and shows the southernmost part of the Kossau valley. An anticline of less than 1000 m in width underlies the erosional valley. Within the central anticline, a near-vertical fault cuts through the post-Permian succession and reaches upwards into the valley fill deposits. Several near-vertical faults influence the western flank of the anticline and one of them reaches into Quaternary deposits. Laterally truncated Cenozoic strata and onlap of the infilling strata identify the valley. The valley fill mainly reveals a chaotic pattern. In Fig. 10, the parametric echosounder data from the central valley show that these faults propagate upwards into the (upper and) Holocene valley fill deposits. The western fault reveals growth.

Summarizing, the erosional valley strikes almost south to north and it could be mapped over a distance of ca 50 km (Fig. 11). It is 1200–8000 m wide and up to 200 ms TWT deep, calculated as the difference between the maximum TWT to the valley axis and to the adjacent valley shoulders. Assuming average interval velocities of the valley fill deposits between 1600 and 2000 m/s, the valley is ca 100–150 m deep. Beneath, a 700–3000 m wide anticline of 20–50 ms TWT in height is visible in the Triassic to Lower Tertiary strata. Its shape varies from triangular to round. Assuming an interval velocity of 2000–3000 m/s, the anticline is 20–75 m high. A near-vertical fault strikes N–S to NNE–SSW and cuts through the entire succession, running towards Langeland (Fig. 11). This fault terminates either a few metres beneath the seafloor and within the uppermost (Holocene) succession, or it pierces the seafloor. The apparent dipping angle varies depending on the assumed interval velocity. Yet, it is >80° in all cases. Growth strata have been observed in one profile. We observe no relationship between the width of the valley and the width of the anticline.

It is noteworthy that similar anticlines exist without an erosional valley above (e.g. beneath shot 2150 in Fig. 5a). An instance where two perpendicular profiles cross such an anticline in the northwestern Bay of Kiel is given in Fig. 12. The W–E striking profile reveals an anticline similar to those beneath the Kossau tunnel valley, including a near-vertical fault. The perpendicular profile suggests a structural reverse fault (Brooks, 2000).

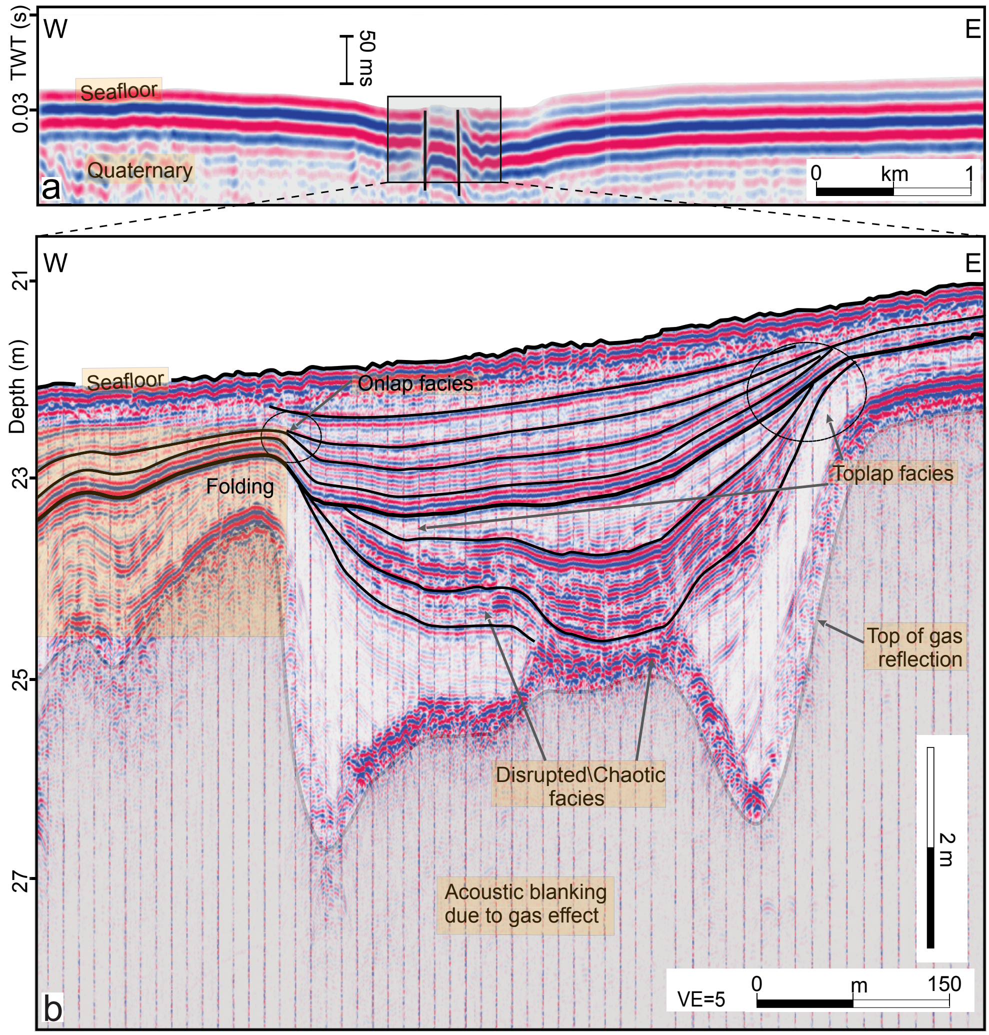

Fig. 8. 250 Hz Sparker (a) and 6 kHz echosounder data (b) from southern Kossau valley (for location, see Fig. 3). The Sparker data show faults piercing the seafloor. The echosounder data reveal shallow basin fill deposits dipping towards the valley center. Cenozoic deposits are folded west of the valley.

5. Interpretation and discussion

The vertical correlation between the near-vertical fault, the anticline and the valley implies a tectonic control on the evolution of the Kossau tunnel valley, particularly, since the growth strata within the valley fill suggests a Late Quaternary evolution of faults and anticline. If this interpretation holds, the valley represents, according to our knowledge, the first Quaternary valley for which this causative correlation is clearly evident. However, the fault–anticline assemblage has a non-typical geometry. Consequently, alternative interpretations have to be considered.

5.1. Velocity pull-ups

Before discussing the structural evolution of the near-vertical fault and the anticline beneath the valley, imaging artefacts have to be ruled out. Velocity pull-ups caused, for example, by an interval velocity of the valley fill deposits higher than the adjacent Tertiary strata could create an apparent antiform beneath. Jørgensen et al. (2003) studied tunnel valleys within Denmark and found clay till within the lower valley that had interval velocities of 2250 m/s. Moreover, the highly reflective characteristics of the lower valley fill deposits (Figs. 5–7) could imply the existence of till deposits.

One could speculate that these till deposits caused the velocity pull-ups. However, there are several arguments against this assumption. First, velocity pull-ups created by high-velocity valley fill deposits, like till, imply a correlation between the geometries of the anticline, the valley and the valley fill deposits. A simple comparison of these geometries shows that such this correlation is not the case (Fig. 13).

Second, velocity pull-ups caused by the valley fill further imply that the average interval velocity of the entire valley fill is higher than that of the neighbouring strata. However, the upper valley fill deposits contain soft, unconsolidated and gassy sediments from the Holocene era. Thus, a lower interval velocity would be expected in the valley fill deposits compared to that of the adjacent Tertiary strata, which were compacted by the ice-load.

Third, an increase of the interval velocity within the valley would result in a pull-up of the valley base itself, which is not observed in any of the profiles. Instead, the valley sometimes cuts into the anticline, as shown in Fig. 5a. This suggests that the anticline evolved prior to the valley's formation.

Fourth, comparable anticlines are also observed in places where no tunnel valleys are present above (e.g. Fig. 5a). The possibility that the observed anticline is a velocity pull-up created by high-velocity valley fill deposits is therefore ruled out.

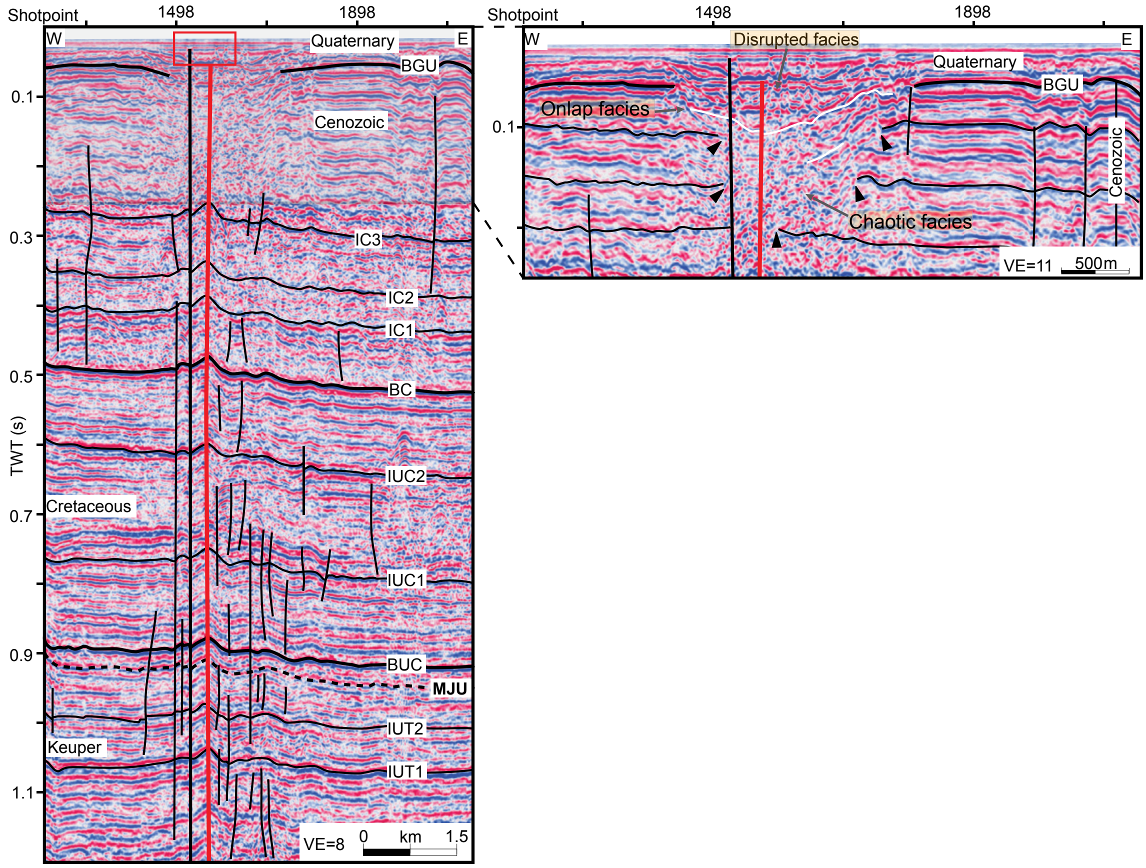

Fig. 9. W–E cross-section from southern Kossau valley (for location, see Fig. 3). The erosional valley, filled by Quaternary deposits, intersected the Cenozoic. Valley boundaries are marked by black arrows. Faults disrupt strata from the anticline beneath the valley, some reach upwards into the Quaternary. The red rectangle marks the location of Fig. 10. IUT 1 and 2: Internal Upper Triassic 1, 2 and 3; MJU: Mid Jurassic Unconformity; BUC: Base Upper Cretaceous; IUC 1 and 2: Internal Upper Cretaceous 1 and 2; BC: Base Cenozoic; IC 1, 2 and 3: Internal Cenozoic 1 and 2; and BGU, Base Glaciogenic Unconformity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

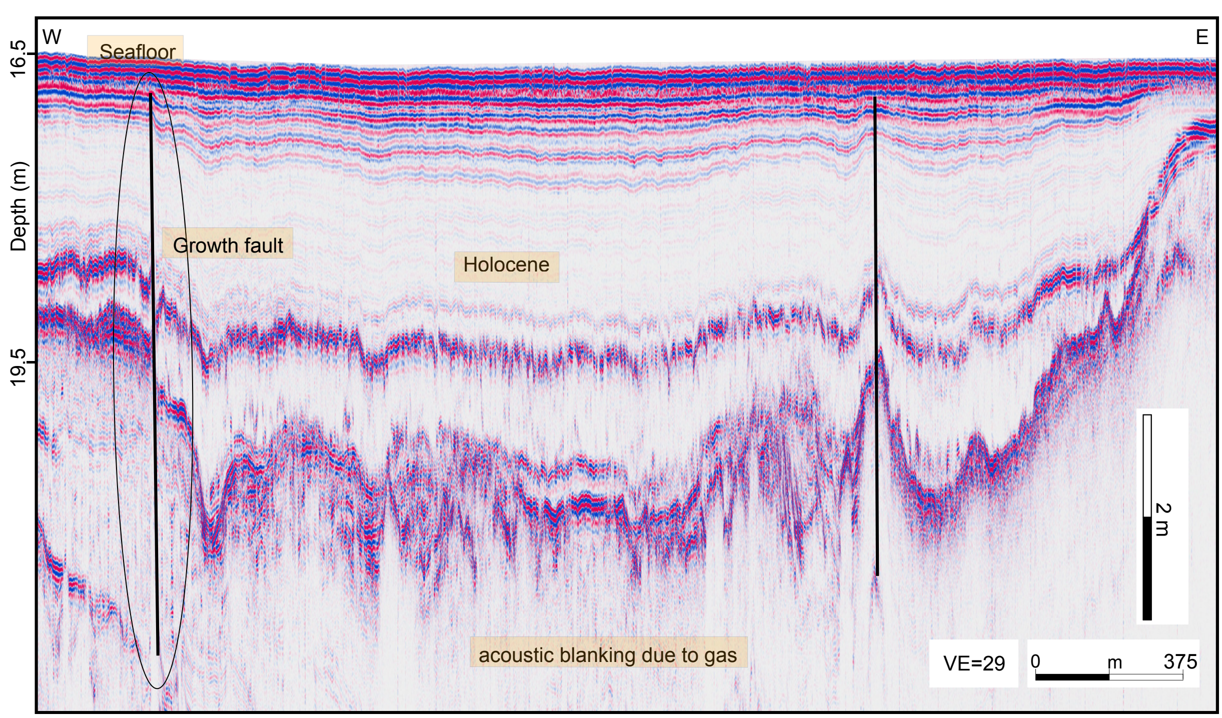

Fig. 10. Parametric echosounder profile from central Fig. 8 showing a typical infill sequence, consisting of a lower seismically disrupted/chaotic unit, followed by seismically a middle well-layered unit (for location, see Figs. 3 and 9). The two faults propagate into the valley fill deposits. The western fault reveals growth indicating syn-kinematic sedimentation.

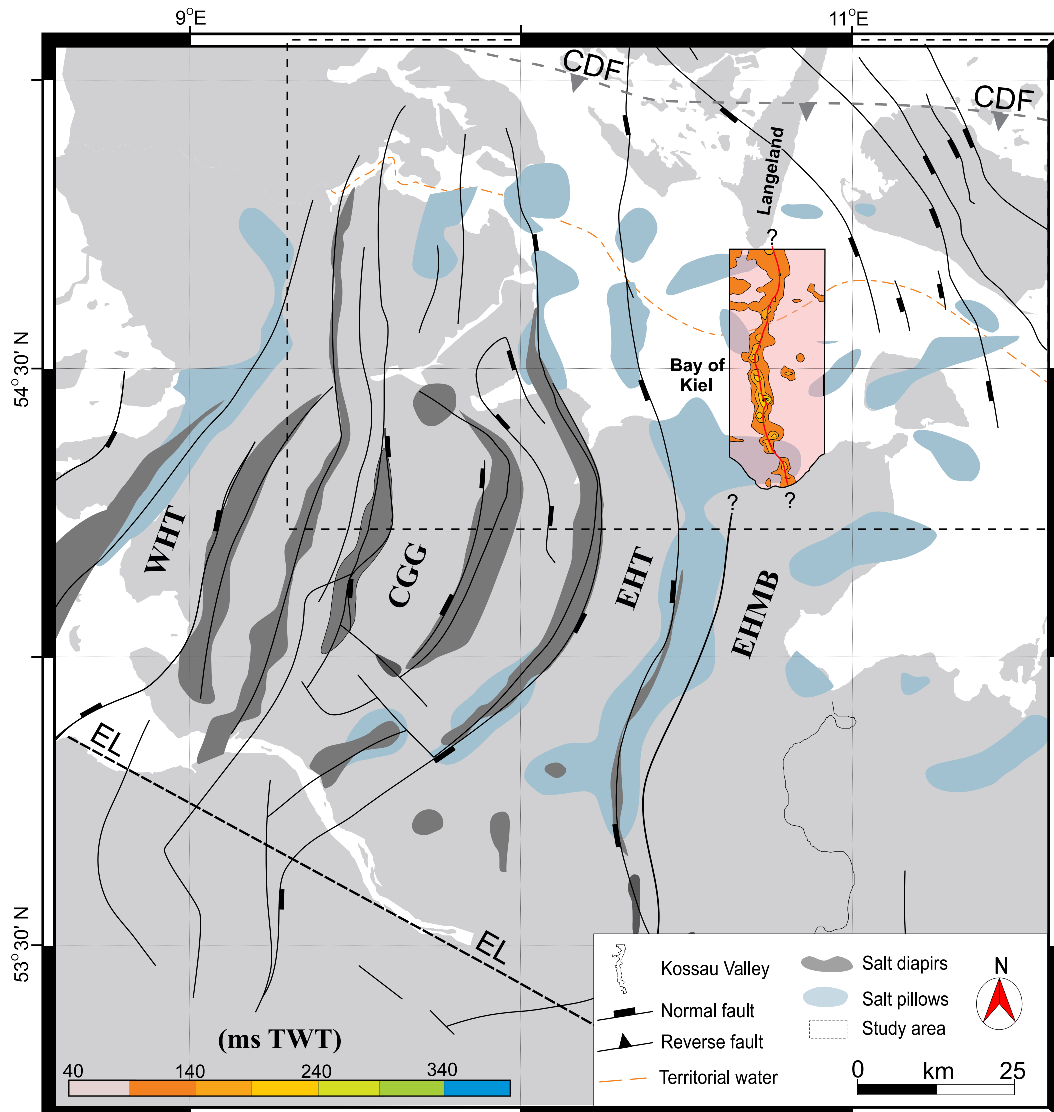

Fig. 11. Base Glaciogenic Unconformity depth map within Bay of Kiel in TWT. Contour interval is 50 ms. Salt structures (according to Lokhorst et al., 1998) and major structural elements (compiled from Baldschuhn et al., 1991; Krauss, 1994; Vejbæk, 1997; Bayer et al., 1999; Clausen and Pedersen, 1999; Kossow et al., 2000). The observed near-vertical fault is marked by red colour. CDF, Caledonian Deformation Front; EL, Elbe Lineament; EHMB, Eastholstein Mecklenburg Block; EHT, Eastholstein Trough; CGG, Central Glückstadt Graben; WHT, Westholstein Trough. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2. Fluid migration and pockmarks

Plaza-Faverola et al. (2011) described a similar fault–anticline pattern in the mid-Norwegian margin. The authors described the feature as a gas chimney formed by the vigorous escape of overpressurized fluids, followed by continuous low-flux fluid leakage, before becoming dormant. Chaotic strata beneath the anticline, within the Upper Cretaceous strata (Chalk Group; Fig. 7), could be interpreted as the consequence of sediment remobilization due to rising fluids or volatiles. The Triassic reflections beneath are well pronounced and continuous. Consequently, the blurred reflections within the Upper Cretaceous and Lower Tertiary are not the result of energy absorption or scattering.

The presence of pockmarks in the Cretaceous provides evidence for ancient fluid rise. Stratigraphic correlation between the seismic data and the Kegnæs-1 exploration well (for location, see Fig. 3) shows that the formation of these pockmarks started in the Santonian stage. Pockmarks (within the chalk) are frequently observed on the Top Chalk surface of the North Sea (e.g. Norwegian-Danish Basin and in the Central Graben; Clausen and Huuse, 1999). These authors interpreted the pockmarks as karst features while other authors related their origin to fluid explosion and subsequent erosion by bottom current (e.g. Hovland and Judd, 1988; Van Weering et al., 1997; Judd and Hovland, 2007).

Alternatively, the undulations in the Upper Cretaceous can be interpreted as a consequence of current-modulated deposition or re-deposition, as observed with chalk deposits in the vicinity of the Sorgenfrei-Tornquist Zone (Lykke-Andersen and Surlyk, 2004; Surlyk and Lykke-Andersen, 2007). The elevated Sorgenfrei-Tornquist Zone influenced the bottom and contour currents, creating contourite drifts and moat channels nearby. However, the depressions observed in this study are much further away from the causative topographic relief and the Cretaceous-Paleogene boundary does not form an elongated antiform, as can be expected for a contourite drift. We therefore favour interpreting the depressions as fluid escape structures (pockmarks). Nevertheless,

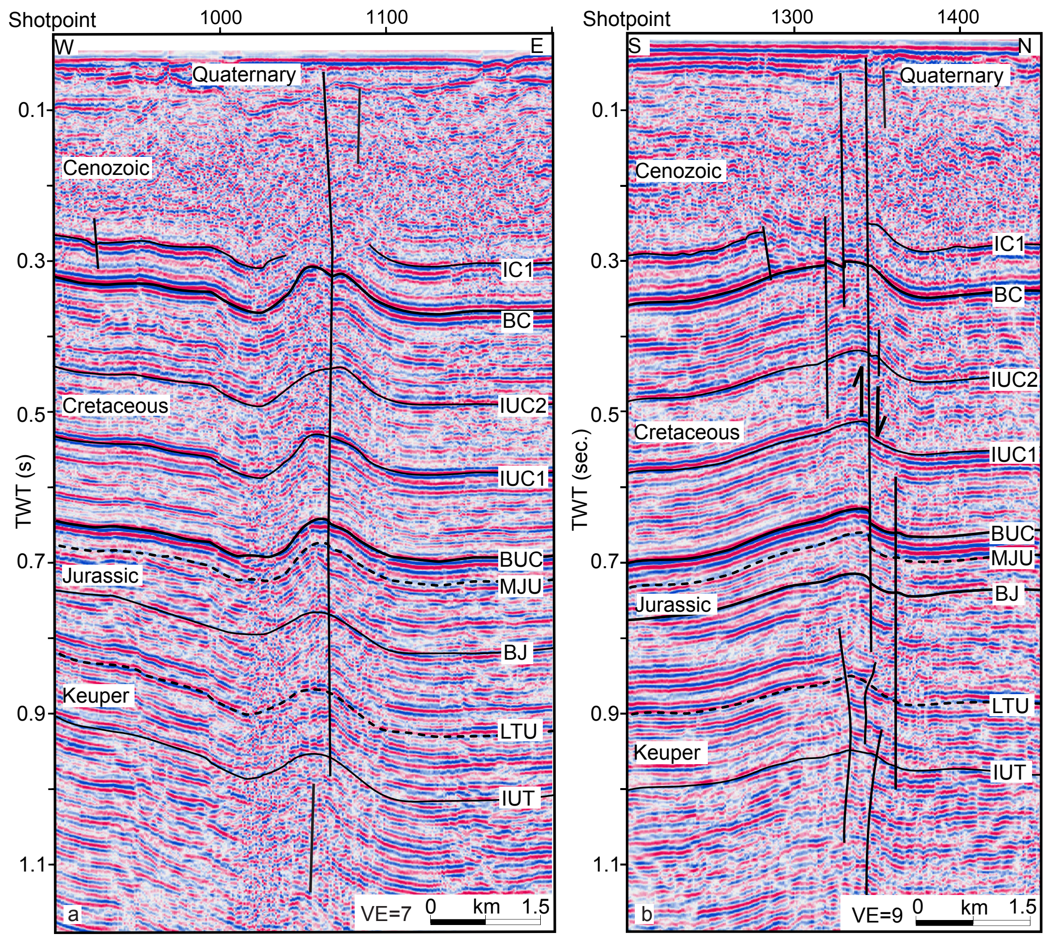

Fig. 12. Perpendicular seismic profiles from northwestern Bay of Kiel (data selected after Brooks, 2000). The W–E striking profile (a) reveals an anticline similar to those beneath the Kossau Valley including a near-vertical fault. The perpendicular profile (b) suggests a structural reverse fault (Brooks, 2000), or flower structure.

the elongated geometry of the fault–anticline assemblage and the local appearance of acoustic turbulences are not consistent with the assumption that fluid migration is the primary causative process for the anticline formation. It might be an associated process, if the relationship exists at all.

The abundant faults in the Lower Tertiary, already observed by Hansen et al. (2005) and Hübscher et al. (2010), have been attributed to dewatering, as previously described by other authors (e.g. Henriet et al., 1991; Cartwright, 1994; Cartwright and Lonergan, 1996). These faults do not propagate to the surface and are also not considered to be as relevant for the observed near-vertical faults.

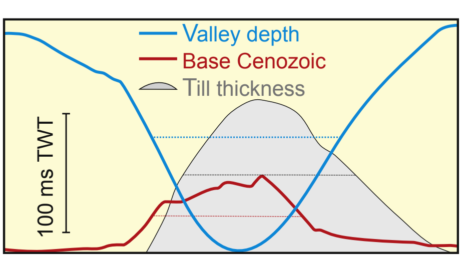

Fig. 13. Valley depth (blue), base of Cenozoic anticline (red) and interpreted till thickness from Fig. 7. Neither maxima, nor minima or the 50% intervals (stippled lines) correlate with each other. Depth or thicknesses are given in TWT. The valley base is not up-bended. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.3. *Structural geological constraints*

The approximate position of the observed N–S to NNE–SSW striking fault is in the prolongation of the fault system at the eastern margin of the Eastholstein Mecklenburg Blocks (Fig. 11). Hence, the observed fault system might have developed above a deep-rooted fault. However, compressional faults (thrusts, reverse fault) typically have lower dipping angles. Typical extensional faults (normal or listric) are also rarely near-vertical, and they should reveal some level of vertical displacement, which cannot be observed beneath the valley.

Generally, near-vertical faults associated with an anticline may result from a strike-slip movement within a transpressional regime. The blind faults in Figs. 6 and 7 can be considered to be flower structures. However, the strata adjacent to both sides of the faults have the same thickness and reflection pattern, and thus, significant transcurrent movement is unlikely. Furthermore, there are neither published strike-slip faults in this area (e.g. Ziegler, 1990; Baldschuhn et al., 1991), nor are there restraining or releasing bends in its prolongation. We conclude that the near-vertical faults, in association with the anticline, do not resemble a common fault–anticline system created by extensional, compressional or strike-slip tectonics.

Fault and anticline combinations above salt are typically thin-skinned extensional structures, such as crestal graben. Gaullier et al. (1993) and Warren (2008) described how normal faulting of the overburden allows the underlying salt pillow to rise and reactivate during inversion (Fig. 14). The observed inward dipping reflections in the echosounder data (Figs. 8 and 10) and the seafloor depressions are consistent with the assumption that there is a crestal graben above a rising diapirs.

However, neither the fault nor the anticline emerged above a significant salt ridge (Fig. 15). In fact, the valley is primarily located along an elongated salt syncline (Hansen et al., 2007). Thus, the hypothesis of pure salt diapirism is not suitable to explain the observations. While the database used by Hansen et al. (2007) was sparse, the presence of some 10 m high and some 100 to a few 1000 m wide elongated salt pillows beneath the anticline cannot be excluded.

6. Conceptual approach

Due to the findings mentioned in the previous discussion, we reject the hypothesis that the elongated fault–anticline pattern beneath the Kossau tunnel valley is the result of extensional, compressional, strike-slip or salt tectonics. It neither results from fluid migration, nor is it an imaging artefact. No syn-kinematic sedimentation is resolved, except for the uppermost metres. Hence, the faults and anticline evolved in the Late Quaternary, which limits the search for possible explanations. This raises the question as to what is actual the cause.

6.1. Ice-load induced tectonics

Our observations are consistent with the conceptual models for ice-load induced tectonics (Stewart et al., 2000; Sirocko et al., 2008). We suggest that the fault–anticline system emerged above an inherited and deep-rooted sub-salt fault or weakness zone, which might be related to the Eastholstein Mecklenburg Block (Fig. 16a). Our proposed model identifies glacio-isostasy as the key factor for reactivation and upward propagation of the sub-salt fault (Fig. 16b).

Ice sheet advance from the east in the early glacial period created a differential load to both sides of the inherited fault that persisted during glaciation due to the westward thinning of the ice cap. The differential load caused differential subsidence and the inherited fault propagated upwards with the hanging wall to the east. This explanation is consistent with observations made by Sirocko et al. (2008) and Brandes et al. (2011). The near-vertical fault, as well as the Kossau valley above, parallel faults related to the eastern GG (Fig. 11), which suggests a causative relationship.

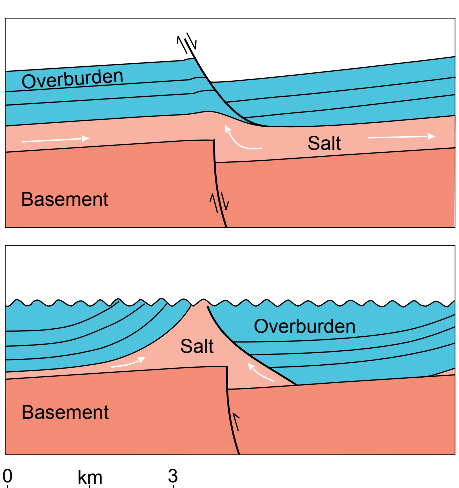

Fig. 14. Salt pillow evolution above normal faults and their rejuvenation during inversion (modified after Gaullier et al., 1993; Warren, 2008). White arrows indicate salt flow direction.

According to Stewart et al. (2000), fault reactivation due to glacio-isostasy is more likely if the ice sheet advances normally in relation to the fault. The assumption of westward ice sheet advance across to the here studied fault is consistent with the observed folds within the Late Tertiary strata west of the Kossau tunnel valley. When the ice overrode the morphological step that emerged due to increased subsidence to the east, the ice front pushed and folded the western strata (Fig. 16b).

It is well-known, due to the available information and observations regarding the Permian Central European Basin System, that salt flow above basement faults create salt anticlines (e.g., Warren, 2008). Salt anticlines of similar width emerged above active subsalt faults in the northern Levant Basin (Reiche et al., 2014). We explain the anticline initialization accordingly (Fig. 16b).

The inversion started after the ice glaciers' retreat, forcing further growth of the salt anticline and the anticline above (Fig. 16c). The uplift continued while glaciogenic sediments were deposited within the valley, creating the observed westward diverging reflection pattern within the valley fill deposits. In addition, high pore pressure due to valley formation might have supported the slip processes along the fault. According to Hambrey and Huddart (1995), substrata folding deformation usually occurs during the ice margins' advance and retreat phases (e.g. Figs. 5–7).

The mode described above is based on the assumption that the lowermost anticline is floored by Zechstein salt, which cannot be directly inferred from the seismic data shown in this study. However, Hansen et al. (2005, 2007) and Hübscher et al. (2010) provided compelling evidence that the post-Permian stratigraphic boundaries generally follow the top Zechstein topography, which corroborates the proposed model.

The ice-load induced tectonics concept offers a refined explanation of Lehné and Sirocko's (2010) findings. The researchers observed recent surface deformation of several millimetres per year along lineaments, which are in accordance with the glacial deposits and salt walls in northern Germany. Lehné and Sirocko (2010) stated that the deformation is most likely caused by ongoing isostatic adjustment since the Weichselian maximum occurred in that area.

6.2. Tectonic impact on tunnel valley evolution

Faulting and folding beneath the ice sheet created a weakness zone that facilitated erosion by pressurized glacial and subglacial melt-water, which is the primary explanation for tunnel valley evolution (Piotrowski, 1994, 1997; Huuse and Lykke-Andersen, 2000; Jørgensen and Sandersen, 2004). This created accommodation space – the valley – for soft and unconsolidated sediments, which are observed in the seismic and hydroacoustic data. Accordingly, the Kossau tunnel valley is considered to have resulted from the interplay between the underlying fault system and subglacial melt-water erosion.

The vertical correlation between the Quaternary tunnel valleys and the faults beneath them was also observed in the Danish North Sea area by Salomonsen (1993, 1995), while other authors noted that the underlying structures may have had a local influence on the orientation of some valleys (e.g. Lykke-Andersen et al., 1993; Schwarz, 1996; Huuse and Lykke-Andersen, 2000; Sandersen and Jørgensen, 2002). The proposed model of ice-load induced tectonics is therefore also suitable to explain the vertical correlation between faulting and the evolution of tunnel valleys in other regions of the Northern Hemisphere.

7. Conclusions

- The Kossau tunnel valley is located in the southeastern Bay of Kiel and was surveyed by means of high-resolution multi-

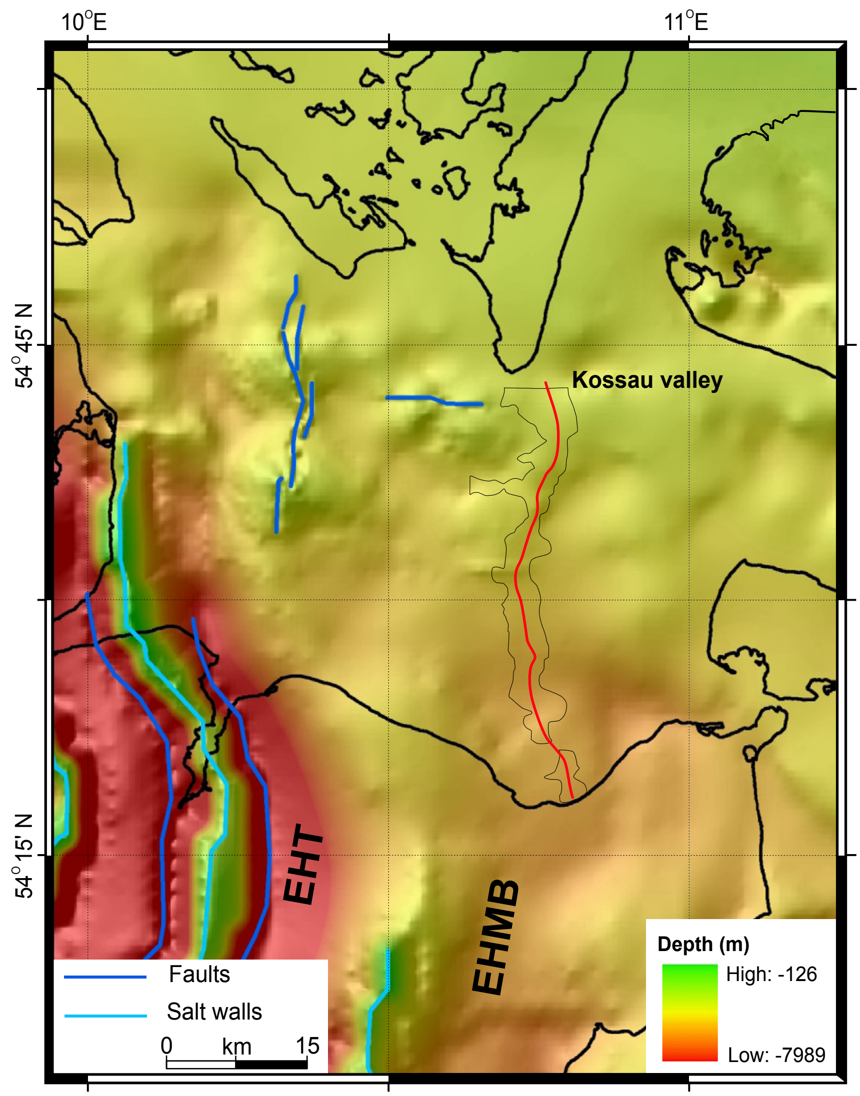

Fig. 15. Depth map of the Base Lower Triassic (Top Zechstein salt) including basement faults and salt walls (based on Hansen et al., 2007), revealing that the observed N–S to NNE–SSW striking fault (red) is not related to salt tectonics. The outline of the Kossau valley is marked based on this study. EHMB, Eastholstein Mecklenburg Block; EHT, Eastholstein Trough. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

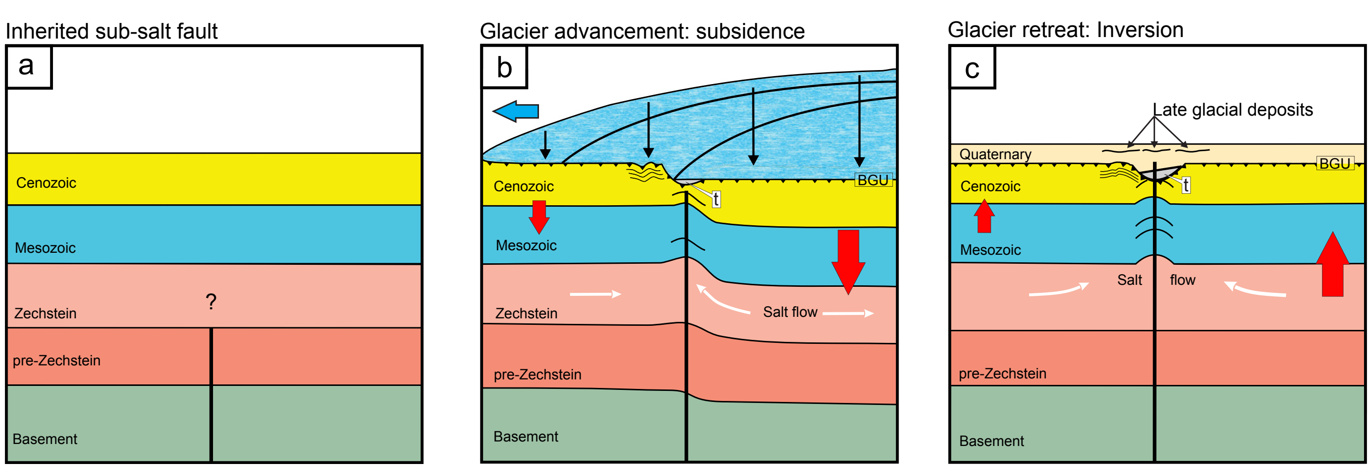

Fig. 16. Ice-loading/unloading and inherited deep-rooted fault interaction in controlling the formation and evolution of the Kossau tunnel valley (modified from Sirocko et al., 2008). (a) Inherited sub-salt fault system related to Eastholstein Mecklenburg Block. (b) Advancing and retreating ice sheets reactivate the fault and cause differential subsidence as well as evolution of a (small) salt anticline. Red arrows indicate relative crustal movements. Blue arrow indicates ice sheet advancement. (c) Inversion of the inherited fault after ice sheet retreat (isostatic rebound). White arrows indicate salt flow direction. Red arrows indicate relative crustal movements. Uplift of eastern segment causes westward till of valley infill. BGU, base glaciogenic unconformity; and t: till. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

channel seismic and echosounder data. The valley strikes almost south to north and could be mapped over a distance of ca 50 km. It is 1200–8000 m wide and up to 200 m deep.
- A near-vertical N–S to NNE–SSW striking fault with an apparent dip angle of >80° and an associated anticline intersects and deform the post-Permian succession directly beneath the Kossau tunnel valley. The observed fault–anticline assemblage does not resemble any typical extensional, compressional or strike-slip deformation pattern.
- The fault–anticline assemblage is also not the result of fluid migration. Yet, pockmarks within the Cretaceous succession provide evidence of local paleo-fluid migration.
- The fault occasionally pierces the seafloor. Growth is only observed within the uppermost Quaternary strata. The fault system that reaches from the surface down to the Zechstein evolved, consequently, in the Late Quaternary.
- We explain the origin of the fault–anticline assemblage as a consequence of ice-load induced tectonics above an inherited and deep-rooted sub-salt fault that is related to the Glückstadt Graben. The westward-directed ice sheet advancement created a differential load and increased the subsidence of the eastern side of the fault. The deep-rooted fault was reactivated and propagated to the surface.
- The westward propagating ice front overrode the evolving topographic step and folded the Late Tertiary strata west of the fault plane.
- The salt flow across the sub-salt fault created a salt anticline and thus initiated the folding of sediments above. During the retreating of the ice sheet, inversion started and the salt, as well as the associated supra-salt anticline grew further.
- Near-surface faulting weakened the upper strata and facilitated erosion, which led to the formation of the Kossau tunnel valley. Syn-kinematic lower valley fill deposits were tilted during the inversion.
- Consequently, the formation and evolution of the Kossau tunnel valley results from the interplay of ice-load induced tectonics and subglacial melt-water erosion.

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