



A comprehensive model of seismic velocities for the Bay of Mecklenburg (Baltic Sea) at the North German Basin margin: implications for basin development

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Abstract

The geometry of sedimentary basins is normally described by the interpretation of seismic reflectors. In addition to that, rock properties of the sedimentary successions between these reflectors give further insight into the subsurface geology. Here, we present a model for the Bay of Mecklenburg, situated at the northeastern margin of the North German Basin. The model consists of eight layers; it covers seismic velocities of sediments from the Neogene down to the base of the Permian Zechstein. We use eight seismic profiles for model building and apply seismic migration velocity analysis in combination with pre-stack depth migration. The results are interval velocities down to a depth of 5000 m. A further aim of the study is to investigate the sensitivity of these indirectly deduced velocities in comparison to direct measurements within drill holes. The velocities from this study are in good agreement with earlier results from vertical seismic profiling at a nearby well. Cenozoic and Mesozoic strata within the Bay of Mecklenburg show clear depth-dependent velocity trends. A comparison of these trends with predicted compaction trends shows that burial anomalies within Lower Triassic units are significantly higher than in Upper Cretaceous units. This finding could be explained by a greater amount of erosion during Upper Jurassic/Lower Cretaceous times than during Cenozoic times. The Zechstein layer shows a decreasing interval velocity with increasing thickness. Our study demonstrates that seismic velocities deduced from surface-based measurements are of high value in areas with sparse drilling coverage.

Introduction

Seismic imaging provides crucial insight for understanding of sedimentary basin development. Seismic data is normally measured in the time domain. The prerequisite for a quantitative data analysis, e.g. in terms of balanced reconstruction, is proper depth imaging, which requires usage of reliable seismic velocities to display lateral varying structures at the correct depth (e.g. Etgen et al. 2009). Seismic velocity variations within particular stratigraphic units are further indicators for differences in lithology of sedimentary rock units. In addition, compaction (reduction in porosity) of the

sediments also influences the seismic velocities during the deposition history of a sedimentary basin.

Many diagenetic processes can cause an increase of seismic velocity within sedimentary layers. The most important influence emerges from increasing pressure (e.g. Densley et al. 2000), which is often related to burial depth. These processes are generally thought to be irreversible (see discussion in Corcoran and Doré 2005). This means that the sedimentary strata will keep its diagenetic stage from the maximum burial of the basin development, and later uplift of sediments will not result in a decrease of seismic velocities. These cases will show a positive velocity anomaly with respect to the current burial depth (Japsen 1993). The amount of this anomaly is proportional to the negative burial anomaly (Japsen 1998) and could therefore be used to estimate the maximum depth of burial. This principle was already used by John (1975) and is still a valid tool to measure vertical movements in a sedimentary basin (Japsen 2018). Up to now, most of the earlier studies discussing seismic velocities are based on the analysis of well logging data (e.g. Japsen 1998; Jaritz et al. 1991; Scherbaum 1982).

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Well data provides high-resolution velocity information with depth, but only in one dimension. Hence, the lateral resolution is restricted to the number of available wells and interpolation in between. In contrast to that, seismic data provides a very high lateral resolution along the acquisition profiles, while the vertical resolution is limited by the wavelength of the used signal.

The primary aim of this study is to derive and discuss a spatial varying velocity model for the Bay of Mecklenburg (Baltic Sea, northeastern North German Basin (NGB)) using migration velocity analysis (MVA). Eight marine seismic profiles were used for velocity analysis. Due to the small spatial extent of the area of investigation (approx. 50×80 km, see Fig. 1), a lateral effect of lithological changes within the sedimentary layers is not expected. However, the base of the Zechstein shows a huge variability in depth within this area, ranging from more than 5000 to less than 3000 m below sea level. Therefore, the Bay of Mecklenburg is a perfect place to estimate the depth-dependent effects of seismic velocity.

The second focus of this study is to link the seismostratigraphy from the Bay of Mecklenburg to an adjacent well, which allows us to refine the lithological interpretation.

Thus, our method focuses on both construction of velocity depth functions for individual units in areas with little well control and gaining insight in the reconstruction of basin development.

Physical setting

The Bay of Mecklenburg is situated at the northeastern NGB and is part of the intracontinental Southern Permian Basin spreading across Central Europe (Fig. 1). The northeastern end of the Bay spatially correlates with the NGB margin (Ahrlichs et al. 2020, and references there in). The NGB was affected by repeated phases of subsidence and uplift during its complex basin history from Palaeozoic to Cenozoic times (e.g. Maystrenko et al. 2008). In the Bay of Mecklenburg, the structural style is affected by salt movement and the development of some salt pillows (Hansen et al. 2007; Zöllner et al. 2008; Scheck-Wenderoth et al. 2008; Hübscher et al. 2010; Ahrlichs et al. 2020). These salt structures consist of late Permian Zechstein evaporites, which were deposited during arid climate conditions and

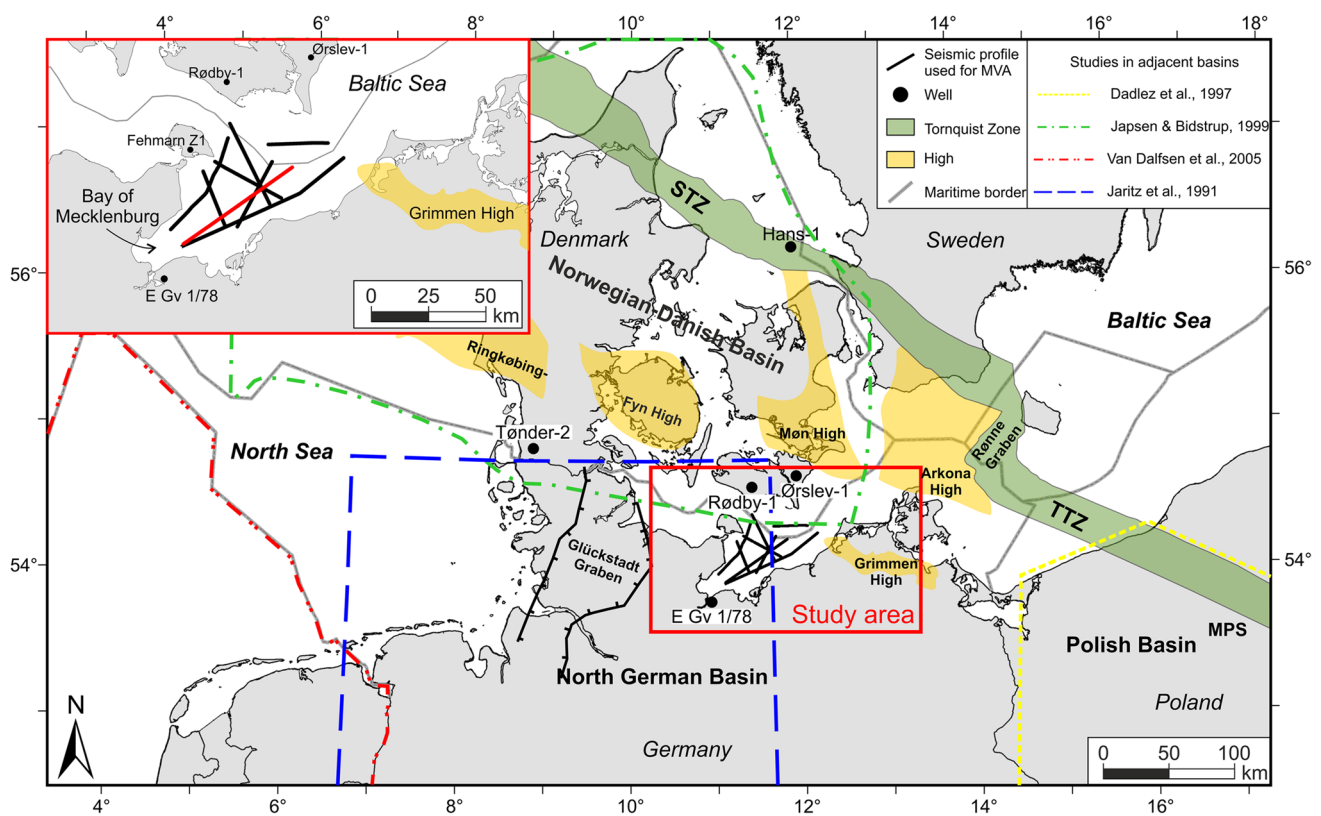


Fig. 1 Structural overview of the North German Basin and adjacent sedimentary basins. Inset shows area of investigation with seismic profiles used for the MVA in the Bay of Mecklenburg. Line BGR16-224 is highlighted in red (Fig. 4b). Study areas of publications on velocity analysis discussed in the text are shown. STZ, Sorgenfrei-

Tornquist Zone; TTZ, Tornquist-Teisseyre Zone; MPS, Mid-Polish Swell. Compiled after Nielsen and Japsen (1991); Hoth et al. (1993); Schlüter et al. (1997b); Baldschuhn et al. (2001); Mazur et al. (2006); Scheck-Wenderoth et al. (2008); Seidel et al. (2018); Erlström (2020); Grimmer High according to Schlüter et al. (1997a)

repeated restricted seawater influx. In the deeper basin of the NGB, the Zechstein evaporite sequence contains seven cyclic sequences made of anhydrite, halite, clay and carbonates (Tucker 1991; Strohmenger et al. 1996). The overlying Triassic successions (Buntsandstein, Muschelkalk and Keuper) are deposited during rapid subsidence (Fig. 2). The Bay of Mecklenburg represented a local depocenter during deposition of the Buntsandstein and Muschelkalk successions (e.g. Scheck and Bayer 1999). In the Late Triassic, basin configuration changed and the depocenter migrated towards the south. In the Bay of Mecklenburg, subsidence decreased towards the end of the deposition of the Keuper successions. Simultaneously, the initiation of salt pillow growth led to locally increased Keuper thickness in rim synclines (e.g. Scheck and Bayer 1999). From the Jurassic onwards, subsidence rates further decreased (Kossow and Krawczyk 2002) (Fig. 2). During Middle to Upper Jurassic times, the development of the Central North Sea Dome (Ziegler 1990b; Underhill and Partington 1993) caused large-scale uplift, leading to erosion of much of the Jurassic strata in the Bay of Mecklenburg (Zöllner et al. 2008; Ahlrichs et al. 2020). Sedimentation was re-established in the Lower Cretaceous (Albian). A phase of relative tectonic quiescence persisted until the Upper Cretaceous accompanied by the deposition of chalk and limestones (Kossow and Krawczyk 2002). The Upper Cretaceous onset of the Africa-Iberia-Europe convergence induced compressional stress within the study area (Kley and Voigt 2008). As a result, the area was again affected by uplift, erosion and the reactivation of pre-existing basement faults as reverse faults. Uplift of the nearby Grimmen High was approximately 400–500 m (Kossow and Krawczyk 2002; Ahlrichs et al. 2020). During the Paleogene, the study area underwent gentle subsidence in conjunction with the rapid subsidence of the North Sea Basin (Ziegler 1990b). Further phases of uplift in the study area are reported for the Palaeocene, late Eocene and Oligocene. However, their existence and spatial extent in the Baltic sector of the NGB are an aspect of recent discussion and remain unclear (Kley 2018). In the Neogene, large-scale uplift of the western and eastern margins of the North Sea Basin is observed (Japsen 1998).

According to the onshore well information near the Bay of Mecklenburg (Hoth et al. 1993), the Cenozoic successions within the working area consist of terrestrial and shallow marine clastic sediments. These are mainly gravel, clay, marl, siltstone and claystone. The underlying successions of limestone and chalk of the Upper Cretaceous and marl of the Lower Cretaceous (Albian) deposits represent marine conditions. Sedimentary rocks of Berrasian up to the lower part of the Albian stage as well as nearly the entire Jurassic deposits are absent. Remnants of Lower Jurassic claystones are preserved especially in rim synclines of salt pillows. Below the Jurassic, or where absent below the Lower Cretaceous

successions, the Triassic Keuper consists mostly of sandstones and mudstones representing predominantly terrestrial and fluvial conditions. Due to marine incursions in the Upper and Lower Keuper, small beds of evaporites are present within the successions. The underlying Muschelkalk successions consist of limestones and marlstones with intercalated evaporates representing marine conditions. The Buntsandstein successions below are characterized by intercalated claystones and siltstones deposited in fluvial and terrestrial conditions. The Upper Buntsandstein succession is characterized by evaporitic deposits which represent marine conditions. The underlying marine Zechstein successions contain five major cyclothems of anhydrite, halite, claystones and carbonates.

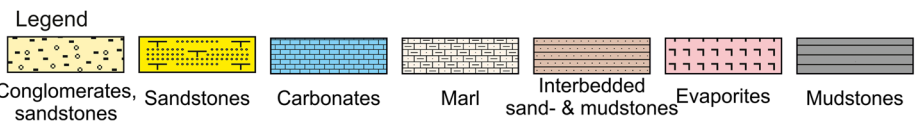
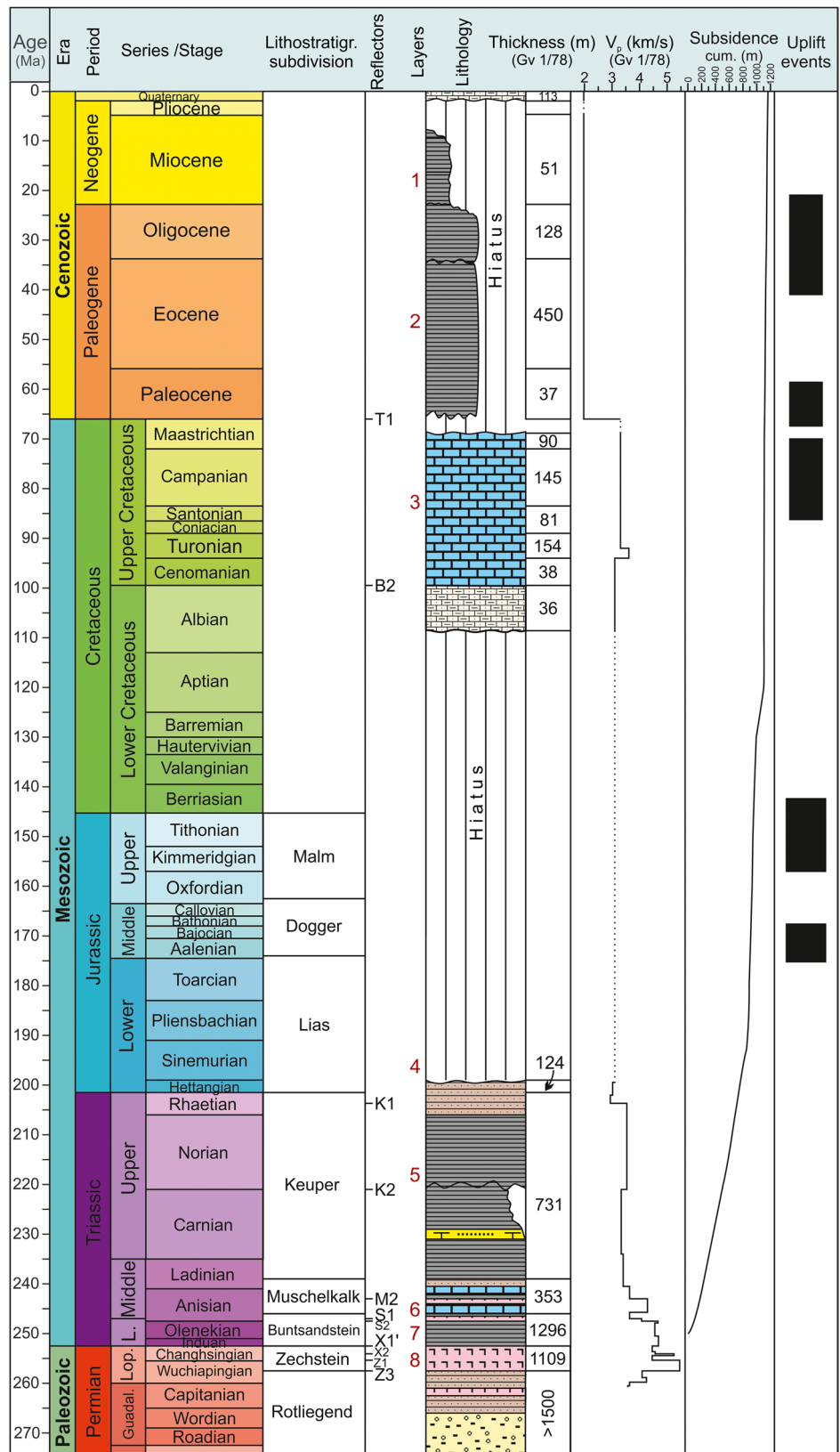
Materials and methods

The multichannel seismic data set was acquired in 2016 using the research vessel *Maria S. Merian* (Hübscher et al. 2017). By minimizing the near-trace offset to 33 m, the acquisition configuration was optimized to record also seismic reflections from shallow horizons at a water depth less than 25 m. Additionally, the active cable length of 2700 m (216 channels) provided sufficient offset to perform velocity analysis down to several 1000-m depth. The seismic source array consisted of eight GI-SOURCE 210 airguns. The source signal (dominant frequency of 80 Hz) delivered a high vertical resolution in the range of 6 to 14 m, while the clustering of eight guns provided deep signal penetration down to a depth of more than 5000 m. The source station interval of 25 m resulted in a 54-fold common midpoint coverage.

We analysed eight seismic profiles with a total length of 336 km (Fig. 1). The pre-processing consisted of geometry binning, designature and bandpass filtering, spherical divergence correction, preliminary velocity analysis, stacking and migration in time domain. Multiple reflections have been suppressed using a predictive deconvolution in the post-stack domain.

To resolve lateral velocity variations, we applied migration velocity analysis (MVA). The benefits of MVA compared to classical normal moveout (NMO) analysis have initially been demonstrated by Al-Yahya (1989). During MVA, common offset gathers are pre-stack depth-migrated, resulting in common reflection point (CRP) gathers along the profile (Stork 1992). For a selected horizon, the overlying velocity model is adjusted until the offset-dependent reflections for this horizon are flat for all (migrated) CRP gathers. This process was iteratively repeated for all horizons (top-down). The resulting velocities reflect the lateral changes of each individual layer. We performed this analysis for eight layers, from the seafloor down to the base of

Fig. 2 Litho-stratigraphic chart of the NGB (modified after Ahlrichs et al. (2020)). Layer numbers (in red) refer to the here presented migration velocity analysis (in red), corresponding regional reflectors after Reinhardt (1993). Litho-stratigraphic subdivision according to Menning (2018). Layer thickness and seismic velocity are based on well Gv 1/78 (Feßer 1980). The cumulative subsidence of the northern NGB margin (Kossow and Krawczyk 2002) is shown together with major uplift events (Bachmann et al. 2008)



the Zechstein layer. In the following, these layers are called seismic layers.

To investigate the sensitivity of the MVA analysis, we varied the final velocity field by 2% and migrated the data again. Figure 3 shows a single migrated CRP gather from line BGR16-212. A velocity variation of 2% produces a significant and visible moveout effect for the far offset traces.

Additionally, this study uses results from vertical seismic profiling (VSP) in the nearby well Gv 1/78 (Fig. 1). The VSP covered a depth down to 5900 m and 26 reflectors have been identified (Feßer 1980). Measured differences in travel time have been converted to interval velocity.

As the porosity of sedimentary rocks decreases during deeper burial, seismic interval velocity increases. This process is considered irreversible, and thus, measured velocity is a proxy for maximum burial depth. Post-depositional uplift reduces burial depth and leads to higher velocities than expected at this depth. This is referred to as a velocity anomaly (see e.g. Japsen et al. 2007 for more details). By MVA, we obtain lateral variant interval velocities of individual seismic layers at varying depth. We compare the depth-dependent velocity trend derived from the MVA with published reference velocity-depth trends from well data in adjacent areas and identify velocity anomalies. Based on the normal velocity trend, the velocity anomaly represents an approximation of the amount of post-depositional uplift of that seismic layer.

Results

The velocity analysis resulted in lateral variable interval velocities for all seismic layers. Figure 4 shows the results for profile BGR16-224, which is located in the centre of the Bay of Mecklenburg (red line in Fig. 1). Within Fig. 4a, the interval velocities from well Gv 1/78 (black line) and the main reflectors from the VSP analysis are plotted. Additionally, this box shows the result from the MVA at CDP 13,200 of profile BGR16-224 (red line in Fig. 4a). The absolute depth of post-Permian strata is variable due to the varying thickness of the Zechstein layer caused by salt tectonics. We chose the position along the line (CDP 13,200) to provide

a good match between the seismic layers and the well (for a detailed discussion see Ahlrichs et al. (2020)). Both curves in Fig. 4a show a similar trend and high correlation. The vertical seismic profiling within well Gv 1/78 has a much higher resolution than the surface-based measurement along profile BGR16-224. With the MVA technique, only layers with a thickness exceeding 100 m could be resolved (Fig. 4a).

The information from well Gv 1/78 (Fig. 2) allows us to link eight seismic layers to the stratigraphy of the sedimentary successions in the Bay of Mecklenburg. The identified bounding reflectors in the MVA are based upon the seismostratigraphic framework in Reinhardt (1993). The uppermost layer from the VSP has an interval velocity of 1976 m/s, while the first layer for the MVA has a velocity of 1931 m/s. The base of seismic layer 2 corresponds to reflector T1 (transgression Cenozoic). According to the well information, the seismic layers 1 and 2 on top of the T1 reflector represent sedimentary rocks of the Cenozoic successions. At a depth of 1570 m, the vertical seismic profiling of Gv 1/78 shows a pronounced velocity increase (from 2940 to 3540 m/s) corresponding to the reflector K1, situated within the Upper Keuper succession. Therefore, seismic layer 3 most probably contains Upper Cretaceous units, while seismic layer 4 may contain Cenomanian, Hettangian and Rhaetian units. From 1570-m depth (reflector K1) to 2265-m depth (reflector M2 – internal reflection of the middle Muschelkalk) data from Gv 1/78 shows quite uniform interval velocities ranging between 3330 and 3640 m/s, while the corresponding seismic layer 5 from the MVA has a velocity of 3465 m/s. At reflector M2, a sharp velocity increase of about 640 m/s is encountered. Therefore, seismic layer 5 consists mainly of sedimentary rocks of the Keuper successions, while seismic layer 6 contains Muschelkalk and possibly Upper Buntsandstein sedimentary rocks. According to Ahlrichs et al. (2020), the reflector S1 (top Salinararröt, lowermost Upper Buntsandstein) represents the boundary between seismic layers 6 and 7. The well data shows uniform velocities between 2800 (reflector S2 – top of Middle Buntsandstein) and 3775-m depth (reflector X1' – top of Zechstein) in the range of 4550 to 4680 m/s. The corresponding seismic layer 7 from the MVA has an interval velocity of 4723 m/s. Accordingly,

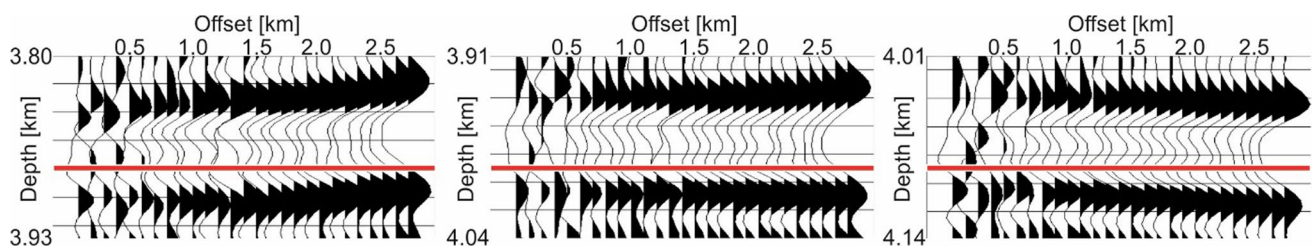


Fig. 3 Migrated gathers showing the base of Zechstein at CDP 16,300. The middle panel is migrated with the final velocity field. For the left panel, the velocity field was decreased by 2%, while the

velocity field for the right panel was increased by 2%. Both variations cause significant moveout effects

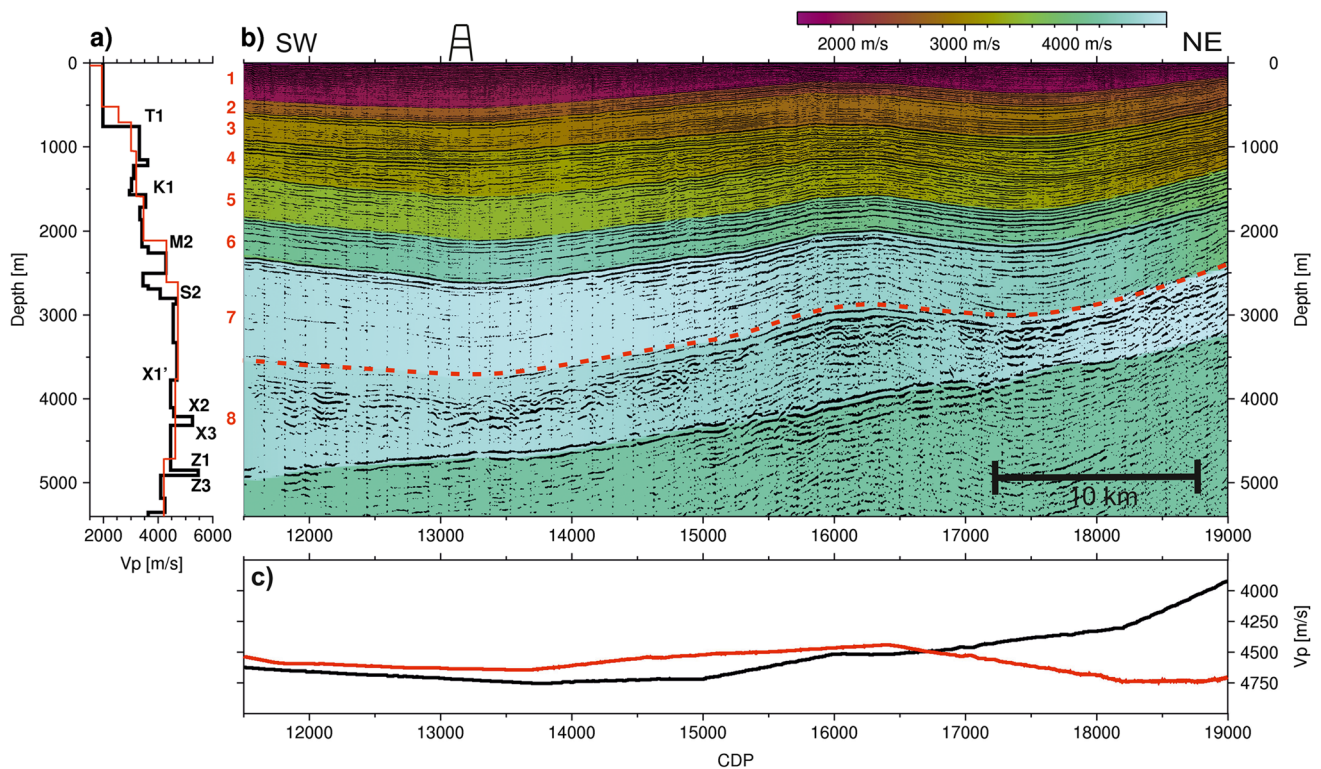


Fig. 4 Seismic profile BGR16-224 and the resulting velocity distribution. **a** Black curve shows results of a vertical seismic survey at well Gv 1/78 (Grevesmühlen), key reflectors are marked. Red curve shows the 1D velocity function at CDP 13,200 (the projected position is highlighted by the drilling rig). The profile in panel **b** is displayed with vertical exaggeration of 4. The boundary between seismic layer 7 and 8 is marked by the red stippled line. Red digits between pan-

seismic layer 7 represents sedimentary rocks of Middle and Lower Buntsandstein successions. The base of seismic layer 8 is the prominent Z3 reflector (base of Zechstein), characterized by a pronounced negative impedance contrast between Zechstein and Rotliegend successions. Therefore, seismic layer 8 represents the Zechstein successions. At the drill site, the Zechstein shows thin zones (105 m between reflectors X2 and X3 and 60 m between reflectors Z1 and Z3) of increased velocities (5250 m/s and 5455 m/s, respectively) which are described as anhydrite. The dominant part of the Zechstein interval shows velocities ranging from 4460 to 4565 m/s. The MVA delivered 4630 m/s for seismic layer 8 at CDP 13,200 (Fig. 4a).

To investigate the velocity variations with depth, we used the MVA results from all 8 seismic profiles. For each CDP, the MVA delivered a mean interval velocity for each seismic layer. Due to the basin configuration, the base of the Zechstein dips from 3000 m in the northeast to more than 5000 m in the southwest. As a consequence, the Zechstein layer and all other layers of the overburden are encountered at a varying depth range. For instance, the mean depth of layer 7 within the area of investigation is between 1540

els **a** and **b** mark numbers of seismic layer. **c** Lateral velocity variation within seismic layer 7 (black) and 8 (red). Layer 7 has a velocity maximum at its deepest part around CDP 14,000, while the velocity decreases towards the northeast. Layer 8 has a velocity minimum at the thickest part of the Zechstein around 16,000, while the velocity increases towards the southeast and the northwest

and 3330 m; even the shallow layer 2 covers a depth range between 100 to 750 m (see Table 1). This allows for a depth-dependent analysis of the observed velocities. For each CDP, we assigned the interval velocity of each layer (V_z) to the mean depth of this layer (Z) at this location. According to Eq. (1), we determined a linear relationship for layers 1 to 7 (e.g. Marsden 1992). The resulting values for starting velocity V_0 and gradient k are given in Table 1.

$$V_z = V_0 + kZ \quad (1)$$

To account for the fact that the velocity increase with depth is greatest for shallow formations, we calculated a velocity-depth-relationship for seismic layers 1 to 5 according to Eq. (2) suggested by Faust (1951). The resulting function (displayed as black line in Fig. 5) shows a reasonable fit to a depth of about 2000 m.

$$V_z = 602 * Z^{1/4.272} \quad (2)$$

Within seismic layer 8 (Zechstein), no relation between depth and velocity can be seen. Instead, this velocity (V_{salt}) inversely correlates to the thickness (D_{salt}) of the Zechstein layer (Fig. 6). This effect is already visible within Fig. 4c.

Table 1 Resulting values for starting velocity V_0 and gradient k for layers 1 to 7

Layer	V_0 (m/s)	k (s^{-1})	Velocity range (m/s)	Range of mean depth (m)	Stratigraphy
1	1730	0.72	1765–1980	50–350	Cenozoic
2	2160	0.56	2215–2580	100–750	Cenozoic
3	2165	1.01	2255–3195	90–1020	Upper Cretaceous
4	2320	0.71	2560–3380	340–1490	Cenomanian, Rhaetian
5	2330	0.67	2730–3655	600–1980	Keuper
6	2845	0.60	3420–4325	960–2470	Muschelkalk
7	3590	0.36	4145–4790	1540–3330	Buntsandstein

Column 5 gives the range of the mean depth for each layer. The last column contains the dominant stratigraphic units for each layer

Here, the Zechstein layer has the lowest velocity within the thick pillow at CDP 16,000, while the velocity decreases within the thinner parts towards southwest and the northeast. A linear fit for all eight seismic lines results in Eq. (3) (displayed as red line in Fig. 6):

$$V_{salt} = 4750 - 0.18 * D_{salt} \tag{3}$$

Discussion

Comparison to existing onshore data

For the onshore area of the northwestern North German Basin, Jaritz et al. (1991) presented an analysis of seismic velocities, based on about 1000 well velocity logs. They

deduced linear velocity laws (Eq. (1)) for 10 post-Permian rock units. The resulting velocity gradients (k in Eq. (1)) are constant for each unit, while the starting velocity V_0 varies laterally. For Cenozoic layers, their gradient amounts to $0.7 s^{-1}$, comparable to our results for seismic layers 1 and 2. The Upper Cretaceous of Jaritz et al. (1991) shows the highest gradient with values between 0.9 and $1.2 s^{-1}$. Our work also found the highest gradient within seismic layer 3 ($1.01 s^{-1}$, Table 1). Seismic layer 4 is dominated by a huge hiatus and contains thin layers of Cretaceous, Jurassic and maybe Upper Triassic sedimentary rocks – so a comparison to existing data is not possible. Jaritz et al. (1991) characterize the Jurassic/Triassic successions by a decreasing gradient in the range of 0.2 to $0.7 s^{-1}$, which is in good agreement with our results for seismic layer 5 to 7. For the Middle and Lower Buntsandstein, the gradient

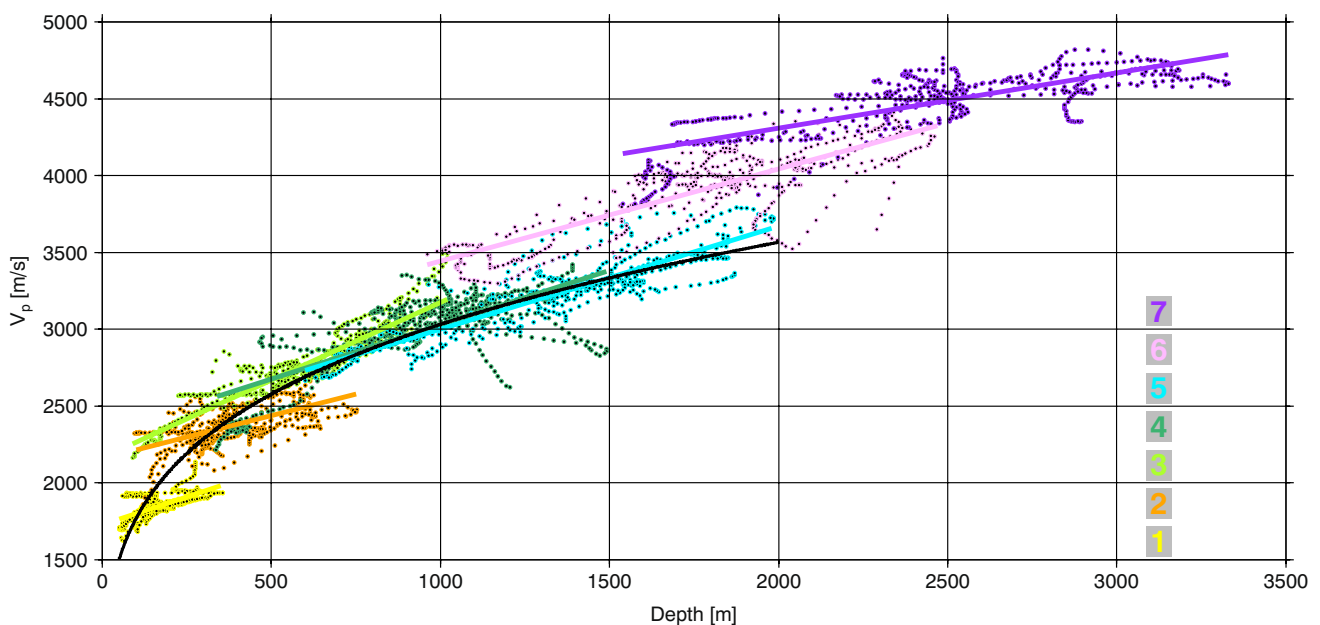
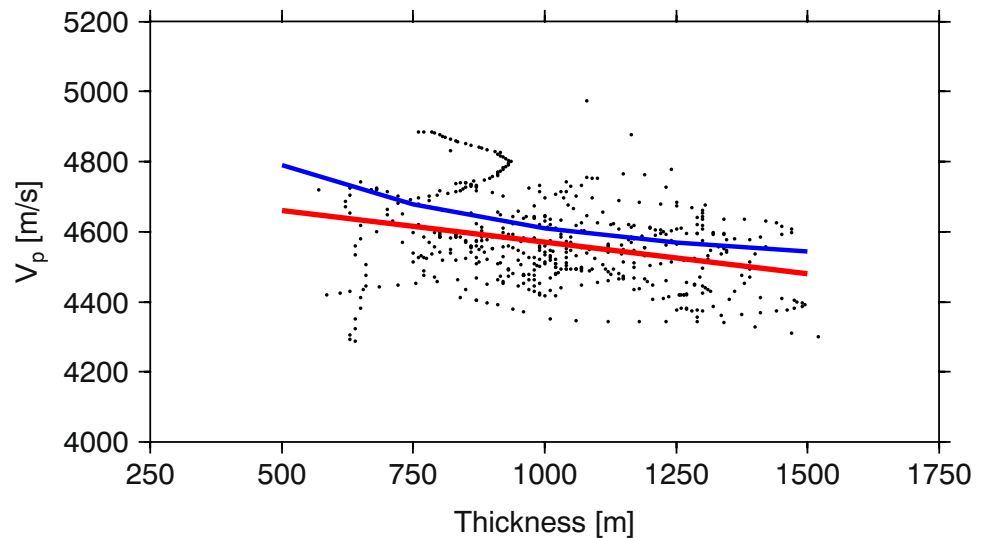


Fig. 5 Interval velocity V_p versus mean depth of the seismic layers. Coloured numbers correspond to numbers of seismic layers. Straight lines represent solutions to Eq. (1). Black curve displays Eq. (2)

Fig. 6 Velocity within the Zechstein layer versus thickness of this layer. Red curve displays the linear relation of this work (Eq. (3)), blue curve covers the Dutch onshore (Wong et al. 2004)



given by Jaritz et al. (1991) is 0.45 s^{-1} , slightly higher than our results for seismic layer 7 (0.36 s^{-1} , Table 1). On the other hand, corresponding values for V_0 differ for both investigations. Therefore, the resulting velocity-depth-relations show a mismatch of not more than 5% at the depth interval between 2000 and 3000 m (see dark blue and black lines in Fig. 7b). Jaritz et al. (1991) used only onshore well data for their analysis, but interestingly they found an increase of seismic velocities in the vicinity of the Bay of Mecklenburg in the range of 500 m/s in comparison to the mean values within the NGB (see comparison of light blue and dark blue lines in Fig. 7b).

Upper Cretaceous burial anomaly

Sonic velocities within Upper Cretaceous Chalk are intensely studied and could be used as a proxy for vertical movements (e.g. Japsen 2018). Figure 7a shows a comparison between our results for seismic layer 3 (interpreted as Upper Cretaceous units) with the Upper Cretaceous-Danian Chalk Group within the North Sea Basin (Japsen 2000). The depth-depending velocity trend of the Upper Cretaceous in the Bay of Mecklenburg is approx. 450 m/s higher than the trend derived for the North Sea Basin (red arrow in Fig. 7a). With respect to the gradient for this layer (1.01 s^{-1} , see Table 1), this velocity anomaly corresponds to a burial anomaly of about -450 m . Hence, it suggests an exhumation/erosion event that must have taken place in post-Cretaceous times. Similar results were derived by a regional study based on Danish well data covering the whole North Sea Basin, including the area just north of the Bay of Mecklenburg (Japsen 1998). The burial anomaly for the Upper Cretaceous unit at well Rødby-1 situated on Lolland was about -634 m , while well Ørslev-1 located on Falster showed a burial anomaly of -483 m (see Fig. 1 for

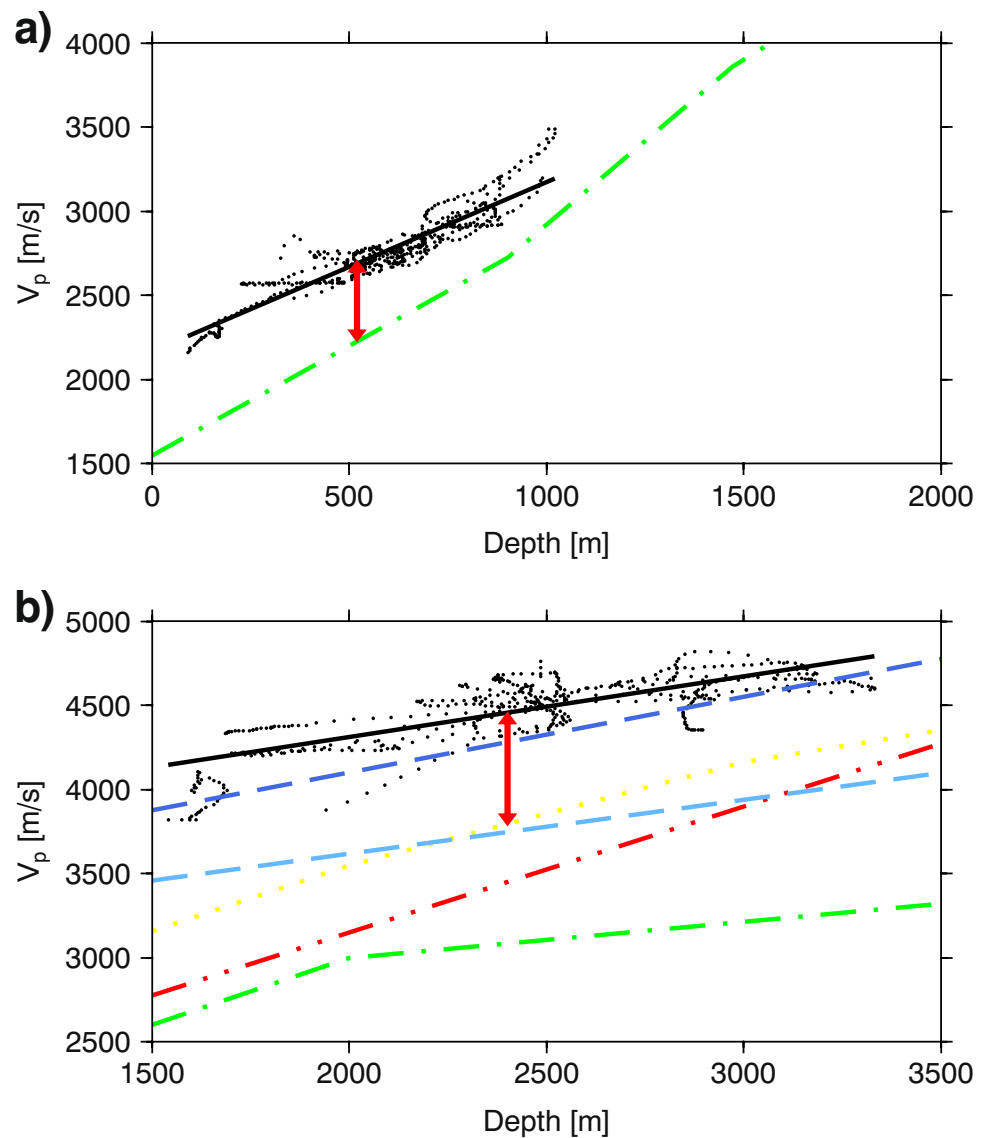
location). Both values are in good agreement with the burial anomaly inferred in this study. Therefore, we can conclude that the Bay of Mecklenburg was uplifted by 450 m during the Cenozoic.

Lower Triassic burial anomaly

Within several previous investigations, the seismic velocities in Lower Triassic formations with respect to burial history and uplift have been analysed within the Southern Permian Basin. The Baltic Formation (Lower Buntsandstein) within the western part of the Polish Basin has been analysed by Dadlez et al. (1997). They used velocities from vertical seismic profiling at 64 wells and compared these to a representative background curve. They found velocity anomalies in the range of 500 to 700 m/s for many of the wells and concluded that the northwestern part of the Mid-Polish Swell was uplifted by about 1500 m in the Upper Cretaceous. A comparable investigation was performed by van Dalfsen et al. (2005) covering sonic logs from 460 Dutch on- and offshore wells. They found velocity anomalies for the Triassic Main Claystone Member as high as 1500 m/s, related to a maximum apparent uplift of 2400 m.

A comparison between the seismic velocities presented here for Middle and Lower Buntsandstein (black line in Fig. 7b) and the background trend for the NGB (light blue line in Fig. 7b) results in a velocity anomaly of about 640 m/s. With respect to the range of gradients within this layer (0.36 to 0.45 s^{-1}), this corresponds to a burial anomaly in the range of -1400 to -1700 m . The magnitude of inferred vertical movements within the Cenozoic is not sufficient to explain a burial anomaly in this range. In the following, we discuss the possibility of additional vertical movements within early Cretaceous/late Jurassic times by using the depth values from CDP 13,200 (Fig. 4).

Fig. 7 a Velocity distribution of Upper Cretaceous layers in comparison with a published background trend (green line) for the North Sea Chalk (Japsen 2000). Results of the MVA in this study shown by black line. The velocity anomaly between both curves (red arrow) shows a mean value of 450 m/s. The velocity anomaly was calculated at the mean depth which is covered by the layer. **b** Velocity with depth distribution within the Middle to Lower Buntsandstein layers in comparison with published background velocity trends from different regions: green for Norwegian-Danish Basin (Japsen and Bidstrup 1999), red for the Dutch on- and offshore (van Dalfsen et al. 2005), yellow for the Polish Basin (Dadlez et al. 1997), and blue for the northwest North German Basin (Jaritz et al. 1991); light blue represents the mean for the whole NGB; and dark blue is the approximation for the southwestern edge of the Bay of Mecklenburg. Results of the MVA in this study shown by black line. The velocity anomaly (red arrow) between our results and the mean values from Jaritz et al. (1991) is about 640 m/s



The interpretation of Fig. 4b in combination with the results from Ahlrichs et al. (2020) shows that the depth of the lowermost Cretaceous successions (Albian) is at 1200 m below sea level. To allow for a burial anomaly between – 1400 and – 1700 m for the Triassic units, a total amount of 2600 to 2900 m of sedimentary rocks had to be removed during the Lower Cretaceous/Upper Jurassic hiatus. Such an amount of uplift is not unusual. Within the Broad Fourteens Basin in the North Sea, a local uplift of Triassic units in the range of 2000 to 3500 m is well known (see discussion in de Jager 2003). The magnitude of this uplift was also confirmed by the analysis of seismic velocity anomalies (van Dalfsen et al. 2005). Another pre-requisite for erosion is the preceding deposition of sediments with the corresponding thickness. Processes which lead to the deposition of thick Jurassic deposits are well documented for parts of the NGB. The Jurassic doming within the North Sea was accompanied

by extensional movements. Within the Danish Central Graben, this resulted in short periods (uppermost Middle Jurassic to lowermost Upper Jurassic time) of rapid subsidence with deposition of more than 4 km of marine mud (Andsbjerg et al. 2001). The local deposition of thick Jurassic sediments in the vicinity of rift structures within the NGB is also well documented. Warsitzka et al. (2017) discuss Jurassic sedimentation in conjunction with the Glückstadt Graben, just west of the Bay of Mecklenburg. In the west of the Glückstadt Graben, the existence of up to 3000-m thick Jurassic successions was proven by Maystrenko et al. (2011), and the eastward-directed late Jurassic erosion of these Jurassic layers was shown by Maystrenko et al. (2005).

Within the literature, different estimates concerning the total amount of Jurassic erosion within the NGB are reported. For the area of the German-Danish Horn-Graben, Kilhams et al. (2018) estimated the amount of missing

Jurassic material to not exceed 500 m. Rodon and Littke (2005) have performed numerical modelling for well data from Fehmarn Z1. Their model incorporated an amount of eroded Lower and Middle Jurassic rocks of about 700 m – this value was originally proposed by Jaritz (1980). However, the modelling results from Rodon and Littke (2005) show that the measured values for the vitrinite reflectance are also in agreement with an amount of Jurassic erosion in the range of 1400 m. The removal of Jurassic rocks at the well Tønder-2 was analysed by Japsen et al. (2007). While the estimation of eroded material based on sonic data resulted in a value of 1200 m, the application of apatite fission track analysis resulted in a value of 3000 m.

Due to missing well data within the Bay of Mecklenburg, we could not exclude lithological variations within the Triassic layers in the Bay of Mecklenburg in comparison to the central NGB. But with respect to existing results, it seems reasonable that the here reported negative burial anomaly within the Buntsandstein layers could be caused by early Cretaceous/late Jurassic erosion with a magnitude between 2600 and 2900 m. This is further supported by paleogeographic maps (Ziegler 1990a): the area of the Bay of Mecklenburg was uplifted during Bajocian as the easternmost part of the Central North Sea Dome and remained subaerial until the Barremian as the northern part of the Pombeckj Swell.

Heterogeneity within the Zechstein

Our data has shown that the velocity within the Zechstein inversely correlates with the thickness of this layer. This effect has previously been shown by an evaluation of Dutch wells (Wong et al. 2004), but here, we show this effect for the first time with indirect (surface-based seismic) methods. Interestingly, the velocity trend from our work is in very good agreement with the findings from Wong et al. (2004) (see Fig. 6). Besides the general increase of Zechstein thickness towards the basin centre, thickness in the Bay of Mecklenburg varies locally due to salt accumulation in salt pillows and depletion in adjacent rim synclines (e.g. Zöllner et al. 2008; Ahlrichs et al. 2020). As salt pillows grow, the lower viscous portions of the Zechstein evaporite sequence (mostly halite) accumulate in the structure, while the higher viscous portions (mostly anhydrite and non-evaporite rocks) remain in the area of salt depletion. Accordingly, the relative content of halite in the Zechstein succession varies with thickness in the area of investigation. The difference in the physical properties of halite, anhydrite and non-evaporites impacts the interval velocity of the layer as generally anhydrite and non-evaporites (5000–6500 m/s) are characterized by higher interval velocities than halite (4500 m/s) (e.g. Urai et al. 2008). Therefore, thinner layers have a higher relative content of

anhydrite and non-evaporites, which increases the interval velocity of this layer.

Conclusions

Within this study, we presented a consistent laterally variant seismic interval velocity model covering Cenozoic and Mesozoic successions. This model helps to depth-convert seismic data in the area of the Bay of Mecklenburg. Further on, we showed that seismic velocities deduced from surface-based measurements, like seismic imaging, can help to understand the evolution of sedimentary basins. We analysed the velocity model to derive depth-dependent velocity trends for the Bay of Mecklenburg and compared them to published reference trends from adjacent areas. Our interpretation of velocity anomalies as a proxy of maximum burial depth modified by vertical tectonic movement results in the conclusions concerning the Bay of Mecklenburg:

- The Upper Cretaceous successions show a velocity anomaly of about 450 m/s. This anomaly is interpreted to be caused by Cenozoic uplift with a magnitude of about 450 m. This interpretation is supported by results from well data just north of the Bay of Mecklenburg.
- The Lower Jurassic successions show a velocity anomaly of about 640 m/s. This anomaly could be caused by an uplift of about 2600 to 2900 m in early Cretaceous/late Jurassic times. Due to missing well data within the Bay of Mecklenburg, lithological variations causing this velocity anomaly cannot be excluded.
- Within the Zechstein unit and as a result of the different rheology, the relative fraction of halite compared to anhydrite is depleted between the salt pillows. This leads to an increase in the interval velocity.

We have shown that seismic velocities derived from migration velocity analysis (MVA) are sensitive enough for a geological interpretation concerning the uplift history. For this analysis, only a basic knowledge about the background velocity trends is needed. Therefore, the here presented method can be used to enhance the spatial coverage as well as the lateral resolution of velocity fields in areas with sparse drilling information.

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Data availability The processed seismic data is available via the pan-European data portal Geo-Seas, https://www.geo-seas.eu/search/welcome.php?query=1678&query_code={558D29F1-65F5-4441-8CAF-8E15926546E9}. Additional raw data is available from the corresponding author upon request.

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