GENERAL AUTHOR RESPONSE

Here we have tried to identify the main points raised in the five reviews and explain in general terms how we dealt with them. Responses to all individual reviewer comments are contained in the file "Author Response to Individual Comments"

Restructure the manuscript

Following the reviewers´ suggestions we have moved all workflow-related text to the respective chapter. Similarly we have tried to move all interpretation to the Discussion section. We have retained the subchapters in the Results section because we feel that maintaining a separation between data sources and workflow enhances reader-friendliness and makes the electronic publication more navigable through hyperlinks.

We did not follow the suggestion to present the balanced cross section before the forward model for the following reason: The idea that the observed Zechstein slivers were created by inversion was conceived during field work. The forward model served to test the general geometric viability of the concept. The line-length balanced cross-sections were constructed in a second step to create more detailed structure models that closely conform to surface data. Thus, the manuscript structure follows the actual work flow.

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Choice of cross-section locations, additional sections

The two balanced section locations were chosen such that the best available data could be used. Section A (Mühlberg) was chosen to include the previously described (Schröder 1925), once easily accessible, outcrop along the train tracks near Sontra. To our knowledge this is the only location where a Zechstein sliver with its hanging wall and footwall was ever exposed. The second traverse was chosen for its proximity to the shallow well demonstrating Muschelkalk underlying a Zechstein sliver, contrasting with the Mühlberg section.

Following the reviewer´s requests we have added four additional, non-balanced cross-sections and one longitudinal section to show the effects of transverse faults vs. varying exhumation levels on the appearance of the graben.

We also included a regional cross-section to illustrate the structural setting of the Sontra Graben and to address the topic of the link between a mostly thin-skinned graben and basement faults.

Dividing the Sontra Graben into segments

Since the main subject of this study are the Zechstein slivers, it makes sense to place emphasis on their distribution along the Sontra Graben. Consequently, we introduced five segments, which subdivide the graben with regard to the existence and/or size of the slivers. This subdivision is obviously non-unique, but coincides with other structural features.

Detachment/Décollement

We changed all instances of "décollement" to "detachment", except when discussing the actual basal décollement, e.g. in line 283 (page 9), where we used the term "décollement" to discuss the problem of horse formation near the basal "décollement", meaning large-scale detachment. "Décollement: Large-scale detachment, i.e. fault or shear zone that is located along a weak layer in the crust or in a stratigraphic sequence (e.g. salt or shale). The term is used in both extensional and contractional settings." (Fossen 2010)

Zechstein strata vs. Zechstein Group

We have adjusted our stratigraphic terminology. However, we retain the term "Zechstein strata" to refer to small parts of the Zechstein Group, sometimes of uncertain stratigraphic position.

Discussing salt models from the North Sea and their interpretations

We now briefly discuss salt models from the North Sea. The general scarcity of salt-bearing horizons in our study area makes for quite different structural configurations.

Simple Shear-Algorithm

We used the Simple Shear algorithm because it was designed for extensional systems. The main aim of the forward model was to explore the necessary magnitude of normal faulting and to obtain an impression of the pre-inversion size of the half-graben, not so much the inversion phase for which Simple Shear is not the ideal choice

A more detailed description of the Zechstein slivers

We hope we have achieved this mostly by restructuring, now presenting all information in the same place. In addition, we have included field photographs for a better impression.

Strike-slip discussion

We briefly (because of existing publications on the subject) discuss the kinematics of inversion in Central Europe and have added key references.

Conclusion

We have rewritten parts of the conclusion to include a statement on the timing of the inversion phase and to make other parts more concise. In general, we feel that the conclusion section should include all main hypotheses of the article and thus inherently resembles a list of statements.

Chronostratigraphical terminology

All chronostratigraphical references now comply with the International Commission on Stratigraphy.

Figure numbering

All figures have been re-ordered and are now correctly referenced throughout the manuscript.

Figures

All major localities and those that are referenced in the manuscript have been added to the geological map. The location of the wells has been added, also. The symbology within the geological map has been updated to comply with USGS standard.

The figure displaying the outcrop along the train tracks near Sontra was enhanced with more of our own field observations and a structural interpretation.

The DEM was removed from the detail map that shows the paleogeography of the Zechstein and has been replaced with just the larger faults for orientation.

We would like to thank all Referees for their detailed comments on our manuscript and hope to have replied satisfactorily to all of them.

Kind Regards,
Jakob Bolz & Jonas Kley

Emplacement of “exotic” Zechstein slivers along the inverted Sontra Graben (northern Hessen, Germany): clues from balanced cross-sections and geometrical forward modelling

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Abstract. Lens-shaped slivers of Permian (Zechstein) amid Triassic units appearing along the main boundary fault of the Sontra Graben in central Germany on the southern margin of the Central European Basin System (CEBS) were studied by means of detailed map analysis, a semi-quantitative forward model and two balanced cross-sections. We show how partial reactivation of the graben’s main normal fault and shortcut thrusting in the footwall during inversion, combined with a specific fault geometry involving flats in low shear-strength horizons, can produce the observed slivers of “exotic” Zechstein. This conceptual model implies that the Sontra Graben was created by about 1200 m of extension followed by some 1000 m of contraction, resulting in the few hundred meters of net extension observed today. Gentle dips and comparatively extensive exposure of some slivers suggest they are backthrust onto the reactivated normal fault´s hanging wall, an interpretation corroborated in one location by shallow drilling. Backthrusting appears to have wedged some Zechstein slivers into incompetent Triassic units of the hanging wall. Based on regional correlation, extension most likely occurred in Late Triassic to Early Cretaceous time while the contraction is almost certainly of Late Cretaceous age. The main aim of this paper is to describe an uncommon structural feature that we interpret to originate from inversion tectonics in an evaporite-bearing succession with multiple detachment horizons but without the presence of thick salt.

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1 Introduction

The Mesozoic tectonic evolution of Central Europe involved long-lasting, Triassic to Early Cretaceous extension followed by a short-lived pulse of mostly Late Cretaceous contractional deformation. This history is best documented by subsidence and inversion in the main sub-basins of the Central European Basin System (CEBS) such as the Broad Fourteens and Lower Saxony basins and the Mid-Polish trough (Brochwicz-Lewiński & Poźarvski, 1987; Hooper et al., 1995; Mazur et al., 2005; Maystrenko & Scheck-Wenderoth, 2013). South of these basins a wide border zone of the CEBS also experienced first distributed extension of low magnitude and then equally dispersed contraction. These movements created an array of narrow grabens or half-grabens affected to different degrees by folding and thrusting. The grabens or fault zones are the most

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prominent structures in the otherwise flat-lying to gently undulating Mesozoic cover of the central German uplands ("Mittelgebirge"). They exhibit two prevailing strike directions: NW-SE and N-S to NNE-SSW, with the former considerably more frequent than the latter. The Sontra Graben discussed here is one of the NW-SE-trending Hessian Grabens. It is located in the north-eastern part of the state of Hessen, approximately 50 km south of the city of Göttingen (Fig. 1). The Hessian Grabens appear as narrow strips of Middle to Late Triassic (Muschelkalk and Keuper) strata, downfaulted by as much as several 100 meters relative to their Early Triassic (Buntsandstein) surroundings. Despite their designation as "grabens" that was coined in the early 20th century (e.g., Schröder, 1925) and persists in their names today, many of them show a pronounced asymmetry, having one boundary fault with considerably larger displacement than the other. The structures of the (half-)graben interiors are highly variable, ranging from gentle synclines over successions of synclines and anticlines to rotated, fault-bounded blocks.

In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics (Rotliegend Group) and an originally continuous sequence of latest Permian (Zechstein Group) through Triassic (Buntsandstein, Muschelkalk and Keuper Groups) sandstones, shales, carbonates and evaporites. Numerous incompetent layers consisting mostly of sulphates and shales occur in the Zechstein Group and at two levels of the Triassic succession (upper Buntsandstein and middle Muschelkalk subgroups), but no thick halite was deposited (Fig. 2).

The Sontra Graben and several of the other graben systems (e.g. Creuzburg Graben, Eichenberg Fault Zone) exhibit enigmatic occurrences of Zechstein strata. The Zechstein rocks are found discontinuously as fault-bounded blocks or slivers/horses along the faults of the grabens. These slivers of Zechstein carbonates are structurally elevated relative to both the downfaulted interior and the footwall blocks that define the regional level. In the Sontra Graben they are some tens to several hundreds of meters along-strike and range in width from meters to a few tens of meters perpendicular to the faults. Internally, the slivers appear almost undeformed. However, in most cases the bedding is moderately to steeply dipping and strikes approximately fault-parallel.

It was previously suggested that the emplacement of the uplifted Zechstein blocks was due to salt diapirism (Lachmann, 1917) or intrusion of salt and other evaporites into the fault zone (Möbus, 2007). However, the absence of evaporites within these slivers and their dominant occurrence in areas of primarily low salt thicknesses provide challenges for this concept. In this paper, we explore the hypothesis that the "exotic" Zechstein slivers were emplaced as a result of inversion tectonics involving bedding-parallel detachments in two evaporitic Zechstein horizons during both extension and contraction.

2 Methods

2.1 Data sources

Data were compiled by detailed analysis of the official geological maps of the area (Beyrich and Moesta, 1872; Moesta, 1876; Motzka-Noering et al., 1987), maps from published thesis papers of the 1920s and 1930s (Schröder, 1925; Bosse, 1934) and

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unpublished maps created during two diploma mapping projects at the University of Jena (Jähne, 2004; Brandstetter, 2006) and on the background of our own field observations. Dip and strike data were also gathered from numerous unpublished reports written by students in the beginner-level mapping courses in the years 2014 and 2015 at the University of Göttingen. To complete the existing data, we mapped the exact position and extent of all Zechstein slivers and took dip readings where possible.

In recent years the area around the Sontra Graben was surveyed for the construction of a motorway which is now underway. In the course of this survey, numerous shallow wells were drilled. We used information from two such wells to constrain the architecture of one fault hosting Zechstein slivers. Topography data for the cross-sections and the geological map were obtained from the topographic map of Hessen (1:25,000) and from a digital elevation model (DEM) kindly provided by the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG). Stratigraphic data (Fig. 2) were taken from Motzka-Noering et al. (1987), which also contains a compilation of various well and outcrop data.

2.2 Workflow

The collected map data were digitised and georeferenced using QGIS (QGIS Development Team, 2015). All geological mapping was done using the app FieldMove (© Petroleum Experts) on an Apple iPad Air 2. Data from the app were fed into QGIS via the .csv import function. Subsequently, a new internally consistent geological map was constructed (Fig. 3). The resulting map and dip data then served as the basis for modelling and cross-section construction using the module 2DMove from the Move Suite (© Petroleum Experts). All data were transferred from QGIS into 2DMove via the shapefile (*.shp) or the ASCII (*.txt) import functions.

2.3 Cross-section construction and modelling

2.3.1 Digital forward structural model

The forward model was constructed in 2DMove (© Petroleum Experts) to test the viability of inversion-related emplacement of the Zechstein slivers. We constructed an undeformed layer cake model with horizontal bedding using the average stratigraphic thicknesses of the study area. For simplicity, the model contains only one fault which represents the main, southwestern boundary fault of the Sontra Graben, similar to the situation in the Mühlberg section. Using the 2D-Move-on-Fault tool with the Simple Shear algorithm and 60° shear angle, we simulated normal fault displacement followed by reverse motion, adjusting the fault geometry and displacement magnitudes until producing a Zechstein sliver wedged between Muschelkalk strata of the hanging wall and footwall which display a small remaining normal offset in the final stage. Finally, the 2D-Unfolding tool with the Simple Shear algorithm and a 60° shear angle was used to create folding of the section at larger wavelength. This step was necessary to produce the northeast dip of the footwall, which otherwise remains horizontal by default.

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2.3.2 Constructing the balanced geological cross-sections from map data

Two sections were constructed and balanced using 2DMove (© Petroleum Experts). Section A was positioned to coincide with the large outcrop shown in Fig. 4 and section B lies very close to one of the wells mentioned. From the dip data, an orientation analysis was conducted to determine the optimal orientation for the cross sections. The calculated fold axis trends WNW-ESE, indicating a shortening direction consistent with the regional NNE-SSW extension and contraction directions deduced from the analysis of small-scale fault populations (Navabpour et al., 2017). Hence, approximately plain strain deformation conditions for the profiles can be assumed for both the extensional and the contractional phase. All geological boundaries were derived from the newly compiled geological map (Fig. 3). The 2D-Unfolding tool with a Flexural slip algorithm was used to flatten the folds. This algorithm conserves bed lengths when applied to a stratigraphy of uniform thicknesses while also allowing to retrodeform faults and the topographic surface. The fault geometries were corrected through trial-and-error-cycles to reduce gaps or overlaps to a minimum. Both sections were constructed with similar structural geometries to ensure consistency and avoid the need to invoke abrupt structural changes between them.

3 Structural geology

3.1 Structure and segmentation of the Sontra Graben

The NW-SE-trending Sontra Graben extends for a length of 35 km between the N-trending Altmorschen-Lichtenau-Graben in the west and the northwestern tip of the Thuringian Forest, a fault-bounded basement anticline in the east (Fig. 1). On both ends the Sontra Graben is reduced to a single fault before linking up with the other structures. Near its centre, the Wellingerode Graben branches off from the Sontra Graben and runs first north-northeastward and then in a more northeasterly direction to meet the NW-SE-trending Netra Graben.

The main part of the Sontra Graben within the study area is subdivided into five segments for the purpose of this paper (Fig. 3), primarily based on the configuration of the Zechstein slivers but also largely coincident with other structural features. In the very northwest (segment I) the graben has a width of approximately 500 metres. It is confined between the southwestern and northeastern boundary faults, both with a throw of 150 to 180 metres when the Zechstein slivers are not considered. The southwestern fault has two strands with a narrow band of Muschelkalk strata between them. Zechstein slivers occur on both strands and are comparatively small (from 1.000 to 16.000 m^2, see Tab. 1 for details of these and the other Zechstein slivers). A second, northeastern band of Muschelkalk appears in the easternmost part of segment I, overlapping with the southwestern one over a few hundred metres. Another Zechstein sliver is present on the fault bounding this Muschelkalk band in the southwest. This fault here takes the position of a central main fault.

Further to the southeast, segment II comprises a short stretch of graben near the village of Stadthosbach, where it becomes quite narrow (250 metres). Only the northeastern band of Muschelkalk strata continues from segment I, confined between the

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northeastern boundary fault and the central fault which here marks the southwestern boundary and has small-sized Zechstein slivers along it. The net throw across the southwestern fault amounts to no more than 80 metres.

In segment III the Sontra Graben widens again to as much as 1.2 kilometres. A more complete succession of Muschelkalk Group strata reappears in the footwall of the central fault. The middle and upper Muschelkalk outcrop reveals an incompletely preserved, southeast trending axial syncline, in certain parts well silhouetted by the Trochitenkalk Formation of the upper Muschelkalk. The outcrop of discontinuous lower Muschelkalk blocks surrounded by upper Buntsandstein along the northeastern border becomes very broad in this part of the graben probably due to fault repetition. The axial syncline of the Sontra Graben in this segment interferes with a similar but NNE-trending syncline belonging to the Wellingerode Graben. West of the Mühlberg hill, a fold interference pattern formed by superposition of the NW- and NNE-trending synclines produces a structural basin where strata of the Keuper Group are preserved. No Zechstein slivers are exposed in this part of the graben.

East of the intersection with the Wellingerode Graben, segment IV comprises the largest Zechstein slivers that appear exclusively along the southwestern border fault and terminate just west of the river Sontra. The graben, again, becomes very narrow (110 metres), where the river transects it. The western end of the Zechstein sliver is exposed in the railroad cut along the foot of the Mühlberg hill that was described by Schröder (1925) and provided the best exposure so far of the Sontra Graben and one of the Zechstein slivers. Despite a much-deteriorated state of the outcrop today (Fig. 4), it still provides insight into fault geometries of the graben and the way the Zechstein slivers are juxtaposed with the shoulder of the graben and its interior. The downward-narrowing Zechstein sliver is bounded on its southwestern side by a low-angle northeast-dipping thrust fault emplacing it onto middle Buntsandstein. On its northeastern side the sliver is bounded by a northeast-dipping normal fault juxtaposing it against lower Muschelkalk which is internally folded. Further uphill, a second, small “exotic” sliver of middle Buntsandstein occurs between the Zechstein and the Muschelkalk. East of the river Sontra, a north-eastern swath of segment IV exhibits oblong tilted blocks of lower Muschelkalk surrounded by upper Buntsandstein shale. This structure contrasts with open folding in a southwestern swath where the axial syncline reappears and becomes quite prominent.

In segment V, the graben widens to more than two kilometres and also changes direction slightly to a more southwesterly trend, skirting the southern edge of the Ringgau, a topographically elevated panel of flat-lying Muschelkalk strata between the Sontra Graben and the Netra Graben. While the southwestern half of the graben is dominated by the widening and deepening axial syncline that preserves Keuper strata in its core, its northwestern half is occupied by a zone of fault-bounded and tilted blocks of lower Muschelkalk surrounded by upper Buntsandstein, similar to the structure of segment II and the western part of segment IV. Small Zechstein slivers occur only on the boundary fault of the graben in segment V but are restricted to its northwestern part (Fig. 3).

The Zechstein slivers vary greatly in size and shape (Fig. 5). A general trend towards larger, more continuous slivers can be observed from the northwest to the southeast, i.e. from segment I to V (Tab. 1, Fig. 3). The lower Muschelkalk appears most commonly as bordering unit on the north-eastern side of the slivers while in the south-west, the slivers are generally bordered on by the upper Buntsandstein. Assigning a stratigraphical unit to the individual outcrops is sometimes difficult. Although

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most of the slivers actually produce conspicuous rocky outcrops and it is often possible to measure bedding dips, they generally consist of poorly bedded to massive, vuggy (cellular) dolomite of either the Hauptdolomit (z2, Staßfurt cycle) or Plattendolomit (z3, Leine cycle) carbonates (Fig. 2b). In addition, weathering has in some cases decomposed the rock to a powdery ash-like substance, rendering bedding unrecognizable.

3.2 Mechanical stratigraphy

This section focusses on the Zechstein stratigraphy, which is of prime importance for our structural model. The latest Permian Zechstein transgression flooded the Southern Permian Basin from the central North Sea into western Poland and from the southern margin of the Baltic shield in the north to the Rhenish massif and the Bohemian massif in the south (Ziegler, 1990). Due to sea-level fluctuations, the Zechstein sediments were deposited in seven recurring cycles (Richter-Bernburg, 1953). These cycles are recorded in seven "Folgen" z1 to z7 (the German term is used for these units by the German Stratigraphic Commission) or correlative formations (Paul et al., 2018). The most complete formations comprise clastic sediments at the base, overlain by carbonates, sulphates, halites and potash/magnesium salts. The full seven formations are restricted to the central parts of the basin (Becker and Bechstädt, 2006). Situated on the southern margin of the Southern Permian Basin, the study area mainly comprises the first three Zechstein formations, the Werra, Staßfurt and Leine formations (or z1 to z3 "Folgen") and contains the subsequent four formations only in a shaly marginal facies. The basin-margin character of the study area resulted in original Zechstein thicknesses in parts as low as 60 metres. From a mechanical viewpoint, the Zechstein constitutes a relatively thin but very heterogeneous succession of alternating competent and incompetent packages. The strongest units are the carbonates of the Werra and Staßfurt formations, traditionally termed "Hauptdolomit" (Main Dolomite, Ca2) and "Plattendolomit" (Platy Dolomite, Ca3). The Zechstein slivers in the Sontra Graben typically consist of poorly bedded to massive vuggy (cellular) dolomite, a facies that occurs in both the Ca2 and Ca3 carbonates.

Prominent weak layers and potential detachment horizons are the evaporites and shales. The Ca2 carbonate is underlain by thick sulphate and shale of the Werra Formation, termed the Werra-Anhydrit (A1) and Braunroter Salzton (brownish red salty clay, T1r). T1r consists of up to 4-metre-thick greyish-green, thin-layered shales originally interspersed with thin layers of halite. There is no indication of primary massive rock salt in the Werra Formation of the study area. Above the Ca2 carbonate and separating it from Ca3 there is another shale horizon. Again, there is no indication for salt in the Staßfurt Formation in this part of the basin. The Ca3 carbonate is either overlain by anhydrite (A3) or grey, clayey carbonates (Ca3T). Near the town of Sontra, the Hauptanhydrit (A3) level is exposed as relatively homogeneous gypsites with thin (1 cm) layers of brownish dolomite. Traditionally, the term "Obere Letten" (upper clays) was used as a collective term for claystones, siltstones and sandstones of small thickness overlying Ca3 or A3 and now attributed to the Leine, Aller, Ohre, Friesland and Fulda formations (or z3 to z7 "Folgen").

The z3 to z7 shales grade upwards into the Triassic Buntsandstein via a succession of siltstones. The Triassic succession comprises three competent units: the thick and mostly sandy lower and middle Buntsandstein, the rather homogenous, thin-bedded limestone sequence of the lower Muschelkalk and the thin but mechanically strong lower part of the upper Muschelkalk

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(Trochitenkalk Fm.) consisting of thick-bedded grainstones and rudstones. Potential detachment horizons between them are formed by the evaporitic and shaly upper Buntsandstein and the evaporitic and marly middle Muschelkalk. These detachments are important for second-order features such as the Zechstein slivers wedged into middle Muschelkalk. The higher part of the upper Muschelkalk and Keuper together represent an incompetent stratal package at the top of the preserved column.

3.3 Forward Model

The forward structural model served to test our working hypothesis, developed from field observations, that the present-day small offset of the Sontra Graben's main southwestern fault(s) represents the sum of a much larger normal offset and reverse reactivation of similar magnitude. The model was designed to simulate the main features of the Mühlberg section which, as described above, is comparatively well-constrained and structurally simple except for the exotic Zechstein sliver. One aim was to estimate the minimum normal displacement required to attain the starting condition for the formation of the Zechstein slivers, i.e. Muschelkalk of the hanging-wall juxtaposed against Zechstein of the footwall. The model was particularly useful in exploring the influence of detachments in the Zechstein units and provided a template for the construction of the two balanced cross-sections. The fault of the final model has an overall listric geometry with a dip angle of 60° at the surface that becomes a bedding-parallel detachment at a depth of 800 metres within the Werra-Anhydrit (Figs. 2b, 6). The listric geometry is broken by three flats or short detachments, sitting in the middle Muschelkalk, the upper Buntsandstein and the Hauptanhydrit (A3) of the Zechstein. An extension of approximately 1.2 kilometres is sufficient to bring the lower Muschelkalk of the hanging wall to Zechstein depth with the listric fault geometry described. A flat in the Hauptanhydrit (A3) creates a step in the fault geometry, which upon inversion promotes the formation of a shortcut thrust. For the inversion phase, such a shortcut thrust was introduced (Fig. 6b) creating a Zechstein horse delimited by the original normal fault as a roof thrust (or non-reactivated fault) and the newly created shortcut thrust as a sole thrust. A backthrust was also modelled that emplaces the Zechstein horse onto the underlying lower Muschelkalk of the hanging wall. This was included into the model because data from a well just 20 metres to the northwest of section B indicate that Zechstein is thrust on top of the lower Muschelkalk of the hanging wall at a shallow depth of approximately 30 metres. Shortening of approximately 1000 metres sufficed to elevate the newly created Zechstein sliver to a regional stratigraphic level within the upper Buntsandstein, a level where the slivers are commonly found. Finally, the 2D-Unfolding tool with the Simple Shear algorithm and a 60° shear angle was used to model wholesale folding of the half-graben at a larger wavelength of about 1.5 kilometres, a feature required to replicate the dip values observed in the field.

Flats in the middle Muschelkalk and the upper Buntsandstein were incorporated to acknowledge the role of these units as detachment horizons. The kinked fault geometry causes strong distortion of the modelled hanging-wall during inversion (Fig. 6d) and would also do so during extension. In nature, the arising stress concentration around the kinks would probably promote straightening of the fault by excision of slivers. Similarly, the sudden drop of Zechstein thickness in the hanging wall where the future exotic sliver was located induces a narrow zone of shearing (Fig. 6b) that would probably correspond to an antithetic normal fault in nature.

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3.4 Balanced Cross-sections

Cross-section A (Mühlberg, Fig. 7a) and cross-section B (Weißenborn, Fig. 7b) were constructed using the same basic geometry. The main, northeast-dipping normal fault has a listric geometry down to the depth of the secondary detachment above the Ca3 carbonates which it follows for a short distance before stepping down to the main detachment in the Werra-Anhydrit, at a depth of approximately 300 metres below the present surface. The southwest dip of the hanging wall is caused by rollover on the listric fault. The northeast dip of the footwall cannot be an effect of the fault but requires additional open folding of the entire structure, including the basement. As stratigraphic horizons in the immediate footwall of the main fault lie lower than their hanging wall counterparts, short southwest-dipping segments of the footwall are necessary in both sections to bring the Zechstein detachment to the regional elevation of the Werra-Anhydrit in the northeast.

The structure of the Zechstein sliver is better constrained in cross-section B where the well has demonstrated it is emplaced on Muschelkalk of the hanging-wall. This suggests the sliver overlies a backthrust that is modelled as an emergent fault. Alternatively, the sliver could be wedged beneath the middle Muschelkalk under a southwest-directed passive-roof thrust. Erosion of potential hanging wall cutoffs and poor exposure of the middle Muschelkalk do not allow to prove or disprove the existence of an emergent backthrust.

For section A we have modelled two scenarios: One includes a backthrust corresponding to the one in section B, the other one has no backthrust. Two fault bounded slivers of Zechstein and middle Buntsandstein appear parallel to the main boundary fault. In the first scenario they are cut off at shallow depth by the backthrust. The space occupied by the slivers tends to make bed lengths of the base and top lower Muschelkalk horizons too short, a problem that is exacerbated by the deeper-reaching slivers of the second scenario. This version therefore includes some distributed shortening and thickening of the upper Buntsandstein and lower Muschelkalk, consistent with field observations. Longer-wavelength basement-involved folding in the final stage of inversion steepens the angle of the main normal fault.

At the location (Fig. 3) of cross-section B (Fig. 7b), the graben has a width of approximately 370 metres and includes the largest of the Zechstein slivers. The boundary fault in the southwest dips at an angle of approximately 70° towards the northeast and flattens out to become a horizontal detachment at a depth of approximately 450 metres. The center of the graben is occupied by an open syncline in middle to upper Muschelkalk. Its southwestern limb is here interpreted to be supported by the underthrust, wedge-shaped Zechstein sliver, masking the southwest dip of deeper units caused by rollover on the boundary fault. The backthrust is modelled with a similar geometry as in section A, parallel to bedding on the northeast limb of the synclinal graben center. Different from cross-section A, it detaches in the middle Muschelkalk instead of the upper Buntsandstein. Basement-involved folding is also required in cross-section B to explain the northeast dip of the southwestern shoulder and the Zechstein depressed to slightly beneath its regional elevation below the graben.

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Deleted: **3.41.1 Cross-section A1: Mühlberg**¶
Cross-section A (Fig. 6 AFig. 6)

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3.5 Additional cross-sections

We have drawn a series of conceptual cross-sections extending basic features of our interpretation to the rest of the Sontra Graben (Fig. 8). Common features along the inverted (half-)graben include a southwestern shoulder dipping towards the graben, a northeast-dipping, listric master fault, one or several synthetic secondary faults and a subhorizontal northeastern shoulder. An antithetic northeastern border fault of substantial throw is only present in the northwestern part of the Sontra Graben between cross-sections a-a´ and c-c´. There, the graben interior comprises two swaths of upper Buntsandstein and lower Muschelkalk, both of overall synclinal geometry and separated by a major longitudinal fault. Both this central fault and the antithetic northern border fault die out towards cross-section c-c´ where the two Muschelkalk swaths coalesce to be eventually crossed by the NNE-trending syncline of the Wellingerode graben. The exotic Zechstein occurrences are bound to the southeastern border fault and the central fault. The southeastern part of the graben has a different structure. Depending on the structural level exposed it exhibits a series of oblong blocks of lower Muschelkalk dipping into faults bounding them on their southwestern sides, or an overlying syncline comprising middle Muschelkalk to Keuper strata. All Zechstein occurrences are aligned along the southeastern border fault. Our inversion tectonic model explains well narrow Zechstein slivers extending along faults and dipping parallel to them, but does not predict structurally elevated, yet gently dipping Zechstein strata occupying larger areas as observed in cross-sections a-a´ and B. These are most easily modelled as overlying north-directed backthrusts as proven for section B (Weissenborn).

In cross-section a-a´, the hanging wall of the central fault with its widely exposed middle Buntsandstein lies too high to be explained by thin-skinned deformation. We have therefore included a southwest-directed basement thrust which represents a more pronounced expression of the basement-involved deformation that produced folding of the basal detachment in the other sections.

4 Discussion

4.1 Overall Structure of the Sontra Graben and Fault Geometries

The Sontra Graben exhibits marked variations in structural style both along and across its strike. The along-strike variations were already described in section 3.1. The most conspicuous across-strike change is from open folding in the southwest, next to the main fault, to block faulting and tilting in the northeast. This difference is best expressed in segments IV and V, and to a lesser degree in segment III. We interpret it to reflect a vertical change in structural style revealed by varying depth of erosion which is in some cases accentuated by changes in the structural level across transverse faults (see longitudinal cross-section, Fig. 8e). Open folding affects middle Muschelkalk to Keuper strata whereas the tilted blocks consist of lower Muschelkalk surrounded by upper Buntsandstein. We interpret this vertical contrast as an effect of detachment in the predominantly marly and evaporite-bearing middle Muschelkalk (Fig. 9). This detachment must already have been active during the extension phase. It was again instrumental for the emplacement of the Zechstein sliver along a backthrust in the Weissenborn section. The

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3.5 Formation of the Backthrust
Well data from 20 metres to the northwest of section B indicate that at least at one location Zechstein is thrust on top of the lower Muschelkalk of the hanging wall at a shallow depth of approximately 30 metres. Backthrusts are a well-documented feature of inverted grabens (Hayward & Graham, 2015). A kinematically viable solution would therefore be a backthrusting movement of the Zechstein horse onto the lower Muschelkalk of the hanging wall.
3.62 Summary of the structural interpretation
A comparison of the two cross-sections clearly demonstrates the widening of the Graben towards the southeast. In both sections, long wave-length folding overprints the original geometry of the listric normal boundary fault and its inversion features, such as the backthrust fault and thus fault angles become somewhat skewed. The sections also expose that the features, which can be observed at the ... [44]

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Well data from 20 metres to the northwest of the profile line indicate that at least at one location Zechstein is thrust on top of the Lowe ... [45]

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The Zechstein slivers that crop out along the graben vary greatly in size and shape. A trend towards larger, more continuous slivers can ... [46]

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Flats at different Zechstein levels play a key role in the formation and shape of the Zechstein slivers. A perfectly listric geometry of the main normal fault where it curves smoothly into the basal detachment would discourage the formation of slivers. A more suitable geometry is created if the fault flattens into a higher detachment for some distance and then steps down via a relatively steep ramp to the basal one. In this configuration, a footwall shortcut thrust can propagate along the basal detachment and then step up over a low-angle ramp to merge with the normal fault, smoothing its trajectory and isolating the sliver (Fig. 10a). The along-strike and across-strike extents of the flat control the size and geometry of the observed Zechstein slivers, whereas height above the basal detachment controls their thickness. Given that the vertical distance between the top of the Hauptanhydrit and the top of the Werra-Anhydrit around the Sontra Graben is only between 60 and 80 metres, the total thickness of a sliver cannot exceed this value.

Backthrusts are a well-documented feature of inverted grabens (Hayward and Graham, 2015). The insertion of Zechstein strata into evaporite-bearing Triassic units during inversion is reminiscent of "salt wedges" (Baldschuhn et al., 1998; Stewart, 2007) but different from those always affects the hanging wall and does not involve thick halite. Backthrusting of Zechstein slivers and wedging into the hanging wall (Figs. 6, 7, 8) is likely to have occurred at an early stage of the inversion phase when normal fault displacement was at a maximum, with lower Muschelkalk of the hanging wall having passed the future sliver and middle Muschelkalk overlying it. Upon inversion, the leading edge of the lower Muschelkalk must have underthrust the Zechstein sliver for some distance before it became detached from the footwall (Fig. 10b).

The comparatively well-exposed Mühlberg Zechstein sliver (Fig. 4) presents two secondary structural features that are not predicted by our model: (1) The sliver is underlain by a low-angle thrust fault that truncates its bedding and cuts stratigraphically downward unless the entire sliver is overturned and (2) it is overlain by folded Muschelkalk whose overturned bedding abuts the roof fault of the sliver. Figure 11 shows possible explanations for these phenomena. The peculiar Muschelkalk-Zechstein relation is probably due to a horse cut from the hanging-wall and left behind at depth. Southwest-verging folds in the Muschelkalk must predate the excision of this horse and suggest buttressing by the steeply dipping normal fault, the trailing edge of the future sliver, or both. Short flats of the main normal fault would promote the creation of horses via fault straightening (Fig. 11a). The bedding of the sliver truncated by the floor thrust could also be due to this mechanism. Alternatively, it could represent the hanging wall of an antithetic normal fault and would then indicate the sliver´s trailing edge. However, a more straightforward solution may be as shown in Figs. 11b and c: The low-angle thrust fault here is not the original floor thrust of the sliver but a later one that has cut across it from the roof fault and displaced its upper part along an upper Buntsandstein detachment of the footwall. This geometry also eliminates the need for mechanically implausible motion

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of the hanging wall rocks through the sharp transition from the low-angle fault to the steeply dipping segment juxtaposing the Zechstein sliver with Muschelkalk of the footwall.

4.2 The Zechstein as a Décollement Horizon

The presence of the Zechstein slivers is strong evidence for bedding-parallel flats or detachments at different Zechstein level in the normal faults that formed the Sontra Graben. Had the initial normal fault of the graben cut straight down into the basement, inversion could not have created isolated horses of Zechstein whose bounding faults follow bedding for tens to hundreds of meters. The Zechstein succession with its multiple evaporite layers is prone to forming detachment horizons (Fig. 2b). Evaporites often play a key role in decoupling the sedimentary cover from the basement, as for instance in the extensional fault systems at the passive margins of the Gulf of Mexico and Brazil (Duval et al., 1992; Demercian et al., 1993; Adam et al., 2012), but also in intracontinental basins such as the North German Basin (e.g., Mazur et al., 2005) where, however, the Zechstein evaporites are much thicker than in the Sontra region. Stewart (2007, his Fig. 25) proposed a „structural style matrix" for the North Sea. The Sontra Graben, owing to its position on the anhydrite-dominated basin margin, is not a typical salt-related inversion structure as described there. It falls between the "one detachment" and "thick detachment plus secondary detachments" categories of salt tectonic influence defined by Stewart (2007). Salt (or other evaporites) are present but not thick enough to form large accumulations, but multiple detachment horizons are required to from the slivers.

In the absence of seismic data, we can only speculate on whether the main Zechstein detachment was of regional extent and where it linked up with basement faults. The long-wavelength folding of the graben (Figs. 6, 7) created structural relief that is much higher than the thickness of the Zechstein and therefore must involve the basement. The monocline south of the Sontra Graben belongs to the broad, gentle Richelsdorf basement anticline (Fig. 1b). Conceivably, the shortening (and possibly also the extension) expressed in the Sontra Graben were accommodated there at basement level. This solution is tentatively shown in Fig. 1b and resembles seismically imaged structures from the North Sea (Sole Pit High and Peripheral Grabens, Stewart & Coward, 1995) or the inverted Mid-Polish Trough (axial part of the Pomerian segment with peripheral fold-thrust structures, (Krzywiec, 2002 a and b)).

4.3 Timing and kinematics of extension and inversion

Since a significant portion of the Sontra Graben including syn-rift and post-rift sediments has been eroded and only its roots remain, it is not possible to directly constrain the ages of extension and inversion. Lower Keuper strata in fault contact with older Triassic units (Buntsandstein) require all deformation to have occurred after the deposition of the lower Keuper. Regional correlation with the better-preserved Lower Saxony Basin suggest that extension started in Keuper time but peaked in the Late Jurassic to Early Cretaceous whereas inversion is of Late Cretaceous age (e.g., Kockel, 2003; Voigt et al., 2008). The inversion phase is also well constrained by exhumation and cooling reflected in thermochronological ages (von Eynatten et al., 2008; 2019; this issue).

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The relative timing for the formation of the NW-trending Sontra and Netra grabens versus the NE-trending Wellingerode Graben poses another difficulty. The Wellingerode Graben has a marked effect on the interior of the Sontra Graben (Figs. 3, 8e) and the Netra Graben, but appears to terminate at their southwestern and northeastern border faults, respectively. Similar to joint propagation (Engelder, 1985), this would imply that the Sontra Graben and Netra Graben already existed when the Wellingerode Graben formed. Nevertheless, the Wellingerode Graben does not appear as a typical hard-link between two overlapping graben segments. The Sontra Graben extends far beyond its intersection with the Wellingerode Graben on either side. The Netra Graben terminates in the west on a NE-striking structure that lies on trend with the Wellingerode Graben and connects to the Unterwerra Basement High (UWBH in Fig. 1a), suggesting that a precursor structure of the Wellingerode Graben existed when the Netra Graben propagated westward. Both the NW- and NE-striking fault sets include very long structures (Fig. 1a), arguing against one of them being a secondary effect of the other.

The kinematics of Late Cretaceous inversion in Central Europe has often been interpreted as transpressive (Betz et al., 1987; Ziegler, 1987; Drozdzewski, 1988; de Jager, 2007; Drozdzewski and Dölling, 2018), or even as being predominantly caused by strike-slip motion on the northwest-striking faults with uplift focused on restraining bends (Wrede, 1988). Other authors proposed predominantly dip-slip contraction (Martini, 1937; Seidel, 1938; Rauche and Franzke, 1990; Kockel, 2003; Kley and Voigt, 2008); see Wrede (2008, 2009) and Voigt et al., (2009) for a focused version of that debate. To our knowledge, conclusive evidence from kinematic indicators has been presented for dip-slip motion (Franzke et al., 2007; Kley and Voigt, 2008; Sippel et al., 2009; Kley, 2013; Navabpour et al., 2017), but not for transpression.

The inversion model requires substantially larger fault displacements in excess of 1000 m in extension and contraction than the small net normal displacement of the Sontra Graben´s present configuration. West of section A (segments I and II) the occurrence of the Zechstein slivers along one main reverse activated normal fault changes to a different pattern with a double-row of slivers along the two faults termed the central and master faults in section 3.5. The westernmost Zechstein sliver in Fig. 3 is bound to yet another fault that appears southwest of the master fault. These three faults are linked by left-stepping relays that approximately coincide with the locations of cross-sections a-a´ and b-b´. We suggest they function as parts of a transfer structure and merge at depth into the same detachment (Fig. 12). Different from this schematic illustration the faults are probably also connected at the present erosion level because their displacements are too large to die out over short distances. Where the master and central faults overlap in the easternmost part of segment I, both carry Zechstein slivers. This part of the graben (cross-section b-b´) should therefore have the largest amounts of extension and shortening. If this inference is correct, the width of the graben is not an indicator of strain.

4.4 Distribution of "Exotic" Slivers

The question why Zechstein slivers only occur on some grabens remains a key issue. We speculate that a specific paleo-geographic configuration gave rise to this phenomenon. Notably, all "exotic" Zechstein slivers appear on two relatively discrete bands near the southern edge of the z1 basin (Fig. 13) and predominantly originate from its carbonate shelf with the exception of localities 1 and 2, relatively small occurrences, which originate from the sulphate slope. The area of the Sontra Graben is

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For the preceding extensional phase, however, traces of a similar extension in the basement have yet to be found. It is possible that, similar to the Sontra Graben, a previous graben structure in the basement has simply been reset to its original regional elevation. The small net offset and the fact that the fault is likely to be covered by sediments would certainly obscure its character as an extensional structure. Given that countless structures throughout the CEBS were reactivated during Iberia-Europe convergence , it seems almost unlikely to find any large basement structure that has not been affected by the contractional push.

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also situated just on the northeastern edge of the Schemmern Swell and close to the centre of the Waldkappel Depression, two paleogeographic features of the Z1 basin (Kulick et al., 1984). We propose that the basin margin facies with its alternation of strong carbonate layers and evaporites that are thick enough to act as detachments but too thin to form proper salt structures (pillows and diapirs) provided the most suitable mechanical stratigraphy for the formation of the slivers. However, other factors must also play a role. The Netra Graben (Fig. 1) is in close proximity to the Sontra Graben and in the same basin realm but has no "exotic" slivers, Zechstein or otherwise. One possibility is that extension and fault displacement in the Netra Graben did not suffice to bring the lower Muschelkalk as far down as the Zechstein. As the Netra Graben is somewhat less eroded than the Sontra Graben with a higher proportion of preserved upper Muschelkalk and Keuper, Zechstein slivers could also be present at depth but not yet exposed.

5 Conclusions

The Sontra Graben is one of the many NW-trending structures in the CEBS. It displays unambiguous signs of both extension and contraction (inversion). Its basic structure is asymmetric with a northeast-dipping master fault bounding it in the southwest. A conjugate northeastern bounding fault is not continuously developed. Variations in structural style along the (half-)graben are due to a combination of different factors including left-stepping relays of the master fault and rapid changes in the level of exposure associated with topography and transverse faults. These changes reveal a middle Muschelkalk detachment separating a block faulting style beneath it from open folding above. The (half-)graben widens where extension was distributed onto a larger number of faults while contraction was focussed around the master fault. There seems to be no correlation between the width of the graben and bulk strain.

The Sontra Graben exhibits an unusually high number of "exotic" Zechstein slivers of varying size. The slivers are lenses of carbonates, up to several hundred metres in length, emplaced along the main graben faults to a structural position higher than either the graben interior or the shoulders. The geometry of the Zechstein slivers suggests that they formed during inversion via shortcut thrusts dissecting a stepped normal fault with ramps and flats. Backthrusts locally emplaced the slivers into incompetent units of the hanging wall. Geometrical forward modelling of the Zechstein slivers and cross-section balancing suggest minimum values of approximately 1.2 kilometres of horizontal extension/shortening for the extensional and contractional phase.

The occurrence and geometry of the Zechstein slivers in the Sontra Graben indicate thin-skinned tectonics with a basal décollement in the Werra-Anhydrit of the lowest Zechstein cycle and at least one additional, higher Zechstein detachment. The corresponding mechanical stratigraphy reflects deposition on the basin margin with thin but strong carbonate levels and no thick halite. At sub-Zechstein level, shortening may have been accommodated on a basement thrust underlying the Richelsdorf Anticline to the south. This hypothetical thrust fault could have fed its displacement into the Zechstein décollement and caused the pronounced northeast dip of the southwestern graben shoulder.

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Author contributions

JK conceptualized the study. JB performed the investigation - field work, forward modelling and cross-section balancing - with some contribution by JK. JB and JK worked jointly on validation, visualization and writing, including draft preparation, review and editing.

Competing interests

The authors declare that they have no conflict of interest.

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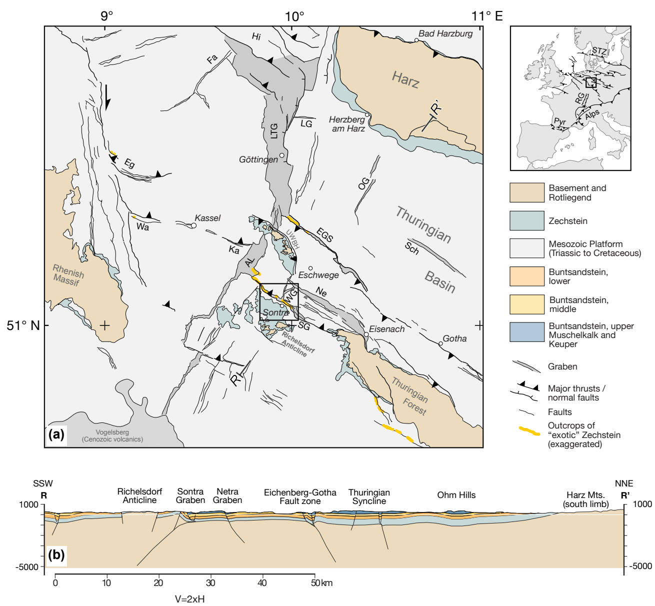
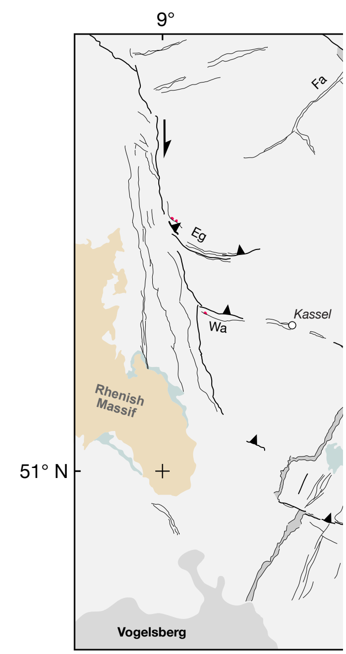


Figure 1. (a) Basin architecture of the southern extent of the Central European Basin System (CEBS). Modified from Kley (2013) and the sources indicated therein. Paleogeography is derived from Ziegler (1990). The major Mesozoic and Cenozoic structural elements of the basin are shown. The black box indicates the study area, shown in greater detail in Fig. 4. (b) Regional cross-section showing the main basement structures and the relation to the overlying sedimentary cover in the area. Section trace (R-R') is shown in (a).

Abbreviations: AL = Altmorschen Lichtenau Graben, Eg = Egge, EGS = Eichenberg Gotha Saalfeld Fault, Fa = Falkenhagen Fault Zone, Hi = Hils Mulde, Ka = Kasseler Stˆrungszone, LG = Langfast Graben, LTG = Leinetalgraben, Ne = Netragraben, OG = Ohmgebirgegraben, RM = Richelsdorf Mountains, Sch = Schlotheimer Graben, UWBH = Unter Werra Basement High, Wa = Warsteiner Störungszone WG = Wellingerodegraben



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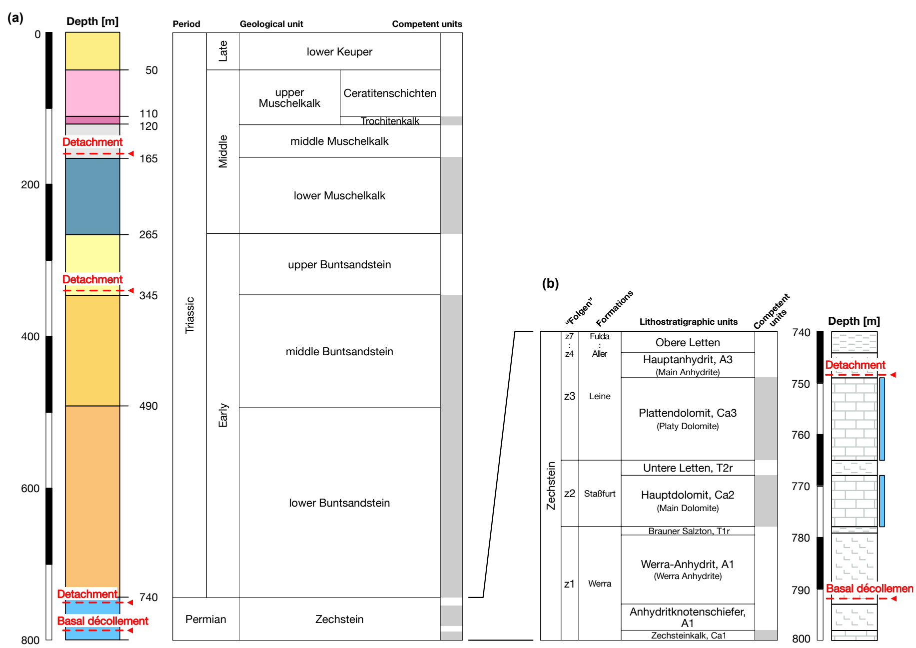
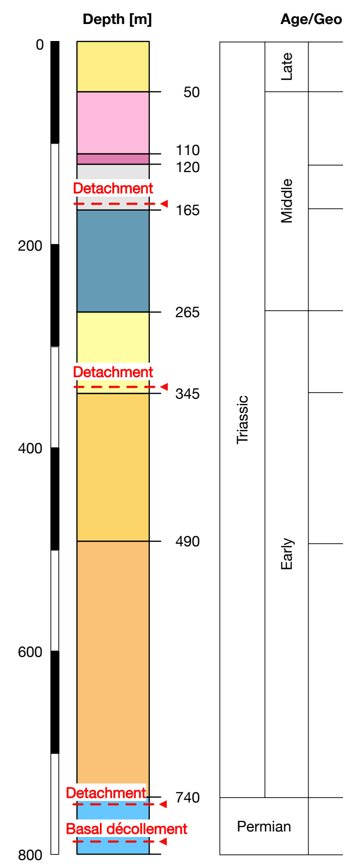


Figure 2. (a) Stratigraphic column across the sedimentary cover within the study area. Major detachment horizons and the basal décollememt are indicated. Competent horizons are highlighted in grey. (b) Detailed Stratigraphic column of the Zechstein Formation. Dolomite bearing horizons, which produce the majority of the "exotic" fragments are indicated in blue. The Hauptanhydrit and the Werra-Anhydrit form the most likely detachment horizons. Zechstein nomenclature after Paul et al. 2018.



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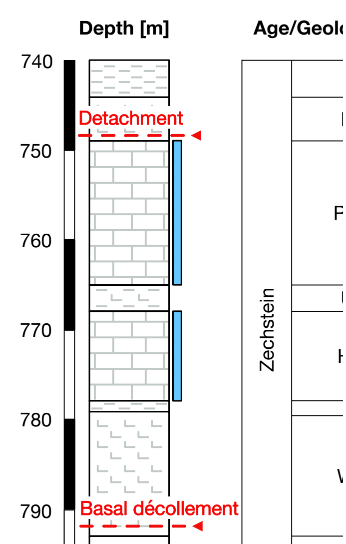

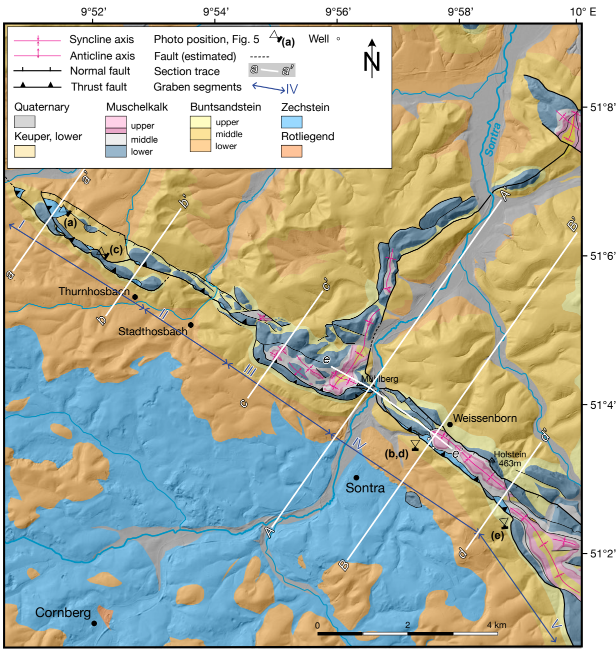

Figure 3. Geological map of the study area. Lines marked A-A' and B-B' indicate the position of the balanced cross sections in Fig. 6. Roman letters define sections of the graben between the dashed lines, which are referred to and further discussed in the text. Topography based on DEM data provided by the Geological Survey of Hessen (Hessisches Landesamt für Naturschutz, Umwelt und Geologie, Wiesbaden).

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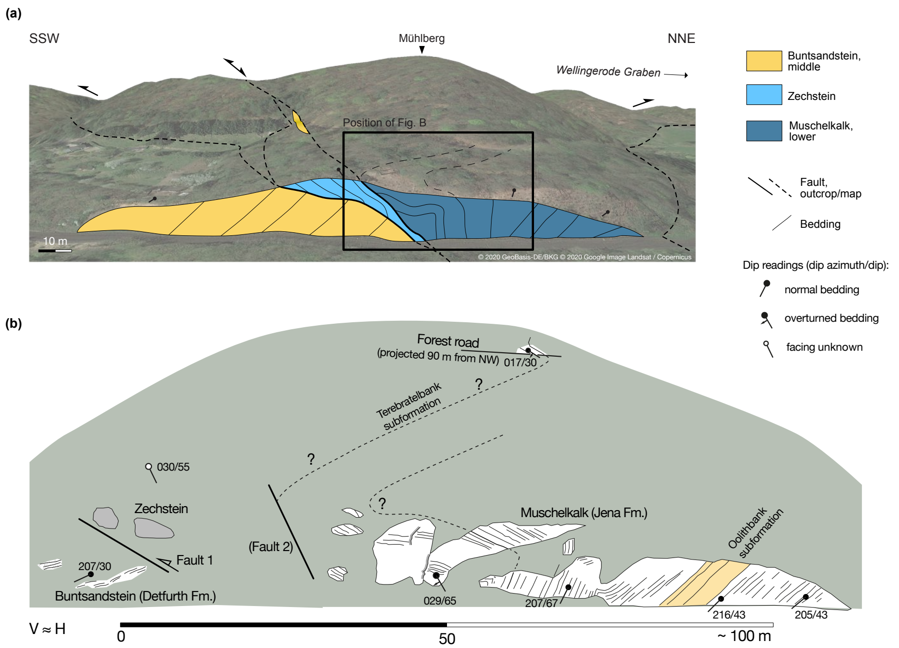

315 **Figure 4. (a) Outcrop along the train tracks west of Sontra (Schröder, 1925) shown as an overlay on a GoogleEarth image with fault traces extrapolated according to our own field data. (Image position 51° 4'57.35"N, 9°56'24.49"E with view towards NNW; © 2020 GeoBasis-DE/BKG, © 2020 Google Image Landsat / Copernicus). One of the "exotic" Zechstein slivers, with approximately fault-parallel bedding, is thrust onto the middle Buntsandstein of the graben shoulder. The lower Muschelkalk overlying the sliver in the NNE is the partly overturned limb of a contractional anticline. (b) The same outcrop in the year 2000, drawn after fieldbook sketches. Key observations by Schröder (1925) could still be confirmed.**

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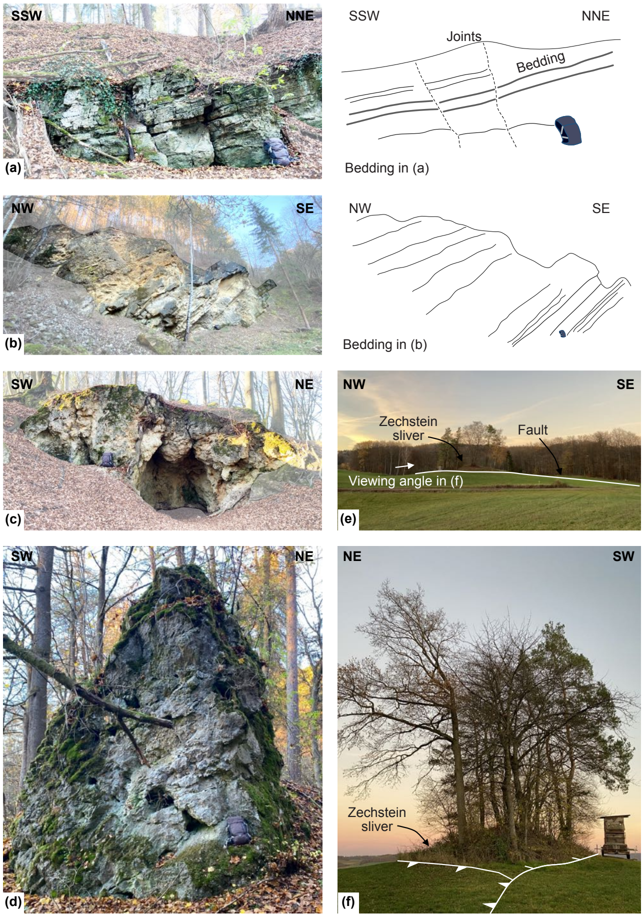

Figure 5. Photo panel of selected outcrops of Zechstein slivers along the Sontra Graben. The backpack is shown for scale. Approximate locations for each photo can be seen in Fig. 3.

Deleted: Figure 4: Geological map of the study area. Lines marked A-A' and B-B' indicate the position of the balanced cross sections in Fig. 6. Roman letters define sections of the graben between the dashed lines, which are refered to and further discussed in the text. DEM courtesy of Hessian Agency for Nature Conservation, Environment and Geology (HLNUG).

Moved up [1]: Geological map of the study area. Lines marked A-A' and B-B' indicate the position of the balanced cross sections in Fig. 6. Roman letters define sections of the graben between the dashed lines, which are refered to and further discussed in the text. DEM courtesy of Hessian Agency for Nature Conservation, Environment and Geology (HLNUG).

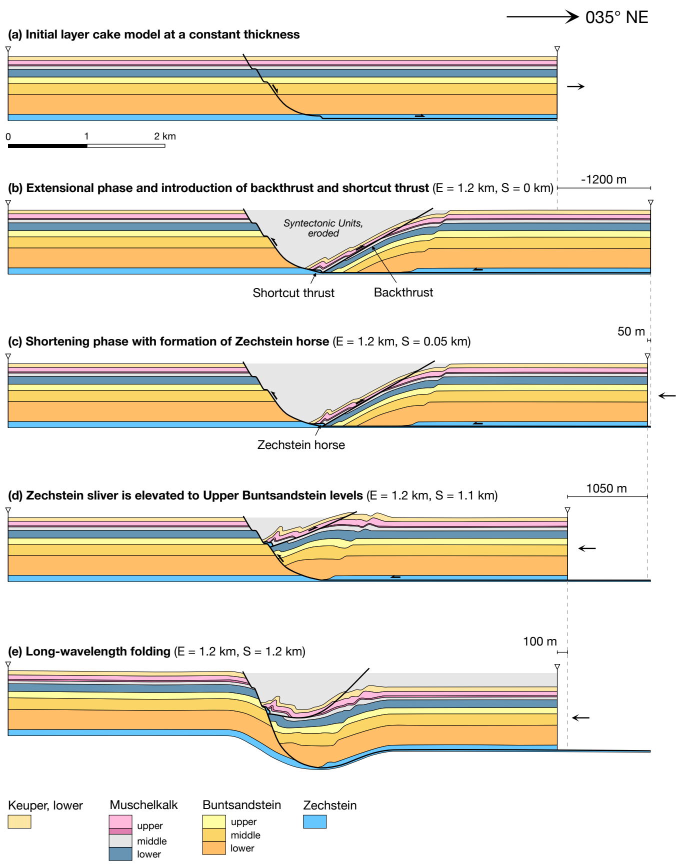

Figure 6. Forward model of the formation of the Sontra Graben. Stratigraphic thicknesses from Motzka-Noering et al. (1987).

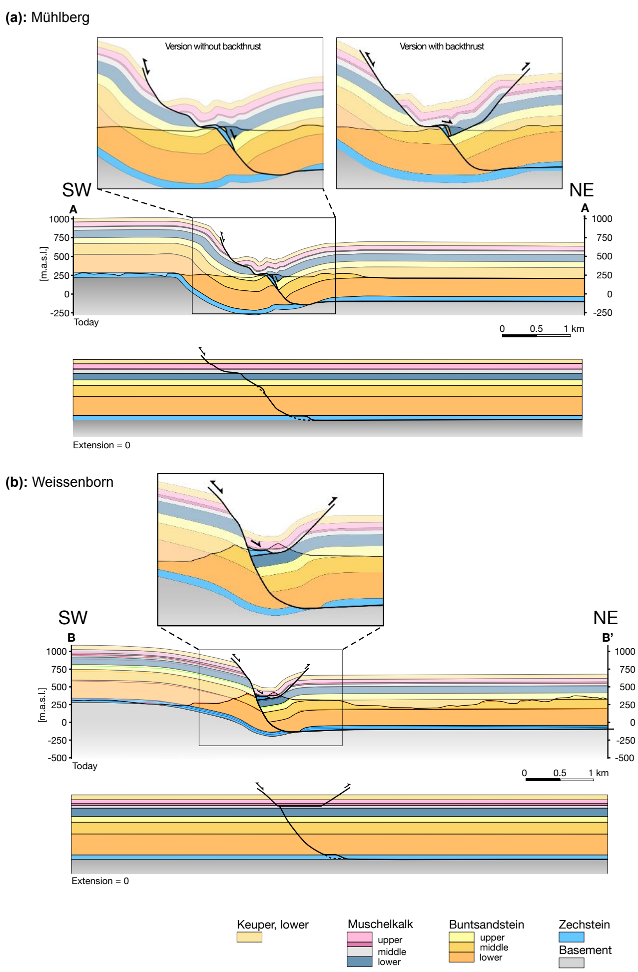

Figure 7. Balanced cross-sections of the Sontra Graben. The Fault geometry was verified through the forward model in Fig. 6. For section traces, see Fig. 3.

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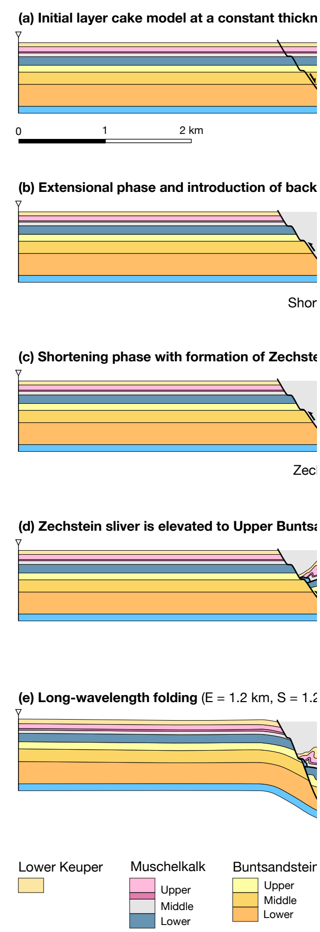

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Figure 5: Forward model of the formation of the Sontra Graben. Stratigraphic thicknesses from Motzka-Noering et al. (1987). ¶

Moved up [2]: Forward model of the formation of the Sontra Graben. Stratigraphic thicknesses from Motzka-Noering et al. (1987).

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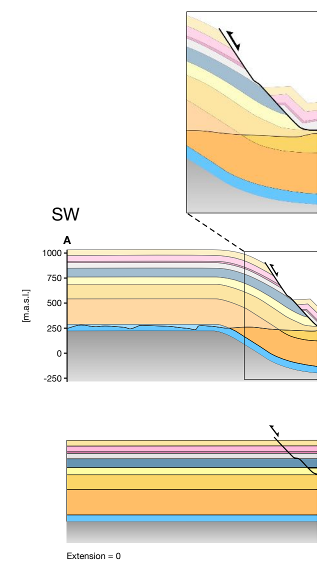

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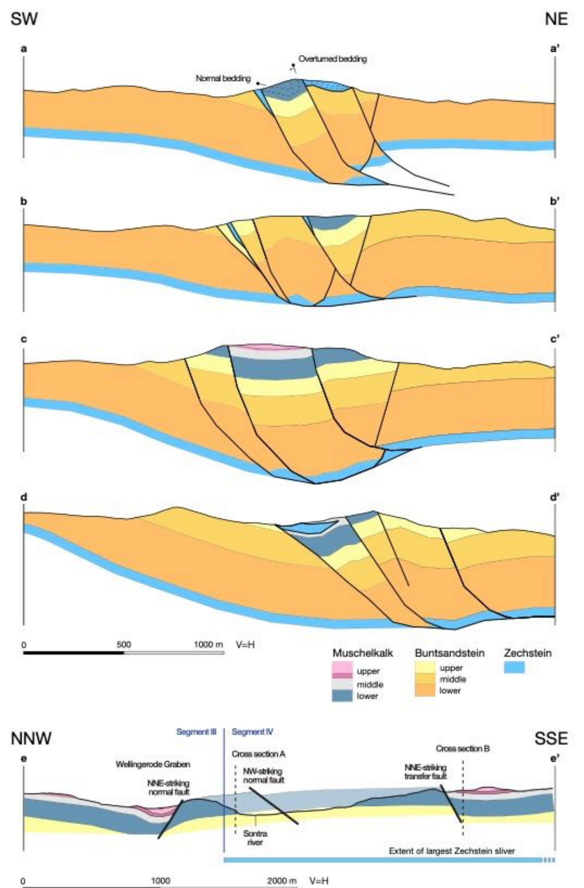

Figure 8. Sections a-d: Conceptual cross-sections of the Sontra Graben northwest and southeast of the balanced cross-sections in Fig. 7. Basic features of our forward model and balanced cross-sections were adopted to interpret surface observations in these sections. Section e: Longitudinal cross-section illustrating the effect of varying erosion levels on the appearance of the graben. Only the hanging wall of the boundary fault to the depth of the upper Buntsandstein is shown. Section traces are shown in Fig. 3.

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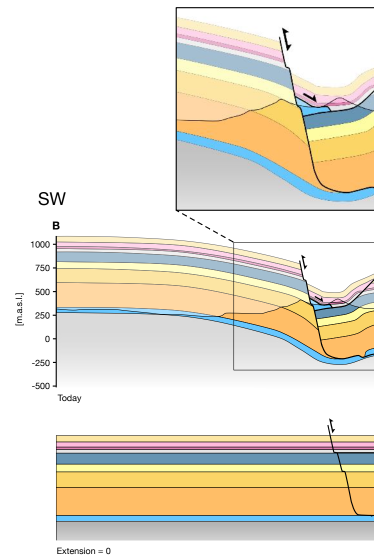

Balanced cross-sections of the Sontra Graben. The Fault geometry was verified through the forward model in Fig. 5. For section traces, see Fig. 4.
Figure 6:

Moved up [3]: Balanced cross-sections of the Sontra Graben. The Fault geometry was verified through the forward model in Fig. 5. For section traces, see Fig. 4.

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Moved up [4]: Outcrop on the train tracks near Sontra, previously documented by Schröder (1925). The outcrop shows the juxtaposition of one of the "exotic" Zechstein slivers, with circa fault parallel bedding, onto the Middle Buntsandstein of the graben shoulder. Position 51° 4'57.35"N, 9°56'24.49"E with view towards NNW. Image from Google, © 2020 GeoBasis-DE/BKG, © 2020 Google Image Landsat / Copernicus.

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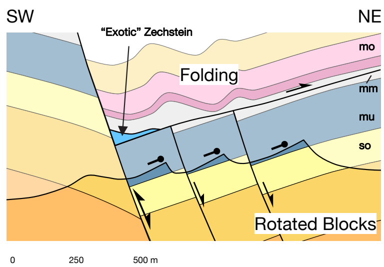

2405 **Figure 9. Schematic model of the relation between a lower structural level with rotated blocks and an upper structural level dominated by folding as a result of a detachment within the middle Muschelkalk. Faults delimiting the rotated blocks within the lower floor peter out into the middle Muschelkalk or merge into the detachment. Through varying degrees of erosion the different styles become visible or predominant in the different segments.**

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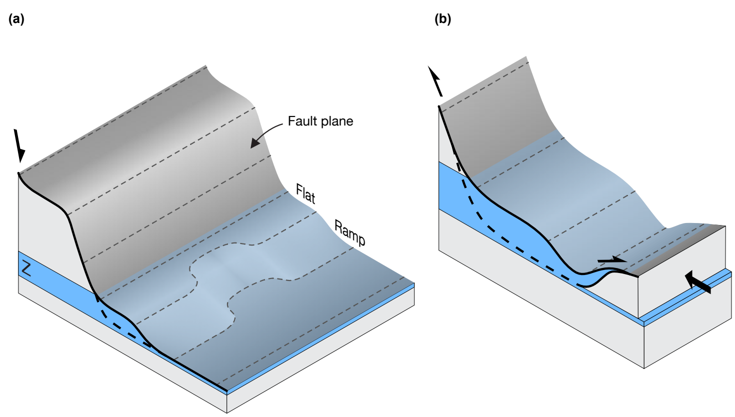
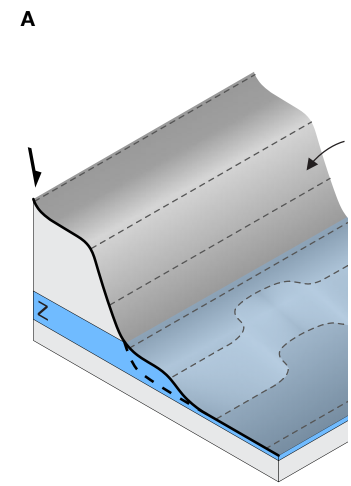


Figure 10. Schematic model of the formation of a horse and the backthrust onto the hanging wall during inversion. The slivers are formed as horses with the newly formed shortcut thrust as floor thrust and the original normal fault as roof thrust. (A) shows the geometry of the original normal fault with areas showing more or less pronounced development of flats. Areas with more pronounced flats produce the afore mentioned "exotic" slivers. Areas with less pronounced flats produce smaller or no slivers. (B) shows the newly formed sliver being backthrust onto the hanging wall during the inversion phase.



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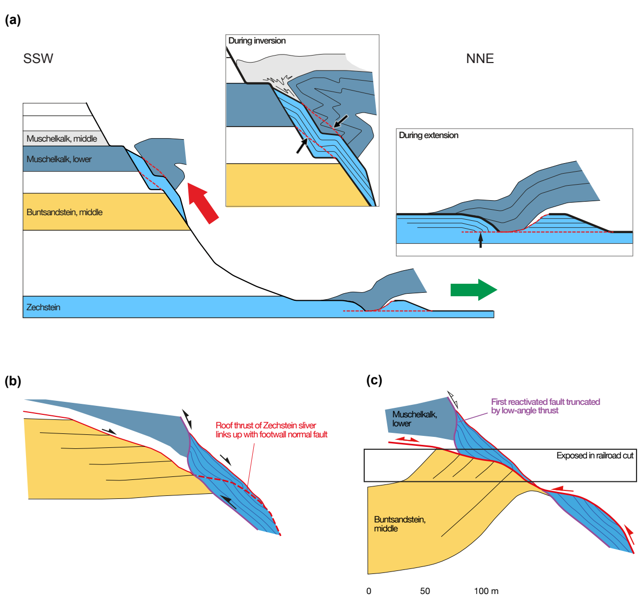

Figure 11. Scenarios for the origin of second-order structural features within and above the Mühlberg Zechstein sliver (Figs. 4 and 7). (a) The floor thrust cutting downsection across bedding in the sliver and the roof fault truncating overturned Muschelkalk strata could be due to straightening of kinked fault segments during inversion (new fault trajectories shown as dashed red lines with fault-bedding relations highlighted by arrows). The truncation of bedding in the sliver by the floor thrust could also be inherited from an antithetic normal fault of the extensional phase. (b) and (c) Alternative model for the floor thrust-bedding relation. After emplacement of the sliver to its present-day structural elevation (b), the roof thrust cuts across it to a detachment in upper Buntsandstein of the footwall, displacing the upper, exposed half of the sliver to the southwest on a low-angle fault (c). We consider a combination of (a) for the truncated Muschelkalk with (b) and (c) for the floor thrust most likely.

Moved up [5]: Schematic model of the formation of a horse and the backthrust onto the hanging wall during inversion. The slivers are formed as horses with the newly formed shortcut thrust as floor thrust and the original normal fault as roof thrust. (A) shows the geometry of the original normal fault with areas showing more or less pronounced development of flats. Areas with more pronounced flats produce the afore mentioned

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Figure 8: Schematic model of the formation of a horse and the backthrust onto the hanging wall during inversion. The slivers are formed as horses with the newly formed shortcut thrust as floor thrust and the original normal fault as roof thrust. (A) shows the geometry of the original normal fault with areas showing more or less pronounced development of flats. Areas ... [84]

Moved up [6]: Paleogeographic map of the first Zechstein cycle (Z1, Werra cycle). Outcrops of "exotic" Zechstein are shown in black for better visibility. Locality 5 is the subject of this study. Zechstein paleogeography from Kiersnowski et al., 1995. Digital elevation model made with GeoMapApp (www.geomapapp.org) / CC BY.

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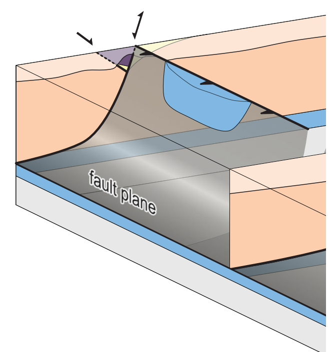

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Moved up [7]: Schematic model for explaining the appearance of multiple rows of Zechstein slivers along imbricated faults as part of a transfer type structure, observed in the western part of the graben (section I, Fig. 4). Different erosion levels determine the width of the graben as it appears on the map.

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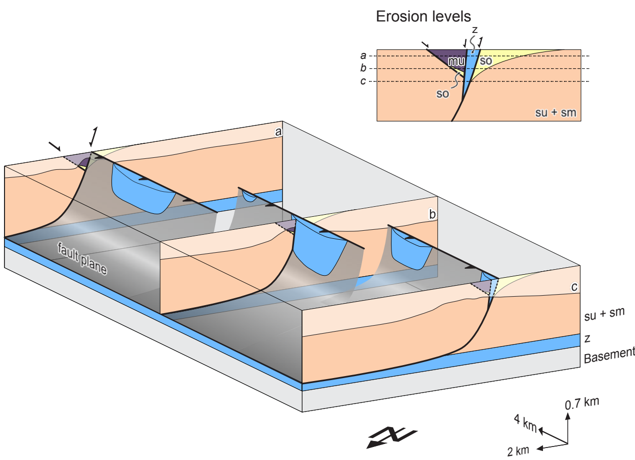
Figure 11: Schematic model for explaining the appearance of multiple rows of Zechstein slivers along imbricated faults as ... [85]



2520 **Figure 12. Schematic model for explaining the appearance of multiple rows of Zechstein slivers along imbricated faults as part of a transfer type structure, observed in the western part of the graben (section I, Fig. 4). Different erosion levels determine the width of the graben as it appears on the map.**

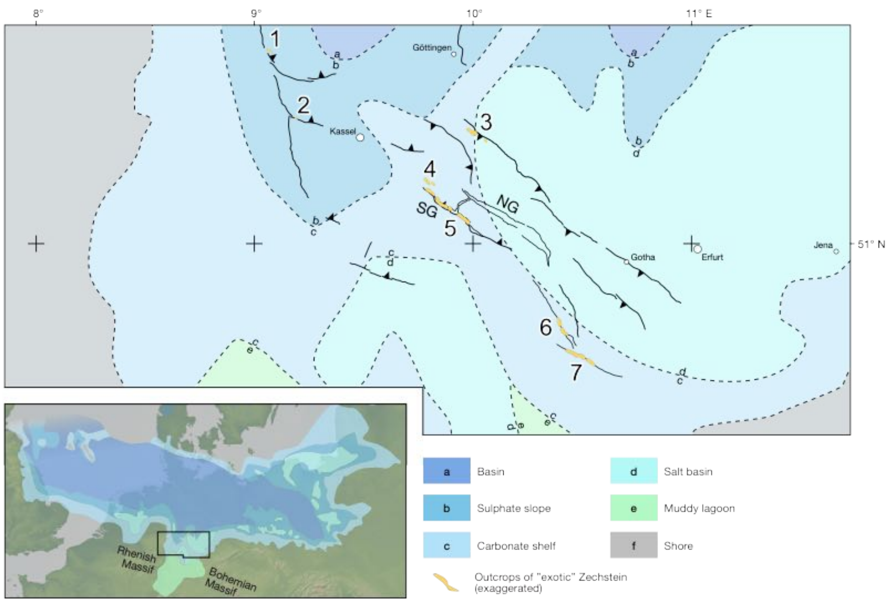


Figure 13. Paleogeographic map of the first Zechstein cycle (Z1, Werra cycle). Outcrops of "exotic" Zechstein are shown in black for better visibility. Locality 5 is the subject of this study. Zechstein paleogeography from Kiersnowski et al., 1995. Digital elevation model made with GeoMapApp (www.geomapapp.org) / CC BY.

Table 1. Statistical compilation of the Zechstein slivers. The values for vertical offset are calculated based on thicknesses given by Motzka-Noering et al., (1987).

Zone	No.	Area [m²]	Long axes [m]	Short axes [m]	Strike (mean)	Dip (mean)	Stratigaphy	Bordering units		Vertical offset [m]	
								SW	NE	SW	NE
I	1	24,96	195	158	70	28	Plattendolomit	sm	sm	250	250
	2	100,33	500	290	131	56	Hauptdolomit	sm	mu	250	475
	3	6,909	172	50	35	45	n.a.	mu	so	475	395
	4	2,11	92	28	n.a.	n.a.	n.a.	mu	so	475	395
	5	963	50	28	n.a.	n.a.	n.a.	mu	so	475	395
	6	7,495	238	65	118	43	Hauptdolomit	sm	mu	250	475
	7	3,218	183	20	126	58	n.a.	mu	so	475	395
	8	1,521	125	17	135	59	n.a.	mu	so	475	395
	9	14,6	227	80	113	23	Plattendolomit	so, mu	so	475	395
	10	5,453	177	57	123	60	n.a.	mu	sm, so	475	395
II	11	1,327	95	21	145	29	n.a.	mu	so	475	395
	12	7,381	165	58	n.a.	n.a.	Hauptdolomit	mu	so	475	395
IV	13	8,778	255	46	117	27	n.a.	mu, sm	sm, so, mu	475	475
	14	3,84	153	28	n.a.	n.a.	n.a.	so	n.a.	395	n.a.
	15a	20,2	634	45	99	27	Anhydritknotensch.	mu	sm, so	475	395
	15b	128,66	1,458	98	136	40	Zechsteinkalk	mm	so	575	395
V	16	45,97	529	136	118	28	n.a.	mm, ku	so, mu	690	475
mean		22.571,47	308,71	72,06	114	43				446	416
median		7381,00	183,00	50,00	119	42				475	395

Moved down [8]: Statistical compilation of the Zechstein slivers. The values for vertical offset are calculated based on thicknesses given by Motzka-Noering et al., (1987).

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Annotation Summary of Referee Comments

Key

accepted
rejected
reply

Highlight [page 1, Line 1]: Emplacement of ”exotic“ Zechstein slivers along the inverted Sontra Graben (northern Hessen, Germany): clues from balanced cross-sections and geometrical forward modelling
and Note: General comment: Please, carefully check the numbers of Figures in the text. I think they sometimes do not refer to the correct figure.

Note [page 1, Line 2]: half-graben?
'Sontra Graben' is a standing term. Explained in new manuscript.

Strikeout [page 1, Line 8]: Lens-shaped slivers of Permian (Zechstein) amid Triassic units, appearing along the main boundary fault of the Sontra Graben in central Germany on the southern edge of the Central European Basin System (CEBS) were studied by means of detailed map analysis,...

Note [page 1, Line 9]: were studied by detailed map analysis, semi-quantitative forward modelling....
they were not studied 'by the map analysis' but through map analysis

Highlight [page 1, Line 9]: Lens-shaped slivers of Permian (Zechstein) amid Triassic units, appearing along the main boundary fault of the Sontra Graben in central Germany on the southern edge of the Central European Basin System (CEBS) were studied by means of detailed map analysis,...
and Note: 'edge' or margin?

Insert [page 1, Line 13]: s
Not sure this is necessary or even correct

Note [page 1, Line 15]: Netra Graben? Why not name it?
By Graben System, we also refer to the Wellingerode Graben, not just the Netra Graben… also, non-experts will not know about these Grabens.

Note [page 1, Line 15]: other graben systems in Hessen and Lower Saxony (before taking the entire CEBS)

"…discuss the dynamic evolution of the graben system in the immediate vicinity and to consider implications for the entire CEBS." We actually do both, as stated in this very sentence.

Highlight [page 1, Line 17]: 1 Introduction

Note [page 1, Line 21]: Brochwicz-Lewiński & Pożaryski

Strikeout [page 1, Line 21]: This history is best documented by subsidence and inversion in the main sub-basins of the Central European Basin System (CEBS) such as the Broad Fourteens and Lower Saxony basins and the Mid-Polish trough (Brochwicz-Lewinski & Pozarvski, 1987; Hooper et al…

Highlight [page 1, Line 21]: This history is best documented by subsidence and inversion in the main sub-basins of the Central European Basin System (CEBS) such as the Broad Fourteens and Lower Saxony basins and the Mid-Polish trough (Brochwicz-Lewinski & Pozarvski, 1987; Hooper et al., 1995; Mazur et al., 2005; Maystrenko & Scheck-Wenderoth, 2013…
and Note: ...and even documented for parts of the North East German Basin (e.g. Altmark-Fläming Basin) or some fault zones on the southern edge of the Central European Basin System (e.g. Thuringian Basin).
not sure, if this needs to be mentioned Finne Fault, Malz 2019

Insert [page 1, Line 21]: Pożaryski

Highlight [page 1, Line]: They exhibit two prevailing strike directions: NW-SE and N-S to NNE-SSW, with the former considerably more frequent than the latter.

Note [page 1, Line 26]: located

Note [page 1, Line 28]: Fig. 1

Highlight [page 2, Line 30]: 30

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(Buntsandstein) surroundings. Many of them show a pronounced asymmetry, having one boundary fault with considerably larger displacement than the other.

Strikeout [page 2, Line 54]:

(Buntsandstein) surroundings. Many of them show a pronounced asymmetry, having one boundary fault with considerably larger displacement than the other. The structures of the graben interiors are highly variable, ranging from gentle synclines over successions of synclines and anticlines to rotated, fault-bounded blocks.

In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics and an originally continuous sequence of Latest Permian (Zechstein) through Triassic sandstones, shales, carbonates and evaporites. Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig. 1, 2, 3).

The Sontra Graben and several others exhibit enigmatic occurrences of Zechstein strata. The Zechstein rocks are found discontinuously as fault-bounded blocks or slivers/horses of Zechstein rocks along the faults of the grabens. These slivers of Zechstein carbonates are structurally elevated relative to both the graben interior and the bounding shoulders. In the Sontra Graben their dimensions vary from tens to several hundreds of meters long parallel to the strike of the graben and from meters to a few tens of meters wide perpendicular to it. Internally, the slivers appear almost undeformed. However, in most cases the bedding is moderately to steeply dipping and approximately fault-parallel.

It was previously suggested that the emplacement of the uplifted Zechstein blocks was due to salt diapirism (Lachmann, 1917). In the present paper we explore the hypothesis that they were emplaced as a result of inversion tectonics involving bedding- parallel decollements in two evaporitic Zechstein horizons during both extension and contraction.

2 Methods 2.1 Data sources Data were compiled by detailed analysis of the official geological maps of the area (Beyrich & Moesta, 1872; Moesta, 1876; Motzka-Noering et al., 1987), maps from published thesis papers of the 1920s and 1930s (Bosse, 1934; Schröder, 1925) as well as unpublished maps created during two diploma mapping projects at the University of Jena (Brandstetter, 2006; Jähne, 2004). Dip and strike data were also gathered from numerous unpublished reports that were written for the beginner-level mapping courses in the years 2014 and 2015 at the University of Göttingen.

To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their…

Highlight [page 2, Line 35]: In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics and an originally continuous sequence of…
and Note: conglomerates, breccia and coarse sandstones
The term 'clastics' includes all of the above, except breccia, which was not meant here.
"clastic rock *Sediment composed of fragments of pre-existing rocks (*clasts). Consolidated clastic rocks include ***conglomerates, *sandstones, and *shales.**" Oxford Dictionary of Earth Sciences (Allaby 2008)

Strikeout [page 2, Line 35]: In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics and an originally continuous sequence of L…

Strikeout [page 2, Line 35]: In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics and an originally continuous sequence of Latest Permian (Zechstein) through Triassic sandstones, shales…
Different types of shale exist, we wish to include more than one.

Highlight [page 2, Line 35]: In the area of the Sontra Graben, Variscan metasedimentary basement consisting of Carboniferous and Devonian phyllites and greywackes (Motzka-Noering et al., 1987) is overlain by discontinuous Early Permian clastics and an originally continuous sequence of Latest Permian…
and Note: What type of rock is it?
our sentence: sequence of latest Permian **through** Triassic **sandstones, shales, carbonates and evaporites.** The lithologies describe all rocks deposited in the time between latest Permian up to Triassic, not just the Triassic.

Insert [page 2, Line 35]: Group

Insert [page 2, Line 35]: I

Strikeouts [page 2, Line 36]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.
see above

Strikeout [page 2, Line 36]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.
It was our intended meaning to refer to the Zechstein beds.
stratum (pl. strata) Lithological term applied to rocks that form layers or beds. Unlike 'bed', 'stratum' has no connotation of thickness or extent and although the terms are sometimes used interchangeably they are not synonymous.
(Allaby 2008)

Strikeout [page 2, Line 36]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.

Insert [page 2, Line 36]: u

Insert [page 2, Line 36]: Group
see above

Note [page 2, Line 37]: (Figs. 2, 3)
added reference Fig. 10 (Paleogeographic map)

Strikeout [page 2, Line 37]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.

Highlight [page 2, Line 37]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.

Highlight [page 2, Line 37]: Numerous incompetent layers consisting mostly of sulfates and shales occur in the Zechstein strata and at two levels of the Triassic succession (Upper Buntsandstein and Middle Muschelkalk), but no thick halite was deposited (Fig.
and Note: Primarily not deposited or not preserved?
Not deposited. See paleogeographic map (Fig. 10), reference added, see above.

Note [page 2, Line 38]: of the other graben systems

Insert [page 2, Line 37]: m

Insert [page 2, Line 37]: Subgroupes

Insert [page 2, Line 38]: (e.g. Creutzburg Graben, Eichenberg Fault, ...)

Strikeout [page 2, Line 39]: The Zechstein rocks are found discontinuously as fault-bounded blocks or slivers/horses of Zechstein rocks along the faults of the grabens.

Note [page 2, Line 39]: footwall blocks?
Used 'footwall block' (singular) instead, because we really only refer to the SW footwall block.

Note [page 2, Line 40]: a length of
used Alex Malz's phrase

Note [page 2, Line 40]: along the strike
used 'along-strike'

Note [page 2, Line 41]: in width

Strikeout [page 2, Line 41]: In the Sontra Graben their dimensions vary from tens to several hundreds of meters long parallel to the strike of the graben and from meters to a few tens of meters wide perpendicular to it.

Strikeout [page 2, Line 41]: In the Sontra Graben their dimensions vary from tens to several hundreds of meters long parallel to the strike of the graben and from meters to a few tens of meters wide perpendicular to it.

Insert [page 2, Line 41]: they are some

Insert [page 2, Line 41]: (along-strike)

Strikeout [page 2, Line 42]: In the Sontra Graben their dimensions vary from tens to several hundreds of meters long parallel to the strike of the graben and from meters to a few tens of meters wide perpendicular to it.

Insert [page 2, Line 42]: the graben

Insert [page 2, Line 44]: text suggestion:
"or intrusion of salt and evaporites into the fault zone. However, absence of evaporites within these slivers and their dominent occurence in areas of primarily low salt thicknesses (Eichsfeld Swell?) stress this concept and incited us to test the hypotheses of …"
We wrote "or intrusion of salt and evaporites into the fault zone. However, the absence of evaporites within these slivers and their dominant occurrence in areas of primarily low salt thicknesses provide challenges for this concept"

Strikeout [page 2, Line 45]: In the present paper we explore the hypothesis that they were emplaced as a result of inversion tectonics involving bedding- parallel decollements in two evaporitic Zechstein horizons during both extension and contraction.

Highlight [page 2, Line 45]: In the present paper we explore the hypothesis that they were emplaced as a result of inversion tectonics involving bedding- parallel decollements in two evaporitic Zechstein horizons during both extension and contraction.
and Note: Make it more clear that these slivers are the exotic zechstein

Insert [page 2, Line 45]: ,

Strikeout [page 2, Line 46]: In the present paper we explore the hypothesis that they were emplaced as a result of inversion tectonics involving bedding- parallel decollements in two evaporitic Zechstein horizons during both extension and contraction.
Combining the last two sentences of the introduction would have made the sentence too long.

Highlight [page 2, Line 46]: In the present paper we explore the hypothesis that they were emplaced as a result of inversion tectonics involving bedding- parallel decollements in two evaporitic Zechstein horizons during both extension and contraction.
and Note: or detachments? You have to decide, but make it uniform in the entire manuscript.
We changed all instances of "décollement" to "detachment", except in line 283 (page 9), where we used the term "décollement" to discuss the problem of horse formation near the basal "décollement", meaning large-scale detachment… "Décollement: Large-scale detachment, i.e. fault or shear zone that is located along a weak layer in the crust or in a stratigraphic sequence (e.g. salt or shale). The term is used in both extensional and contractional settings." (Fossen 2010)

Insert [page 2, Line 46]: é

Highlight [page 2, Line 48]: 2.1 Data sources Data were compiled by detailed analysis of the official geological maps of the area (Beyrich & Moesta, 1872; Moesta, 1876; Motzka-Noering et al., 1987), maps from published thesis papers of the 1920s and 1930s (Bosse, 1934; Schröder, 1925)…
and Note: The separation of the paragraphs data source and workflow seems a little odd. There is workflow in the data (e.q. description of how the topographic data were uploaded
We prefer maintaining this separation between data sources and workflow to enhance reader-friendliness through a larger number of headings and subheadings, making the electronic

publication more navigable through hyperlinks but have moved all workflow-related sections to the actual chapter.

Strikeout [page 2, Line 49]: 2.1 Data sources Data were compiled by detailed analysis of the official geological maps of the area (Beyrich & Moesta, 1872; Moesta, 1876; Motzka-Noering et al., 1987), maps from published thesis papers of the 1920s and 1930s (Bosse, 1934; Schröder, 1925)…
We actually do refer to the 'official' geological maps of the area, here, meaning 'official', as in 'published by the relevant government agencies'.

Strikeout [page 2, Line 49]: 2.1 Data sources Data were compiled by detailed analysis of the official geological maps of the area (Beyrich & Moesta, 1872; Moesta, 1876; Motzka-Noering et al., 1987), maps from published thesis papers of the 1920s and 1930s (Bosse, 1934; Schröder, 1925)…

Insert [page 2, Line 49]: Sontra Graben
The maps, necessary to view the entire Sontra Graben show more than just the Sontra Graben. Hence, we maintain the phrase 'area'.

Highlight [page 2, Line 52]: Dip and strike data were also gathered from numerous unpublished reports that were written for the beginner-level mapping courses in the years 2014 and 2015 at the University of Göttingen.

Strikeout [page 2, Line 52]: Dip and strike data were also gathered from numerous unpublished reports that were written for the beginner-level mapping courses in the years 2014 and 2015 at the University of Göttingen.
We wrote '*also* gathered' because dip and strike data were gathered from both diploma mapping projects as well as from unpublished reports.

Strikeout [page 2, Line 54]: To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their exact positions and extents and took dip readings where possible.
Intended meaning is lost.

Highlight [page 2, Line 54]: To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their exact positions and extents and took dip readings where possible.

Insert [page 2, Line 54]: Additionally
s.a.

Strikeout [page 2, Line 55]: To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their exact positions and extents and took dip readings where possible.

Strikeout [page 2, Line 55]: To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their exact positions and extents and took dip readings where possible.

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Strikeout [page 2, Line 55]: To complete the existing data, we visited all Zechstein slivers, the main focus of this study, along the length of the Sontra Graben, mapped their exact positions and extents and took dip readings where possible.

Insert [page 2, Line 55]: mapped the

Insert [page 2, Line 55]: of all Zechstein slivers

Note [page 2, Line 56]: wells

comment: not shown on map -> please add locations

Strikeout [page 2, Line 57]: We used information from two of those to constrain the architecture of one fault hosting Zechstein slivers.
We wrote ‘two such wells’

Note [page 2, Line 58]: software
Phrase was removed.

Strikeout [page 2, Line 59]: Topography data for the cross sections were obtained from the topographic map of Hessen (1:25,000) and imported into Move (© Petroleum Experts) via the ASCII file import function.

Note [page 3, Line 61]: (1987)

Strikeout [page 3, Line 61]: Stratigraphic data (Fig.

Strikeout [page 3, Line 61]: 2) were taken from Motzka-Noering et al., 1987, which contains a compilation of various well and outcrop data.

Insert [page 3, Line 61]: descriptions

Insert [page 3, Line 61]: adopted from the actual geological map (Motzka-Noering et al., 1987)

Highlight [page 3, Line 63]: 2.2 Workflow The collected map data was digitised and georeferenced using QGIS (QGIS Development Team, 2015).

Highlight [page 3, Line 63]: 2.2 Workflow The collected map data was digitised and georeferenced using QGIS (QGIS Development Team, 2015).

and Note: I suggest to combine "Data" and "Workflow" in one chapter. At least, you did "classical scientific geology" (map analysis, geological mapping, etc.). You can eliminate some technical details, here. Is the usage of an Apple iPad Air 2 really relevant? If yes, you should explain why (e.g. discuss the precission of the GPS of an iPad Air 2).
We prefer maintaining this separation between data sources and workflow to enhance reader-friendliness through a larger number of subheadings, making the electronic publication more navigable through hyperlinks.
We prefer including the technical details in the interest of transparency and as a guideline to readers, who wish to learn about the possibility of digital mapping.

Highlight [page 3, Line 63]: 2.2 Workflow The collected map data was digitised and georeferenced using QGIS (QGIS Development Team, 2015).

Highlight [page 3, Line 65]: All geological mapping was done using FieldMove (© Petroleum Experts) on an Apple iPad Air 2 and data from the app were fed into QGIS via the .csv import function.

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Strikeout [page 3, Line 65]: All geological mapping was done using FieldMove (© Petroleum Experts) on an Apple iPad Air 2 and data from the app were fed into QGIS via the .csv import function.
s.a.

Strikeout [page 3, Line 65]: All geological mapping was done using FieldMove (© Petroleum Experts) on an Apple iPad Air 2 and data from the app were fed into QGIS via the .csv import function.
s.a.

Highlight [page 3, Line 66]: Subsequently, a new internally consistent geological map was constructed (Fig.

Strikeout [page 3, Line 66]: All geological mapping was done using FieldMove (© Petroleum Experts) on an Apple iPad Air 2 and data from the app were fed into QGIS via the .csv import function.
s.a.

Strikeout [page 3, Line 67]: The resulting map and dip data from the aforementioned publications then served as the basis for modelling and cross-section construction in 2DMove (© Petroleum Experts).

Highlight [page 3, Line 68]: The resulting map and dip data from the aforementioned publications then served as the basis for modelling and cross-section construction in 2DMove (© Petroleum Experts).

Strikeout [page 3, Line 68]: The resulting map and dip data from the aforementioned publications then served as the basis for modelling and cross-section construction in 2DMove (© Petroleum Experts). All data was fed into 2DMove via the shapefile (*.shp) or the ASCII (*.txt) import functions.
s.a.

Note [page 3, Line 71]: Synthetic forward model?
All models are technically synthetic. If the intention is to highlight the fact that ours is a digital, rather than an analogue model, we accept this.

Highlight [page 3, Line 71]: 2.3.1 Forward structural model

Strikeout [page 3, Line 72]: The forward model was constructed in 2DMove (© Petroleum Experts) to test the viability of inversion-related emplacement of the Zechstein slivers.
Again, in the interest of transparency, we prefer to indicate the software used.

Highlight [page 3, Line 73]: We constructed an undeformed layer cake model with horizontal bedding using the averaged stratigraphic thicknesses of the study area.

Strikeout [page 3, Line 73]: We constructed an undeformed layer cake model with horizontal bedding using the averaged stratigraphic thicknesses of the study area.
'averaged' is a correct term and widely used in scientific publications.

Note [page 3, Line 74]: Well, yes, but you have to show where the second border fault of the graben is...
By the statement 'For simplicity, our model contains only one fault which is assumed to represent the principal boundary fault..', we refer to the fact that in nature, faults are in fact fault zones with a multitude of more or less interlinked fault planes. In a forward model, this complexity is, however, impractical and would require a great amount of speculation resulting in no scientific gain. In our geological map, we do include more than one fault.

Strikeout [page 3, Line 75]: For simplicity, the model contains only one fault which is assumed to represent the principal boundary fault of the Sontra Graben.

Highlight [page 3, Line 75]: Using the 2D-Move-on-Fault tool with the Simple Shear algorithm and 60° shear angle, we simulated normal fault displacement followed

by reverse motion, adjusting the fault geometry and displacement magnitudes until a satisfactory approximation of the obser…
and Note: What are the geometrical and mechanical assumptions of the simple shear algorithm? What is the influence of shear angle? Are there any dependencies of material (e.g. weak shale or evaporites) to the shear angle? Not all readers will be familar with "forward" structural modelling. So, help them to understand what you did.

At some point of your manuscript you should discuss the methods for forward structural modelling and why you use explicitely "simple shear".
Explanation added. We will address this.

Insert [page 3, Line 75]: main

Highlight [page 3, Line 77]: Using the 2D-Move-on-Fault tool with the Simple Shear algorithm and 60° shear angle, we simulated normal fault displacement followed by reverse motion, adjusting the fault geometry and displacement magnitudes until a satisfactory approximation of the observed structures…
and Note: What is a "satisfactory approximation ob observation"? What is the observation? The observation from geological maps? Or from published/constructed cross sections? Did you construct these "observations" based on your new data?

Highlight [page 3, Line 77]: Using the 2D-Move-on-Fault tool with the Simple Shear algorithm and 60° shear angle, we simulated normal fault displacement followed by reverse motion, adjusting the fault geometry and displacement magnitudes until a satisfactory approximation of the observed structures…

Highlight [page 3, Line 79]: 2.3.2 Constructing the balanced geological cross-sections from map data Both sections (Fig.
and Note: For me, it seems totally unclear why you did forward modelling before cross section construction.
Our aim was to deliver a proof-of-concept for the idea that the slivers could be brought to the surface in the observed fashion through inversion of the graben. Since this a dynamic process, we chose a forward model, which is inherently dynamic, as opposed to balanced sections, which represent only the present state. To undermine our argument, we then used the fault geometry tested in the forward model and used it as the basis for the two balanced sections. The goal with this step was to show that using the proposed fault geometry we would be able to produce balanced sections that matched all surface data.

Note [page 3, Line 80]: Two

Strikeout [page 3, Line 80]: 2.3.2 Constructing the balanced geological cross-sections from map data Both sections (Fig. 6) were constructed and balanced using 2DMove (© Petroleum Experts).
and Note: References to figures should be at these positions where you describe the structure. This is the methods chapter and you should only refer to figures that are necessary to understand these methods.
While we agree in principle, for the readers' convenience we still prefer to keep a reference to the figures at this point.

Highlight [page 3, Line 80]: 2.3.2 Constructing the balanced geological cross-sections from map data Both sections (Fig. 6) were constructed and balanced using 2DMove (© Petroleum Experts).

Highlight [page 3, Line 80]: 2.3.2 Constructing the balanced geological cross-sections from map data Both sections (Fig. 6) were constructed and balanced using 2DMove (© Petroleum Experts).
and Note: Referred to ahead of Figure 5.
Not sure about the meaning of this comment.

Highlight [page 3, Line 80]: 6) were constructed and balanced using 2DMove (© Petroleum Experts).

Strikeout [page 3, Line 80]: 6) were constructed and balanced using 2DMove (© Petroleum Experts).
Copyright Regulations.

Highlight [page 3, Line 81]: From the dip data, an orientation analysis was conducted to determine the optimal orientation for the cross sections.

Highlight [page 3, Line 81]: Slickensides on fault surfaces and small- scale faults and folds associated with the Sontra Graben exhibit signs of shortening predominantly in a north-north-easterly direction.
and Note: Did you acquire these data? If yes, analysis and interpretation should be described as well. Otherwise you should give references to the analysis.

What about observations of the regional fault trend? How does your shortening direction fit to published ones (e.g. Navabpour et al. 2017)?

Strikeout [page 3, Line 82]: Slickensides on fault surfaces and small- scale faults and folds associated with the Sontra Graben exhibit signs of shortening predominantly in a north-north-easterly direction.

Highlight [page 3, Line 82]: Slickensides on fault surfaces and small- scale faults and folds associated with the Sontra Graben exhibit signs of shortening predominantly in a north-north-easterly direction.

Insert [page 3, Line 82]: ...indicate NNE-SSW contraction.

Note [page 3, Line 83]: new geological map (Fig. 4)
New geological map might mislead the reader to assume that a new 'official' geological map was used instead of the map we compiled for this study. We did include a reference, however.

Highlight [page 3, Line 85]: The 2D-Unfolding tool with a Flexural slip algorithm was used to flatten the folds, conserving bed lengths.
and Note: Flexural Slip (in Move) does not conserve bed lengths.
We addressed this in the new version.

Note [page 3, Line 86]: not clear what exactly was considered
We clarified this.

Note [page 3, Line 88]: Where (and why) do you suspect the transition between the secondary (Triassic) detachments? That should be described somewhere.

Note [page 3, Line 88]: Figure 7!!!!! All figure references hereafter have to be checked! Many of these are wrong!!!

Strikeout [page 3, Line 89]: Section A (Fig. 6) was positioned such that the cross-sectional plane coincides with the outcrop shown in Fig.

Strikeout [page 3, Line 89]: 8, previously described by Schröder (1925), thus giving us an insight into the fault geometry of the graben and the way the Zechstein slivers

Highlight [page 3, Line 89]: Section A (Fig. 6) was positioned such that the cross-sectional plane coincides with the outcrop shown in Fig.
and Note: Why did you choose both cross section positions in the eastern Sontra Graben? At least it is crucial for your theory that it can be used for the western part, too. Furthermore, what's the reason for the eastern section trace? How can the "exotic" Muschelkalk blocks (L. Muschelkalk south of Holstein [next to Z slivers] and quarry in Sontra) be integrated in the model?
We will provide further sections in the western part of the Graben. The integration of the 'exotic' lower Muschelkalk south of the Holstein exceeds the scope of this paper.

Highlight [page 3, Line 89]: 6) was positioned such that the cross-sectional plane coincides with the outcrop shown in Fig. 8, previously described by Schröder (1925), thus giving us an insight into the fault geometry of the graben and the way the Zechstein slivers
and Note: This should be Figure 7.

Highlight [page 3, Line 89]: 8, previously described by Schröder (1925), thus giving us an insight into the fault geometry of the graben and the way the Zechstein slivers

Note [page 3, Line 90]: providing

Insert [page 3, Line 89]: 7?

Strikeout [page 3, Line 90]: 8, previously described by Schröder (1925), thus giving us an insight into the fault geometry of the graben and the way the Zechstein slivers

Highlight [page 4, Line 61]: 95

are juxtaposed with the graben shoulder and its interior. The outcrop shows one of the Zechstein slivers bounded on its south- south-westerly side by a thrust fault and on its north-north-easterly side by a normal fault. The Lower Muschelkalk adjacent to the Zechstein is internally folded. Further uphill the appearance of a second ”exotic” sliver of Middle Buntsandstein is likely linked to the normal fault in the NNE and could have been transported down during the extensional phase. Upon inversion, together with the Zechstein, it was raised to its current position. and Note: This is very important, but has nothing to do with "methods". At some point you should provide a detailled description of your "exotic" slivers.

`We moved this to the Results section`

Strikeout [page 4, Line 109]: 110

are juxtaposed with the graben shoulder and its interior. The outcrop shows one of the Zechstein slivers bounded on its south- south-westerly side by a thrust fault and on its north-north-easterly side by a normal fault. The Lower Muschelkalk adjacent to the Zechstein is internally folded. Further uphill the appearance of a second ”exotic” sliver of Middle Buntsandstein is likely linked to the normal fault in the NNE and could have been transported down during the extensional phase. Upon inversion, together with the Zechstein, it was raised to its current position.

3 Results

3.1 Structural segmentation of the Sontra graben

The NW-SE-trending Sontra Graben extends for a length of 35 km between the N-trending Altmorschen-Lichtenau-Graben in the west and the northwestern tip of the Thuringian Forest, a fault-bounded basement anticline in the east (Fig. 1). On both ends the Sontra Graben is reduced to a single fault before linking up with the other structures. Near its centre, the Wellingerode Graben splays from the Sontra Graben and runs first north-northeastward and then in a more northeasterly direction to meet the NW-SE-trending Netra Graben.

The main part of the Sontra Graben within the study area is subdivided into five segments for the purpose of this paper (Fig. 4). In the very northwest (segment I) the Graben has a width of approximately 500 metres. It is confined between two major faults, both with vertical offsets around 150 to 180 metres. Zechstein slivers occur at both faults and are comparatively small (from

1.000 to 16.000 m2, Table 1 for comparison).

Further to the southeast, segment II comprises a short stretch of graben near the village of Stadthosbach, where it becomes quite narrow (250 metres). The Graben continues to show two main faults with small-sized Zechstein slivers at the southwestern fault. Vertical offset amounts to no more than 80 metres.
The comparatively narrow width could be an artefact of topography…
and Note: Speculative.
We explain this in the following sentence.

Strikeout [page 4, Line 115]: 115

120

are juxtaposed with the graben shoulder and its interior. The outcrop shows one of the Zechstein slivers bounded on its south- south-westerly side by a thrust fault and on its north-north-easterly side by a normal fault. The Lower Muschelkalk adjacent to the Zechstein is internally folded. Further uphill the appearance of a second "exotic" sliver of Middle Buntsandstein is likely linked to the normal fault in the NNE and could have been transported down during the extensional phase. Upon inversion, together with the Zechstein, it was raised to its current position.

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Segment III is strongly influenced by interference with the Wellingerode Graben. The Sontra Graben reaches a width of up to

1.2 kilometres and shows first hints at a southeast trending axial syncline, in certain parts well silhouetted by the Trochitenkalk formation. of the Upper Muschelkalk. The Lower Muschelkalk outcrop becomes very broad in this part of the graben probably due to fault repetition…
and Note: Speculative.

Strikeout [page 4, Line 92]: The Lower Muschelkalk adjacent to the Zechstein is internally folded.

Insert [page 4, Line 92]: l

Strikeout [page 4, Line 93]: Further uphill the appearance of a second ”exotic” sliver of Middle Buntsandstein is likely linked to the normal fault in the NNE and could have been transported down during the extensional phase.

Highlight [page 4, Line 92]: Further uphill the appearance of a second ”exotic” sliver of Middle Buntsandstein is likely linked to the normal fault in the NNE and could have been transported down during the extensional phase.

Insert [page 4, Line 93]: ,

Insert [page 4, Line 93]: m

Highlight [page 4, Line 96]: 3 Results
and Note: "Structural Description”?
We restructured the new version.

Highlight [page 4, Line 96]: 3 Results

and Note: This should be 'Geological setting' including sections 3.1 and 3.2.

Highlight [page 4, Line 96]: 3.1 Structural segmentation of the Sontra graben
and Note: I do not think that it is a result. It is a description of the geometries observed using a geological map. The description and analysis and final the interpretation needs some geosections , at least one per segment, in order to explain the effect of erosional depth, and the final model presented in figure 9. The mechanical variations needs to be introduced beforehand

Note [page 4, Line 97]: A geological cross-section showing the entire structure would be nice
We will provide a strike parallel section for the length of the graben within the study area as well as a regional cross-section.

Highlight [page 4, Line 100]: On both ends the Sontra Graben is reduced to a single fault before linking up with the other structures.
and Note: How does a single fault correspond with the large with of segment 5 which is the southermmost part.....
The convergence of the graben to one fault towards its SE end near the Thuringian forest lies outside the study area and is not shown in our geological map but can be seen on the regional map in Fig. 1.

Highlight [page 4, Line 101]: Near its centre, the Wellingerode Graben splays from the Sontra Graben and runs first north-northeastward and then in a more northeasterly direction to meet the NW-SE-trending Netra Graben.
and Note: is this a correct term?
replaced with 'branches off'
As I see it is the Sontra garben and the Netra garben overlapping structures which are linked by the Wellingerode graben (fig 1) I.e a simple geopmetry described in the literature by overlapping faults (and grabens) which hardlink by the means of faults at a high angle to the original structure. Or am I wrong... you suggest something similar in the discussion
The SG and NG are not overlapping. They run more or less parallel and are "connected" via the Wellingerode Graben, which connects to the SG at a right angle and to the NG at n oblique angle.

Note [page 4, Line 101]: What are the criteria for that subdivision? A first view on your map show a subdivision in segment IV: tilted Lower MK + Upper BS in the W and c. 700 m wide anticline in the E. This is exactly where cross section B straddles the Sontra Graben, which seems problematic due to (yet undetected) transfer faults.
We addressed this in the new version.

Highlight [page 4, Line 103]: The main part of the Sontra Graben within the study area is subdivided into five segments for the purpose of this paper (Fig. 4).

and Note: why for the purpose of this paper and the problems adressed in it.
The purpose of this paper is to investigate the "exotic" Zechstein slivers. Hence, the graben was subdivided with regard to the presence and shape/size of the slivers.

Strikeout [page 4, Line 104]: I) the Graben has a width of approximately 500 metres.

Insert [page 4, Line 104]: g

Note [page 4, Line 104]: throw? vertical dip separation?

Note [page 4, Line 106]: Later you will present a nice compilation (last table) with numbers and stratigraphic units involved. Is there any systematic relationship? Notwithstanding it would be great to integrate that into the description here.

Strikeout [page 4, Line 108]: The Graben continues to show two main faults with small-sized Zechstein slivers at the southwestern fault.

Highlight [page 4, Line 108]: The Graben continues to show two main faults with small-sized Zechstein slivers at the southwestern fault.
and Note: Where? Highlight these crucial features in figures.
This can be seen in the geological map. We added a reference.

Insert [page 4, Line 108]: g

Highlight [page 4, Line]: Vertical offset amounts to no more than 80 metres.
and Note: Vertical or stratigraphic?
We have added 'stratigraphic' thickness.

Note [page 4, Line 109]: too detailed
Necessary to explain our theory about the influence of topography.

Strikeout [page 4, Line 110]: At this point, a small river has incised a 100-metre-deep valley at a right angle to the graben, which could explain a narrower outcrop, assuming that the graben becomes narrower with depth.

Insert [page 4, Line 110]: perpendicular

Note [page 4, Line 111]: I cannot follow this argumentation. Delete sentence. Don't mix observation and interpretation.
We will move this sentence to the Discussion part.

Highlight [page 4, Line 112]: Segment III is strongly influenced by interference with the Wellingerode Graben.
and Note: I prefer interaction with, the word interference indicates/suggests that there is a timing difference.

The standing term for such a structure is called 'interference structure'. I suppose it is derived from the interference of waveforms in Physics. Personally, I feel that the term 'interaction' actually invokes a much stronger sense of timing, since it suggests an active process rather than a mere result.

Highlight [page 4, Line 113]: 1.2 kilometres and shows first hints at a southeast trending axial syncline, in certain parts well silhouetted by the Trochitenkalk formation.
and Note: All strat. nomenclature must be shown in Fig. 2!

Strikeout [page 4, Line 114]: 1.2 kilometres and shows first hints at a southeast trending axial syncline, in certain parts well silhouetted by the Trochitenkalk formation.

Strikeout [page 4, Line 114]: 1.2 kilometres and shows first hints at a southeast trending axial syncline, in certain parts well silhouetted by the Trochitenkalk formation.

Strikeout [page 4, Line 114]: of the Upper Muschelkalk.

Strikeout [page 4, Line 114]: The Lower Muschelkalk outcrop becomes very broad in this part of the graben probably due to fault repetition (see also Fig.

Insert [page 4, Line 114]: F

Insert [page 4, Line 114]: u

Insert [page 4, Line 114]: l

Highlight [page 4, Line 115]: The Lower Muschelkalk outcrop becomes very broad in this part of the graben probably due to fault repetition (see also Fig. 9).
and Note: Ahead of Figures 5 & 7.

Strikeout [page 4, Line 115]: The aforementioned axial syncline interferes with the Wellingerode Graben in this segment.

Note [page 4, Line 118]: OK, but this depends on your subjective border of segments. The best known sliver is only tens of meters east of that border.
The segmentation was not chosen arbitrarily but in the case of segment 3, so that it would show the extent of the influence of interference from the Wellingerode Graben.

Strikeout [page 4, Line 119]: East of the Mühlberg mountain, segment IV comprises the largest Zechstein slivers that appear exclusively along the southwestern border fault.

Insert [page 4, Line 119]: hill

Strikeout [page 4, Line 121]: In the north-eastern part of segment IV, tilted blocks of Lower Muschelkalk surrounded by Upper Buntsandstein shale appear, while open folding is the dominant structural style in its southwestern part where the axial syncline becomes quite prominent.

Strikeout [page 4, Line 121]: In the north-eastern part of segment IV, tilted blocks of Lower Muschelkalk surrounded by Upper Buntsandstein shale appear, while open folding is the dominant structural style in its southwestern part where the axial syncline becomes quite prominent.

Insert [page 4, Line 121]: l

Insert [page 4, Line 121]: u

Highlight [page 5, Line 123]: These apparently lateral variations in structural style along the graben more likely are expressions of different vertical styles obscured by the effects of topography.
and Note: How can you say that? are there other explanations. It should perhaps be adressed in a discussion before

As I see it do you suggest that the variations are due to the stratigraphical controlled strength and not the variations in extension as indicated by the decrease in offset towards the ends of the graben. Being the devils advocate, I would suggest that the variations is just as well a result of lateral variations in displacement along the entire Sontra graben...
`Longitudinal cross-section added. Briefly discussed in new version.`

Highlight [page 5, Line 123]: These apparently lateral variations in structural style along the graben more likely are expressions of different vertical styles obscured by the effects of topography.
and Note: Is that sure? If yes, that would imply various facts:
1) The mu-so-blocks are "extensional duplexes" with a "roof normal fault" in Middle MK.
2) They are even below the "Central Syncline".
3) There was a central syncline on top of the mu-so-blocks.

Explaining the segmentation in segment IV by effects of topography implies that the eastern part lies 100 m higher than the west. So, please check your interpretation critically.
`This was actually our original point. We changed the wording to include your statements. See also longitudinal cross-section.`

Strikeout [page 5, Line 125]: We interpret this vertical contrast as an effect of decoupling, occurring between the Lower and the Upper Muschelkalk due to the low competence of the mainly marl bearing Middle Muschelkalk.

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Strikeout [page 5, Line 125]: We interpret this vertical contrast as an effect of decoupling, occurring between the Lower and the Upper Muschelkalk due to the low competence of the mainly marl bearing Middle Muschelkalk.

Highlight [page 5, Line 125]: All units below the Middle Muschelkalk exhibit a block style deformation and rotation, dominated by faulting, whereas units above the Middle Muschelkalk more frequently produce axial folds (Fig. 9).
and Note: this is actually poorly documented. Please document it by showing sections. proper geosections not modelled. Perhaps a boxdiagram.... to get the 3D effect

Insert [page 5, Line 125]: l

Insert [page 5, Line 125]: u

Insert [page 5, Line 125]: m

Strikeout [page 5, Line 125]: All units below the Middle Muschelkalk exhibit a block style deformation and rotation, dominated by faulting, whereas units above the Middle Muschelkalk more frequently produce axial folds (Fig.

Note [page 5, Line 127]: But that is ONLY in segment IV.
No, in segment III and V, i.e. all segments where units above mm exist, also show this.

Insert [page 5, Line 126]: m

Highlighted [page 5, Line 127]: All units below the Middle Muschelkalk exhibit a block style deformation and rotation, dominated by faulting, whereas units above the Middle Muschelkalk more frequently produce axial folds (Fig.
and Note: I do not understand. The axial plane of folds? Maybe it's just better to write - folds
'axial' means the fold axis is parallel to the striking direction (or long axis) of the graben.

Highlight [page 5, Line 131]: Small Zechstein slivers occur on several faults of the graben interior but are restricted to the northwestern part of the segment.
and Note: Where can I see this? Show it on your map.
It says in that sentence: segment V on the geological map. We have added a reference to the geological map.

Highlight [page 5, Line 134]: 3.2 Mechanical stratigraphy
and Note: This chapter needs to be located earlier, perhaps in the geological setting in the intro. A lot of the localities mentioned are impossible to find in fig 10. Please allign the figures and the text.
We have restructured the manuscript.

Strikeout [page 5, Line 135]: In Late Permian times, the Zechstein transgression flooded the Southern Permian Basin from the central North Sea into western Poland and from the southern margin of the Baltic shield in the north to the Rhenish massif and the Bohemian massif in the south (…

Highlight [page 5, Line 135]: In Late Permian times, the Zechstein transgression flooded the Southern Permian Basin from the central North Sea into western Poland and from the southern margin of the Baltic shield in the north to the Rhenish massif and the Bohemian massif in the south (…
and Note: or Central European Basin System?

Insert [page 5, Line 135]: l

Highlight [page 5, Line 139]: Situated on the southern edge of the Southern Permian Basin, the study area mainly comprises the first three Zechstein cycles, termed the Werra, Staßfurt and Leine (or Z1 to Z3) cycles and contains the subsequent four cycles only in a shaly marginal facies…
and Note: margin?

Strikeout [page 5, Line 144]: The strongest units are the carbonates of the Z2 and Z3 cycles, traditionally termed “Hauptdolomit” (main dolomite, Ca2) and “Plattendolomit” (platy dolomite, Ca3).

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Strikeout [page 5, Line 144]: The strongest units are the carbonates of the Z2 and Z3 cycles, traditionally termed “Hauptdolomit” (main dolomite, Ca2) and “Plattendolomit” (platy dolomite, Ca3).

Insert [page 5, Line 144]: M

Insert [page 5, Line 144]: D

Insert [page 5, Line 144]: P

Strikeout [page 5, Line 145]: The strongest units are the carbonates of the Z2 and Z3 cycles, traditionally termed “Hauptdolomit” (main dolomite, Ca2) and “Plattendolomit” (platy dolomite, Ca3).

Insert [page 5, Line 145]: D

Strikeout [page 6, Line 145]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them a…

Strikeout [page 6, Line 156]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them a…

Strikeout [page 6, Line 156]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them a…

Insert [page 6, Line 156]: l

Insert [page 6, Line 156]: m

Insert [page 6, Line 156]: l

Strikeout [page 6, Line 158]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them a…

Insert [page 6, Line 158]: u

Strikeout [page 6, Line 158]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them are formed by the evaporitic and shaly U…

Strikeout [page 6, Line 159]: The Triassic succession also comprises three competent units: the mostly sandy and competent Lower and Middle Buntsandstein, the Lower Muschelkalk and the lower part of the Upper Muschelkalk (Trochitenkalk Fm.). Potential detachment horizons between them are formed by the evaporitic and shaly Upper Buntsandstein and the evaporitic and marly M…

Insert [page 6, Line 159]: u

Insert [page 6, Line 159]: m

Note [page 6, Line 160]: Regarding the international readership you should describe your stratigraphy and rheology. At the moment there is a detailed description for Zechstein and a very brief explanation for Triassic, which, nonetheless, covers 99 % of your research area.
We give some indication of the units' rheological properties in the stratigraphic column.

Is it possible for you to decide whether the slivers comprise Z2 or Z3 strata? If yes, this seems to be important for your description and interpretation.
Not really. We think it's mostly Hauptdolomite and Platy Dolomite.

Strikeout [page 6, Line 160]: The higher part of the Upper Muschelkalk and Keuper represent an incompetent stratal package at the top of the column.

Insert [page 6, Line 160]: s

Insert [page 6, Line 160]: u

Highlight [page 6, Line 161]: 3.3 Forward Model
and Note: Results?
s.a.

Strikeout [page 6, Line 163]: The forward structural modelling helped us to better constrain the possible geometry of the Sontra Graben main fault and its role in the formation of the Zechstein slivers.
We actually specifically want to address the role the fault geometry played in the formation of the slivers.

Strikeout [page 6, Line 162]: The forward structural modelling helped us to better constrain the possible geometry of the Sontra Graben main fault and its role in the formation of the Zechstein slivers.

Strikeout [page 6, Line 162]: The forward structural modelling helped us to better constrain the possible geometry of the Sontra Graben main fault and its role in the formation of the Zechstein slivers.
Previously, we used small letters.

Strikeout [page 6, Line 162]: The forward structural modelling helped us to better constrain the possible geometry of the Sontra Graben main fault and its role in the formation of the Zechstein slivers.
s.a.

Highlight [page 6, Line 162]: The forward structural modelling helped us to better constrain the possible geometry of the Sontra Graben main fault and its role in the formation of the Zechstein slivers. It was particularly useful in exploring the

influence of decollements in the incompetent rock units and provided guidance in the construction of the two balanced cross-sections.
and Note: This is a conslusive remark, as a result it is unconstrained at the present location in the of the paper
We have moved this to Conclusions.

Insert [page 6, Line 162]: M
s.a.

Insert [page 6, Line 162]: F
s.a.

Strikeout [page 6, Line 163]: It was particularly useful in exploring the influence of decollements in the incompetent rock units and provided guidance in the construction of the two balanced cross-sections.
We do not wish to discuss detachments in general.

Strikeouts [page 6, Line 163]: It was particularly useful in exploring the influence of decollements in the incompetent rock units and provided guidance in the construction of the two balanced cross-sections.
By it, we refer to the forward model.

Strikeout [page 6, Line 163]: It was particularly useful in exploring the influence of decollements in the incompetent rock units and provided guidance in the construction of the two balanced cross-sections.

Insert [page 6, Line 163]: thus provides the regional geologic context for the
We use the model for more than that. We actually make it the basis for our balanced cross-sections.

Insert [page 6, Line 163]: to determine
s.a.

Insert [page 6, Line 163]: potential detachments/décollements (please use one of these names in the entire manuscript).

Strikeout [page 6, Line 164]: It was particularly useful in exploring the influence of decollements in the incompetent rock units and provided guidance in the construction of the two balanced cross-sections.
s.a.

Insert [page 6, Line 164]: geometric and kinematic constraints for cross-section construction and balancing.
s.a.

Strikeout [page 6, Line 165]: The fault of the final model has an overall listric geometry with a dip angle of 60° at the surface that becomes a low-angle detachment at a depth of 800 metres within the Werra anhydrite (Fig.

For a broader readership it may help to keep our original phrasing in understanding the nature of a listric geometry.

Strikeout [page 6, Line 165]: The fault of the final model has an overall listric geometry with a dip angle of 60° at the surface that becomes a low-angle detachment at a depth of 800 metres within the Werra anhydrite (Fig.
s.a.

Highlight [page 6, Line 165]: The fault of the final model has an overall listric geometry with a dip angle of 60° at the surface that becomes a low-angle detachment at a depth of 800 metres within the Werra anhydrite (Fig.
and Note: Give a number! What means "low", here?

Insert [page 6, Line 165]: flattening from
s.a.

Insert [page 6, Line 165]: to
s.a.

Highlight [page 6, Line 166]: The fault of the final model has an overall listric geometry with a dip angle of 60° at the surface that becomes a low-angle detachment at a depth of 800 metres within the Werra anhydrite (Fig. 5a).
and Note: After Fig. 10
Not sure, what you are referring to. Have added reference to stratigraphic column.

Strikeout [page 6, Line 167]: The listric geometry is broken by three flats or short detachments, sitting in the Middle Muschelkalk, the Upper Buntsandstein and the main anhydrite (A3) of the Zechstein.

Strikeout [page 6, Line 167]: The listric geometry is broken by three flats or short detachments, sitting in the Middle Muschelkalk, the Upper Buntsandstein and the main anhydrite (A3) of the Zechstein.

Insert [page 6, Line 167]: m

Insert [page 6, Line 167]: u

Strikeout [page 6, Line 168]: 1.2 kilometres is sufficient to bring the Lower Muschelkalk of the hanging wall to the depths of the Zechstein when assuming a listric fault geometry.

Note [page 6, Line 168]: How did you estimate:
1) the lengths of detachments? Is there a geometric relationship between e.g. wavelengths of fault-related folds (central syncline?) to detachment lengths?
2) the amount of extension?

Did you assume some mechanical properties (friction angle, cohesion) for typical fault angles?
Explained in new version.

Insert [page 6, Line 168]: I

Highlight [page 6, Line 169]: A flat in the “Hauptanhydrit” (main anhydrite, A3) creates a step in the fault geometry, which upon inversion promotes the formation of a shortcut thrust, allowing for the creation of a Zechstein horse.
and Note: Not only in "Hauptanhydrit". Even in other weak horizons.

Highlight [page 6, Line 171]: 5b) creating a Zechstein horse with the original normal fault as a roof thrust and the newly created shortcut thrust as a sole thrust (Fig.
and Note: Completely confusing wording! Rephrase! "Orig. NORMAL fault as a roof THRUST”?
What was originally a normal fault during extensional phase is now reactivated as a thrust fault.

Highlight [page 6, Line 171]: For the inversion phase, a shortcut thrust was introduced (Fig. 5b) creating a Zechstein horse with the original normal fault as a roof thrust and the newly created shortcut thrust as a sole thrust (Fig.
and Note: This is not visible in Fig. 5b. You should enlarge that picture.
This is shown in fig 8a in great detail, which is referenced in that same sentence.

Note [page 6, Line 171]: Figure Numbers!!!!

Highlight [page 6, Line 172]: A backthrust (Fig. 7b) was also created and the Zechstein horse emplaced onto the underlying Lower Muschelkalk of the hanging wall.
and Note: Even if there is borehole indication for that, I cannot fully understand the necessity of this backthrust. Where is the location of the mentioned borehole (not shown!)?
We have added the location of the well.
Is the backthrust only a local feature or is it necessary to be present in the entire graben? To clarify this it becomes necessary to show the structure of Z slivers in other parts of the graben.
For example the railway outcrop north of Sontra does not show any MK in the footwall of Z sliver.
We address this through 4 more sections.

Highlight [page 6, Line 172]: 5b) creating a Zechstein horse with the original normal fault as a roof thrust and the newly created shortcut thrust as a sole thrust (Fig. 7a).
and Note: Should be 8a

Highlight [page 6, Line 172]: A backthrust (Fig. 7b) was also created and the Zechstein horse emplaced onto the underlying Lower Muschelkalk of the hanging wall.
and Note: Should be 8b

Strikeout [page 6, Line 173]: 7b) was also created and the Zechstein horse emplaced onto the underlying Lower Muschelkalk of the hanging wall.

Insert [page 6, Line 173]: was
grammatically not necessary

Insert [page 6, Line 173]: l

Strikeout [page 6, Line 174]: This was included into the model to provide an explanation for the fact that in one of the wells, the Zechstein was found to overlie the Lower Muschelkalk.

Highlight [page 6, Line 174]: This was included into the model to provide an explanation for the fact that in one of the wells, the Zechstein was found to overlie the Lower Muschelkalk.
and Note: OK! This is important. If you explain this situation with backthrusting, the "upper" detachment is in Middle MK. Why do you postulate such a backthrust in Röt Fm. even in the second cross section? Where is the transition from Middle MK to Röt Fm. detachment and how does this look like in three dimensions?
The detachment in the Röt footwall originated during the extensional phase, along with the other detachments in the weak horizons in the footwall. The backthrust started during contraction and we propose that a mm detachment makes sense here, because of the scraping of motion of the mu against the Zechstein slivers. Please see the forward model.

Insert [page 6, Line 174]: l

Strikeout [page 6, Line 176]: Shortening of approximately 1000 metres sufficed to elevate the newly created Zechstein sliver to a regional stratigraphic level within the Upper Buntsandstein, a level where such slivers are commonly found along the Graben.

Insert [page 6, Line 176]: u

Highlight [page 6, Line 180]: Flats in low shear-strength layers were also observed in other grabens in the general area (Arp et al., 2011).
and Note: What does it mean?
We refer to outcrops in the Leinetalgraben and surrounding structures.

Highlight [page 6, Line 182]: After its formation, further contraction of the graben results in the Zechstein horse being thrust onto the hanging wall and ultimately becoming elevated to the observed stratigraphical position.
and Note: This is partly a repetition of lines 174-176.

Strikeout [page 6, Line 183]: Flats in the Intermediate Muschelkalk and the Upper Buntsandstein were merely incorporated to acknowledge their similar behaviour to the anhydrite-bearing Zechstein horizons, due to comparable physical properties.

Strikeout [page 6, Line 183]: Flats in the Intermediate Muschelkalk and the Upper Buntsandstein were merely incorporated to acknowledge their similar behaviour to the anhydrite-bearing Zechstein horizons, due to comparable physical properties.

Strikeout [page 6, Line 183]: Flats in the Intermediate Muschelkalk and the Upper Buntsandstein were merely incorporated to acknowledge their similar behaviour to the anhydrite-bearing Zechstein horizons, due to comparable physical properties.

Insert [page 6, Line 183]: i

Insert [page 6, Line 183]: u

Insert [page 6, Line 183]: Middle

Highlight [page 6, Line 186]: Shortening of approximately 1.2 km is necessary to elevate the sliver into the stratigraphical positions that are observed in the field.
and Note: This is partly a repetition of lines 174-176.

Highlight [page 7, Line 190]: 190

195

200

205

210

215

3.1 Balanced Cross-sections
and Note: What is the result here...
That it is possible to reconstruct the present observed geoetry using the same model in alll segments or have you tried to use a different model since the erosional depth leaves room for a large number of different fault geometries.
Is that discussed later
Yes! We were able to construct balanced section using the fault geometry, resulting from the forward model.

Note [page 7, Line 190]: wrong order!

Note [page 7, Line 192]: A-A’
We have included the titles in the figure (Section A, Section B)

Note [page 7, Line 192]: graben or half-graben?
Or if the authors prove that the Sontra structure is a graben, then it has to be written here that part of the graben …
We addressed this.

Note [page 7, Line 192]: A-A' (Fig. 6 A)

Highlight [page 7, Line 194]: At the surface the main boundary fault in the southwest dips to the northeast at an almost vertical angle, following a listric geometry down to the depth of the Werra-Anhydrite.
and Note: It is not 'almost vertical' on Figure 6.

Highlight [page 7, Line 197]: The central block in the graben is backthrust over the north-eastern shoulder and appears stratigraphically lowered relative to the southwestern shoulder.
and Note: As it is a half-graben there is no north-eastern shoulder. As mentioned above, the necessity for the backthrust is unclear. Surface outcrop suggest a south-dipping normal fault.
We changed this to hinge and explained the necessity for backthrust.

Strikeout [page 7, Line 201]: Due to the deformation associated with the long-wavelength syncline, fault angles and geometries of the graben faults appear somewhat unintuitive.
and Note: Either explain this or delete sentence.

Note [page 7, Line 204]: B-B'

Note [page 7, Line 204]: B-B' (Fig. 6B)

Strikeout [page 7, Line 205]: The NW-trending long- wavelength syncline continues well visible in this section.

Highlight [page 7, Line 206]: The boundary fault in the southwest dips at an angle of approximately 70° towards the northeast and flattens out to become a horizontal decollement at a depth of approximately 450 metres.
and Note: How does this steep dip angle correlate with your forward model?
Well.

Strikeout [page 7, Line 207]: The backthrust has a similar geometry as in section 1, dipping towards the SW at an angle of approximately 45° and flattening out, parallel to bedding in the centre of the graben.

Incorrect grammar.

Strikeout [page 7, Line 207]: The backthrust has a similar geometry as in section 1, dipping towards the SW at an angle of approximately 45° and flattening out, parallel to bedding in the centre of the graben.
Incorrect grammar.

Highlight [page 7, Line 207]: The backthrust has a similar geometry as in section 1, dipping towards the SW at an angle of approximately 45° and flattening out, parallel to bedding in the centre of the graben.
and Note: Yes, but it roots in another detachment.
Yes, this is based on surface data and borehole data.

Insert [page 7, Line 207]: A

Strikeout [page 7, Line 208]: The backthrust has a similar geometry as in section 1, dipping towards the SW at an angle of approximately 45° and flattening out, parallel to bedding in the centre of the graben.

Insert [page 7, Line 208]: s

Highlight [page 7, Line 211]: 3.1.3 Transfer structure Map analysis shows that west of section A the occurrence of the Zechstein slivers along one single main inverted thrust changes to a different pattern, in which a double-row of the slivers along a series of imbricated faults prevai…
and Note: Why don't you use your segmentation from the map?

Highlight [page 7, Line 211]: 3.1.3 Transfer structure Map analysis shows that west of section A the occurrence of the Zechstein slivers along one single main inverted thrust changes to a different pattern, in which a double-row of the slivers along a series of imbricated faults prevai…
and Note: No! Reverse reactivated normal fault.

Strikeout [page 7, Line 213]: We suggest these faults function as part of a transfer structure, where the seemingly disconnected individual faults link up at depth conjoining into one single detachment (Fig.
'to link up with' is correct.

Highlight [page 7, Line 213]: We suggest these faults function as part of a transfer structure, where the seemingly disconnected individual faults link up at depth conjoining into one single detachment (Fig. 11).
and Note: Yes, of course. But when looking at Fi. 11 severeal questions arise:
1) Are there any transfer structures documented in map view? I guess in your model strike-slip or transfer faulting is essential.
2) If this scenario is true I would expect that Z slivers occur where one single fault exists. Then total extension/shortening would concentrate there. However "doubled Z slivers" occur mostly in segment I. Would that imply that total amount of extension/shortening is at least 2x as much as estimated in the forward model?

We addressed this in the new version.

Note [page 7, Line 213]: impossible to understand with mistakes in figure labels.

Highlight [page 7, Line 214]: Said fault geometry could comfortably facilitate the previously developed model (Fig. 7) for explaining the emplacement of the Zechstein slivers in this particular configuration.
and Note: Should be Figure 8

Highlight [page 7, Line 215]: We also show how erosion functions as the main controlling mechanism for determining the width of the graben at the surface, where advanced erosion leaves only a narrow band of fault-bounded Zechstein.
and Note: Do you then mean that the graben has the same amount odf extension along the entire length and that the narrowing towards the north is only an effect of stratigraphically deep erosion... I do not think that you have shown that
Yes, that is what we mean. This is our theory anyway. For proving this, there would need to be more balanced sections along the entire length of the graben to determine the shorting. The focus of this study is however, to show a model for the emplacement of the Zechstein slivers.

Highlight [page 7, Line 215]: We also show how erosion functions as the main controlling mechanism for determining the width of the graben at the surface, where advanced erosion leaves only a narrow band of fault-bounded Zechstein.
and Note: This has nothing to do with the transfer structure as the heading suggests.
added erosion to the subheading

Highlight [page 8, Line 218]: 3.2 Summary of the structural interpretation
and Note: Check numbering of chapters.

Highlight [page 8, Line 218]: 3.2 Summary of the structural interpretation
and Note: This subchapter is not a summary of interpretation but an additional description.
We disagree. Everything that is stated here are statements made previously within this chapter.

Highlight [page 8, Line 225]: 3.4 Formation of the Backthrust
and Note: Should that not be before the summry of structural interpretation

Note [page 8, Line 226]: where are they on the map?
Well location has been added.

Highlight [page 8, Line 226]: Well data from 20 metres to the northwest of the profile line indicate that at least at one location Zechstein is thrust on top of the Lower Muschelkalk of the hanging wall at a shallow depth of approximately 30 metres.
and Note: Which section?

Strikeout [page 8, Line 227]: Well data from 20 metres to the northwest of the profile line indicate that at least at one location Zechstein is thrust on top of the Lower Muschelkalk of the hanging wall at a shallow depth of approximately 30 metres.

Highlight [page 8, Line 228]: Backthrusts are a well-documented feature of inverted grabens (Hayward & Graham, 2015).
and Note: Yes, fore-thrusts as well. How good is indication for backthrusting? When does that happen? Sequence of contractional fault activity?
Which point are you making regarding fore-thrusts? Indication for backthrusting stems from the borehole data. For timing, please see forward model.

Insert [page 8, Line 227]: I

Strikeout [page 8, Line 229]: A kinematically viable solution would therefore be a backthrusting movement of the Zechstein horse onto the Lower Muschelkalk of the hanging wall.

Insert [page 8, Line 229]: I

Highlight [page 8, Line 230]: 3.5 Exotic Zechstein Slivers
and Note: An interesting sub-chapter, but:
1) What can we learn/interpret from your observation? Why isn't this described much earlier in the manuscript?
2) Show these internal differences in map and interpret/describe variations extensively.
3) Otherwise - but I wouldn't prefer that - leave this out.
We are restructuring this.

Highlight [page 8, Line 231]: A trend towards larger, more continuous slivers can be observed from the northwest to the southeast, i.e. from segment I to V (Table 1, Fig.
and Note: No they are absent in segment III. so what goes on…
We are obviously only discussing slivers that are actually there.

Strikeout [page 8, Line 233]: The Lower Muschelkalk appears most commonly as bordering unit on the south-western side of the slivers while in the north-east, the slivers are generally bordered on by the Upper Buntsandstein.

Insert [page 8, Line 232]: I

Strikeout [page 8, Line 233]: The Lower Muschelkalk appears most commonly as bordering unit on the south-western side of the slivers while in the north-east, the slivers are generally bordered on by the Upper Buntsandstein.

Strikeout [page 8, Line 233]: The Lower Muschelkalk appears most commonly as bordering unit on the south-western side of the slivers while in the north-east, the slivers are generally bordered on by the Upper Buntsandstein.

Insert [page 8, Line 233]: north-eastern

Insert [page 8, Line 233]: south-west

Insert [page 8, Line 233]: a
Incorrect.

Strikeout [page 8, Line 234]: The Lower Muschelkalk appears most commonly as bordering unit on the south-western side of the slivers while in the north-east, the slivers are generally bordered on by the Upper Buntsandstein.

Insert [page 8, Line 234]: u

Highlight [page 8, Line 240]: 4 Discussion
and Note: The discussion needs to adress the application of modelling
the regional implications of the results,
a discussion of salt models from the North sea and inclusion of the interpretations and models presented there. As an example of a similar problem
We feel that the discussing salt models from the North sea offers little benefit to this manuscript because of the general scarcity of salt-bearing horizons in this study area.

Note [page 8, Line 218]: wrong order

Note [page 8, Line 225]: leave away
This part is essential in explaining the position of the Zechstein sliver on top of lower Muschelkalk, as found in well.

Note [page 8, Line 230]: leave away
We prefer keeping the subheadings.

Note [page 9, Line 243]: re-write!

Highlight [page 9, Line 243]: Apart from the general rules of mechanical stratigraphy the existence of such flats in incompetent horizons is based on field observations, made by Arp, Tanner and Leiss, 2011 and Möbus, 2007 on normal faults that are associated with the Leinetal Graben, c…
and Note: It looks like the first sentence of this paragraph is missing.

Highlight [page 9, Line 243]: Apart from the general rules of mechanical stratigraphy the existence of such flats in incompetent horizons is based on field observations, made by Arp, Tanner and Leiss, 2011 and Möbus, 2007 on normal faults that are associated with the Leinetal Graben, c…

and Note: Which flats?

Note [page 9, Line 244]: (2011)

Note [page 9, Line 244]: (2007)

Highlight [page 9, Line 252]: According to the Mohr-Coulomb fracture criterion, upon inversion, a new shortcut thrust fault is only likely to form, if the original normal fault is significantly steeper than 30° relative to a subhorizontal σ 1(thrust regime).
and Note: What does that mean? How much is "significant"?

Strikeout [page 9, Line 257]: Therefore, the formation of flats in low shear-strength horizons on the original normal fault during the extensional phase plays a key role in my model for the creation of the Zechstein slivers.

Highlight [page 9, Line 257]: Therefore, the formation of flats in low shear-strength horizons on the original normal fault during the extensional phase plays a key role in my model for the creation of the Zechstein slivers.
and Note: Why 'my'? There are two authors of the paper.

Insert [page 9, Line 257]: our

Note [page 9, Line 259]: figure number!

Highlight [page 9, Line 259]: Without the flats, the angle of the normal fault near the basal decollement would not be steep enough to induce the formation of shortcut thrusts, necessary to create a horse between the normal fault and the newly developed shortcut thrust (Fig. 7).
and Note: Fig. 8

Note [page 9, Line 260]: check comment 2

Highlight [page 9, Line 260]: For this model, we assumed that immediately below the flat, the fault returns to a dip of 60° a typical angle for normal faults, and then flattens out again towards the following flat and eventually towards the basal detachment.

The geometry of the fault plays a key role in the formation and shape of the Zechstein slivers. In particular, the length of the flat and its height above the basal detachment are the main factors that control the final geometry of the observed Zechstein slivers, whereas height above the basal detachment controls their thickness.
and Note: Hence the thickness of competent Zechsteins triggers sliver geometry? Can you prove this in your area? How is the length-geometry relationship? Please, explain.
These are geometrical deductions and are not confined to this area.

Note [page 9, Line 260]: these parts of text are too detailed
In what sense are they too detailed?

Note [page 9, Line 266]: Is that reached anywhere? If estimated, you can show this in your table.
This would be difficult to figure out, because we would need to know the exact angle of the Zechstein sliver across its entire width to determine the thickness of the sliver perpendicular to bedding.

Strikeout [page 9, Line 267]: Another important feature, which was observed in the field, is the superimposition of "exotic" Zechstein over Lower Muschelkalk which is most likely part of the hanging wall.

Insert [page 9, Line 268]: I

Highlight [page 9, Line 268]: We therefore suggest backthrusting of the Zechstein sliver onto the Muschelkalk during inversion (Fig. 5, 6).
and Note: Said again and again and again. Delete it here.
This is the first time this is stated in the Discussion.. not all readers will read the whole article.

Insert [page 9, Line 268]: ,

Insert [page 9, Line 269]: s

Highlight [page 9, Line 270]: Thrusting is likely to have occurred during early stages of the inversion phase.
and Note: I suspected that thrusting have occured during the entire inversion phase. What happend during late inversion? How well-proved is the timing?
Reactivation of the normal faults as thrust faults during early inversion. Last stage included long-wavelength folding. Constrained through forward model.

Note [page 9, Line 276]: which are???
We discuss this in the following sentence.

Strikeout [page 9, Line 276]: MOVE offers a limited choice of algorithms that are suited for the modelling of normal faults.
We addressed this in the new version.

Strikeout [page 9, Line 278]: Running the simulation with either the Fault Parallel Flow algorithm or the Simple Shear algorithm proved to have little effect on the amount of extension required to lower the hanging wall Lower

Insert [page 9, Line 278]: I

Insert [page 10, Line 279]: .

Note [page 10, Line 280]: But as said above you should keep in mind that these are minimum amounts. If two slivers occur within the direction of transport, this gives you a hint for overall extension/shortening amounts of the Sontra Graben.
Correct, they are minimum amounts.

Highlight [page 10, Line 281]: 4.2 The Zechstein as a Detachment Horizon
and Note: I suggest to change that chapter to "cover vs. basement deformation”.

However, keep in mind that you need a basement fault anywhere. This is even on of the most important questions: Where is the basement fault?
We address this in the a regional schematic cross-section.

Note [page 10, Line 282]: evaporites?

Highlight [page 10, Line 284]: Any such fault would most likely, if any, produce slivers of basement rock.
and Note: Not necessarily. The Z evaporites are the deepest incompetent layers. There are two effects you should keep in mind:
1) Weak material holds some "healing potential" for old fracturs. - Reactivation is hampered or excluded.
2) The mechanical properties of Z are ideal for the generation of new thrusts. - No reactivation of existing normal faults.

Assuming that fault reactivation can even occur under non-ideal conditions (steep dips) in the basement, such reactivation probably do not happen in Z.
Interesting points, but our entire model is based on the assumption, that faults new faults (shortcuts) are created in the Zechstein upon inversion. Do you have any references for the difficulties in reactivating faults in the Zechstein?

Note [page 10, Line 285]: (Fig. 3)

Note [page 10, Line 287]: If thick salt is present, even smaller dips would be possible (2-3°). But here you neither have a passive margin situation nor such thick salt. I suggest to have a look at more similar structures. Is thin-skinned extension documented somewhere else in an intracontinental basin? Maybe you should have a look at the Allertal Structure (Best & Zirngast, BGR report; analogue models of Ge & Vendeville 1997), the Leinetal Graben or the western border of the Altmark Swell (Malz et al. 2020).
We merely use this to show that detachments in Zechstein are possible.

Highlight [page 10, Line 290]: The NGB lies much further to the north than the Hessian Grabens and has considerably thicker Zechstein.

and Note: Yes, but if you look at the northern margin of the NGB or at the rims of the Northern Permian Basin there are a large number of extensional structures terminating at the Zechstein. Please include these in the discussion
We address this in the new version.

Note [page 10, Line 290]: delete paragraph break

Strikeout [page 10, Line 295]: Basement up-thrusts like the Harz Mountains or the Thuringian Forest could certainly drive deformation in the sedimentary layer, at least for compressional forces.

Highlight [page 10, Line 296]: The exhumation ages of the Harz Mountains (Voigt et al., 2008) coincide with the proposed time of the graben inversion.
and Note: When?

Note [page 10, Line 297]: Late Cretaceous

Highlight [page 10, Line 297]: The exhumation ages of the Harz Mountains (Voigt et al., 2008) coincide with the proposed time of the graben inversion.
and Note: When was graben inversion? How dated? Name your arguments.
We addressed this in the new version.

Highlight [page 10, Line 298]: Thus, it would seem plausible for deformation in the basement to occur elsewhere in or on the edge of the basin and for the sedimentary cover to act more or less independently.
and Note: Independently from what? Different timing or kinematics?
Deformation in the sedimentary cover need not be in the immediate vicinity of a large basement structure but deformation may be transferred from the edge of the basin or a basement uplift like the Harz.

Strikeout [page 10, Line 299]: For the preceding extensional phase, however, traces of a similar extension in the basement have yet to be found.

Note [page 10, Line 303]: provide timing for this

Highlight [page 11, Line 333]: 335

the Sontra Graben is also situated just on the northeastern edge of the Schemmern-Swell and close to the centre of the Waldkappel Depression, two paleogeographic features of the Z1 basin (Kulick et al., 1984). This could have produced a special facies-type with physical properties that might favour this kind of structure, most likely an alternation of strong carbonate layers and evaporites that are thick enough to act as detachments but too thin to form proper salt structures (pillows and diapirs). In order to test this hypothesis, a comparative study of all the structures in which exotic slivers occur would have to be made with special focus on their paleogeographic setting.

Another possibility is extension in the Netra Graben simply did not suffice to bring the Lower Muschelkalk as far down as the Zechstein. A theory, supported by the fact that Zechstein does not appear in any immediate vicinity of the Netra Graben. During the contractional phase, the formation of shortcut thrusts in the Sontra Graben will have released some of the stress on the graben system and strain on the Netra Graben's footwall might have been insufficient to produce shortcut thrusts.

4.4 Timing of the Deformation Phases

Since such a significant portion of the graben has been eroded and only its roots remain, it is not possible to directly infer a deformation age due to the lack of syn-rift and post-rift sediments. However, the fact that Upper Triassic units (Muschelkalk and Lower Keuper) are in fault contact with Lower Triassic units (Buntsandstein) requires the deformation to have occurred after the deposition of the Lower Keuper.

Graben inversion, typically recognizable through stratigraphic constraints such as the thickening of the syn-rift sediments towards the boundary fault (Williams et al., 1989), cannot be proven by these means, again due to the lack of syn-rift deposits. Another way to recognize inversion on a map is through faults that, following the strike of the graben, change from normal to thrust fault (Williams et al., 1989). This is clearly the case with the Sontra Graben (Fig. 4). Finally, the position of the Zechstein slivers can be seen as evidence for graben inversion, when the assumptions of the forward model are accepted.

The timing for the extension and contraction of the different graben directions, Sontra Graben and Netra Graben versus Wellingerode Graben, poses another difficult question. Generally, it can be said that the Wellingerode Graben appears to terminate at both the Sontra Graben and the Netra Graben. Using an analogy from joint propagation (Engelder, 1985), this would imply that the Sontra Graben and Netra Graben already existed when the Wellingerode Graben formed, releasing its tension once their boundary faults had connected.
and Note: A rather old reference. Please update on all the published results on how faults (extensionnal structures) probagate, interlink (soft link and hardlink etc) please rewrite.

Note [page 11, Line 317]: Nice idea!
Thanks!

Strikeout [page 11, Line 318]: Another possibility is extension in the Netra Graben simply did not suffice to bring the Lower Muschelkalk as far down as the Zechstein.

Note [page 11, Line 317]: this sentence does not make sense

Insert [page 11, Line 317]: I

Insert [page 11, Line 317]: that

Highlight [page 11, Line 321]: A theory, supported by the fact that Zechstein does not appear in any immediate vicinity of the Netra Graben.
and Note: How, does it mean that zechstein is absent in the area or deeply buried.... and how deep
added “outcrops”

Note [page 11, Line 322]: see comment 1

Strikeout [page 11, Line 323]: Since such a significant portion of the graben has been eroded and only its roots remain, it is not possible to directly infer a deformation age due to the lack of syn-rift and post-rift sediments.

Note [page 11, Line 322]: syn-tectonic?
are all these deposits associated with the rifting processes?
This refers only to the units above lower Keuper (indicated in grey in the forward model).

Strikeout [page 11, Line 324]: However, the fact that Upper Triassic units (Muschelkalk and Lower Keuper) are in fault contact with Lower Triassic units (Buntsandstein) requires the deformation to have occurred after the deposition of the Lower Keuper.

Insert [page 11, Line 324]: l

Strikeout [page 11, Line]: However, the fact that Upper Triassic units (Muschelkalk and Lower Keuper) are in fault contact with Lower Triassic units (Buntsandstein) requires the deformation to have occurred after the deposition of the Lower Keuper.

Insert [page 11, Line 325]: l

Note [page 11, Line 323]: syn-tectonic?
No.

Note [page 11, Line 324]: stratigraphically

Strikeout [page 11, Line 324]: Graben inversion, typically recognizable through stratigraphic constraints such as the thickening of the syn-rift sediments towards the boundary fault (Williams et al., 1989), cannot be proven by these means, again due to the lack of syn-rift deposits.

Strikeout [page 11, Line 325]: The timing for the extension and contraction of the different graben directions, Sontra Graben and Netra Graben versus Wellingerode Graben, poses another difficult question.
We refer to a specific extension, namely that of the SG etc.

Note [page 11, Line 335]: cite correctly!

Note [page 11, Line 336]: This requires detailed discussion!
Please see the notes on the text.
We will discuss this further.

Highlight [page 11, Line 336]: Previous authors (Vollbrecht et al.
and Note: Reference is missing in your ref. list.
We will add this.

Highlight [page 11, Line 336]: in Leiss et al., 2011) have suggested a dextral strike-slip regime for Lower Saxony and Northern Hessen and the simultaneous formation of the grabens in both direction (NW-striking and NNE-striking).
and Note: Yes, but in such a strike-slip regime the Wellingerode Graben would be the LARGE graben structure accommodating most strain. That seems unplausible.
Agreed!

Note [page 11, Line 339]: this

Note [page 11, Line 339]: ok but what is the result of the discussion.
We address this in the Conclusion part.

Highlight [page 12, Line 340]: 340

345

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5 Conclusions
and Note: The consclusion needs to be rewritten.
It is merely a number of statements2
This is not uncommon in scientific articles. Oftentimes conclusions merely include bullet points of the most important statements.

Highlight [page 12, Line 345]: 345

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5 Conclusions

The Sontra Graben is one of the many NW-trending structures in the CEBS. It displays unambiguous signs of both extension and contraction.

Variations in structural style along the graben are the basis for distinguishing five segments. To the northwest, segment I shows one major boundary fault in the southwest with many small “exotic” slivers and a second possibly conjugate fault in the northwest. Segment II comprises the narrowest part of the graben and the transition from fault dominated blocks to the emersion of a longer wave-length central syncline. Segment III is dominated by the intersection of the Wellingerode Graben. The central synclines of the Sontra Graben and the Wellingerode Graben form a cumulative structure. Zechstein slivers do not appear in this segment. Segment IV is dominated by fault-bounded and rotated blocks in the northwest and contains the longest continuous Zechstein sliver. Segment V shows the widening of the graben and the continuation of the syncline.
and Note: Too detailed and local for a 'Conclusions' section.
`Conclusions have been shortened in the new version.`

Strikeout [page 12, Line 341]: The Sontra Graben is one of the many NW-trending structures in the CEBS.
and Note: This sentence says nearly nothing.

Highlight [page 12, Line 344]: To the northwest, segment I shows one major boundary fault in the southwest with many small “exotic” slivers and a second possibly conjugate fault in the northwest.
and Note: I cannot see that conjugated fault.

Highlight [page 12, Line 345]: To the northwest, segment I shows one major boundary fault in the southwest with many small “exotic” slivers and a second possibly conjugate fault in the northwest.
and Note: east?

Highlight [page 12, Line 355]: For the extensional and contractional phase, maximum values of approximately…
and Note: These are minimum values.

Note [page 12, Line 340]: some information on the timing of deformation needed in this chapter
`We referenced this from this volume.`

Note [page 13, Line 375]: Brochwicz-Lewiński W. & W. Pożaryski

Note [page 13, Line 380]: rift?
`No.`

Note [page 15]: thecolorscale is poor, very hard to distinguish the units (zechstein, and grabens.
what is the ligth grey

Insert [page 15]: see the fig. 1 with suggested solutions...

Note [page 15]: Color of Cenozoic volcanics missing in legend.

Why do you distinguish Rotliegend and Basement? How is your definition of basement? There is even much sediment of Carboniferous age.

Attachment [page 15]: fig 1.jpg

Attachment [page 15]: refraction.jpg

Note [page 16]: Lower Keuper is still Middle Triassic. Check chronostratigraphy and lithostratigraphy of Triassic.

Seeing lithologies would be nice!

Note [page 17]: (1953)

Note [page 17]: I suggest to combine that figure with Fig. 2.

Note [page 18]: Not all these "thrust faults" are really thrusts.

Line [page 18]: Line

Line [page 18]: Line

Line [page 18]: Line

Line [page 18]: Line

Note [page 18]: the authors should supplement the map with symbols of individual rock units.

Attachment [page 18]: intersection.jpg

Attachment [page 18]: fold axes do not comply with the standard symbols of anticline and syncline axes
see e.g.: symbols.jpg

Note [page 18]: Where are the used boreholes?
Numbering of Z slivers?

Note [page 19]: vertical scale? 800m?

Note [page 19]: Shorten the sections and enlarge the details.

Maybe it would be better to show this in a schematic/synthetic style (e.g. simplified stratigraphy of detachment and brittle rock). That would enhance the understanding of the readership.

Note [page 20]: name of the section

Note [page 20]: Figure 6A

Note [page 21]: fault

Note [page 21]: by

Note [page 21]: Figure 6B

Note [page 21]: einzige Möglichkeit: im SW die Schichten auch zur Störung hin verflachen lassen

Note [page 22]: this figure should be shown in fig. 4

Note [page 22]: Overturned bedding in Motzka-Nöring and Schröder.

Note [page 22]: misreferenced many times in text

Note [page 22]: How evident is the bedding of the individual blocks? Some considerations should be shown. Depending on the real bedding and the decission of footwall and hanging wall cutoffs a limited number of admissible scenarios exist.

Note [page 23]: misreferenced many times in text; would be good after Figure 5

Note [page 24]: why is the vergence of a fold opposite to the adjacent fold?

Note [page 24]: The "main normal fault" bringing Muschelkalk to Zechstein level is missing here.

Note [page 24]: What shows that line?

Note [page 24]: Where can I see this situation in the field?

Note [page 24]: This scenario would only occur if thick weak material in Middle MK is present. Is that the case?

Note [page 25]: Note

Note [page 25]: I would suggest to eliminate the DEM, which has nothing to do with paleogeography.

Why don't you use fill colors for the different facies areas?

What does the numbers mean?

Note [page 26]: It is difficult to detect the crucial details in this sketch.

What about strike-slip/transfer structures between these faults?

Note [page 27]: difficult to understand! Explain differently - maybe re-name into vertical offset between graben-shoulder and graben-fill stratigraphy.... or similar

Note [page 27]: check numbers!

Note [page 27]: It would be nice to see the pattern of these "slivers" in the map.