

Surface cracks—geomorphological indicators for late Quaternary halotectonic movements in Northern Germany

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Abstract

Loading and unloading effects of the Scandinavian Ice Sheet triggered halotectonic movements in Northern Germany. We present newly detected geomorphological features—termed surface cracks—which indicate a relation between ice sheet-induced salt movement and surface processes. As a part of the Central European Basin System, numerous Zechstein salt structures are abundant in the North German Basin. On the basis of high-resolution digital terrain data, more than 160 surface cracks were mapped in Northern Germany, which were grouped into 30 clusters. Almost all of the surface cracks occur above the top regions of Zechstein salt structures. The surface cracks can be several kilometres long, up to more than 20 m deep and more than 100 m wide. The comparison of the shape of the salt structures and the orientation of the cracks reveals a geometric dependency, indicating that the cracks preferably occur near the crest margins of the salt structures. Furthermore, 3D seismic data from two sites show that subsurface faults originating from salt movement exist beneath the surface cracks. We interpret the cracks as surface ruptures due to ice sheet-induced halotectonic movements. The cracks occur in a variety of Quaternary sediments and landforms. This indicates that widespread halokinetic movements occurred in the region after the last (Weichselian) deglaciation and likely before the thawing of the permafrost, possibly in a time frame from c. 30–20 ka until c. 15 ka.

KEYWORDS

Central European Basin System, halotectonics, Permian Zechstein salt structures, Quaternary glaciations, Quaternary processes, salt dome, salt pillow, Scandinavian Ice Sheet, surface cracks

1 | INTRODUCTION

Large parts of Northern Germany and the adjoining areas were shaped by the advances of the Scandinavian Ice Sheet (SIS) during the Pleistocene (Böse et al., 2012). Throughout the last decade, significant progress has been achieved in the understanding of the timing and dynamics of the ice advances (Hughes et al., 2016; Lauer & Weiss, 2018; Lüthgens et al., 2020; Roskosch et al., 2015; Stroeven et al., 2016), as well as in deciphering the related surface processes. For the latter, the growing availability of high-resolution digital terrain models is of substantial importance, as these models allow precise mapping of landforms, leading to new insights in ice-related geomorphic processes, such as drumlin formation (Clark et al., 2009), erosion

by subglacial meltwater (Lesemann et al., 2010), formation of ice-marginal fans (Hardt et al., 2015) and ice-stream patterns (Szuman et al., 2021), as well as glacitectonic deformations (Gehrmann & Harding, 2018).

Glacitectonic deformations of sediment or bedrock, such as folds or thrusts, are the direct result of the ice sheet overriding the surface (Phillips, 2018). Apart from these deformations, the load of the SIS pressed down the Earth's crust, significantly affecting several spheres of the Earth system (Spada, 2017). A number of complex adjustment processes are still active, responding to the pressure relief (unloading) caused by the ice decay. These processes are summarized under the term glacial isostatic adjustment (GIA; Lambeck et al., 2014). One aspect of GIA, which is still ongoing, is the postglacial rebound:

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Fennoscandia is in an upward movement, whilst areas south of the Baltic Sea are subsiding (Spada, 2017). Among other effects, this rebound results in the reactivation of tectonic faults. As an example, it has been shown that major rivers of Northern Germany follow deep-seated tectonic faults in response to GIA (Reicherter et al., 2005; Sirocko et al., 2008). Additionally, the occurrence of historic earthquakes along Late Cretaceous fault zones in Germany was attributed to GIA (Brandes et al., 2015). However, GIA-related tectonic processes are difficult to differentiate from long-term tectonic processes related to plate movements, such as the Alpine convergence (Liszkowski, 1993; Reicherter et al., 2005; Sirocko et al., 2008; Stewart et al., 2000).

As part of the Central European Basin System (CEBS; Warren et al., 2008), numerous salt structures exist in the subsurface of Northern Germany and adjacent areas at top depths ranging from less than a few hundred to a few thousand metres. The response of salt structures to ice load and GIA adds an additional degree of complexity to the understanding of subsurface and surface processes in the CEBS. The influence of subsurface salt structures on the present-day geomorphology has been investigated previously: relations with the distribution of terminal moraines (Gripp, 1952; Schirrmeyer, 1998), subglacial tunnel valleys (Kristensen et al., 2007; Wenau & Alves, 2020) and modern river valleys (Reicherter et al., 2005; Sirocko et al., 2008) have been shown. These correlations may result from halotectonic movements which were triggered by oscillations of the SIS in the Pleistocene (Lang et al., 2014). However, distinct landforms in the Quaternary landscape, which can be directly related to ice sheet-induced salt movements, have so far not been recognized.

In this paper, we present more than 160 negative linear landforms (here termed *surface cracks*) in Northern Germany, which are up to several tens of metres wide, up to several kilometres long and cut up to several tens of metres into the surface. These landforms were detected on the basis of high-resolution LiDAR terrain data. The cracks cannot be categorized as any previously described landform of the glacial landscape. Through a deeper investigation into the morphology and spatial occurrence of these newly detected geomorphic features, it has become apparent that beneath almost all of them, salt structures are present in the deeper subsurface or close to the surface.

We describe the geomorphological characteristics of the cracks and their spatial distribution in the glacial landscapes of Northern Germany, as well as their spatial correlation to salt structures. For three specific localities, we present a more detailed description. At two of them, we additionally analyse 3D seismic subsurface data to investigate a possible correlation with structures of the deeper subsurface and the observed surface cracks. We present a theory on the possible development of the observed cracks which is based on the loading and unloading effects that ice sheets have on salt structures (Lang et al., 2014). We propose that the cracks are the geomorphic imprint of surface expansion that are due to ice sheet-induced salt rise, and we establish a time frame for their possible formation.

2 | SETTING

2.1 | Geological background

The CEBS (Warren et al., 2008) ranges from the North Sea in the west to Poland in the east (Figure 1, inset map). The basin development

was initiated in the Permo-Carboniferous time period and is today filled with sedimentary deposits of more than 7 km in thickness (Hoth et al., 1993). During the Zechstein (c. 258–252 Ma; STD, 2016), several marine transgressions flooded this vast basin. The seawater evaporated under arid tropical climate conditions, resulting in a characteristic depositional sequence of evaporitic rocks, such as rock salt (halite), anhydrite, gypsum and carbonate. Seven main evaporitic cycles can be differentiated (STD, 2016).

These evaporitic rocks, which consist of a large volume of rock salt (halite), were subsequently buried by Mesozoic and Cenozoic sediments. Due to the increasing sedimentary load and the relatively low density of rock salt compared with other sedimentary rock types, the salt can start to flow and move upward in certain areas, causing a deformation of the overburden (Nettleton, 1987; Warren, 2016). The resulting salt-related structures can develop into different geometries and are known, for example, as salt pillows, salt domes and salt diapirs. The respective structures form under the influence of gravity and tectonic extension or compaction (Brandes et al., 2012; Scheck et al., 2003b; Trusheim, 1987). The tectonic processes related to the salt movement are termed *halotectonics*. Salt movement and the formation of salt structures started in the mid- to late Triassic and continued in the late Cretaceous to the earliest Cenozoic until the Neogene (Scheck et al., 2003a; Scheck-Wenderoth et al., 2008). Halotectonic processes not only deform the overburden, but also affect the sedimentation in the CEBS (Maystrenko et al., 2008). For example, rim synclines, which developed in the surroundings of rising salt structures due to salt migration, were filled with thick Cenozoic sediments (Brandes et al., 2012; Scheck-Wenderoth et al., 2008). Apart from the tectonic events, the loading and unloading of ice sheets during the Pleistocene may additionally have influenced salt movements (Lang et al., 2014; Strozyk et al., 2017).

Salt structures in the subsurface can be mapped by using indirect (geophysical) and direct methods (e.g. by measurements of the gravity field, seismic exploration and deep drilling). The occurrence of salt structures in the CEBS is well known, as they provide an important economic resource for the storage of renewable energies or for geothermal energy (Donadei et al., 2015; Pollok et al., 2015), as well as for the possible storage of radioactive waste (BGE, 2020; Warren, 2016). Depending on the evolution and stage of a salt structure (pillow, diapir), different fracture styles or graben structures may develop in the overburden in reaction to the respective salt activity (Yin & Groshong, 2006). However, the details of the deformations and structural layering around a salt structure are often less resolved and require a thorough in-depth interpretation of all available subsurface data.

In the Cenozoic, large parts of the CEBS were flooded by the paleo North Sea, resulting in about 80 m-thick marine clay deposits of the Oligocene ('Rupelton'; Knox et al., 2010). The Rupelton acts in many areas as a hydraulic barrier between the deeper saline aquifer system and the upper utilized drinking water (Yordkayhun et al., 2009a) that is most often related to Quaternary sediments.

2.2 | Brief quaternary landscape history

The SIS oscillated several times into Northern Germany during the Pleistocene (Ehlers et al., 2011). While the Elsterian and Saalian ice

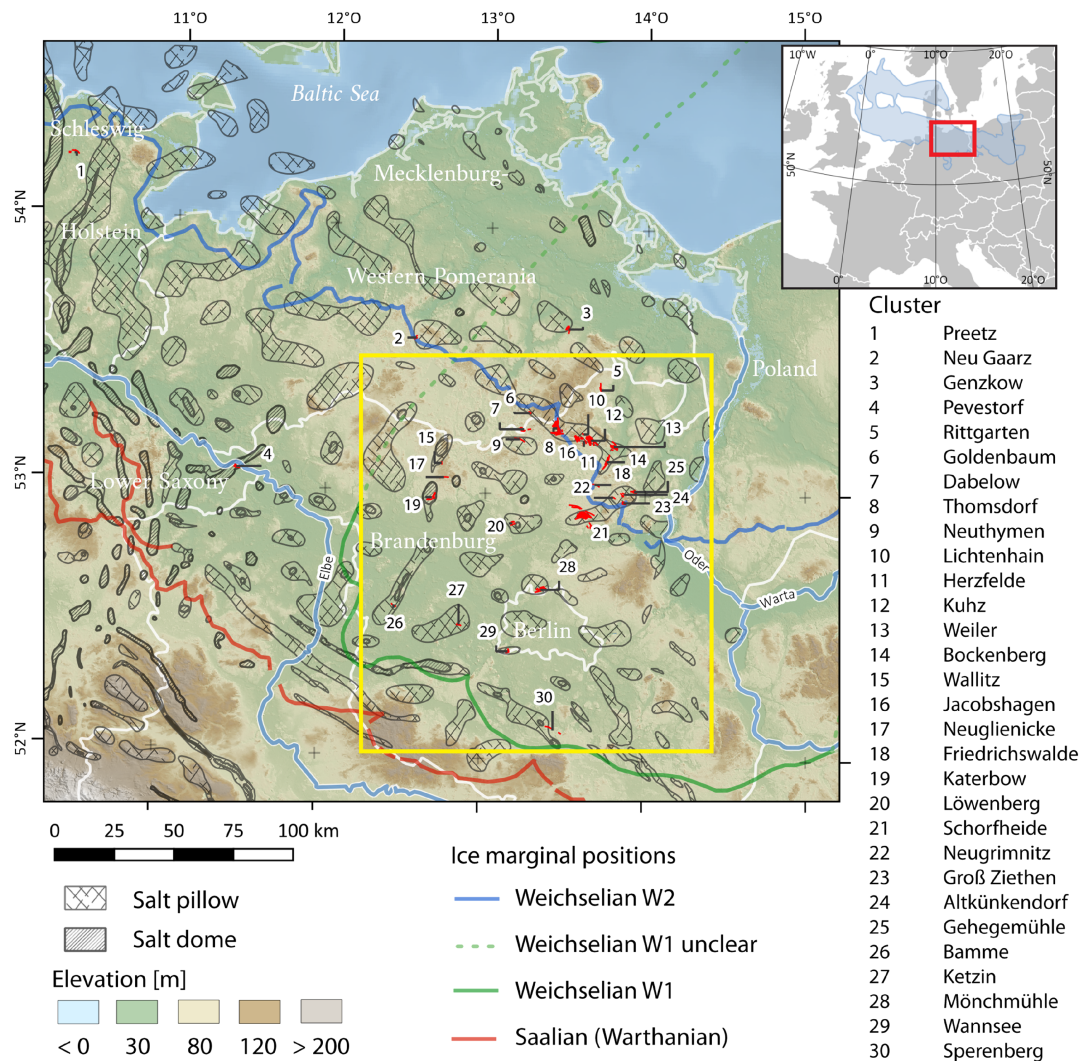


FIGURE 1 Overview map showing the distribution of salt structures and surface crack clusters (red lines, indexed by numbers) in Northeast Germany. The yellow box indicates the extent of Figure 4. Ice marginal positions of Saalian and W2 advance according to Liedtke (1981). Ice marginal position of W1 advance according to Lüthgens et al. (2020). Salt structures by InSpEE (2015), land surface by Shuttle Radar Topography Mission (Jarvis et al., 2008), bathymetry by IOWTOPO (Seifert et al., 2001). The blue area in the inset map shows the extent of the Zechstein basin (Słowakiewicz et al., 2018). Inset map based on data provided by NaturalEarth (free vector and raster map data available at naturalearthdata.com) [Color figure can be viewed at wileyonlinelibrary.com]

masses reached as far as the low mountain ranges, the ice advances of the last glacial cycle (Weichselian) were less extensive in Germany (Böse et al., 2012; Figure 1). As a result, glacial landscapes of different ages are present: the old morainic (last glaciated during the Elsterian or Saalian) and the young morainic landscapes (last glaciated during the Weichselian). During the Weichselian, at least two ice advances reached Northern Germany, with the older advance (W1, late MIS 3 to early MIS 2, c. 30 ka) reaching farther south than the younger (W2, MIS 2, c. 20 ka). Thus, the Weichselian glacial landscapes can be differentiated in an older (W1 advance) and a younger (W2 advance) young morainic area (Hardt et al., 2016; Lüthgens et al., 2011, 2020).

After the ice decayed, and also in the non-glaciated areas, periglacial climate conditions prevailed for several thousands of years in Northern Germany (Vandenberghe et al., 2014), resulting in a deeply frozen ground (permafrost). Based on paleoclimate data and numerical modelling, Grassmann et al. (2010) report that permafrost had ranged

from 100 m up to more than 300 m deep during the cold phases of the Pleistocene in the state of Schleswig-Holstein. Govaerts et al. (2016) modelled permafrost depths during the Weichselian ranging from 155 m up to 195 m for the Netherlands. When considering the influence of salt structures, subsurface salt domes may reduce the thickness of the permafrost above the structures up to 40 m according to modelling results (Sirocko et al., 2008). This can be explained by a relatively high thermal conductivity of rock salt, leading to an increased heat flow towards the surface.

The formation and transformation of dunes and aeolian cover sands was favoured in different phases of the Late Glacial and Holocene. A first sign of strong aeolian activity occurred in the study area from 15 ka onwards in geochronological records (Kappler et al., 2019). A stability phase around 12.7–11.5 ka, as indicated by the Usselow and Finow soil formation, was followed by another aeolian activity phase during the Younger Dryas (Kaiser et al., 2009; Kappler et al., 2019).

2.3 | The influence of ice sheet-induced tectonics and halotectonics on the modern surface

The morainic landscape of Northern Germany shows an underlying pattern of the three main tectonic strike directions NW–SE, NNE–SSW and NE–SW, as seen in the direction of river valleys and coastlines (Sirocko et al., 2002, 2008). Likewise, there is a correlation between deep-seated faults and the location of subglacial tunnel valleys (Dobrcki & Krzyszkowski, 1997; Stackebrandt, 2009). Additionally, ice-marginal valleys and ice-marginal positions have been observed to run parallel to major tectonic lineaments or boundaries (Reicherter et al., 2005).

As the GIA is still in progress, related processes may reactivate pre-Quaternary tectonic fault zones and thus influence Quaternary surface processes (Sirocko et al., 2008). According to Brandes et al. (2015), the ice decay after the Weichselian glaciation triggered the reactivation of Late Cretaceous reverse faults in Northern Central Europe, as seen in the spatial distribution of historic earthquake epicentres. The Late Cretaceous faults of Northern Central Europe strike in a WNW–ESE direction, which is generally parallel to the extent of the Weichselian ice margin in Northern Germany. Thus, the ice-induced stress field matches the paleostress field, leading to a relatively high reactivation potential of these faults, in contrast to faults with a different orientation to ice marginal positions (Brandes et al., 2015; Stewart et al., 2000). Similarly, Ihde et al. (1987) determined recent vertical crustal movements on the basis of relevelings in Northeast Germany and found that especially the NW–SE and NNE–SSW striking faults have been recently mobile.

In addition to ice sheet-induced tectonics, it has been recognized that halotectonic processes have an influence on Quaternary landscape development. For example, Weichselian (Schirrmeister, 1998) and Saalian (Lehné & Sirocko, 2007) ice marginal positions correlate with the distribution of subsurface salt structures (Figure 1). This phenomenon can be explained by a loading effect of the advancing ice sheet which triggers salt rise and the subsequent formation of a topographic obstacle that the ice sheet cannot pass (Lang et al., 2014; Lehné & Sirocko, 2007). Alternatively, the elevated terrain above a salt structure may form a sediment trap between the advancing ice sheet and the salt structure. The sediments accumulated in this trap would be compressed by the advancing ice, and the formation of push moraines in the vicinity of salt structures would be favoured (Sirocko et al., 2008). Wenau and Alves (2020) report that the formation of tunnel valleys in the North Sea basin are coupled to subsurface faults originating from salt walls.

The loading and unloading effects of the advancing and downwasting ice sheets have had a significant effect on the activity of the salt. The basic mechanisms behind these processes were previously described by Liszkowski (1993) and modified by Sirocko et al. (2008). Their concepts were later tested in a numerical model by Lang et al. (2014). The model results show that the load of a 300–1000 m-thick ice sheet which transgresses the structure will force the salt downwards, leading to a lateral extension of the upper sections of the diapir. After the ice vanished (unloading), the diapir will start to rise again and deform the overburden. The load of an ice sheet also influences diapirs outside the actual ice extent. The surface pressure that the ice applies on thinner salt layers forces them to flow towards diapirs not covered by the ice sheet (Lang et al., 2014).

3 | METHODOLOGY AND METHODS

During the investigation of high-resolution terrain model data of Northern Germany, the repeated occurrence of linear negative landforms that were, for the most part, previously unrecognized was discovered. A first description of these features, only for the Schorfheide region, was given by Krambach et al. (2016) but without going into detail on the formation process. The Schorfheide region served as reference area, and accordingly we concentrated on digitizing elongated, negative linear landforms (surface cracks) with a minimal depth of at least 50 cm, with a clearly distinguishable slope, which may be straight or curved, but which do not meander or display any other characteristic of fluvial landforms.

In order to further investigate the characteristics of these landforms (i.e. their basin-wide distribution and whether they represent a rare or a more common geomorphologic feature) and the possible processes involved in their formation, the following methods were applied.

3.1 | Terrain data, geological data and mapping

In Northern Germany, the federal states of Brandenburg, Mecklenburg-Western Pomerania and Schleswig-Holstein were systematically analysed in a search for geomorphic landforms that might resemble cracks. The analysis was explicitly not restricted to the vicinities of salt structures but was carried out on the whole territory of the aforementioned states. However, the available quality of terrain data differed between the federal states.

The LiDAR digital terrain model (DTM) of Brandenburg has a horizontal resolution of 1 m/pixel and is freely available as a download in .XYZ format (GeoBasis-DE/LGB, 2020). The DTM resembles the bare earth surface; the vegetation was removed by the supplier using the last pulses of the laser scan (Tarolli, 2014). The subsets were merged and resampled into geoTIFF datasets using the GDAL warp utility with a cubic resampling to 2 or 5 m. The resampled 5 m version was used for initial scanning of the whole area. If an area with suspicious landforms was found, the 2 m version of the DTM was used for detailed analysis and mapping. Outside the state of Brandenburg, preprocessed hillshade terrain data were accessed via the web map service (WMS) interfaces provided by the geoportals of Mecklenburg-Western Pomerania (<https://www.geoportal-mv.de/portal/>) and Schleswig-Holstein (https://www.gdi-sh.de/DE/GDISH/Geoportal/geoportal_node.html).

In order to reduce mapping bias that results from certain hillshade options (Smith & Clark, 2005) and other subjective properties, the results were always compared to aerial imagery. If applicable, profile tools for the validation of cross-sections and contrast enhancement on the source DTM were applied. Furthermore, the mapping was independently performed by three people. Areas of interest were mutually evaluated, and they were discarded or combined where necessary.

The distribution and properties of the salt structures (InSpEE, 2015; Pollok et al., 2015) were freely available from the geoportal of the German Federal Institute for Geosciences and Natural Resources (BGR; <http://geoviewer.bgr.de>) as a download in .SHP format. Additional data on the depth of the top Zechstein layer in

TABLE 1 Description of surface cracks in Northern Germany

No. (Figure 1)	Cluster	Salt structure	Federal state	Type	Surface cracks (no.)	Average length + std dev. (m)	Direction ^a	Geology and phase
1	Pretz (PZ)	No structure	S-H	/	5	1321 +/- 1008	SE-NW	*
2	Neu Gaarz (NGA)	Himrichshagen	M-P	pillow	2	1357 +/- 417	SW-NE	*
3	Genzkow (GK)	Brunn	M-P	pillow	7	1114 +/- 265	SSW-NNE	*
4	Pevestorf (P)	Gorleben	LS	dome	6	983 +/- 687	SE-NW	*
5	Rittgarten (RG)	Groß Schönebeck	BB	pillow	2	2883 +/- 2031	N-S	W2 gm
6	Goldenbaum (GB)	Triepkendorf	M-P	pillow	2	467 +/- 381	SW-NE	*
7	Dabelow (D)	No structure	BB/M-P	/	5	1138 +/- 452	E-W	W2 sdr
8	Thomsdorf (TD)	Triepkendorf	BB	pillow	19	1585 +/- 1411	E-W, N-S	W2 sdr, crosses W2 em
9	Neuthymen (NT)	Himmelpfort	BB	pillow	2	2567 +/- 1701	SE-W	W2 sdr
10	Lichtenhain (LH)	Klaushagen	BB	pillow	1	601	SE-NW	W2 gm
11	Herzfelde (HF)	Klaushagen	BB	pillow	5	1010 +/- 143	N-S to ESE-WNW	W2 gm
12	Kuhz (K)	Klaushagen	BB	pillow	9	2253 +/- 1065	S-NW	W2 gm
13	Weiler (W)	Flieth	BB	pillow	8	1407 +/- 793	SE-NW	W2 gm, W2 sdr
14	Bockenber (BB)	Flieth	BB	pillow	4	3227 +/- 1906	NNE-SSW	W2 gm
15	Wallitz (WA)	Zechlin	BB	pillow	1	688	N-S	W1 sdr
16	Jacobshagen (JH)	Klaushagen	BB	pillow	7	1160 +/- 666	S-NNW	W2 gm
17	Neuglicke (NEG)	Netzeband/Zühlen	BB	dome	1	3492	E-W	W1 sdr, crosses W1 em
18	Friedrichswalde (FW)	No structure	BB	/	2	1747 +/- 110	SE-W	W2 gm/sdr
19	Katerbow (KB)	Netzeband	BB	dome	6	1208 +/- 961	NE-SW to E-W	W1 sdr
20	Löwenberg (LB)	Grüneberg	BB	pillow	4	1360 +/- 436	ENE-WSW	W1 gm/gf
21	Schorfheide (SH)	Groß Schönebeck	BB	pillow	25	1509 +/- 1232	SE-W, SE-WSW	W2 sdr/W1 gf/gm
22	Neugrimnitz (NG)	Wolletz	BB	pillow	1	1509	SE-W	W2 gm
23	Groß-Ziethen (GZ)	Wolletz	BB	pillow	4	690 +/- 296	E-W	W2 gm/sdr, crosses W2 em
24	Altkünkendorf (AD)	Wolletz	BB	pillow	3	1824 +/- 1080	SE-NW	W2 gm/gf, crosses W2 em
25	Gehegemühle (GM)	Wolletz	BB	pillow	10	506 +/- 464	ESE-W	W2 e/gm, crosses W2 em
26	Bamme (BA)	Kotzen	BB	pillow	1	2000	SE-NW	W1 gf/e, WA gm, crosses W2 em
27	Ketzin (KT)	Ketzin	BB	pillow	2	1355 +/- 285	SE-W	W1 gm
28	Mönchmühle (MM)	Schönfließ	BB	pillow	10	1377 +/- 596	ENE-WSW	W1 gm/gf
29	Wannsee (WS)	Dreilinden	B	pillow	7	605 +/- 229	N-SSE	W1 gf
30	Sperenberg (SB)	Sperenberg	BB	dome	2	1918 +/- 1235	SE-W	W1 gf, crosses W1 em

Summary	
Total	141
Berlin/Brandenburg	
Lower Saxony	6
Mecklenburg-Western Pomerania	11
Schleswig-Holstein	5
N-Germany	163

Federal states: S-H = Schleswig-Holstein; M-P = Mecklenburg-Western Pomerania; LS = Lower Saxony; BB = Brandenburg; B = Berlin. Abbreviations used for geology and phase: e/em = end moraine/till plain; gf = glaciofluvial; sdr = sandar/outwash plains; WA = Saalian Warthe advance; W1 = Weichselian Brandenburg advance (late MIS 3 to early MIS 2); W2 = Weichselian Pomeranian (MIS 2, LGM) advance.

^aNote that due to the mostly curved nature of the cracks, a precise determination of their orientation is impeded. The given directions are rough estimates based on visual interpretation.

^{*}Not included in geological statistics of Figure 4.

Brandenburg was part of the dataset for the reflection seismic horizon map and was accessed through a Web Feature Service (WFS) (LBGR; <http://www.geo.brandenburg.de/ows>). Geological map data in the scale of 1:25 000 were accessed through WFS and provided by the geological survey of Brandenburg (LBGR; <http://www.geo.brandenburg.de/lbgr>).

The clusters were named after nearby villages (e.g. Bockenbergr) or landscapes (e.g. Schorfheide) and received an abbreviation (e.g. BB for Bockenbergr or SH for Schorfheide). Nearby surface cracks were subsequently grouped into clusters. The cracks received the abbreviation of the cluster followed by a sequential number (Table 1). Furthermore, for each crack and each cluster, the name of the salt structure and the type of salt structure (pillow or dome) were recorded, if applicable. The digitized lines along the cracks were used to calculate the length. A buffer of 100 m width with flat line ends was used to extract the main geological units along the cracks from the 1:25 000 geological map WFS. As it was intended to obtain an overview of the geological and stratigraphical properties of the surface in which the cracks developed, the buffer size of 100 m was chosen to account for the cracks often containing secondary infills on the central line. Secondary infills, such as water (lakes) or peat post-date the formation of the cracks, and a wider buffer reduces (but does not completely exclude) their influence on the statistics. As the raw DTM data were only available in Brandenburg, these analyses were restricted to this state.

Compilation of the data, digitization of the cracks and the production of maps was done using QGIS. The swath profiles were created using the SwathProfiler Add-In for ArcGIS (Pérez-Peña et al., 2017). The database containing all mapped surface cracks is available as a download in geopackage (*.gpkg) and KML format in the online Supporting Information for this paper (Data S1).

3.2 | Geophysical data

At two sites, we could consider 3D seismic surveys for studying the deeper subsurface. They were initially conducted for geothermal exploration and CO₂ sequestration, respectively. The first example is the Groß Schönebeck structure for the exploitation of deep geothermal energy (Bauer et al., 2020; Krawczyk et al., 2019); the second refers to the CO₂ storage pilot site Ketzin (Lüth et al., 2020).

In 2017, a 3D seismic survey was carried out in the Groß Schönebeck area (21 in Figure 1) to shed light on the geological structure and the existence of possible fault systems in the deeper subsurface. The study aimed to investigate the geological constraints of a subsequent geothermal development of the geothermal research platform Groß Schönebeck (Krawczyk et al., 2019). The 3D reflection seismic survey area extends 8 × 8 km at the surface and focuses down to reservoir depths of 4 km. Details of the seismic survey and a general evaluation are given in Krawczyk et al. (2019). Data processing was performed to interpret the 4 km-deep target zone. Nevertheless, the setting of the salt structure and of the main salt doming-related faults can be deciphered from the data.

A 3D seismic survey was acquired in 2005 for the CO₂ storage pilot site in Ketzin (27 in Figure 1). It comprises a subsurface coverage of 12 km² and was designed to image the uppermost 1000 m of the subsurface. Details of the survey are given in Juhlin et al. (2007).

Based on the survey, Yordkayhun et al. (2009a,b) conducted a study that investigated the shallow surface by applying refraction static corrections, careful muting and filtering, velocity analysis, and 3D time migration and seismic tomography to enhance the resolution and coherence of shallow seismic reflections. The results of the surveys and their interpretation are used in this study.

4 | RESULTS

4.1 | Geomorphological characteristics and spatial distribution of the surface cracks

A total of 163 surface cracks, grouped into 30 clusters, were identified in Northern Germany (Table 1). The lengths of the cracks range from c. 100 m to c. 6500 m. Their widths range from only a few metres to up to a few hundred metres. The depths of the cracks (from shoulder to bottom) range from c. 1 m to more than 20 m. Some cracks are curved; some are rather straight. Common to all cracks are the relatively steep slopes of their flanks (Figure 2).

Almost all of the detected surface cracks (93%) are located above salt structures. Those few cracks that are situated not directly above a salt structure (7%) all appear within a 7 km radius around one. Further outside the reach of salt structures, no similar landforms were detected (Figure 3).

In terms of geology, the largest population of surface cracks in Brandenburg was recorded on the till plains (>30%). Within the till plains, the landscapes of the W2 advance (c. 22%) have the greatest share, followed by the till plains of the W1 advance (c. 9%) and the

plains of the Saalian (Warthian) advance (c. 0.5%). Roughly 20% of the cracks were detected in the outwash plains of the young morainic landscape, of which c. 16% of all cracks belong to the W2 advance and c. 4% to the W1 advance. About 13% of the cracks were found in glaciofluvial deposits, almost all of which are attributed to the W1 advance. Roughly the same number of cracks were mapped in landscapes dominated by periglacial–fluvial deposits. About 4% of the cracks cut through end moraines, which mostly belong to the W2 advance. The total amount of cracks filled with peat or water accounts for c. 20% of the cracks. To our understanding, peat bogs, lakes and other Holocene deposits or landforms post-date the formation of cracks. In summary, the landforms that correlate with the W2 advance are affected the most (c. 41%) by the surface cracks, followed by the landforms that correlate with the W1 advance (c. 27%). The till plains (c. 31%) and the sandy meltwater-dominated landforms (outwash plains and glaciofluvial; together c. 33%) have an almost identical share (Figure 4, Table 1).

4.2 | Description of three selected clusters

4.2.1 | Schorfheide cluster

The Schorfheide cluster is located about 30 km north of Berlin. It is situated above a subsurface salt pillow structure near the village of Groß Schönebeck. The salt pillow is part of a larger, elongated salt structure which extends farther towards the northeast. The cluster area is observed in the foreland of the end moraines of the W2 advance. The Toruń-Eberswalde ice marginal valley (IMV) marks the

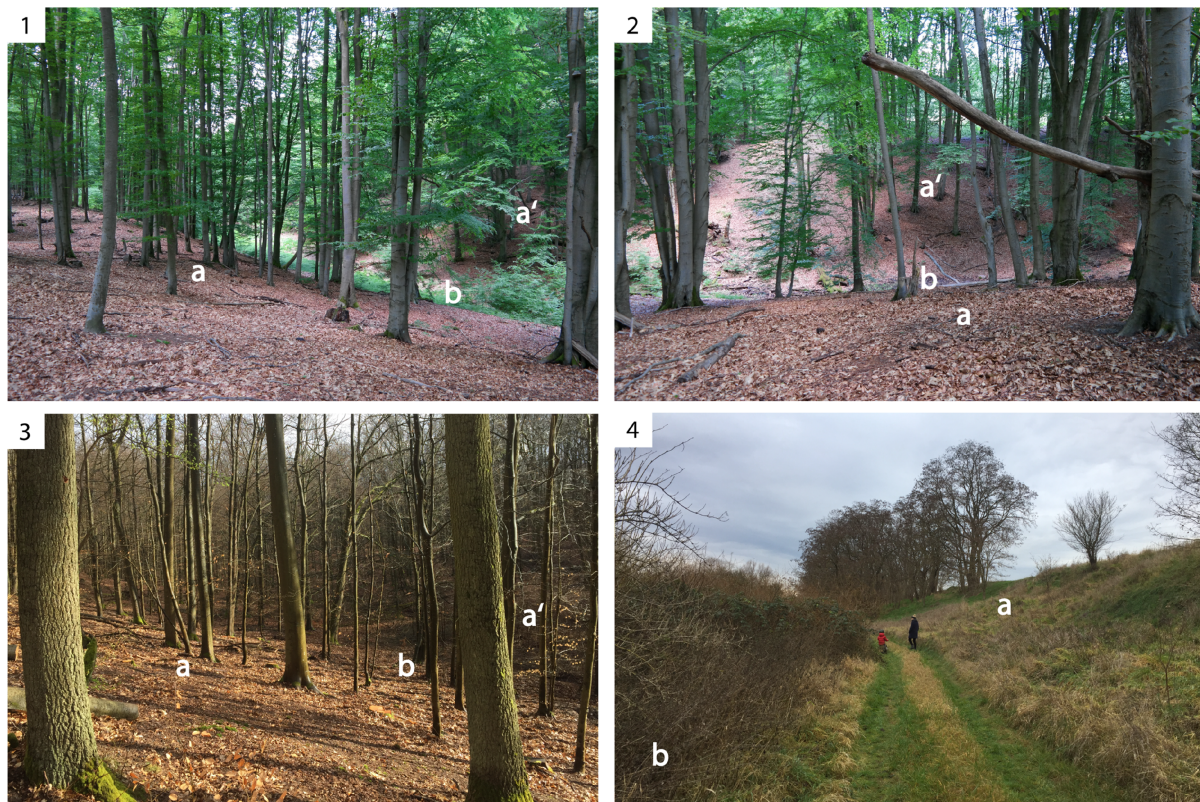


FIGURE 2 Exemplary pictures of surface cracks from the Schorfheide cluster (1–3) and Ketzin KT-1 (4): a—slope of a crack; a'—opposite slope; b—bottom of a crack. Pictures 1 and 2 taken on 4 June 2015; picture 3 taken on 13 March 2020; picture 4 taken on 20 December 2020 [Color figure can be viewed at wileyonlinelibrary.com]

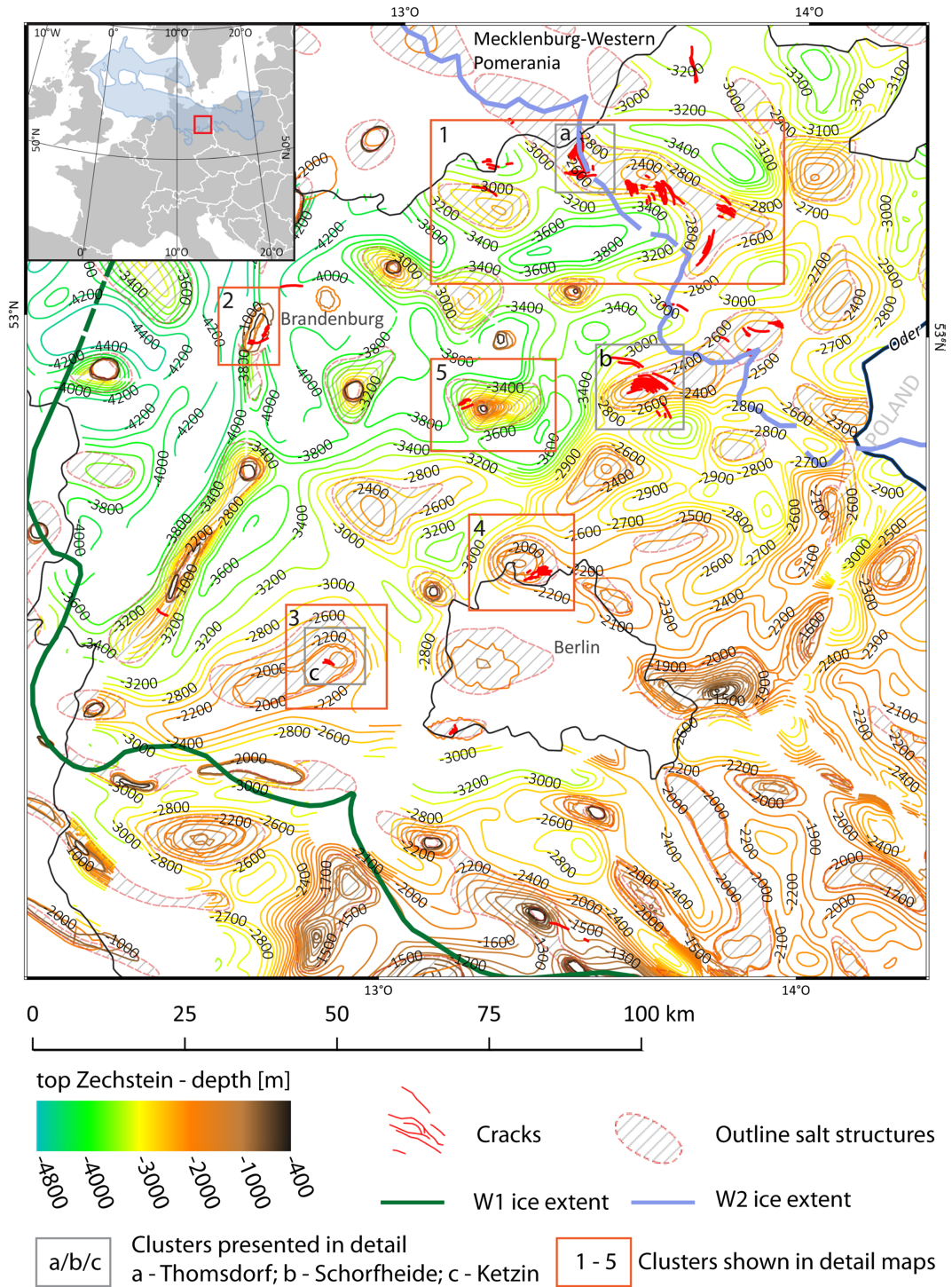


FIGURE 3 Depth of the top Zechstein in Brandenburg and distribution of surface cracks. Grey boxes indicate the extent of the three clusters presented in detail. Orange boxes indicate the extent of the detail maps seen in Figure 9. Data on Zechstein depth compiled from InSpEE (2015) and reflection seismic horizon map dataset WFS, as provided by LBGR. Blue area in inset map shows the extent of the Zechstein basin (Słowakiewicz et al., 2018). Inset map based on data provided by NaturalEarth (free vector and raster map data available at naturalearthdata.com) [Color figure can be viewed at wileyonlinelibrary.com]

southern border, while the NW-SE trending Lake Werbellinsee borders the region to the east (Figure 5A). A first brief description of these landforms in the Schorfheide region was given by Krambach et al. (2016).

Of the 24 surface cracks, almost all strike in a SE-W direction and have an arcuate, parabolic shape with the bulge facing towards the north. Occasionally the cracks cross-cut each other (Figure 5B-a). They cut through two main geological and geomorphological units: the till plains of the W1 advance and the outwash plains of the W2

advance. Their orientation is not altered by the transition into a different geological substrate (Figure 5B-b). To the northwest, late glacial dunes traverse two cracks, which are situated outside the outline of the salt pillow (Figure 5B-c). The cracks of the till plain generally cut deeper into the surface and their bottom is usually dry, while the cracks of the outwash plain are shallower, wider and form lakes or have favoured the formation of peat bogs.

Periglacial-fluvial landforms oriented towards Lake Werbellinsee and Lake Meelake are disrupted by cracks (Figure 5B-d), indicating

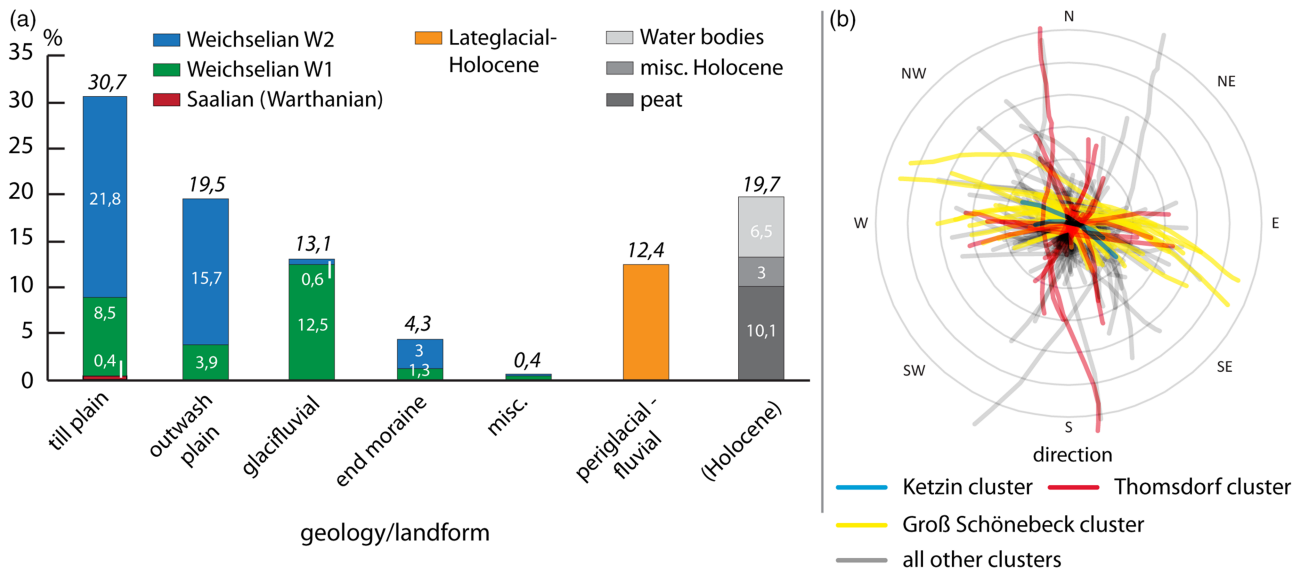


FIGURE 4 (a) Frequency distribution of all recorded surface cracks in Brandenburg in different geomorphological units, subdivided by chronostratigraphy. Note that ‘outwash plain’ and ‘glacifluvial’ are differentiated in the geological map, although both belong to the glacifluvial process regime. The term ‘outwash plains’ refers to the sandar areas, which developed in the foreland of terminal moraines. The term ‘glacifluvial’ refers to other meltwater-related deposits, found for example in subglacial or proglacial valleys, kames or eskers. (b) Orientation comparison of all recorded cracks. All features were proportionally resized, aligned and centred. The clusters selected for detailed description were coloured for identification [Color figure can be viewed at wileyonlinelibrary.com]

that discharge in these valleys occurred under periglacial conditions prior to the development of the cracks. To the south, the cracks also cut through Lake Meelake (Figure 5B–e).

In the context of geological mapping of the area in the 19th century, Berendt (1894) interpreted the cracks as fluvial valleys, suggesting discharge westwards from Lake Werbelinsee. Krumbach et al. (2016) recognized that there is no direct connection to Lake Werbellinsee, that there is a lack of corresponding alluvial fans and that the length profile does not conform with the flow direction; this is not the case regionally, and less so locally. In addition, the height differences and intersections between the cracks do not at all support the theory of a fluvial regime.

Liedtke (1956) interpreted the Großer and Kleiner Pinnowsee basins as dead-ice depressions, without discussing their prominent elongated shape. Both lakes are visibly integrated into cracks; therefore, it can be assumed that the origin of the basins is a consequence of surface ruptures.

The considered Groß Schönebeck 3D seismic survey comprises only the southernmost subregion of a larger salt structure termed ‘Groß Schönebeck-Joachimsthal-Wolletz’ that represents an elongated, pillow-shaped SW–NE oriented salt bulge (structure No. 23 in Stackebrandt & Beer, 2015). The salt structure is characterized by a smooth doming of the Zechstein salt showing a thickness from 0.6 to more than 1 km above the flat base located in about 4 km of depth (Krawczyk et al., 2019). The Mesozoic horizons above the salt show gentle undulations and normal faulting, especially at the top of the pillow structure at the top of Zechstein. The movement of salt during the Late Triassic caused the formation of synclines and highs, and it affected post-Triassic sedimentation and erosion processes. For Groß Schönebeck, the Jurassic to Cretaceous sedimentary succession shows therefore only Lower Jurassic (Northern Lias Group) sediments and early Upper Cretaceous deposits above the salt pillow, reflecting the salt doming activity. In the western central part of the seismic

cube (located at the top of the salt structure), a crestal collapse graben structure within the Zechstein is recognizable in the seismic data, which might continue westwards as a graben structure (Krawczyk et al., 2019; Figure 6A). The main faults are oriented NW–SE and NE–SW (Figure 6). Due to the lower resolution of the seismic data in the shallower subsurface (which was designed to decipher structural information for the target horizon in more than 4 km depth), the detailed behaviour of subsurface faults above the Zechstein is less distinct. Although the overall seismic reflectivity in that area is reduced, the seismic horizons seem not to be strongly affected by faults (Figure 6C and 6D) and the observed ruptures may be caused by internal Zechstein stringer deformations primarily. Notably, the orientation of the surface cracks shows a remarkable accordance with the positioning of the salt structure doming (Figure 6B).

4.2.2 | Ketzin cluster

The Ketzin cluster is situated about 20 km to the west of Berlin in central Brandenburg. The corresponding salt pillow, Roskow-Ketzin (structure No. 36 in Stackebrandt & Beer, 2015), is a c. 25 km-long SW–NE striking structure. The two surface cracks appear on a ridge of a till plain associated with the W1 phase of the Weichselian glaciation; they are curved and 1.7 (KT-1) and 1.2 (KT-2) km long. The northern crack (KT-1) is more than 9 m deep with a bog developed along its bottom line. The southern crack (KT-2) is only 1–2 m deep (Figure 7) and under agricultural use. To the east, the northern crack (KT-1) extends from the till plain into a depression with a Holocene infill (Figure 7A). To the west, both cracks end at the transition from the till plain into a fen. Holocene infill and the landfill might conceal the cracks on this side (Figure 7B).

The subsurface seismic data reveals some further information on the deeper geological structure. The Ketzin structure represents the

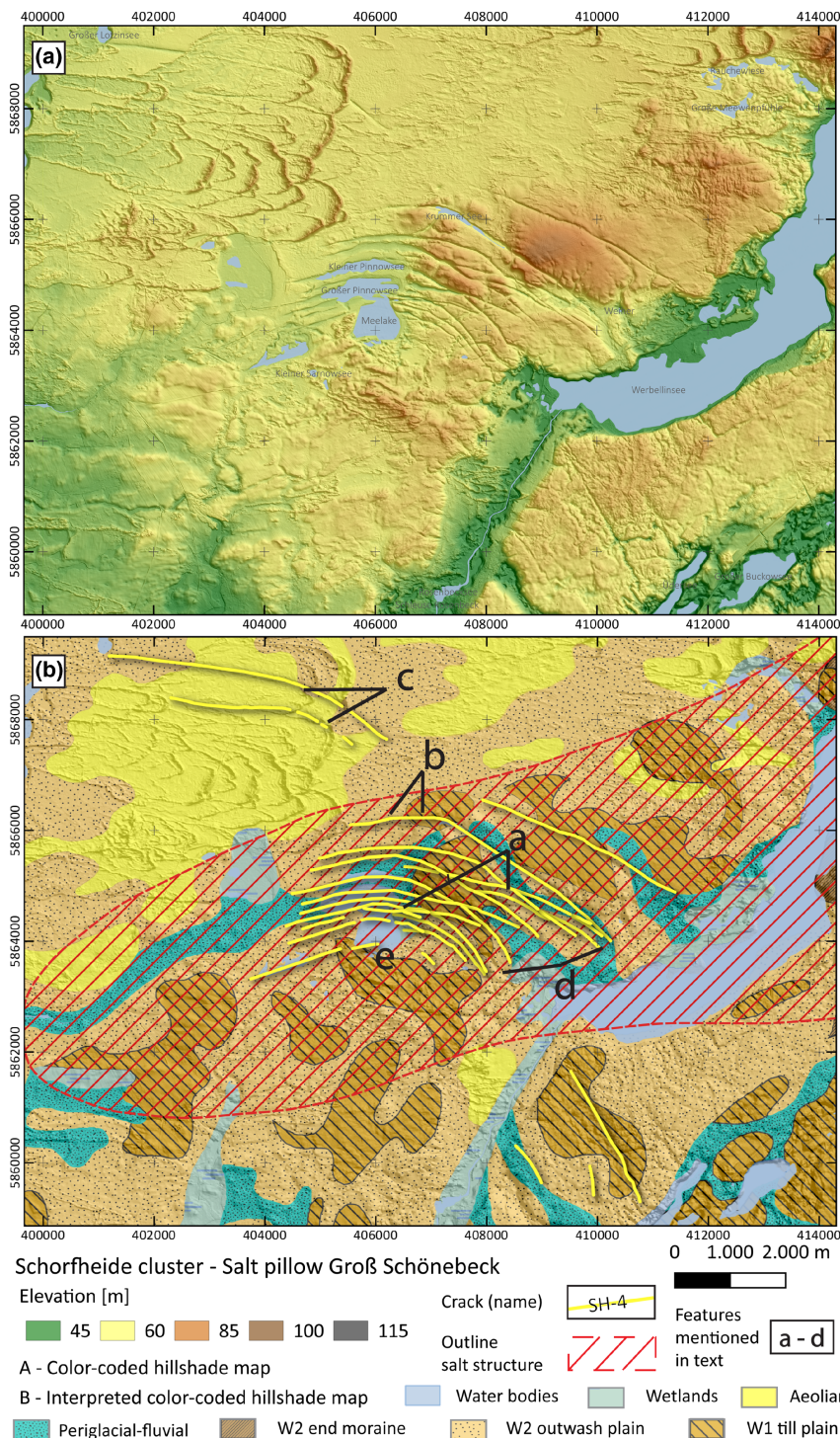


FIGURE 5 Detail map of the Schorfheide cluster. (A) Colour-coded hillshade map (6× vertical exaggeration). (b) Interpreted geological map. Features mentioned in (B): a—cross-cutting cracks; b—transition between till plain and outwash plain; c—dunes traversing cracks; d—periglacial-fluvial landforms dissected by cracks; e—cracks continue into Lake Meelake. Figure 10-1 Provides more information on the shape of the salt structure. Base map: DTM1 (GeoBasis-DE/LGB, 2020). Geology simplified after geological overview map (GeoBasis-DE/LGB/LBGR, 1997). Coordinates in UTM-WGS84 (zone 33) [Color figure can be viewed at wileyonlinelibrary.com]

eastern part of a WSW–ENE trending double salt anticlinal structure that gently dips about 15°. The Zechstein top is thereby located at a depth of about 1500–2000 m below ground level (Förster et al., 2006). The seismic survey was designed to provide a profound baseline for testing the storage of CO₂ in a saline aquifer at a depth of about 700 m. Therefore, there are no details resolved for the deeper-situated Permian salt structure in the seismic data (see Figure 8). Instead, the volume allows for a more detailed mapping of salt structure-related faults in the near surface (Figure 8). At the top of the examined Ketzin anticline, a NE–SW trending graben zone was mapped from the data, showing a fault throw of several metres. In contrast to the arcuate surface cracks in Groß Schönebeck, the

surface cracks in Ketzin are not in strong alignment with the topography of the anticlinal structure that is made visible by the deformed top of the Weser Fm (Upper Triassic; Figure 8A). Nevertheless, the surface cracks show some general similarities in terms of their spacing related to the mapped fracture zone. They are developed in close relation to the deeper mapped faults (Figures 8B, C and D), but they show a different course. The detailed information of the seismic data does not resolve how the deeper faults propagate through the Cenozoic soft rocks. From the seismic tomography (Yordkayhun et al., 2009b), the Cenozoic units could be characterized in some more detail. According to the study of Yordkayhun et al. (2009a), the faults could be traced at least into the lowermost Rupelian clay.

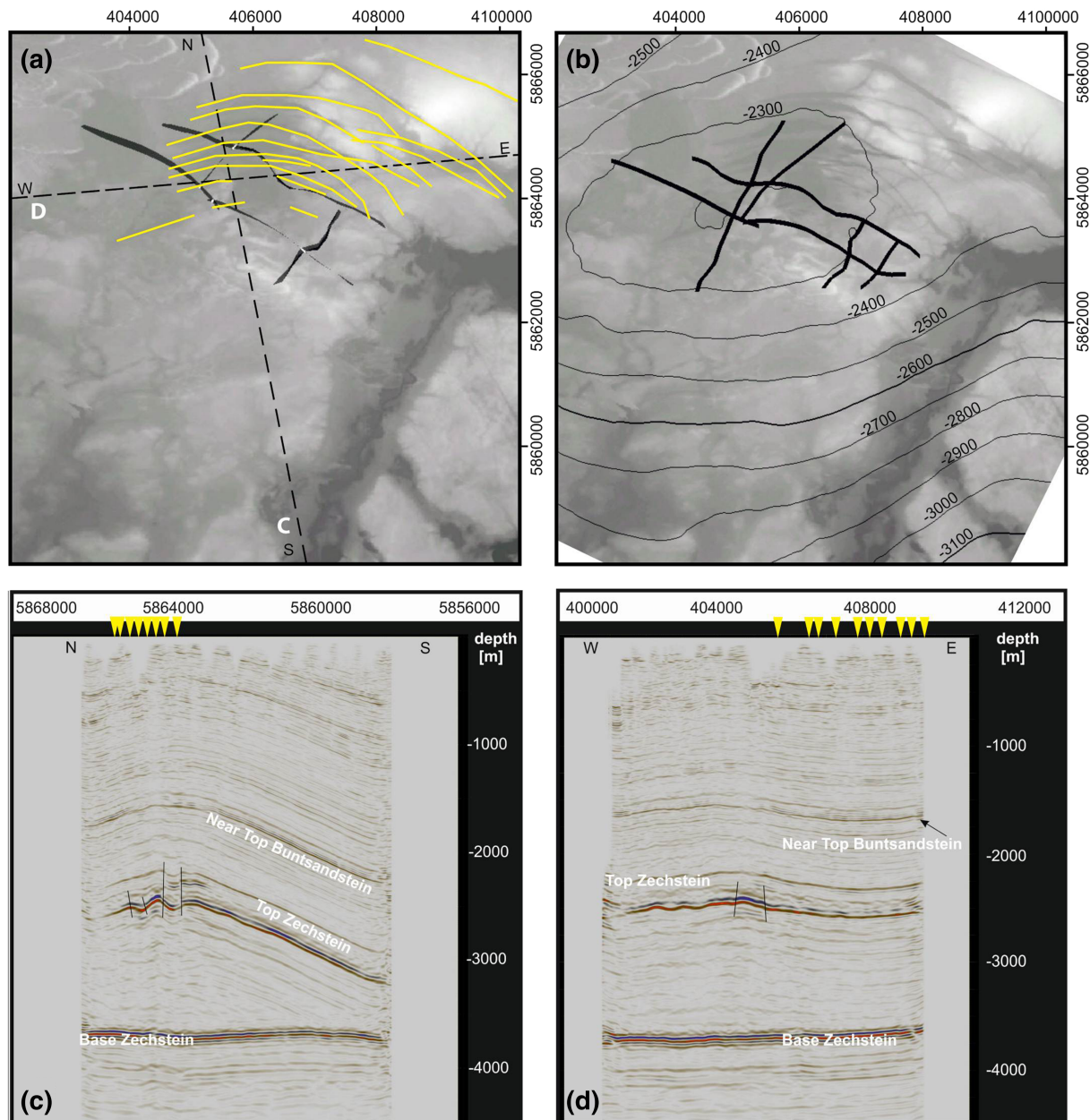


FIGURE 6 The deeper structure of the Groß Schönebeck area from seismic data. (A) Digital terrain model (GeoBasis-DE/LGB, 2020) with an extrapolation of deeper salt fractures mapped in the seismic to surface level (thick black lines). Dashed black lines show the position of the seismic profiles in (C) and (D). Yellow lines indicate the surface cracks. (B) Digital terrain model superimposed on the topography of the top Zechstein reflector and corresponding fractures, mapped in the seismic volume (contour lines with depths in metres below ground level). (C) View from west to east showing a N–S oriented seismic line and some of the picked deep fractures at the top of the Zechstein (black lines). (D) View from south to north showing a W–E oriented seismic line and some of the deeper salt-related fractures. In (C) and (D), the depth below ground level is given in metres for rough orientation and yellow triangles indicate the position of cracks. Coordinates in UTM-WGS84 (zone 33) [Color figure can be viewed at wileyonlinelibrary.com]

4.3 | Thomsdorf cluster

The Thomsdorf cluster is situated approximately 70 km north of Berlin in Northern Brandenburg. The landforms in this area are mostly associated with the W2 phase of the Weichselian glaciation. The subsurface salt structure is the 50 km-long NW–SE striking salt pillow Flieth, which is connected to several more clusters (Table 1, Figure 10-1). Altogether, 14 surface cracks were detected (Figure 9). Most of them are found in the outwash plain of the W2 ice marginal position. A special feature of the cracks in this cluster is that they show two main directions. Most of the cracks more or less follow a N–S direction, whereas four cracks to the south are aligned in an E–W direction. The terminal moraines and

the till plain of the W2 ice advance are situated to the east, which are also affected by cracks (TD-10, TD-13, TD-14). Some cracks are very long (TD-13: 6 km; TD-10 + TD-14: 3 km) and some cracks are very deep (TD-1: >19 m; TD-16: >20 m; TD-18: >25 m). As the swath profile in Figure 9 shows, the bottom of TD-1 is flat due to its infill with water. Given the very steep flanks of this crack, it probably extends several more metres into the ground. A similar situation is found at TD-16, TD-17 and TD-18. The swath profile also shows the parallel existence of cracks of different depths in the same geological substratum. While TD-1 is exceptionally deep (>19 m), it is located adjacent to the relatively shallow cracks TD-3, TD-4, TD-5 and TD-9 (1–3 m). TD-10 and TD-13 are in the transition region from the outwash plain towards the

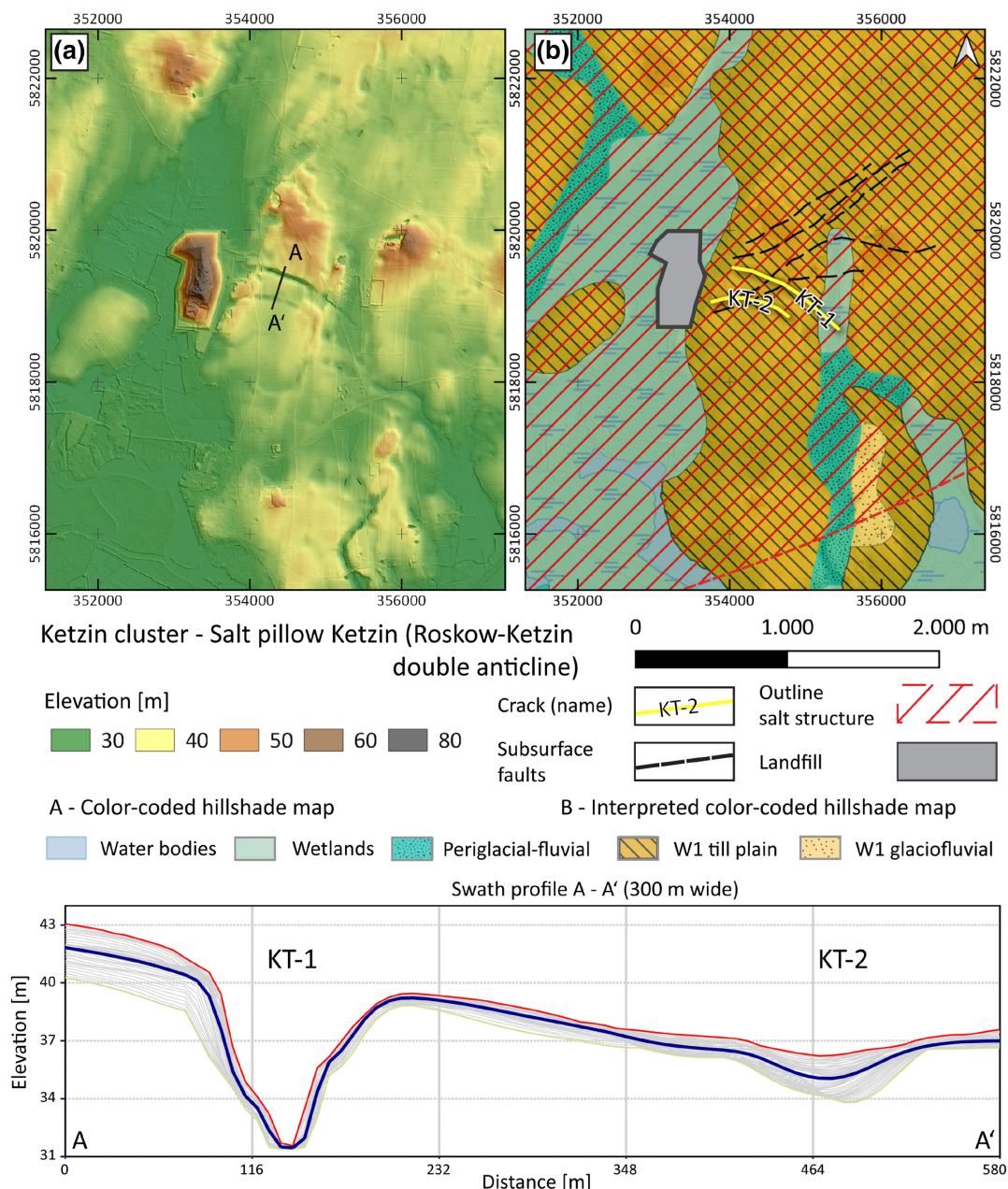


FIGURE 7 Detail map of the Ketzin cluster including swath profile. (a) Colour-coded hillshade map (6× vertical exaggeration). (b) Geological map with interpretations. Swath profile with 300 m width: red line = maximum values; blue line = mean values; green line = minimum values. Base map: DTM1 (GeoBasis-DE/LGB, 2020). Geology simplified after geological overview map (GeoBasis-DE/LGB/LBGR, 1997). Figure 10-3 provides more information on the shape of the salt structure. Coordinates in UTM-WGS84 (zone 33) [Color figure can be viewed at wileyonlinelibrary.com]

till plain. Although they occur in different substrata (TD-10: outwash plain, TD-13: till plain), they are very similar in shape and depth. In their southern sections, TD-11, TD-13 and TD-14 cut through an E-W trending depression with several connected basins. The cracks are concealed by the infill of the depression (peat, water).

5 | DISCUSSION

Can we differentiate between tectonics and halotectonics?

The complex geological history of Northern Central Europe results in geomorphic features responding to major tectonic lineaments. As

previously shown, ice-induced stress led to reactivation of some tectonic faults in the region (Brandes et al., 2015). Local, probably ice sheet-induced, halotectonic movements are therefore challenging to differentiate from large-scale tectonic processes. Brandes et al. (2013) showed that at the Elm salt pillow, the salt-induced stress vectors are dominated by local effects such as the shape of the Zechstein salt structure. They form radial vectors around the salt structure and deviate up to 90° from the tectonic paleostress fields. As WNW-ESE is a main tectonic strike direction in Northern Germany with recently mobile faults (Brandes et al., 2015; Ihde et al., 1987; Sirocko et al., 2002, 2008), and according to the results of Brandes et al. (2013), we expect to find a mixed signal of WNW-ESE to NW-SE oriented features and local features which primarily adapt to the shape of the local salt structures.

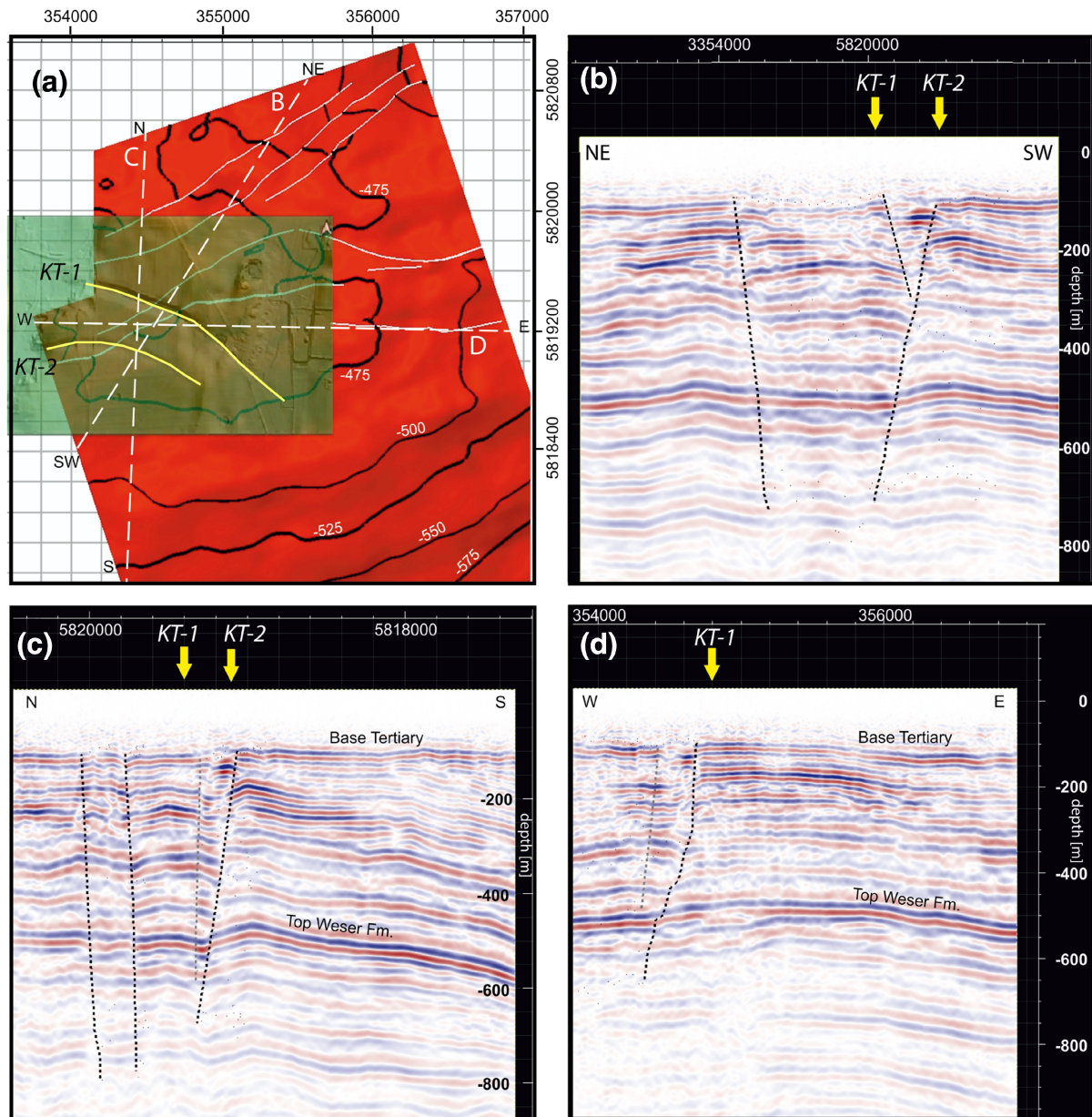


FIGURE 8 The subsurface of Ketzin as revealed from the 3D seismic data. (A) NW-SE trending graben zone (white lines) and the doming structure of the Ketzin anticline as resolved from the picked horizon top of the Triassic Weser Fm (depths in metres below ground level) superimposed as yellow lines are the observed surface cracks and hillshade model (GeoBasis-DE/LGB, 2020) of the surface (Figure 7). White dashed lines indicate the positions of the seismic profiles (B), (C) and (D). (B) NE-SW oriented seismic line and some of the picked fractures (stippled lines). (C) View of a N-S oriented seismic line and some of the picked fractures (stippled lines). (D) View of a W-E oriented seismic line and some of the picked salt-related fractures. In (B) and (C) the depth below ground level is given in metres for rough orientation. Yellow arrows in (B), (C) and (D) indicate the position of surface cracks (with respective names). Figure 9-3 Provides more information on the shape of the salt structure. Coordinates in UTM-WGS84 (zone 33) [Color figure can be viewed at wileyonlinelibrary.com]

Consequently, many surface cracks are oriented more or less in a WNW-ESE to W-E direction, while others are N-S (e.g. Thomsdorf: Figures 9, 10-1) or ENE-WSW oriented (Figures 10-4 and -5; Table 1). As the shape of the salt structures is also controlled by tectonic lineaments (Scheck-Wenderoth et al., 2008), a WNW-ESE to W-E direction is tectonically inherited, as previously shown (Kossow et al., 2000). It should be noted that many of the cracks are curved; hence, a precise determination of a strike direction is impeded. Notwithstanding this, the shape and orientation of the cracks appear to be primarily controlled by the shape of the underlying salt structure (Figure 10).

In the case of the Schorfheide cluster, where the surface of the Groß Schönebeck salt structure is displayed in 3D seismic data, the surface cracks appear mostly in the area to the north/northeast of the peak of the salt structure. The curved cracks show a tendency to adhere to the shape of the salt pillow, although it is at a depth of more than -2000 m. Similar observations were made at several other sites. In the example of the Flieth salt pillow, the Bockenbergl and Weiler clusters seem to follow the shape of the salt structure (Figure 10-1), similar to the Thomsdorf cluster (Triepkendorf salt pillow; Figure 10-1). In Katerbow, a number of surface cracks align along the southeastern edges of the Netzeband salt dome (Figure 10-2). As a

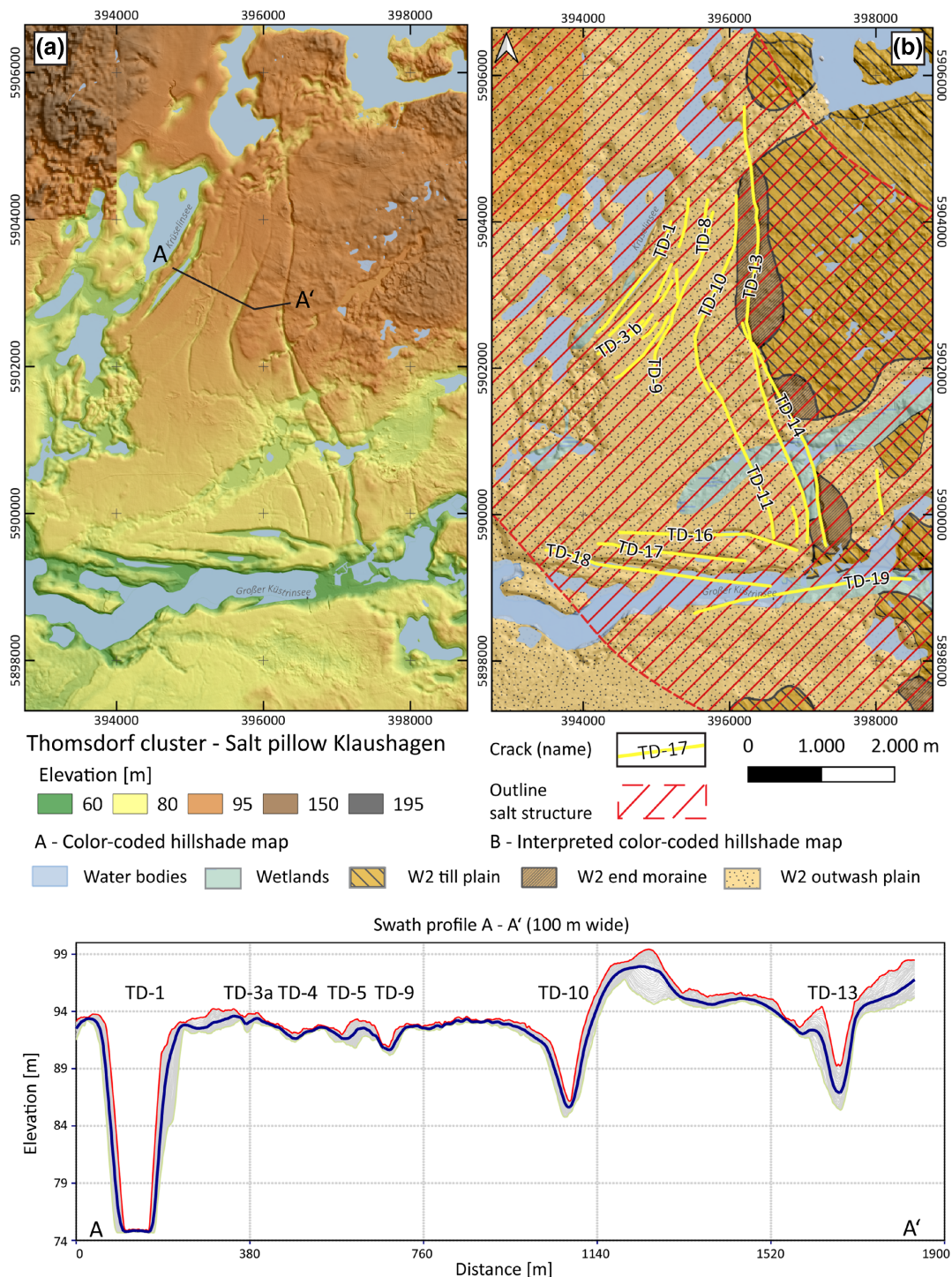


FIGURE 9 Detail map of the Thomsdorf cluster including swath profile. (a) Colour-coded hillshade map (6× vertical exaggeration). (b) Geological map with interpretations. Swath profile with 100 m width: red line = maximum values; blue line = mean values; green line = minimum values. Base map: DTM1 (GeoBasis-DE/LGB, 2020). Geology simplified according to the geological overview map (GeoBasis-DE/LGB/LBGR, 1997). Figure 10-1 provides more information on the shape of the salt structure. Coordinates in UTM-WGS84 (zone 33) [Color figure can be viewed at wileyonlinelibrary.com]

general observation, the surface cracks occur along the margins of the salt crests and not directly above the highest point of the salt structures (Figures 3 and 10). The cracks mostly occur only on one side of the structure and do not surround the structure in a radial pattern, as might be expected. However, as revealed by structural analyses of fracture patterns in the overburden around a salt wall in the Dead Sea region, radial patterns do not necessarily develop in tectonically active regions (Alsop et al., 2018). Furthermore, the occurrence of the cracks

may also be influenced by pre-existing structures and lithological variations underground.

Seismic data were analysed to investigate a possible correlation between subsurface faults or structures and the mapped surface cracks. At the Schorfheide cluster, several subsurface faults, which originate from salt movement, were detected beneath the area affected by surface cracks (Figure 6). However, the faults at depth do not propagate in the same way towards the surface and may

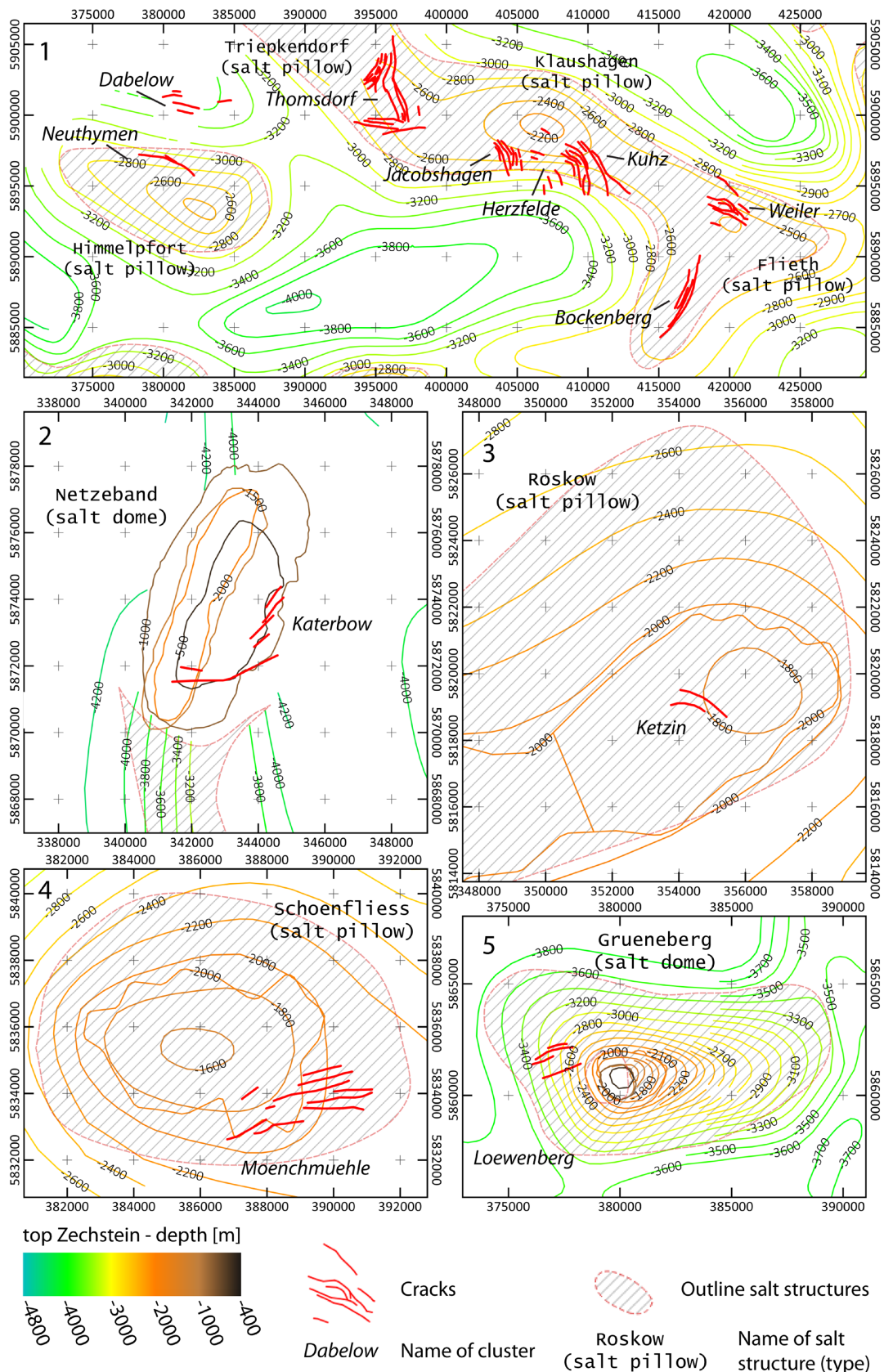


FIGURE 10 Detail maps showing the depth of the top Zechstein layer (isolines); the cracks at the surface are superimposed (red lines). Names of the clusters (italics) and corresponding salt structures (typewriter font) are given. Locations of detail maps in Brandenburg are given in Figure 3. Tick marks and coordinates as reference scale. Coordinates are given in metres (UTM 33 N). Data on the Zechstein depth compiled from InSpEE (2015); reflection seismic horizon map dataset based on the WFS provided by LBGR [Color figure can be viewed at wileyonlinelibrary.com]

reflect an internal fault pattern only within the top Zechstein unit. Furthermore, the seismic data do not reveal the uppermost 1000 m.

A clearer picture of near-surface faults could be drawn at the site of Ketzin. In close vicinity and directly beneath the cracks, several faults related to salt activity could be traced up to a depth of less than

100 m, extending at least into the Paleogene (Rupelton) sediments (Figure 8). As for almost the entire North German Basin, the Oligocene 'Rupelton' separates the usable groundwater system from the deeper saline aquifers. This 70–100 m-thick clayey aquitard may in addition represent a relevant cushion zone, acting as a kind of pressure separator between the deeper and shallower stress fields. The Rupelian clay was perhaps also more sensitive to glacial pressure effects due to its high content of clay-bound water and high plasticity, possibly forcing a decoupling in the fracture development. The faults of the Ketzin salt structure were active at least until or in the Oligocene. Based on the results of the seismic tomography of Yordkayhun et al. (2009a,b), it cannot be excluded that the faults had also perhaps been active in the Quaternary, which may support the theory that the forming of the cracks could possibly be caused by salt movement. However, in contradiction to this assumption, an open question remains as to why no further surface cracks exist at other locations in which subsurface faults were mapped (Figures 8B and C).

5.1 | Suggested formation process

According to their geomorphological characteristics, the surface cracks cannot be of a fluvial or other erosional origin (Krambach et al., 2016). If the landforms were frost cracks due to permafrost thawing, which might be favoured above salt structures due to the increased heat flow through the salt (Sirocko et al., 2008), we would expect the cracks to be more homogeneously distributed above other salt structures in the region. Additionally, we would expect to see a stronger correlation with the depth of the salt structures, as the thickness of the overburden attenuates the heat flow effect (Sirocko et al., 2008). If the surface cracks were fractures caused by differential compaction due to ice load, a process suggested for the development of the Hugin Fracture in the North Sea (Landschulze & Landschulze, 2021), we would also expect them to be more widespread in the region. Most of the cracks were detected in areas where salt rise due to ice load was proposed earlier, especially along the W2 ice marginal position (Figure 1; Lang et al., 2014; Schirrmeister, 1998) or at the salt diapir of Sperenberg (W1 ice marginal position; Figure 1; Stackebrandt, 2005).

From the high spatial correlation between surface cracks and salt structures, the presence of subsurface faults beneath the cracks and the morphological fit between the cracks and the shape of the salt structures (Figures 3, 6 and 10), we conclude that the cracks are most likely a result of ice-induced halotectonic processes.

Most possibly, these landforms represent expansion cracks of the surface which result from upward movements of salt structures caused by the loading and unloading effects of the Pleistocene inland ice sheets. The existence of permafrost exceeding depths of more than 100 m, resulting in a relatively thick rigid (frozen) surface, may have favoured the formation and preservation of the cracks and their relatively steep slopes. Most of the cracks appear in a sandy (glaciofluvial/outwash plains) or diamictic (till plain) substrate. Even cracks which run through both substrates do not show a significant shift in morphology after their transition from one to another (e.g. Schorfheide cluster; Figure 5). Sandy or diamictic substrates should react differently to surface expansion owing to their different cohesion strengths (Regmi et al., 2015). However, both substrates might react similarly if

they are frozen. Nonetheless, loose sediment can also react rigidly in non-permafrost environments, as illustrated (e.g. by earth fissures as reported from presently tectonically active regions; Zang et al., 2021). These earth fissures can develop at the surface in unconsolidated sediment under the influence of tectonism, faulting and human intervention (e.g. subsidence due to groundwater extraction; Asfaw, 1998; Peng et al., 2020). Although these fissures are smaller in width and depth than the surface cracks and are not related to halotectonics, they may serve as a modern example illustrating the interplay between subsurface processes and surface ruptures.

The loading and unloading effects of advancing and decaying ice sheets on subsurface salt structures can cause uplift in front of the ice sheet (Sirocko et al., 2008) and intrasalinic flow (Lang et al., 2014). Both effects help to explain the formation of surface cracks (Figure 11): cracks can form either outside the extent of the ice sheet cover (Figure 11b) or within the formerly glaciated area after the ice vanished (Figure 11c). In the first case, the loading effect of the ice sheet would trigger intrasalinic flow towards a salt structure outside the reach of the ice sheet. The positive mass budget of this salt structure would trigger an upward movement. As the land surface is rigid due to the existence of permafrost, the surface expansion would cause ruptures, regardless of geomorphological or sedimentological boundaries (Figure 11b). In the latter case, the ruptures of the surface would have taken place after the ice sheet decayed, but possibly still under periglacial conditions with frozen ground (Figure 11c). Here, the reversal of the salt flow after the unloading would cause an upward movement of the salt structure.

Sirocko et al. (2002) calculated a vertical displacement of the Wedehof diapir in Northwestern Germany of around 50 m since the Elsterian. At the Sperenberg cluster in southern Brandenburg (30 in Figure 1), the caprock of the salt diapir pierces the surface. The rise of this diapir during the Quaternary is attributed to loading effects of the SIS (Stackebrandt, 2005). The existence of surface cracks in Sperenberg, where salt rise during the Quaternary has been documented, supports the suggested formation process. According to their model results, which returned a maximum uplift of 4 m, Lang et al. (2014) claim that the estimated vertical displacement of the aforementioned studies is too high. However, our results may indicate that the high uplift rates, as stated by Sirocko et al. (2002) and Stackebrandt (2005), are not necessarily overestimated.

5.2 | Timing

The cracks must have formed after the respective areas were last glaciated by the Weichselian ice sheet because any pre-existing cracks must have been deformed by the advancing ice or filled with sediment in the glacial or paraglacial depositional environments. Central and parts of southern Brandenburg were last glaciated during the late MIS 3/early MIS 2 (W1 advance) and were ice-free after 30 to 25 ka onwards (Hardt et al., 2016; Lüthgens et al., 2020). Only Northern Brandenburg and regions to the north were glaciated again during the MIS 2 (W2 advance) and ice-free from c. 19–18 ka onwards (Lüthgens et al., 2011, 2020).

Surface cracks were found in the older young morainic area of the W1 advance (e.g. Sperenberg, Ketzin) as well as in the younger

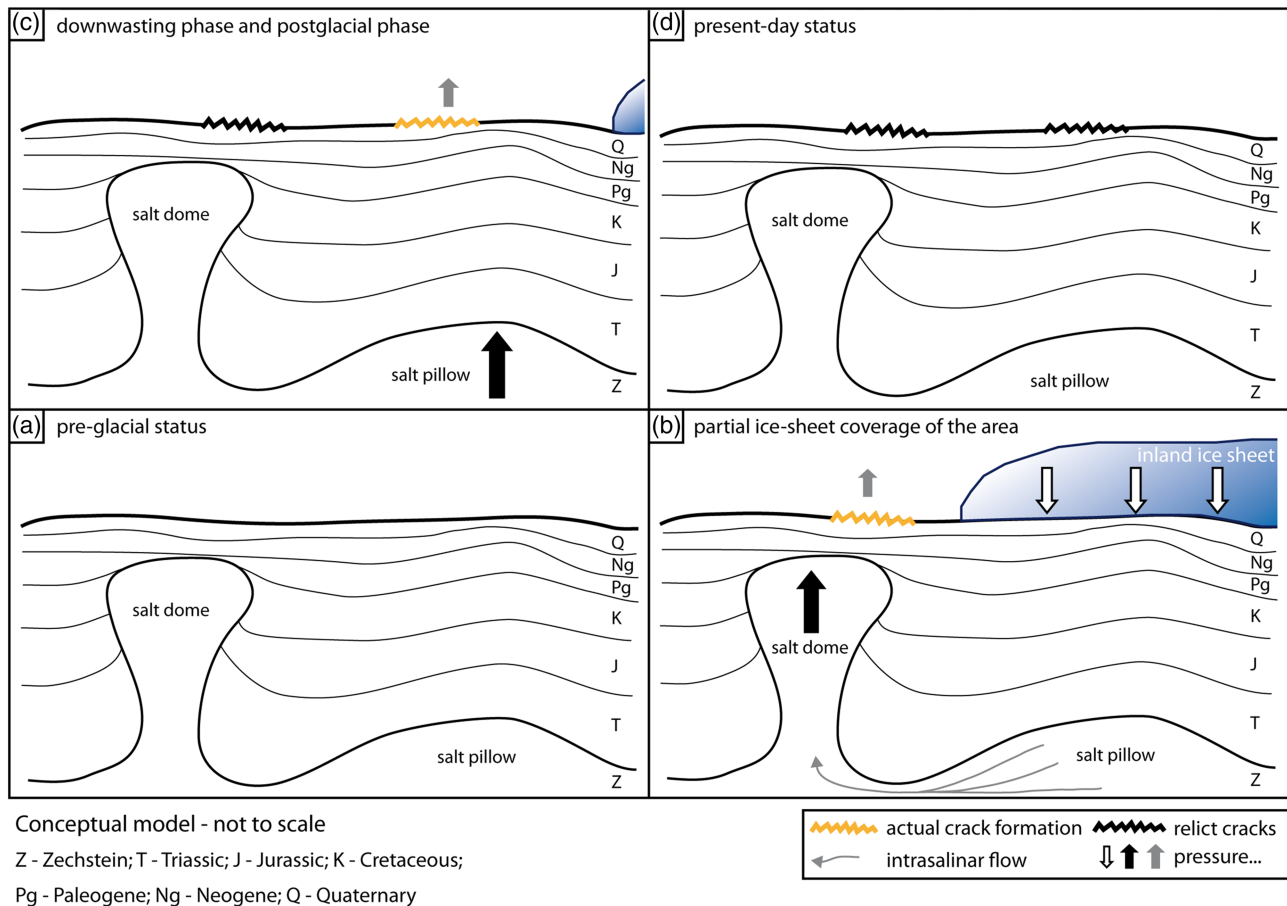


FIGURE 11 Conceptual model of surface crack formation. White arrows: downward pressure of the ice sheet. Black arrow: upward pressure of the salt structures. Grey arrows: upward movement of the surface. (a) Configuration of the subsurface salt structures prior to the ice advance. (b) An inland ice sheet advances into the region and covers part of it. Consequently, pressure is applied to the subsurface that would trigger intrasalinine flow towards regions outside the ice sheet cover where the positive mass budget would force an upward movement of a salt structure, which would eventually result in expansion of the land surface and formation of cracks. (c) The ice sheet vanishes, and subsequently the pressure on the subsurface would be released. The stress relief would cause an upward movement of the salt structure in the formerly ice-covered region, facilitated by reversal of the salt flow. The upward movement would result in the expansion of the land surface and the formation of cracks. (d) Present-day status with cracks in the land surface above salt structures which were covered by the last inland ice sheet and which were not covered by the last inland ice sheet. Sketch modified after Lang et al. (2014) and Sirocko et al. (2008) [Color figure can be viewed at wileyonlinelibrary.com]

young morainic area of the W2 advance. Thus, the cracks of Southern Brandenburg could be more than 10 ka older than those to the north of Brandenburg or in the areas of Mecklenburg-Western Pomerania and Schleswig-Holstein.

The minimum age we consider is related to the thawing of the permafrost. Most of the permafrost soils in the region had probably vanished due to the climate amelioration of the Bølling-Allerød interstadial, starting at c. 14.6 ka (Köhler et al., 2014), although patches of discontinuous permafrost may have prevailed until the Younger Dryas (Isarin, 1997) and Preboreal (early Holocene), as shown in different palaeoenvironmental studies in the wider region (Błaskiewicz, 2011; Dietze et al., 2016; Kaiser et al., 2009; Krüger et al., 2020).

Dunes were occasionally accumulated inside surface cracks (SH-1, SH-2; Figure 5). These cracks must be older than the dunes or more or less of the same age. Strong aeolian activity with dune formation in the region started at c. 15 ka and lasted, with interruptions, until the Younger Dryas (late Pleistocene; Kappler et al., 2019). Thus, the majority of cracks have most likely formed in the time span between the last deglaciation and the Bølling-Allerød interstadial.

5.3 | Relation to Weichselian ice dynamics

From the spatial distribution of the surface cracks in Northern Germany (Figure 1) and the statistics presented in Figure 4A, it becomes apparent that the majority of these landforms exist in the landscapes of the W2 advance (c. 60%), whereas significantly fewer cracks were detected in the landscapes of the W1 advance (c. 40%). In addition, the clusters with a larger number of cracks tend to be found in the W2 landscapes. Almost all cracks correlated with the W2 advance are in the vicinity of the W2 ice marginal position, whereas the other cracks are located in the hinterland of the W1 ice marginal position (Figure 1).

It might be expected that salt domes that are closer to the surface would correlate with more surface cracks, because there is less overburden acting as a potential buffer to salt movements. At the surface above the Netzeband salt dome (Katerbow cluster; Figure 10-2), which is at a depth of c. 500 m, only six relatively small cracks were found. At the salt dome Sperenberg, where the caprock pierces the surface, only two cracks were mapped (Figure 1). In contrast, by far the most cracks were detected along the salt structures of Groß

Schönebeck, Triepkendorf, Weiler and Flieth (Figure 10), which are all buried by more than 2000 m of sediment.

This phenomenon may relate to different ice dynamics of both ice advances. The W1 advance of the SIS in the study region was guided by topographic obstacles such as the horst of Bornholm or the depression of the Oder basin and had a distinct lobate form (Hardt et al., 2016; Lüthgens et al., 2020). As such, the ice thickness and the corresponding pressure on the subsurface were comparably smaller, presumably resulting in the formation of fewer cracks (e.g. Netzeband, Sperenberg). In contrast, the W2 advance occurred during the Last Glacial Maximum (LGM) when the ice sheet was presumably thicker and the ice front more uniform. Thus, the ice applied comparably more pressure on the ground and caused more intense salt movement, as indicated by the higher number of cracks occurring along the W2 terminal moraine—regardless of the depth of the salt structures. The relationship between ice thickness and intensity of salt movement is in agreement with the model results of Lang et al. (2014).

Further analyses are necessary to understand the detailed mechanisms involved in the ice-induced salt movements regarding paleostress fields and whether the surface cracks are remnants of fossil uplift processes or if the uplift processes are still ongoing. The halotectonic processes behind salt uplift and the formation of cracks at the surface require further research to understand the mechanism behind different crack patterns (single cracks, swarms of cracks, linear cracks, curved cracks). Site-based dating of the sedimentary infill of the cracks and of the surrounding sediments will provide a more detailed chronology of the involved processes. Further investigations should reveal whether the described landforms are unique to Northern Germany or whether they occur elsewhere in the CEBS or other comparable settings.

6 | CONCLUSIONS

More than 160 newly described surface cracks were mapped in the Northeast German sector of the CEBS. The cracks are up to 20 m deep, more than 10 m to some 100 m wide and can be several kilometres long. They are found in the various sediments and landforms of the glacial landscape. Our analyses reveal that these landforms occur exclusively atop or within the 7 km vicinity of a subsurface Permian salt structure and that their shape and orientation are controlled to some degree by the shape of the salt structure, whereas the thickness of the overburden seems to play only a minor role. Many of the cracks occur in areas where salt rise due to ice sheet loading has been proposed earlier, especially along the W2 (LGM) ice marginal positions in Northeast Germany or at the Sperenberg diapir (Southern Brandenburg).

While previous studies predicted ice sheet-induced halotectonic movements by numerical modelling and deduced it from geological or geomorphological observations (e.g. stratigraphic interpretations; position of fluvial valleys, tunnel valleys or end moraines), here we present landforms which can be directly associated with salt movement. We suggest that their formation was most likely triggered by upward movements of salt structures induced by the loading and unloading effects of Weichselian ice sheet advances. Accordingly, we interpret the cracks to be expansion ruptures of the surface, probably while the ground was still frozen under periglacial climate conditions

(permafrost). Although the Permian rock salt is covered with several hundred to more than one thousand metres of sedimentary rocks, it continues to influence the present-day surface topography, and the surface cracks are a visible evidence of this.

An analysis of the shape and orientation of salt structures added by 3D seismic reflection data of the Groß Schönebeck salt pillow (Schorfheide cluster) reveals geometric similarities between the surface of the salt structure and the alignment of the cracks in the present-day land surface. At Ketzin, subsurface faults in 3D seismic data can be traced close to the surface where two cracks occur.

The maximum age of the presented surface cracks is the ice decay after the last Weichselian ice advances, which is between 30 and 25 ka in Southern and Central Brandenburg and c. 20 ka in Northern Brandenburg. The minimum age is the thawing of the permafrost and the onset of intense aeolian activity in the region starting at c. 15 ka (Bølling-Allerød interstadial). Thus, in Southern Brandenburg the inferred maximum time frame for the formation of the cracks is from c. 30 to 15 ka and in Northern Brandenburg and Mecklenburg-Western Pomerania, the time frame is from c. 20 to 15 ka.

Our study is another indication that during geologically recent time spans, significant halokinetic movements of salt structures in Northern Germany occurred. Further investigations will reveal whether the described processes also occurred in other areas of the CEBS and in other comparable settings. Beyond the geomorphological imprint, and in the context of the ongoing search for radioactive waste disposals, the described processes suggest that further research is necessary to assess the long-term stability of salt structures.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

JH: conceptualization, methodology, investigation, resources, writing—initial draft, writing—reviewing and editing.

BN: resources, investigation, writing—reviewing and editing.

KB: resources, investigation, writing—reviewing and editing.

OT: methodology, investigation, writing—reviewing and editing.

JK: methodology, investigation, software, writing—reviewing and editing.

DATA AVAILABILITY STATEMENT

The database of surface cracks is available in the online Supporting Information in geopackage format for use in GIS and as a KML file for use (e.g. in Google Earth).

Except for the 3D seismic data from Groß Schönebeck and Ketzin, all other data are publicly available online:

- Laser scan data of Federal State Brandenburg: <https://data.geobasis-bb.de/geobasis/daten/dgm/>
- Preprocessed laser scan-based hillshade terrain model (WMS) of Federal State Brandenburg: https://isk.geobasis-bb.de/ows/dgm_wms
- Preprocessed laser scan-based hillshade terrain model (WMS) of Federal State Schleswig Holstein: https://www.gdi-sh.de/DE/GDISH/Geoportal/geoportal_node.html
- Preprocessed laser scan-based hillshade terrain model (WMS) of Federal State Mecklenburg-Western Pomerania: <https://www.geoportal-mv.de/portal/>
- Geological map of Federal State Brandenburg 1:25 000 (WFS): https://inspire.brandenburg.de/services/ge-core_gk25_wfs
- Geological map of Federal State Brandenburg 1:300 000 (WFS): https://inspire.brandenburg.de/services/ge-core_guek300_wfs
- Salt structures in Germany (InSPEE): <https://download.bgr.de/bgr/Geologie/inspee-INSPIRE/gml/InSpEE-INSPIRE.zip>
- Depth contours Zechstein layer Federal State Brandenburg ('X1 reflector'): http://www.geo.brandenburg.de/geoserver_2d/b3d_maps/wms

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