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PAPER

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Evaluation of deep crustal earthquakes in northern Germany – Possible tectonic causes

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Abstract
We present new evidence for seven deep crustal, intraplate earthquakes in northern Germany, a region regarded as an area of low seismicity. From 2000 to 2018, seven earthquakes with magnitudes of M_L 1.3–3.1, were detected at depths of 17.0–31.4 km. By placing the earthquake hypocentres in a geological three-dimensional model, we can correlate two of the earthquakes with the Thor Suture, a major fault zone in this area. Five of the earthquakes group in the lower crust near the Moho, which implies that parts of the lower crust and the crust/mantle boundary in northern Germany act as a structural discontinuity on which deformation localizes. Numerical simulation implies that stress changes due to glacial isostatic adjustment most likely triggered these deep crustal earthquakes.

1 | INTRODUCTION

A major challenge in seismology is to understand the controlling factors of earthquakes in intraplate settings, that is areas with low-strain rates (Johnston, 1989) and long intervals of seismic quiescence (Gangopadhyay & Talwani, 2003). Different earthquake trigger mechanisms have been discussed, such as fluid pressure variations (Costain, Bollinger, & Speer, 1987), changes in the stress state due to deglaciation (Wu & Johnston, 2000) or erosion (Calais, Freed, Van Arsdale, & Stein, 2010). However, the controlling factors of intraplate seismicity are not completely understood (Calais et al., 2010). Deep crustal earthquakes present a special challenge, because they are rare in continental interiors (Frohlich, Gan, & Herrmann, 2015), and their signals are often attenuated (Inbal, Ampuero, & Clayton, 2016).

Northern Germany is considered a low-strain intraplate region with low seismic activity (e.g. Leydecker & Kopera, 1999). Nevertheless, historical catalogues show that earthquakes took place over the last 1,200 years, with intensities up to VII (MSK) (Grünthal, Wahlström, & Strohmeyer, 2009; Leydecker, 2011). Palaeoseismology studies suggest that, in part, the decay of the Scandinavian ice sheet after the Weichselian glaciation triggered the seismicity (Brandes, Steffen, Steffen, & Wu, 2015). Some of the seismic events that affected northern Germany in the last 20 years, such as the Rotenburg (Wümme) earthquake (magnitude 4.4) in 2004, are interpreted to have been caused by hydrocarbon production (Dahm, Cesca, Hainzl, Braun, & Krüger, 2015; Dahm et al., 2007).

The aim of this study is to show that: (a) deep crustal natural earthquakes have recently occurred in northern Germany; (b) this seismicity is probably controlled by inherited structures; and (c) the earthquakes were likely triggered by stress changes due to glacial isostatic adjustment (GIA).

2 | GEOLOGICAL SETTING

The lithosphere of northern Central Europe is an assemblage of crustal blocks that were amalgamated during the Caledonian (Krawczyk et al., 2008) and Variscan Orogenies (Franke, 2000) (Figure 1a). Subsequently, the area was affected by late Palaeozoic–Mesozoic rifting (van Wees et al., 2000), during which the Central European Basin

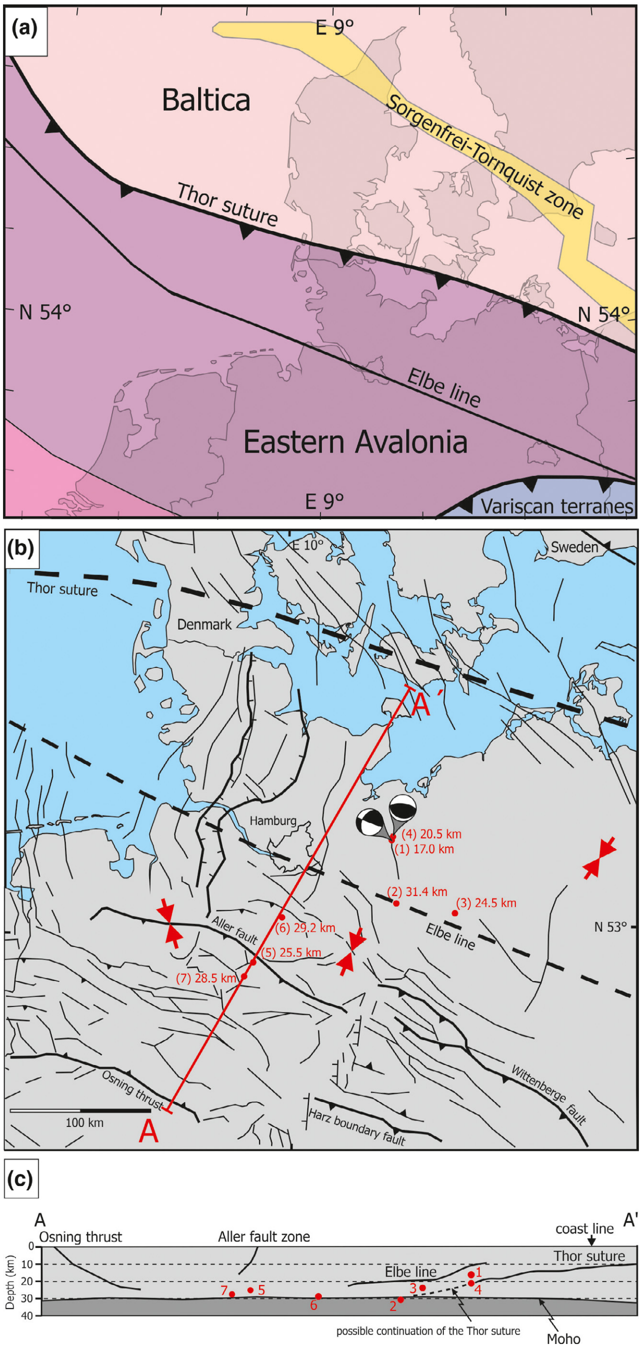

FIGURE 1 (a) Crustal structure of northern Germany and adjacent areas, based on Pharaoh et al. (2006). The Thor Suture is a fossil megathrust that represents the Ordovician–Silurian subduction of the Tornquist Sea. (b) Fault map of northern Germany, based on Kley and Voigt (2008). The fault-plane solution of event 1 is taken from Bock et al. (2002), and the focal mechanism for event 4 was determined in this study. (c) Cross-section of the study area derived from the 3D subsurface model shown in Figure 2. The dashed line shows the possible continuation of the Thor Suture based on the earthquake hypocentres. The size of the earthquake hypocentres indicates the localization error [Colour figure can be viewed at wileyonlinelibrary.com]

System (CEBS) formed (Littke, Scheck-Wenderoth, Brix, & Nelskamp, 2008). The CEBS was overprinted by late Mesozoic–early Cenozoic basin inversion (Kley & Voigt, 2008; Kockel, 2003). These tectonic phases created a fault pattern that can be subdivided into NNE–SSW- to NNW–SSE-striking normal faults and WNW-ESE striking reverse faults (Kley, 2013; Kley et al., 2008; Lohr et al., 2007) (Figure 1b). Until now, the faults have not shown recent activity, except for induced seismicity (Dahm et al., 2007).

3 | DATABASE

3.1 | Geological model

We constructed a regional three-dimensional (3D) fault model of northern Germany in the software package 3D-Move™, based on published geological cross-sections (Figure 2): (a) the DEKORP Basin 9601 line (DEKORP-Basin Research Group et al., 1999), and those of (b) Smit, Van Wees, and Cloetingh (2016) and (c) Kley et al. (2008). The nomenclature was taken from Pharaoh, Winchester, Verniers, Lassen, and Seghedi (2006). The model was constructed by placing these sections in their correct geographical position. Subsequently, the two-dimensional (2D) fault traces on the cross-sections were interpolated to create 3D fault planes. We incorporated a 3D surface of the Moho, based on Guterch et al. (2010).

3.2 | Seismological data and its evaluation

Typically, earthquake hypocentres in Germany lie in upper crustal levels (5–15 km), (https://www.bgr.bund.de/EN/Themen/Seismologie/Erdbebenauswertung_en/Kataloge_en/Kataloge_Bulletins/kataloge_bulletins_node.html). Many earthquakes in northern Germany have been classified as induced events because of their vicinity to the gas fields or the beginning of gas extraction, (e.g., Dahm et al., 2007, 2015), with hypocentres at depths of 3–6 km (Figure 3). Only some rare tectonic events have occurred (e.g., Bock, Wylegalla, Stromeyer, & Grünthal, 2002; Grünthal et al., 2008).

The seismicity in Germany and adjacent areas is investigated every day at the Seismological Central Observatory (SZO) of the Federal Institute for Geosciences and Natural Resources (BGR). Seven events, with hypocentres at depths of 17–31.4 km and magnitudes of M_L 1.3–3.1 were detected in northern Germany between 2000 and 2018 (Table 1). These events were recorded by seismic stations (Figure 4) and detected by various algorithms (e.g. STA/LTA, FK analysis and energy summation over travel time curves) that analyse the data. Subsequently, the seven detected deep crustal events underwent a detailed manual analysis. This includes iterative-linearized localization with the LocSAT algorithm (Bratt & Bache, 1988; Nagy, 1996), in combination with two distinct, one-dimensional (1D) layered velocity models (Figure 5, models A in (a) and B in (b)).

Model A is an averaged, 1D model used for events dominated by larger epicentral distances (events 1–4 in Table 1). It was derived for the routine analysis to localize events in Germany. Model B is a modification of the SED model of Dahm et al. (2007) and contains three near-surface layers of comparable low velocities that simulate the thick sediments in northern Germany. We applied this latter model to the three most recent events (events 5–7 in Table 1) that

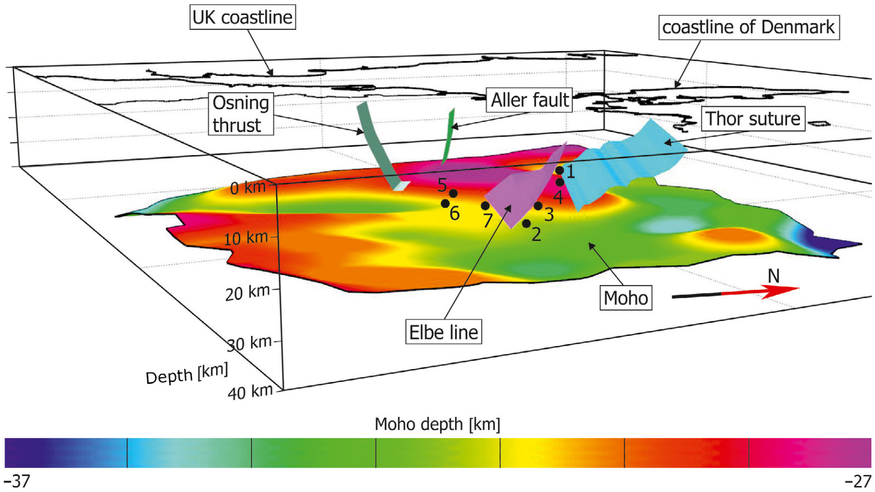

FIGURE 2 Regional 3D subsurface model of northern Germany that was constructed in the software package 3D Move™, based on three published crustal cross-sections (see Figure 1b for location): (a) the DEKORP Basin 96 line (Dekorp Basin Research Group, 1999), and those of (b) Smit et al. (2016) and (c) Kley et al. (2008). The Moho surface is based on Guterch et al. (2010) [Colour figure can be viewed at wileyonlinelibrary.com]

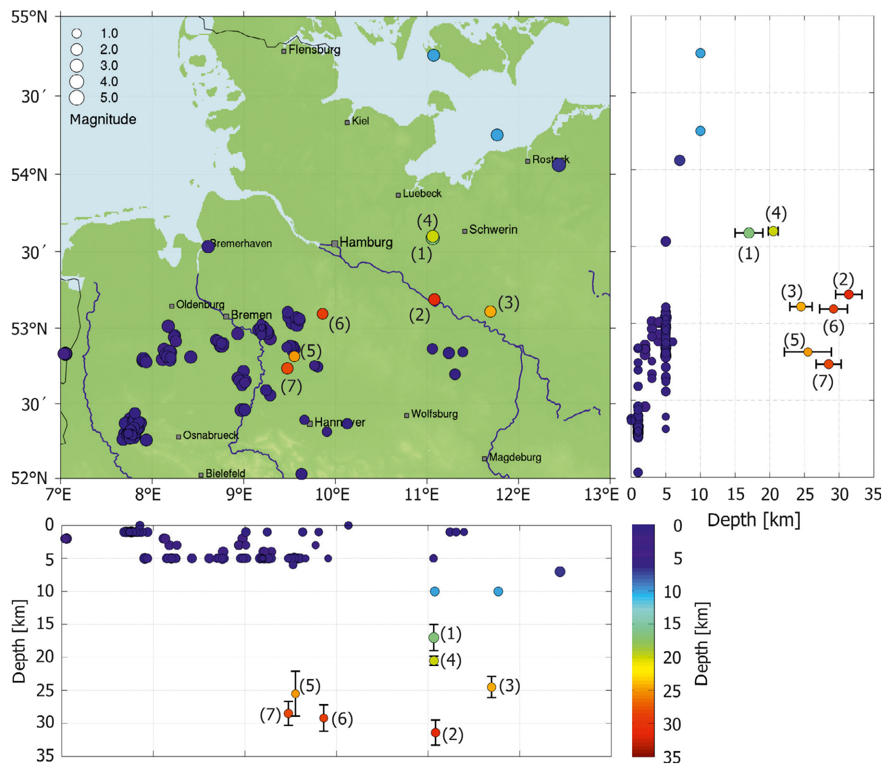

FIGURE 3 Map of seismicity in northern Germany and depth distribution. Earthquake hypocentres are colour coded by depth. The two sections show the hypocentres in E–W and N–S projections. Clearly, shallow and deep crustal earthquakes can be separated (all hypocentral parameters are from the German earthquake catalogue of the BGR. https://www.bgr.bund.de/EN/Themen/Seismologie/Erdbebenauswertung_en/Kataloge_en/Kataloge_Bulletins/kataloge_bulletins_node.html [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Source parameters of the seven deep crustal seismic events that occurred in northern Germany between 2000 and 2018. The magnitude M_L is the Richter magnitude estimated from the maximum displacement on the horizontal components of Wood–Anderson simulated seismograms. The minimum distance to the nearest station is given in the last column

			Location [° ±km]					
Event	Date	Origin time UTC	Latitude °N	Longitude °E	Depth (km)	Magnitude M_L	Phases P/S	Minimum Distance (km)
1	19.05.2000	19:22:41.9	53.588 ± 1.0	11.062 ± 1.4	17.0 ± 2.0	3.1	27/17	58
2	16.03.2012	20:47:11.7	53.188 ± 1.9	11.081 ± 3.8	31.4 ± 1.9	2.0	22/8	20.1
3	09.08.2012	22:53:04.7	53.109 ± 2.6	11.693 ± 3.2	24.5 ± 1.6	1.9	23/14	19.3
4	20.07.2014	22:34:15.1	53.600 ± 1.6	11.063 ± 1.4	20.5 ± 0.7	2.2	26/27	11.0
5	02.11.2014	11:34:48.7	52.814 ± 2.3	9.552 ± 1.6	25.5 ± 3.4	1.3	20/38	5.9
6	01.06.2018	04:51:46.9	53.094 ± 1.6	9.860 ± 1.7	29.2 ± 2.0	1.6	18/28	9.6
7	02.08.2018	21:11:30.1	52.735 ± 1.6	9.475 ± 2.6	28.5 ± 1.8	2.0	42/28	8.7

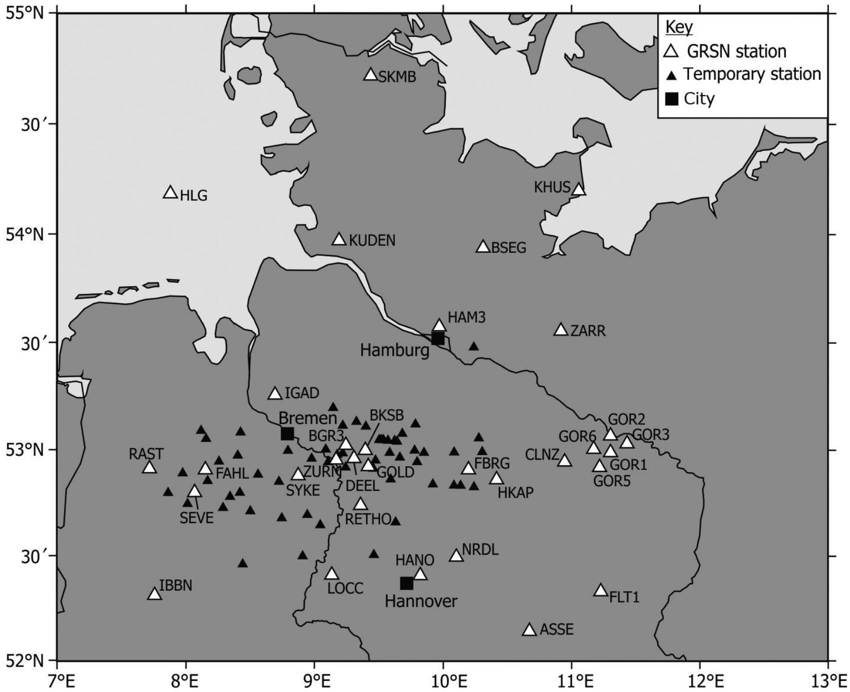

FIGURE 4 Location of seismic stations used in this study. Stations marked by white triangles are part of the German Regional Seismic Network (GRSN) or associated stations with a real-time data transmission and high quality standards. They were available for a longer period (first stations since 1991) and were used for the detection process. The remaining stations (black triangles) are part of temporary projects since 2012 (e.g. Bischoff, Bönnemann, Fritz, Gestermann, & Plenefisch, 2013) or part of industrial monitoring projects (since 2012)

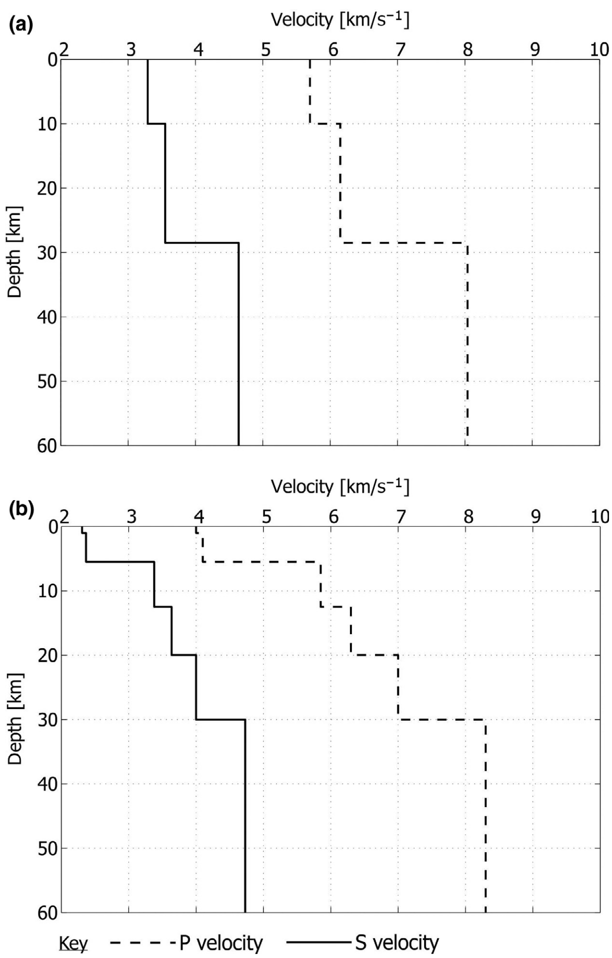

FIGURE 5 One-dimensional P-wave and S-wave velocity models shown by dashed and solid lines, respectively, which were used for the localization process (for further explanation, see text)

were detected by stations at smaller epicentral distances. Record sections are exemplarily shown for events 3 and 4 in Figure 6.

The reliability of source depth estimations of seismic events depends on the number of seismic stations and azimuthal distribution near the source location. For most of the deep events, the number of stations is low. Consequently, the calculated source depths exhibit large confidence regions. However, three lines of evidence advocate the inferred depths.

Firstly, the hypocentres, as calculated from P and S onsets, reveal a clear absolute minimum in the time residuals down to Moho depth (27–37 km, in this area) for each event (Figure 7). This is supported by small crossover distances (ca. 40–80 km) of Pn over Pg or Sn over Sg (Figure 8). Secondly, the Pn phase is visible for considerably larger distances than for events in the upper crust, an observation we explain by the lack of a downgoing ray path of the Pn in the upper crust, which then would be affected by stronger upper crustal attenuation. This is shown for events 3 and 4, where energetic Pn onsets occur over a range greater than 300 km, which is untypical for small magnitude (ca. 2.0 M_L) events located in the upper crust (Figures 6 and 8). Thirdly, the apparent velocities of Pg and Sg are higher than for the case of shallow events; for example, for the two events shown in Figure 8, Pg is between 6.3 and 7.1 km/s, which is indicative of at least partial propagation in the lower crust.

For event 4, we were able to calculate a focal mechanism; in addition, a focal mechanism for event 1 was taken from Bock et al. (2002); (see Figure 1b). Our focal mechanism is calculated with the FOCMEC program (cf. Snoke, 2003; Snoke, Munsey, Teague, & Bollinger, 1984), based on P polarities and corresponds to an E-W striking reverse fault. For the other events, we were not able to calculate reliable focal mechanism solutions, because the station-event geometry was limited and the polarities of the more distant Pn phases were not unequivocal.

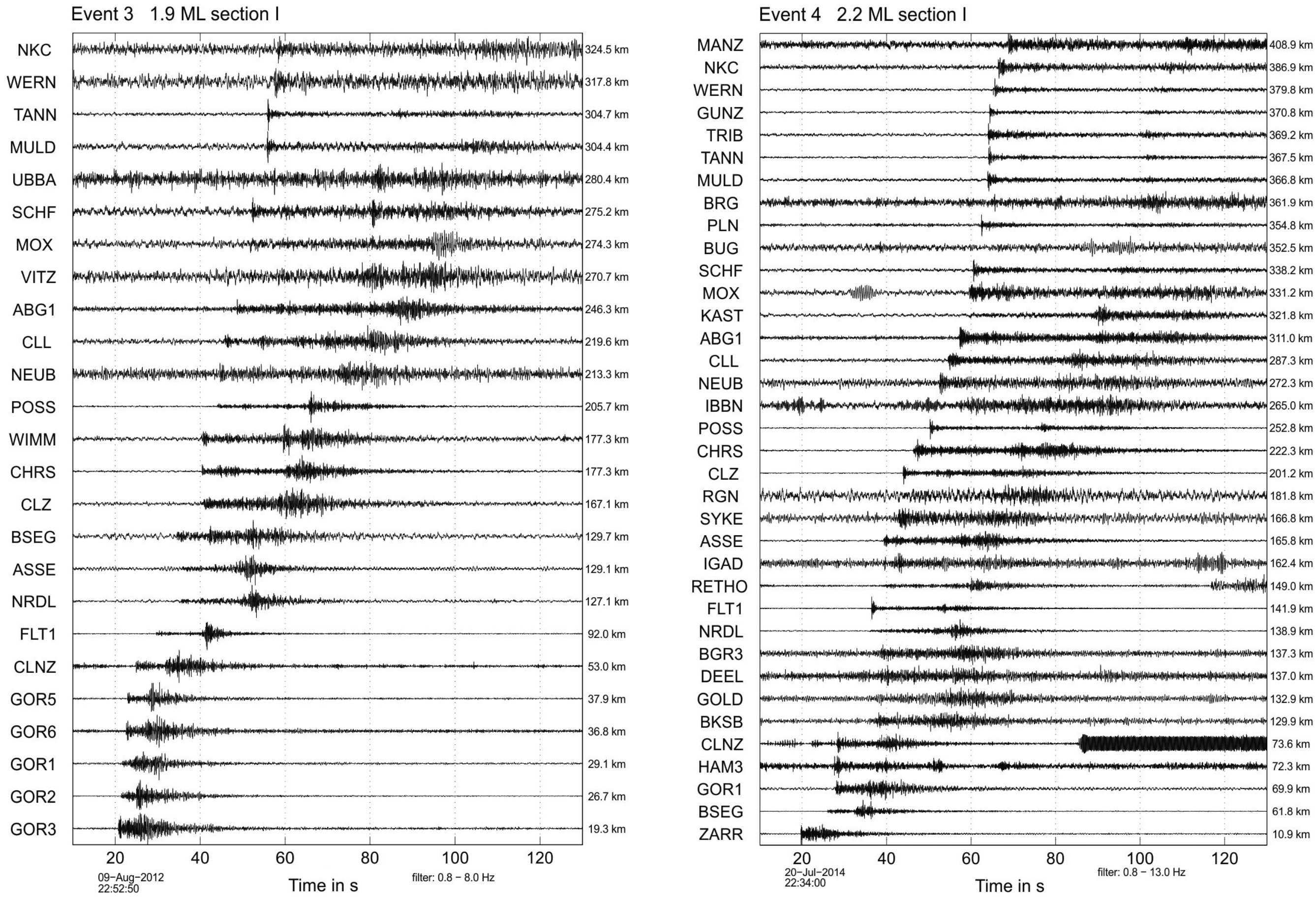

FIGURE 6 Seismic record section for events 3 (a) and 4 (b) showing vertical components of distinct seismic stations in an epicentral distance range from 19 to 325 km for event 3 and from 11 to 409 km for event 4 (in equidistant arrangement for better visualization). Note the energetic Pn onsets clearly visible at distances above 200 km, which are untypical for an event with a small magnitude of 1.9 M_L. Most of the stations, indicated by the abbreviations on the *y*-axis, belong to the German Regional Seismic Network (GRSN) and the seismic networks of the federal states of Saxony and Thuringia. Stations GOR1 to GOR6 belong to the Gorleben network and NKC belongs to the Czech Regional Seismological Network (CRSN)

4 | DISCUSSION

4.1 | Controlling factors for the localization of the deep earthquakes

Events 2 and 4 are located on the Thor Suture. Events 1 and 3 are located between the Elbe Line and the Thor Suture (Figure 1b, c). Both features are first-order structural elements. The Elbe Line is a crustal boundary (Bayer et al., 1999) that is characterized by a substantial drop in P-wave velocity (e.g. Scheck et al., 2002). It is interpreted as an intra-Avalonian structure (Krawczyk et al., 2008), or as strike-slip fault that defines the northeastern extent of eastern Avalonia and the southwestern margin of the Baltic shield (Tanner & Meissner, 1996). The Thor Suture originated from the southward subduction of the Tornquist Sea in Ordovician–Silurian times (Torsvik & Rehnström, 2003). The fault-plane solution of event 4 is a WNW-ESE trending thrust (Figure 1b). Because the hypocentre of event 4 is situated at the Thor Suture as well, this suggests neotectonic reactivation of major thrusts in northern Germany. Our data may indicate that the Thor Suture reaches deeper and potentially soles out on the Moho (Figure 1c). This remains speculative with the small dataset. The presence and location of these deep crustal earthquakes show that seismicity in northern Central Europe is controlled by the inherited structural grain of the lithosphere and underlines the idea of Sykes (1978) and Talwani and Rajendran (1991) that earthquakes in intraplate regions concentrate along reactivated zones of weakness.

4.2 | The deep crustal intraplate earthquakes of northern Germany in the global context

Deep crustal earthquakes in intraplate settings outside of orogens are either related to rifts (Camelbeeck & Iranga, 1996; Doser & Yarwood, 1994), transform faults (Inbal et al., 2016) or stress concentrations along lower crustal intrusions (Rao, Tsukuda, Kosuga, Bhatia, & Suresh, 2002). They are important, as they provide information about the rheology and strength of the crust and the upper mantle (Frohlich et al., 2015). The depth distribution of earthquakes in the continental crust is controlled by the lithology, strain rate, temperature and stress levels on faults (Wong & Chapman, 1990). Continental lithospheric strength profiles are still under debate (Cloetingh & Burov, 1996; Ranalli &

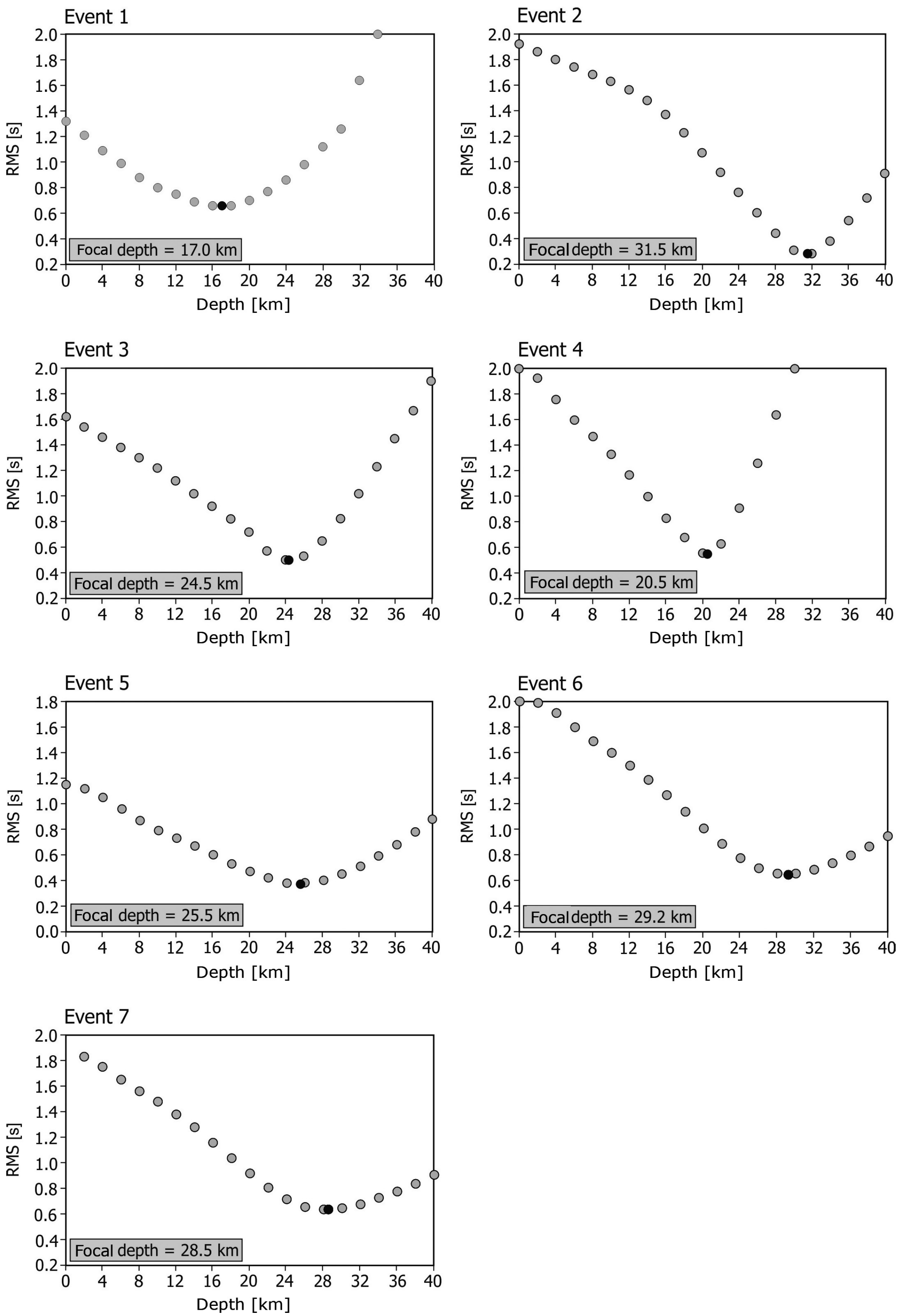

FIGURE 7 The root mean square error (RMS) between observed onset times and theoretical onsets from the calculated model for various fixed source depths. The RMS minimum defines the most likely source depth

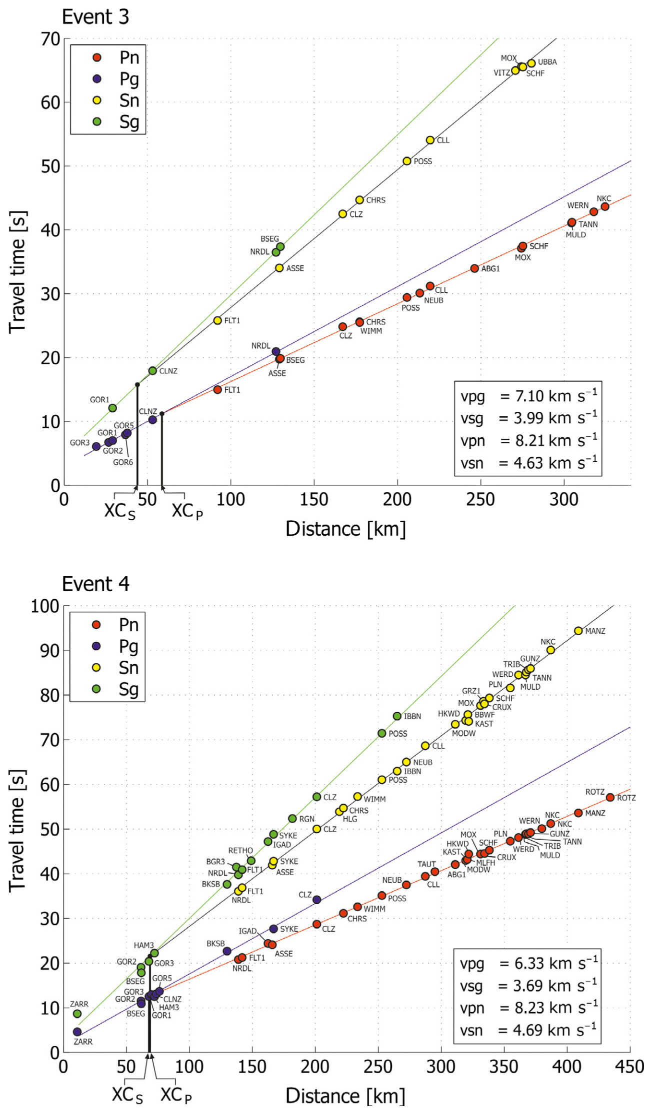

FIGURE 8 Travel time curves for events 3 (a) and 4 (b). The small crossover distances for S-phases (XSc) and P-phases (XPc) are clear indication of a deep source in the lower crust [Colour figure can be viewed at wileyonlinelibrary.com]

Murphy, 1987) and whether the lower crust or upper mantle is stronger has not yet been resolved ("jelly sandwich model" vs. "seismogenic crust only" model, see Afonso & Ranalli, 2004).

The presented deep crustal events in northern Germany, especially those with focal depths around 30 km, are not typical of most other seismically active areas in Germany and Central Europe, with exception of the Lake Constance and the Swiss border region. There, deep crustal events at depths of around 30 km, close to Moho, are observed and are interpreted as related to the southward subduction beneath the Central Alps (e.g., Deichmann et al., 2000).

Five of the deep earthquakes presented here are located near the base of the lower crust (Figure 1c) and indicate that rupture processes are possible at this depth and the latter model may be applicable to northern Germany. Chen and Molnar (1983) propose that subcrustal earthquakes in intraplate settings indicate a low-strength zone in the lower crust that allows the detachment of basement nappes from the underlying mantle lithosphere. The lower crust in northeast Germany is characterized by a layer with high seismic velocity (6.8–7.1 km/s) at depths of 20–30 km (Bayer et al., 1999). Marotta, Bayer, and Thybo (2000) suggest decoupling of the crust and mantle in northern Germany is possible. From the Alpine, Pyrenees and Taiwan orogenic foreland areas, mid-crustal detachments have been described that occur at the brittle–ductile transition, accommodating basin inversion (Lacombe & Mouthereau, 2002). These deep crustal earthquakes, together with faults that reach depths of 20 km and more (Tanner & Krawczyk, 2017), underline the possibility of a comparable deep tectonic detachment in northern Germany that might be located near the base of the lower crust.

4.3 | Trigger mechanisms for the deep crustal earthquakes

A common view is that intraplate earthquakes are the result of far-field stresses derived from plate boundaries (Talwani, 2017). In northern Germany, these are the Atlantic ridge push and the ongoing Alpine Orogeny (Reicherter, Kaiser, & Stackebrandt, 2005). Nevertheless, the mechanism that activates and deactivates faults in intraplate settings remains unclear (Stein, 2007).

Induced seismicity due to gas production can be excluded because only one of the earthquakes is located in an area with active hydrocarbon extraction and its estimated hypocentre is located five times deeper than the reservoir horizons (Figure 3). We rule out erosion effects because the young tectonic activity is concentrated on certain reverse faults (Brandes et al., 2015); other faults were not reactivated.

A potential trigger of these events is stress change due to GIA. Numerical simulations are able to quantify the interplay of glaciation-induced stress changes and fault activity (Hampel, 2017; Hampel & Hetzel, 2006; Hampel et al., 2009; Hampel et al., 2010; Hetzel & Hampel, 2005; Steffen, Steffen, Wu, & Eaton, 2014c; Steffen, Wu, Steffen, & Eaton, 2014a,b; Turpeinen, Hampel, Karow, & Maniatis, 2008; Wu, 1997, 1998; Wu & Hasegawa, 1996a,b; Wu & Johnston, 2000). Modelling results of Grollimund and Zoback (2001) and Hampel et al. (2009) imply that post-glacial tectonic activity is even possible in areas outside former ice sheets, for example northern Germany. Brandes et al. (2012, 2015) showed that Lateglacial seismicity and the historic earthquakes in northern Central Europe were triggered by stress changes related to GIA. They also showed that recent tectonic activity is possible on thrust faults along which the GIA stress has not been yet released. Therefore, GIA is one of the most likely triggers for deep crustal earthquakes.

We use GIA models, based on the technique described in Wu (2004) and Steffen, Kaufmann, and Wu (2006), to test the reactivation potential along the faults where the deep earthquakes occurred. Figure 9 shows the change in Coulomb failure stress (δCFS), over the last 26 ka, for the locations of the seven deep earthquakes, for reverse fault, strike-slip fault and normal fault regimes. We show results of three different rheological profiles (Figure 9) to give the reader a feeling for potential modelling uncertainty due to many input parameters

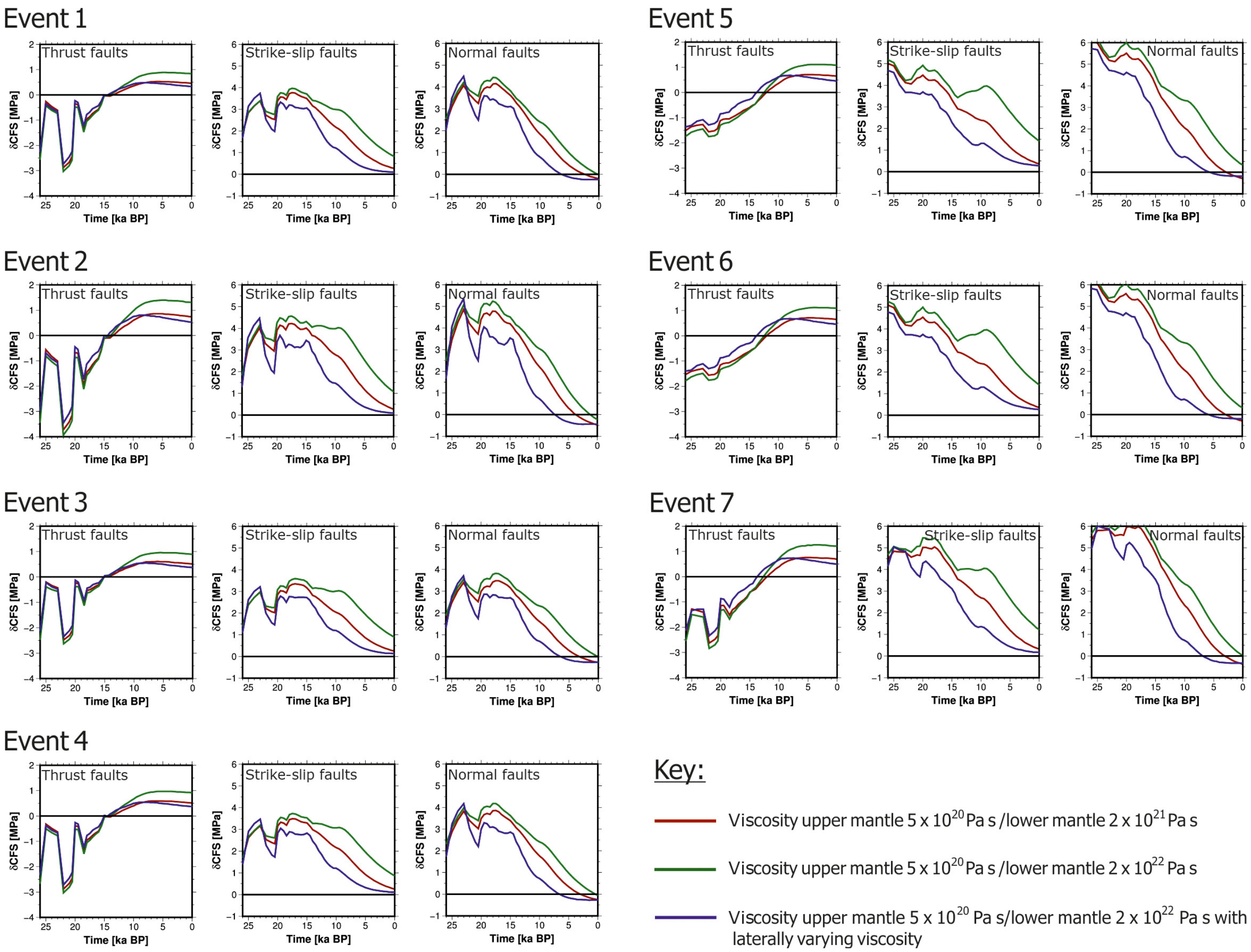

FIGURE 9 Results of the numerical simulations of GIA-related stress changes. The δCFS change over time is shown for the last 26 ka at the locations of the seven events, for reverse faults, strike-slip faults and normal faults. ICE-6G_C (Peltier, Argus, & Drummond, 2015) is used as an ice load history model. The red, green and blue curves represent three different rheology models: red has a 90-km thick lithosphere and viscosities of 5×10^{20} Pa s and 2×10^{21} Pa s in the upper and lower mantle, respectively; green is the same as red, but with a higher viscosity of 2×10^{22} Pa s in the lower mantle; blue keeps the lithospheric thickness as above, but has a laterally varying viscosity distribution in the upper and lower mantle based on Grand, Van Der Hilst, and Widiyantoro's (1997) seismic tomography model (see Kierulf et al. (2014) for details). A detailed model description can be found in Brandes, Steffen, Sandersen, Wu, and Winsemann (2018). Around 15 ka, the δCFS became positive for reverse/thrust faults at the locations of events 1–4 and would therefore allow fault slip along optimally oriented reverse faults. For events 5–7, the δCFS became positive later, at around 13–11 ka, which might be the effect of their greater distance to the former ice margin [Colour figure can be viewed at wileyonlinelibrary.com]

that affect the Earth's behaviour. The δCFS for strike-slip faults was positive over the last 26 ka and thus these faults were potentially instable. For normal faults, δCFS was positive before 7 ka and therefore these faults became stable during the last 7 ka. Around 15 ka, the δCFS became positive for reverse/thrust faults at the locations of events 1–4 and would consequently allow fault slip along suitably oriented reverse faults, such as the Thor Suture. This result is supported by the fault-plane solution of event 4 that has evidence of a thrust mechanism. This implies that GIA not only potentially triggered the Lateglacial and historic earthquakes, but it also triggered parts of the recent seismicity in northern Germany (see also Brandes et al., 2015).

5 | CONCLUSIONS

Over the last 18 years, seven earthquakes with magnitudes of M_L 1.3–3.1 were detected at depths of 17.0–31.4 km in northern Germany. We consider that the inherited lithosphere structure is the first-order controlling factor of the distribution of these deep crustal earthquakes and show that the major faults of the Thor Suture are under reactivation. Numerical simulation suggests that the trigger can potentially be stress change due to GIA. The modelling results imply that earthquakes are possible along optimally oriented reverse faults, if the GIA stress has not yet been released.

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