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Intraplate seismicity in northern Central Europe is induced by the last glaciation

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ABSTRACT

There is growing evidence that climate-induced melting of large ice sheets has been able to trigger fault reactivation and earthquakes around the migrating ice limit. Even today, the stress due to Glacial Isostatic Adjustment (GIA) can continue to induce seismicity within the once glaciated region. Northern Central Europe (NCE) lies outside the former ice margin and is regarded as a low seismicity area. However, several historic earthquakes with intensities of up to VII occurred in this region during the last 1,200 years. Here we show with numerical simulations that the seismicity can potentially be explained by the decay of the Scandinavian ice sheet (SIS) after the Weichselian glaciation. Combination of historic earthquake epicenters with fault maps relates historic seismicity to major reverse faults of Late Cretaceous age. Mesozoic normal faults remained inactive in historic times. We suggest that many faults in NCE are active during postglacial times. This is a novelty that sheds new light on the distribution of postglacial faulting and seismicity. In addition, we present the first consistent model that can explain both the occurrence of deglaciation seismicity and the historic earthquakes in NCE.

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INTRODUCTION

Continental intraplate tectonics can cause large intraplate earthquakes even in low strain rate areas (Johnston, 1989). Also the intervals between the seismic events are commonly long (Gangopadhyay and Talwani, 2003). Key to the occurrence of large intraplate earthquakes are pre-existing zones of crustal weakness (Sykes, 1978) and a trigger mechanism such as changes in the stress state due to erosion (Calais et al., 2010), fluid pressure variations (Costain et al., 1987) or deglaciation (Wu & Hasegawa, 1996; Wu et al., 1999; Sauber and Molnia, 2004, Hampel & Hetzel, 2006; Hampel et al., 2009).

Paleoseismological studies show that large-magnitude (>6 Mw) intraplate earthquakes occurred around ~13 ka - 9 ka in Scandinavia (Mörner, 2011), implying a connection to deglaciation of the SIS (Wu et al., 1999). For NCE, there is also evidence for post-glacial seismicity (Brandes et al., 2012; Brandes & Winsemann, 2013), although the seismic activity there is supposed to be low (Leydecker and Kopera, 1999) and some instrumentally recorded earthquakes of the last decades are thought to have resulted from hydrocarbon recovery (Dahm et al., 2007). There is also evidence for historic earthquakes with intensities of up to VII (Leydecker, 2011). A strong damaging earthquake (intensity VI-VII, MSK-64 scale) took place in 1612 at the Osning thrust in Germany (Vogt and Grünthal, 1994) followed by an event in 1767 with an intensity of V-VI (Grünthal and Bosse, 1997). This raises the question: Is seismicity in NCE during post-glacial times related to unloading of the SIS?

NUMERICAL MODELLING

Northern Central Europe is characterized by several major faults that belong to the Central European basin system (CEBS) (Fig. 1). This Permian rift basin experienced extension throughout the Mesozoic (Scheck-Wenderoth and Lamarche, 2005) and contraction in the Late

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Cretaceous (Kley and Voigt, 2008), resulting in a distinct fault pattern with major WNW-ESE trending reverse faults: the Thuringian Forest Fault, the Osning Thrust, the Aller Valley Fault, the Haldensleben Fault, and the Gardelegen Fault. All faults were active during the Late Cretaceous (Kley and Voigt, 2008), e.g., apatite fission track data imply uplift in the Lower Saxony Basin north of the Osning Thrust between 89 and 72 Ma with erosion of as much as 7 km (Senglaub et al., 2005). At the Harz boundary fault, 2.5 km of Late Cretaceous syn-tectonic sediments were deposited in the footwall of the thrust (Voigt et al., 2006).

With commonly used three-dimensional finite element models that describe the process of GIA together with those of Coulomb Failure Stress (CFS) calculations (see Data Repository for more material on the CFS, a summary of the models used, input parameters for software Coulomb 3.3 and further results), we tested the reactivation potential of these faults due to ice unloading after the Weichselian glaciation in Scandinavia (Wu et al., 1999; Mörner, 2011). For all major epicenters along the faults in Figure 1 which showed activity in postglacial times, we calculated the change in CFS (δCFS). The δCFS_E due to a possible earthquake is computed using Coulomb 3.3 (Stein, 2003) and this change is applied to the GIA-induced δCFS_{GIA} as shown in Figures 2 and 3.

δCFS (Supplementary Fig. S1) represents the minimum stress required to reach faulting. A negative δCFS value (e.g. Figure 2) indicates that the fault is stable, while a positive value means that GIA stress is potentially available to induce faulting or cause fault instability or failure unless released temporarily by an earthquake. Thus, δCFS = 0, i.e., the zero line in Figure 2, is an indication of the onset of fault motion. We also show how a potential GIA induced earthquake at a certain fault affects the δCFS once it reaches the zero line if intraplate slip values are known (for the Osning Thrust) or assumed.

At the major reverse faults the zero line is crossed mainly between 16 ka and 10 ka (Fig. 2), suggesting that these postglacial faults are activated by SIS deglaciation.

DISCUSSION AND CONCLUSIONS

The recognition of postglacial faults outside the former glaciated area is a novelty for NCE, sheds new light on the distribution of postglacial faults in general and provides the possibility to explain the seismicity pattern in NCE.

To verify the models we combined a historic earthquake catalogue that envelops the time period from A.D. 800 to 2008 (Leydecker, 2011), with the fault map of NCE (Kley and Voigt, 2008) (Fig. 1). Only historical earthquakes with tectonic origin are used while earthquakes due to human impact (e.g. mining) are excluded. Notable are the1977 Soltau event with an oblique thrust mechanism and the nearby 2004 Rotenburg event with a normal fault focal mechanism. They are marked to be of tectonic origin in Leydecker's (2011) catalogue, but are thought to be triggered by gas production (Dahm et al., 2007).

Except for the cluster of the Bohemian earthquake swarm in the southeast, the historic seismicity is concentrated along major WNW-ESE trending reverse faults. The 1770 earthquake with an intensity of VI (Leydecker, 2011) was probably related to the Rheeder Moor reverse fault (Fig. 1). Earthquake activity increases gradually towards the Fennoscandian Shield (delineated by the Sorgenfrei-Tornquist zone and other faults (Gregersen & Voss, 2014)).

None of the major Mesozoic normal faults in northern Germany, not even the large normal faults of the Glückstadt graben (Fig. 1), show significant historic seismicity, revealing a gap in tectonic activity between the Late Cretaceous contractional phase and historic seismicity. Apatite fission track cooling ages point to only one uplift phase in the Late Cretaceous (Senglaub et al., 2005) that corresponds to the shortening of the CEBS (Kley and Voigt, 2008). The subsequent Cenozoic period was characterized by tectonic quiescence (Kley et al. 2008). This raises the questions: Why is there historic seismicity, and why does it have this distinct relation to the Late Cretaceous reverse faults?

GIA-induced stress changes due to the growth and decay of the SIS during the Pleistocene may provide the solution. As shown in Figure 1, historic seismicity is concentrated along the WNW-ESE trending Late Cretaceous reverse faults, which are almost parallel to the southern ice margin (Fig. 1). Such faults have a high reactivation potential because the maximum horizontal components of the ice sheet-induced stress are in line with the palaeostress field (Stewart et al., 2000). Faults with large angles to the paleo-ice margin, e.g., the Glückstadt Graben faults, have a lower reactivation potential. In addition, the δCFS in a normal fault regime had mostly negative values in historic times for NCE, which minimized the possibility of seismic activity and would explain the lack of historic seismicity along Mesozoic normal faults. Numerical simulations (Fig. 2) show that all WNW-ESE trending reverse faults became unstable between 16 – 10 ka. Seismic events are confirmed at the Osning Thrust where OSL ages of syn-tectonic growth strata and soft-sediment point to earthquakes with a magnitude of at least 5.5 between 15.9 ± 1.6 to13.1 ± 1.5 ka. (Brandes et al., 2012; Brandes and Winsemann, 2013).

The elastic rebound theory (Reid, 1910) implies that the deglaciation seismicity caused a stress release along the faults. To cause new earthquakes, new stress can be accumulated by the ongoing Alpine collision and the Atlantic ridge-push (Reicherter et al. 2005). The maximum horizontal stress in the central part of northern Germany is NNE-SSW directed and rotates into a NNW-SSE direction toward the west (Marotta et al., 2002; Reicherter et al. 2005) (Fig. 1). Many reverse faults in northern Germany strike almost perpendicular to the recent maximum horizontal stress direction. In general, strain rates are low (Marotta et al., 2002) as well as the slip rates along the faults (Kaiser, 2005). Historic seismicity along the faults might be possible because GIA-induced stress perturbation overcame the friction along the faults.

As intracontinental faults have long aftershock sequences (Stein and Liu, 2009), we speculate that the historic seismicity in NCE is an aftermath, a kind of aftershock sequence, of the GIA seismicity. This is supported by Figure 2: All graphs show a change from negative to positive values during deglaciation. An earthquake occurred when δCFS first becomes zero and the released stress caused a jump to more negative (stable) values. For the Osning Thrust, seismic events between 15.9 ± 1.6 to 13.1 ± 1.5 ka (Brandes & Winsemann, 2013) have fault slips of 1.0 – 1.5 m (Wells and Coppersmith, 1994). To constrain the aftermaths, 3 slip values between 1.0 and 1.5 m are used in panel A and B to compare with the case where no slip occurred. Panel A & B show that after the first event, the zero line is crossed again if the slip is less than 1.5 m. The likelihood of another event in the last 10 ka is highlighted in Figure 3 with a gray shaded range of ~0.3 MPa in the last 8,000 years. The best model in panel A (blue line) that gives good agreement to observations at the Osning Thrust, points to an activity 1,000 years ago. Based on the models and their uncertainty tested in this study, the 1612 and 1767 events are likely related to the Weichselian deglaciation.

Figures similar to Figure 3 for the other areas cannot be provided yet as fault slips cannot be derived. Nonetheless, using 3 typical values of fault slips between 0.5 and 1.5 m, Figure 2 shows that events along the Sorgenfrei-Tornquist zone (STZ) and in Magdeburg Börde appear to have a strong relation to GIA, while the 1751 event in the Thuringian Forest is potentially influenced by GIA.

However, the geological evidence for a post-glacial reactivation of the faults is very limited. So far only data from the Osning Thrust (Brandes et al., 2012) and the STZ (Pedersen &

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Gravesen, 2010) provide hints. Finding further evidence is a future challenge for Quaternary geologists.

Wiprut and Zoback (2000) showed that some faults in northern Europe are critically stressed and may only require small stress changes to (re-)activate. Our modeling shows that fault movements are possible if the GIA-induced stress has not been fully released yet. This can explain the deglaciation seismicity, the historic earthquakes in NCE. The results can be transferred to similar areas in North America and Russia. The wide spread occurrence of postglacial faulting makes it indispensable to re-analyze the intraplate tectonics in NCE and also beyond. Just recently a magnitude 4.7 earthquake happened in an area of very low activity in western central Sweden (Earthquake-Report.com, 2014), so, understanding the driving mechanisms for this type of seismicity is an important step toward a profound hazard risk evaluation.

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FIGURE CAPTIONS

Figure 1. **Faults of northern Central Europe and epicenters of historic earthquakes.** Bold lines are major Late Cretaceous reverse faults. Yellow dots are historic earthquakes from 800 to 2008; some are labeled with event year. Green squares are earthquakes from 1930 to 2005. Map based on Kley and Voigt (2008) earthquake locations from Gregersen et al. (2005) and Leydecker (2011). Red arrows indicate the recent stress field orientation based on Marotta et al. (2002) and Reicherter et al. (2005). Red ellipses indicate potential earthquake clusters. Blue line delineates swarm earthquakes in Bohemia. LGM – Last Glacial Maximum.

Figure 2. **Change in Coulomb Failure Stress (δCFS) for major reverse faults in northern Central Europe and southern Sweden induced by the Weichselian glaciation in the last 23 ka and the effect of the first fault slip (when zero line is reached for the first time).** Fault names are preceded by year(s) (in A.D.) of historical event(s). Three different rheological models (U1L1_V1, U3L3_V1, U3L3_V3) are used for calculation, see data repository for more information. Numbers in legend indicate fault slips in m derived for the Osning Thrust based on the inferred magnitude of the Late Glacial seismicity. Numbers in parentheses are typical intraplate fault slips in m from Wells and Coppersmith (1994). Graphs without earthquake influence ("none") are exemplarily shown for A and B only. More locations are shown in the Data Repository Fig. DR8 (see footnote 1).

Figure 3. **Models that can explain both the geological fault slip and historical earthquakes at the Osning Thrust (Central Europe) simultaneously.** Solid lines show best–fitting model estimates (for rheological models U1L1_V1 and U3L3_V3): (A) For the A.D. 1612 event, fault slip of 0.98 m indicates activity at 3 and 1 ka (blue line). (B) For the A.D. 1767 event, fault slip of 1.03 m indicates activity at 5 and 3 ka BP (red line); fault slip of 0.93 m indicates activity between 7 and 6 ka BP (blue line). Shaded area is range of predicted change in Coulomb failure stress (δCFS) by our models after the first earthquake.

[1]GSA Data Repository item 2015xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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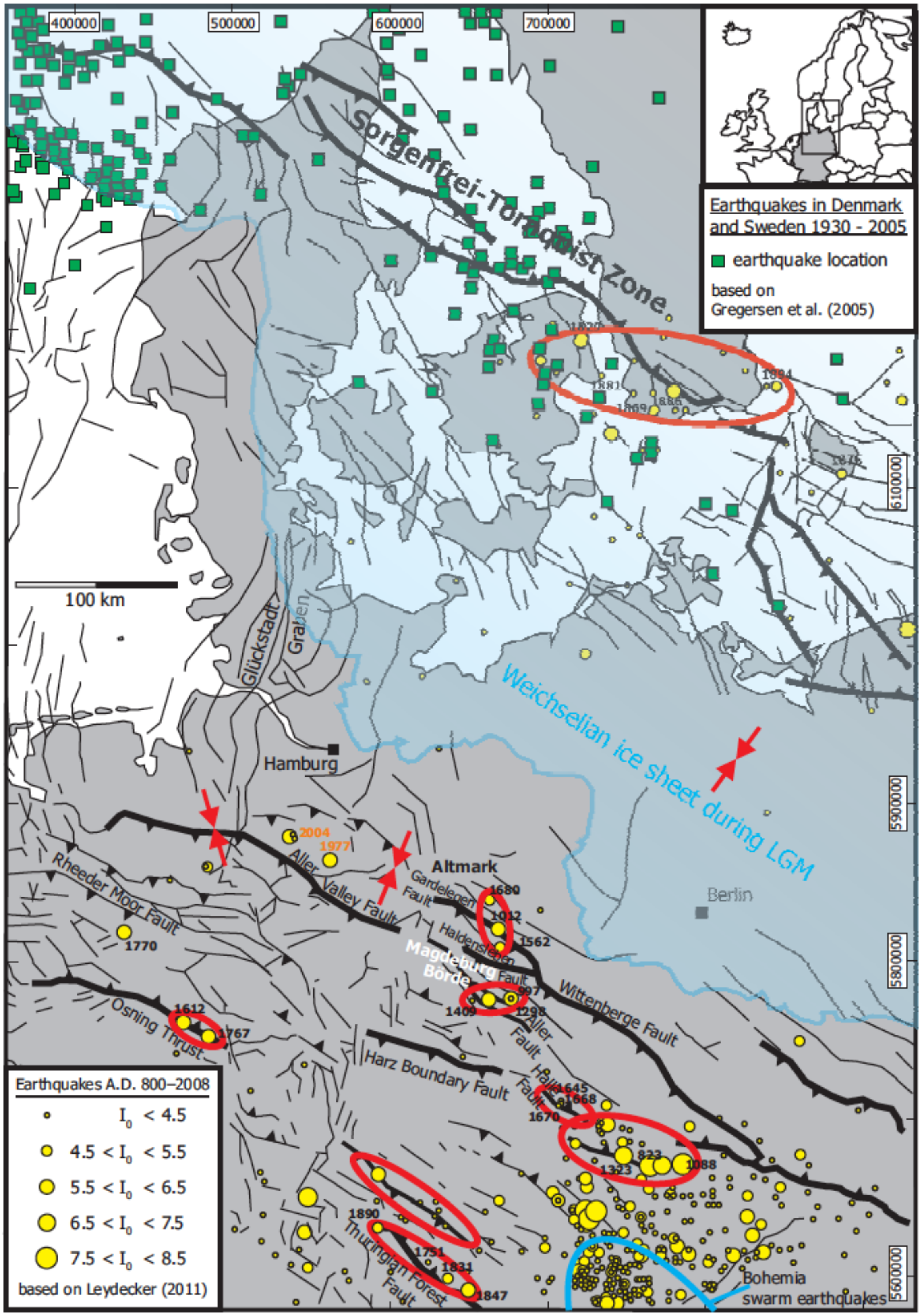

Fig. 1

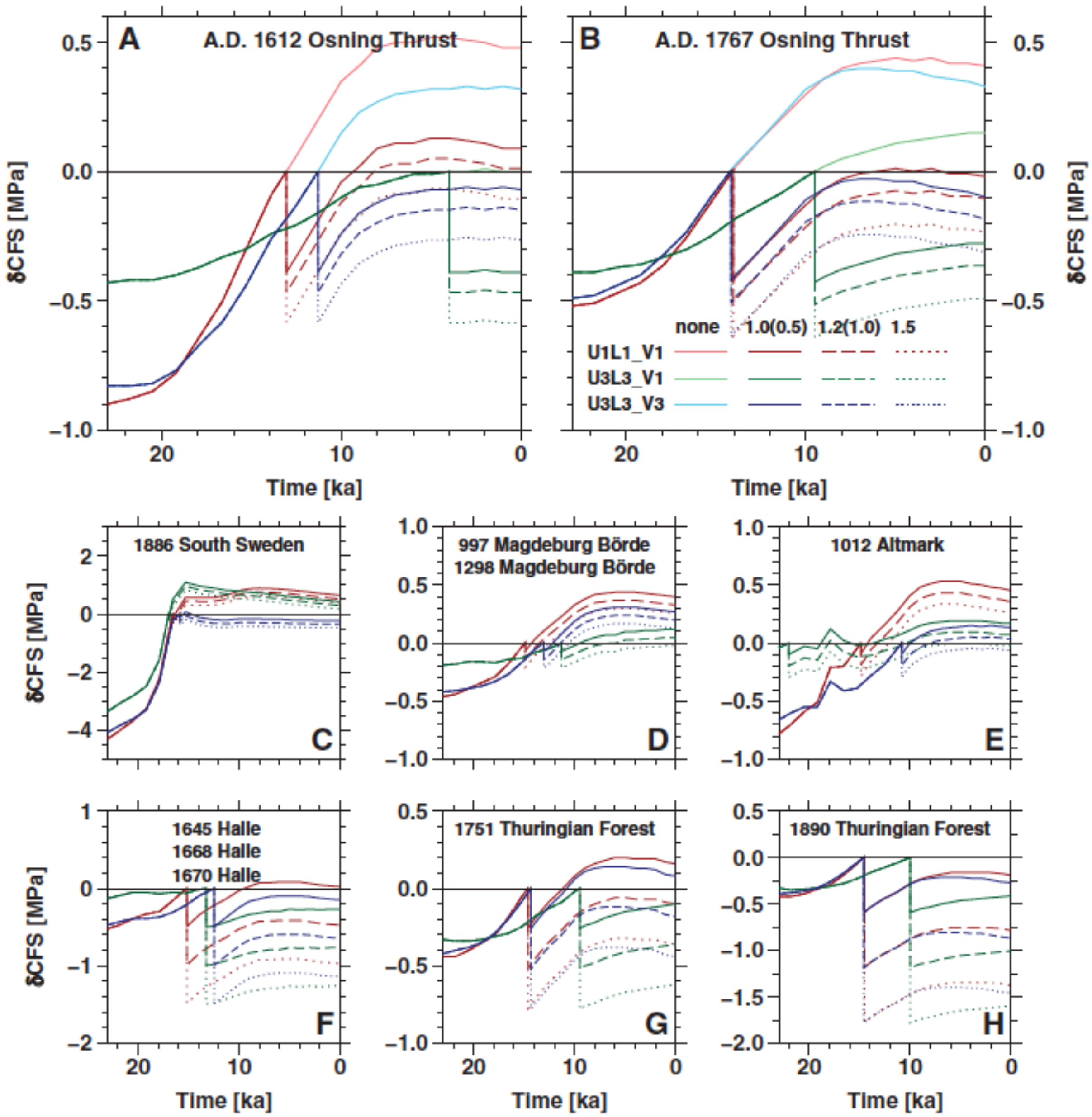
A
A.D. 1612 Osning Thrust
B
A.D. 1767 Osning Thrust
δCFS [MPa]
Time [ka]
none
1.0(0.5)
1.2(1.0)
1.5
U1L1_V1
U3L3_V1
U3L3_V3
1886 South Sweden
C
997 Magdeburg Börde
1298 Magdeburg Börde
D
1012 Altmark
E
1645 Halle
1668 Halle
1670 Halle
F
1751 Thuringian Forest
G
1890 Thuringian Forest
H

Figure 2

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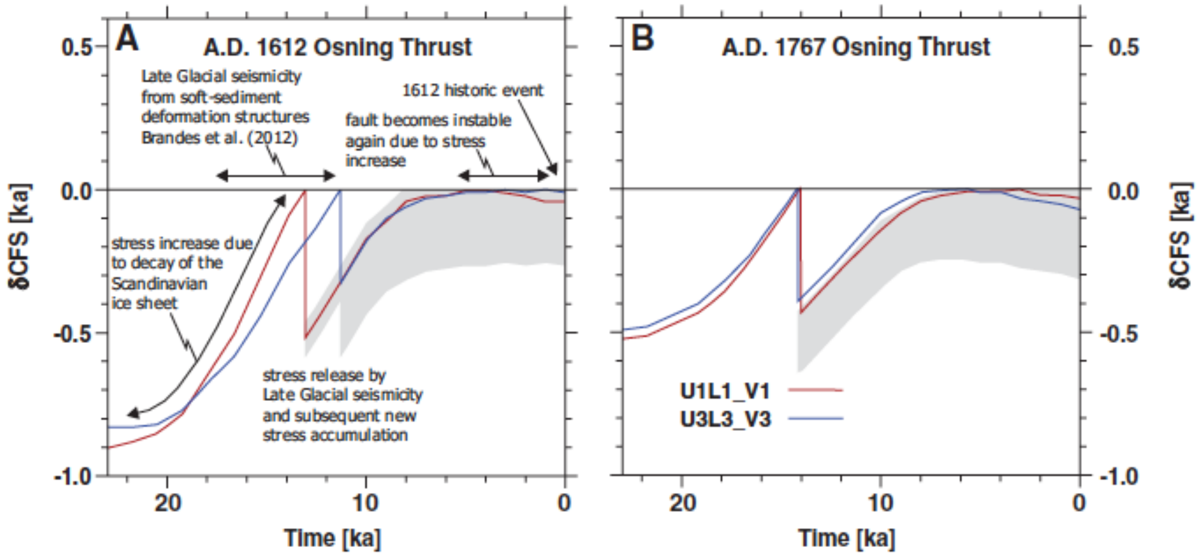

Figure 3