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1 **Intraplate seismicity in northern Central Europe is induced** 2 **by the last glaciation**

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9 **ABSTRACT**

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

23 **INTRODUCTION**

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

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

42 **NUMERICAL MODELLING**

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

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

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

62 δCFS (Supplementary Fig. S1) represents the minimum stress required to reach faulting.
63 A negative δCFS value (e.g. Figure 2) indicates that the fault is stable, while a positive value
64 means that GIA stress is potentially available to induce faulting or cause fault instability or
65 failure unless released temporarily by an earthquake. Thus, $\delta\text{CFS} = 0$, i.e., the zero line in Figure
66 2, is an indication of the onset of fault motion. We also show how a potential GIA induced
67 earthquake at a certain fault affects the δCFS once it reaches the zero line if intraplate slip values
68 are known (for the Osning Thrust) or assumed.

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

71 **DISCUSSION AND CONCLUSIONS**

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

75 To verify the models we combined a historic earthquake catalogue that envelops the time
76 period from A.D. 800 to 2008 (Leydecker, 2011), with the fault map of NCE (Kley and Voigt,
77 2008) (Fig. 1). Only historical earthquakes with tectonic origin are used while earthquakes due to
78 human impact (e.g. mining) are excluded. Notable are the 1977 Soltau event with an oblique
79 thrust mechanism and the nearby 2004 Rotenburg event with a normal fault focal mechanism.
80 They are marked to be of tectonic origin in Leydecker's (2011) catalogue, but are thought to be
81 triggered by gas production (Dahm et al., 2007).

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

87 None of the major Mesozoic normal faults in northern Germany, not even the large
88 normal faults of the Glückstadt graben (Fig. 1), show significant historic seismicity, revealing a
89 gap in tectonic activity between the Late Cretaceous contractional phase and historic seismicity.
90 Apatite fission track cooling ages point to only one uplift phase in the Late Cretaceous (Senglaub
91 et al., 2005) that corresponds to the shortening of the CEBS (Kley and Voigt, 2008). The

92 subsequent Cenozoic period was characterized by tectonic quiescence (Kley et al. 2008). This
93 raises the questions: Why is there historic seismicity, and why does it have this distinct relation
94 to the Late Cretaceous reverse faults?

95 GIA-induced stress changes due to the growth and decay of the SIS during the
96 Pleistocene may provide the solution. As shown in Figure 1, historic seismicity is concentrated
97 along the WNW-ESE trending Late Cretaceous reverse faults, which are almost parallel to the
98 southern ice margin (Fig. 1). Such faults have a high reactivation potential because the maximum
99 horizontal components of the ice sheet-induced stress are in line with the palaeostress field
100 (Stewart et al., 2000). Faults with large angles to the paleo-ice margin, e.g., the Glückstadt
101 Graben faults, have a lower reactivation potential. In addition, the δ CFS in a normal fault regime
102 had mostly negative values in historic times for NCE, which minimized the possibility of seismic
103 activity and would explain the lack of historic seismicity along Mesozoic normal faults.
104 Numerical simulations (Fig. 2) show that all WNW-ESE trending reverse faults became unstable
105 between 16 – 10 ka. Seismic events are confirmed at the Osning Thrust where OSL ages of syn-
106 tectonic growth strata and soft-sediment point to earthquakes with a magnitude of at least 5.5
107 between 15.9 ± 1.6 to 13.1 ± 1.5 ka. (Brandes et al., 2012; Brandes and Winsemann, 2013).

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

115 along the faults (Kaiser, 2005). Historic seismicity along the faults might be possible because
116 GIA-induced stress perturbation overcame the friction along the faults.

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

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

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

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

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

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265

266 **FIGURE CAPTIONS**

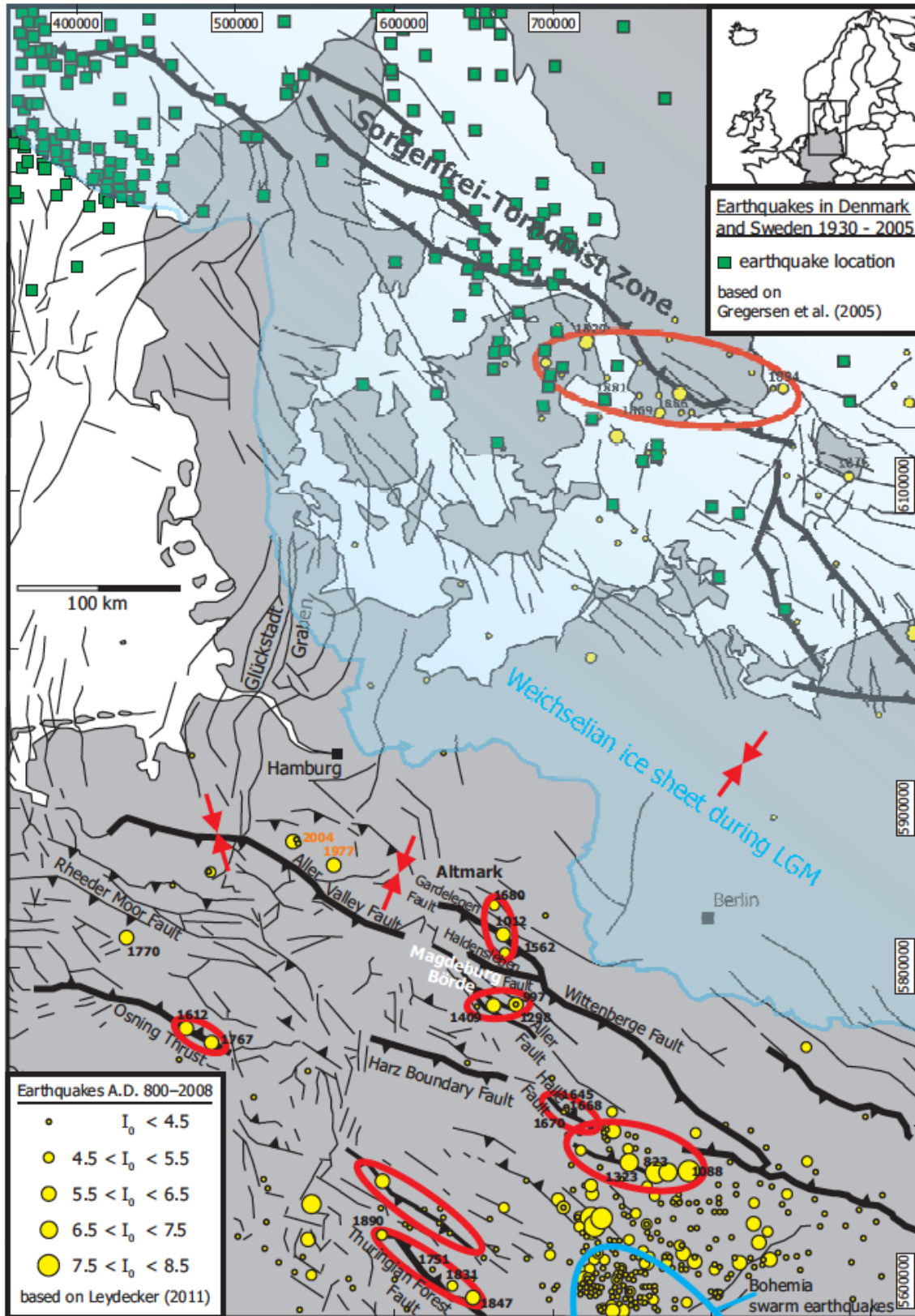
267 Figure 1. **Faults of northern Central Europe and epicenters of historic earthquakes.** Bold
268 lines are major Late Cretaceous reverse faults. Yellow dots are historic earthquakes from 800 to
269 2008; some are labeled with event year. Green squares are earthquakes from 1930 to 2005. Map
270 based on Kley and Voigt (2008) earthquake locations from Gregersen et al. (2005) and
271 Leydecker (2011). Red arrows indicate the recent stress field orientation based on Marotta et al.
272 (2002) and Reicherter et al. (2005). Red ellipses indicate potential earthquake clusters. Blue line
273 delineates swarm earthquakes in Bohemia. LGM – Last Glacial Maximum.

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

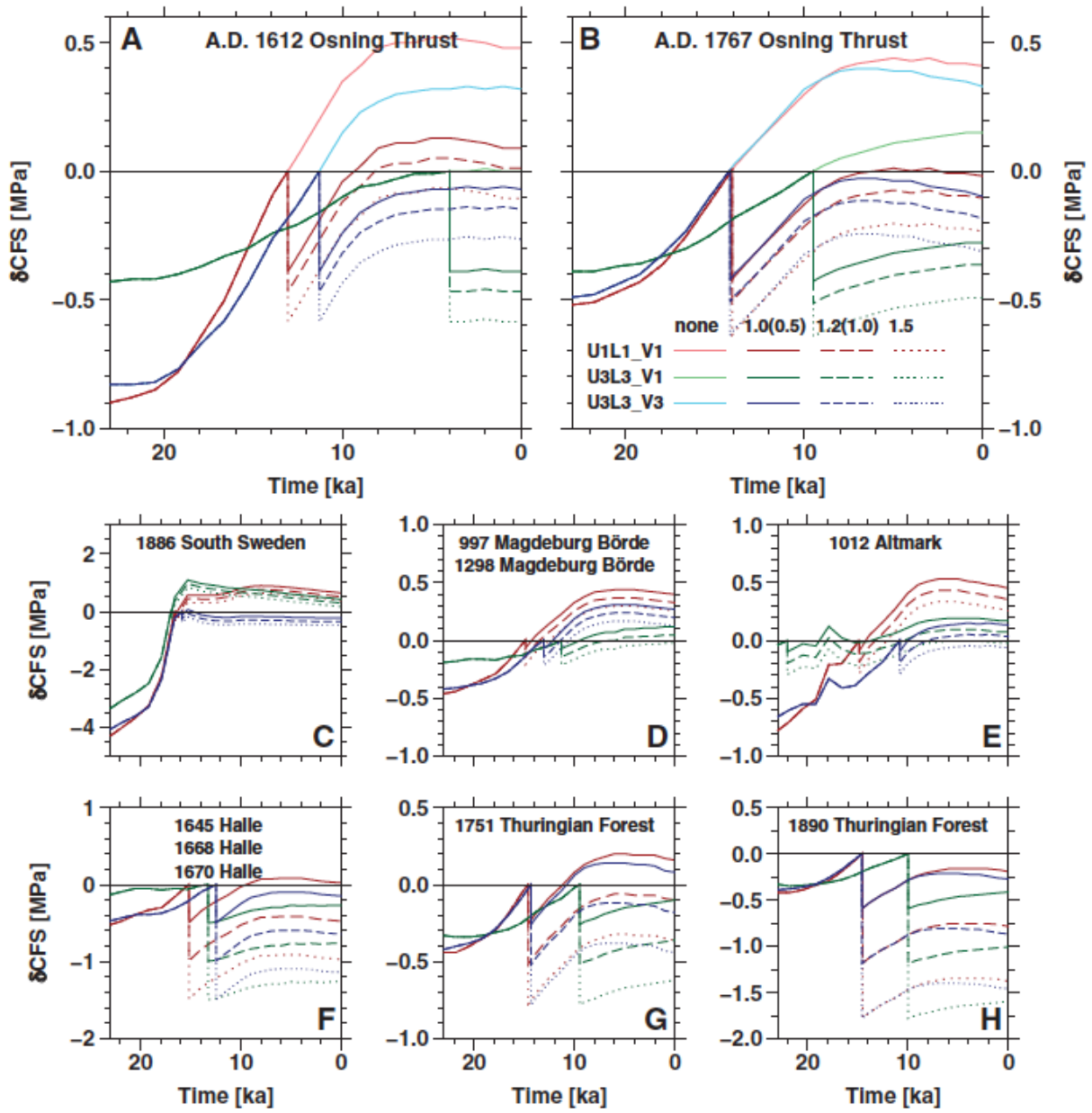
284 **Figure 3. Models that can explain both the geological fault slip and historical earthquakes**
285 **at the Osning Thrust (Central Europe) simultaneously.** Solid lines show best-fitting model
286 estimates (for rheological models U1L1_V1 and U3L3_V3): (A) For the A.D. 1612 event, fault
287 slip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

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

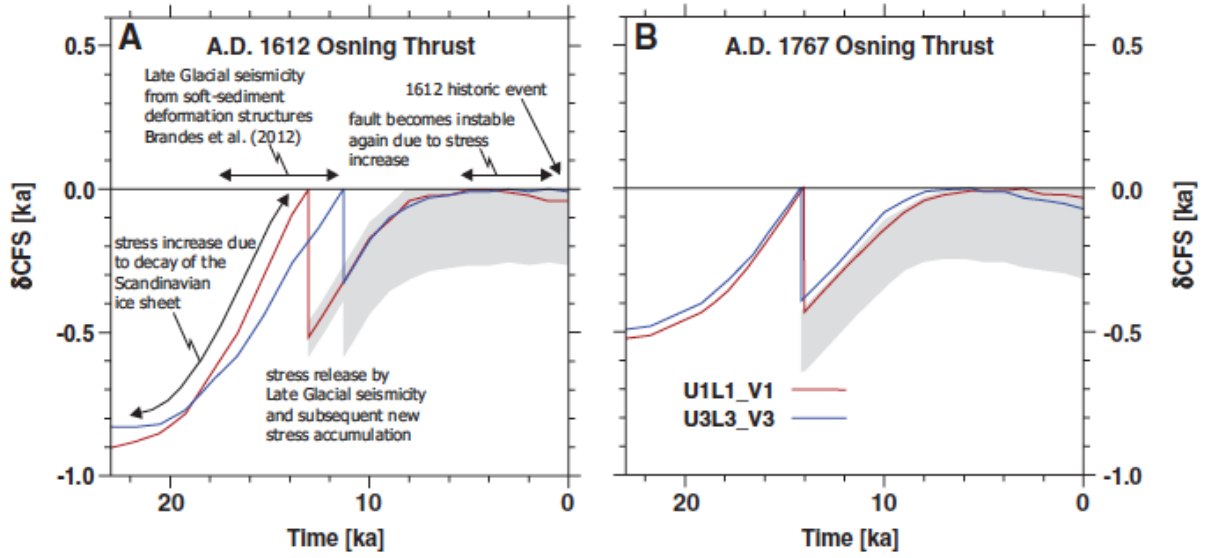
294



295
 296 Fig. 1



297
298 Figure 2



299
300 Figure 3