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Comment

The Børglum fault was active in historical times. Comment on 'The near-surface structure in the area of the Børglum fault, Sorgenfrei-Tornquist Zone, northern Denmark: Implications for fault kinematics, timing of fault activity and fault control on tunnel valley formation' by Brandes et al. [Quat. Sci. Rev. 289 (2022) 107619]

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ABSTRACT

Brandes et al. (2022) provided a detailed study of the Børglum fault, a branch of the Sorgenfrei-Torquist Zone, in northern Denmark, based on seismic profiles, borehole, and outcrop data. They suggest that the last fault displacement occurred between 14.5ka and 12ka. We wish to highlight the widespread deformed churches in the region: their damage was caused by seismic activity in historical times (13–16th century). Displacement along the Børglum fault, therefore, did not cease before the Holocene but rather has been active at least up to the 16th century.

Brandes et al. (2022) provided an excellent study of the Quaternary activity of the NW-SE-trending Børglum fault, which is the northern boundary fault of the Sorgenfrei-Tornquist Zone in northern Denmark (STZ; Sørensen et al., 2011). Their in-depth study is based on two, dedicated shallow seismic profiles and two boreholes. Based on the shear-wave reflection seismic sections, they interpret a complex fault system with a strike-slip component active at the end of the Saalian glaciation, i.e., before approx. 130ka. They illustrated normal faults (as part of a negative flower structure) on the profiles both at depth and in close proximity to the surface. Their interpretation of the seismic profiles is corroborated by observations in outcrops nearby (normal faults expressed by shear deformation bands and soft-sediment deformation structures). A glaciotectonic origin was excluded based on the occurrence of frequent shear bands within Late Pleniglacial glaciolacustrine deposits. Their interpretation is that the Børglum fault is a glacially triggered fault that was active in the Late Glacial, when ongoing deglaciation released stresses accumulated in the lithosphere via earthquakes up to magnitude 7 (as previously suggested by Brandes et al., 2018). In addition, they also review the problems around glacially-induced faulting in Scandinavia, Central Europe, and North America. The age of the normal component of the faults is bracketed between 14.5 and 12 ka (Brandes et al., 2022). They are aware of younger tectonic deformation of a 9000 yr lacustrine succession disturbed by faulting in South Denmark (Sandersen and Jørgensen, 2015). Their suggestion is that as glacial-isostatic uplift is still ongoing in the region, stress buildup is still possible, which might activate the Børglum fault in the future.

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As the Børglum fault has a minimum length of 250 km, any future seismicity would have potentially disastrous consequences, producing earthquakes well above M7 in an extreme case scenario (Wells and Coppersmith, 1994). Estimating recurrence times would be a key factor in assessing seismic hazard.

As part of an ongoing systematic study of the historical activity

Table 1
Dating and intensity of potential seismic events, implied by construction, destruction, and reconstruction history of damaged churches in nearby the Børglum Fault in NW Denmark.

Nr.	Name	Construction	Destruction	Intensity[a]	Reconstruction	Reference
1	Hune	1100s	1634 - tower torn wall	VIII	1646, 1885 - rebuilt	Gaarsted-Jörgensen (1996)
2	Saltum	~1150	Folded and torn walls	VIII	~1450 tower, chor, apsis demolished	saltumastrupkirker.dk
3	Furreby	1200s	Triumphal arch deformed to polygonal	VII		danske-kirker.dk
4	Vennebjerg	~1150	Torn tower, tilted walls, keystone drop in triumphal arch	VIII		www.kirkehistorie.dk
5	Skallerup	1100s	1490s: gable torn down, reused; tower fractured	VII	Tower built 1500s	http://www.svmpastorat.dk/Skallerup-Kirke
6	Em	1100s	14th century	VIII	1300s - rebuilt with recycled material	https://www.xn--vrkirke-fxa.dk/om-kirkerne/em-kirke
7	Vrå	1150–1200	Romanesque N wall tilted, collapsed S wall rebuilt as Gothic	VII-IX	<1500 Gothic	danmarks-kirker.dk
8	Vrejlev	~1160	Early Gothic walls deformed in Late Gothic time	VII	Remodeling before 1460-1500	Lindholt and Larsen (2019), Pedersen et al., (2019)
9	Serritslev	~1150	Torn wall, deformed triumphal arch	VIII	1500s northern porch added	https://da.wikipedia.org/wiki/Serritslev_Kirke
10	Brønderslev	1100s	In-plane extension + torn wall	IX	Late Gothic tower	www.kirkehistorie.dk
11	Aalborg	1542 – three aisles	Northern aisle – differential settlement after 1542	VII		Horskjaer (1968)

[a] Intensity after Rodríguez-Pascua et al. (2013).

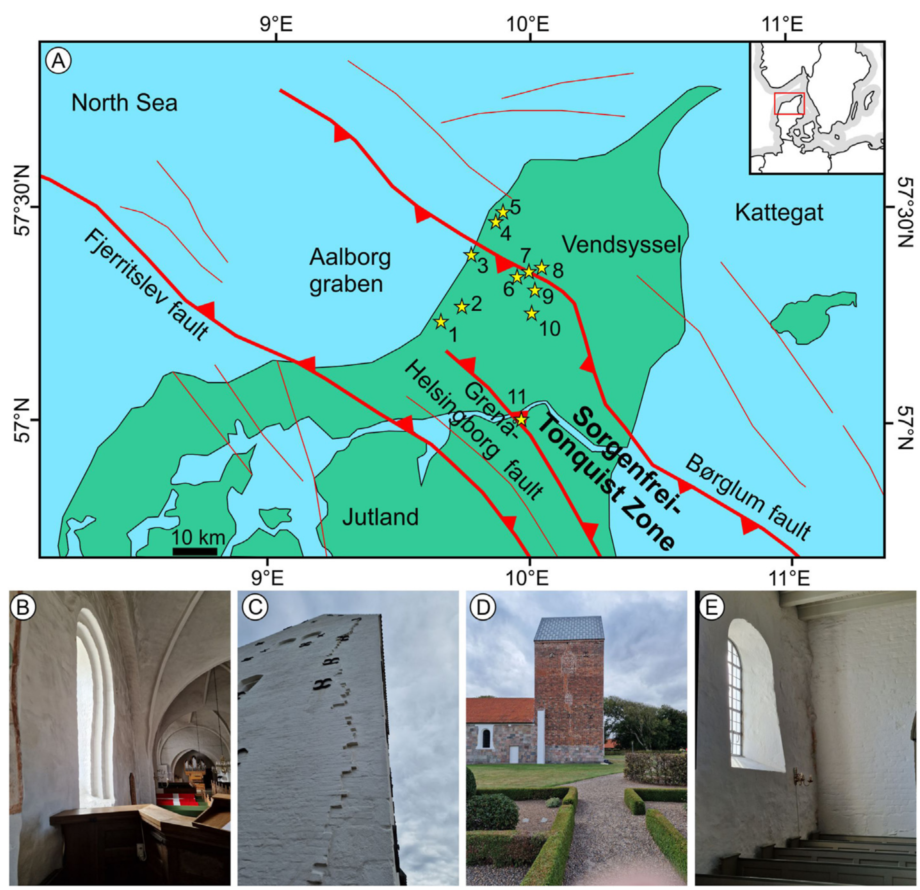

Fig. 1. Earthquake-damaged churches in North Jylland, Denmark, record seismic activity in Medieval times at the Børglum Fault, a branch of the Sorgenfrei-Tornquist Zone, northern Denmark. **A.** Tectonic map of NW Jylland (based on Brandes et al., 2022). Numbers denote churches displaying seismic damage near the Børglum Fault. 1 – Hune, 2 – Saltum, 3 – Furreby, 4 – Vennebjerg, 5 – Skallerup, 6 – Em, 7 – Vrå, 8 – Vrejlev, 9 – Serritslev, 10 – Brønderslev, 11 – Aalborg. (Selected deformation features ranged in seismic damage classes of Ceroni et al., 2022). **B.** Saltum (2). Damage class M22: north wall of nave: lower part tilted outward, upper part vertical, shifted inward. **C.** Vennebjerg (4). Damage class M16: west face of tower with torn wall. Class M16. **D.** Skallerup (5). Damage class M27: tower fractured from top to bottom; strip of light-coloured bricks marks repair. **E.** Vrå (6). Damage class M5: south wall of nave tilted outwards.

of the Teisseyre-Tornquist Zone in Poland (Gaidzik and Kázmér, 2022), we visited adjacent regions for comparison purposes. Inspired by the papers of Kammann et al. (2016) and Al Hseinat and Hübscher (2017), who documented faults transecting Holocene sediments in the southern, maritime part of Denmark, we looked for evidence of historical earthquakes on land.

Archaeoseismology investigates man-made constructions to find earthquake-caused damage Studying buildings of a traditionally-defined form, e.g., medieval churches, is preferred over randomly built constructions. Deviation from accepted building patterns (e.g. unusually located or exaggerated buttresses, dropped/shifted/rotated/extruded blocks, dropped keystones, etc.) can be attributed to unusual, rare processes, e.q., earthquakes, especially if traces of lateral loading can be seen on structures (Galadini et al., 2006; Sintubin, 2015; Kázmér, 2015, 2017; Kázmér et al., 2021). While building deformations can be caused by uneven subsidence, poor workmanship, warfare, etc., there are established ways to distinguish seismic deformation from the latter. In general, the deformation of walls caused by lateral – as opposed to vertical – loading is a good indicator of seismic influence (Stiros, 2020).

Near the Børglum fault, we studied 11 medieval churches (Table 1). Most of these are located within the range of <10 km from the fault (no. 3–10). Churches no. 1, 2, and 11 are located further from the Børglum fault (up to c. 15 km), but close to the Grena-Helsingborg fault. All of them display conspicuous features of deformation (Fig. 1), which we assigned to various categories of damage according to the post-seismic first response survey system used in Italy (Emergenza, 2006; modified by Ceroni et al., 2022). The seismological literature supplied us with photos of identical co-seismic damage features: Fig. 1B – wall tilted inward: Volturno, Italy (Bottari et al., 2020, Fig. 4d); Fig. 1C – torn wall: Lorca, Spain (Susagna-Vidal et al., 2012, Fig. 11b); Fig. 1D – tower fissured from top to bottom: Broadstairs, England (Musson, 2007, Fig. 10); Fig. 1 E – wall tilted outwards: Manjal, Gujarat, India (Satuluri et al., 2020, Fig. 6a).

Even though the historical archives do not mention earthquakes in this area, analysis of historical data on the demolition and reconstruction of churches allows us to bracket the time of the deformation. In the absence of direct historical records, it is an established practice to bracket the time of deformation between the construction date and the reconstruction date (Rajendran et al., 2013). There was one destruction event in the 1300s (Em church), at least one in the 1450–1500 interval (Saltum, Skallerup, Vrå, Vrejlev, Serritslev, Brønderslev churches), and potentially one more in 1634 (Hune church).

On this basis, we suggest that seismic activity along the STZ fault did not cease before the Holocene; rather, it has been continued up to historical times.

Author contributions

Krzysztof Gaidzik and Miklós Kázmér shared all jobs in this study, including data gathering, field surveys, and writing the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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