BGR Bundesanstalt für Geowissenschaften und Rohstoffe
GEOZENTRUM HANNOVER

Leibniz Universität Hannover

Limitations of Soft-Sediment Deformation Structures as Indiactors for Paleo-Earthquakes in Formerly Periglacial and Glaciated Areas

Müller, K.,[1] Winsemann, J.,[1] Pisarska-Jamroży[2], M., Lege, T.,[3] Spies, T.[3] and Brandes, C.[1]

[1]Institut für Geologie, Leibniz Universität Hannover, Callinstr. 30, 30167 Hannover, Germany; [2]Institute of Geology, Adam Mickiewicz University, Krygowskiego 12, 61-680 Poznań, Poland
[3]Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hannover

1. The Problem of the use of SSDS as Earthquake Indicator

Soft-sediment deformation structures (SSDS) are used as indicators for past seismic events (e.g. Tuttle et al., 2019). However, in regions that were frequently affected by ice-sheet loading/unloading and periglacial processes, the use of SSDS for interpreting seismic events is challenging. In these regions glacial, and periglacial processes affected the near-surface sediments and led to the formation of SSDS (Fig. 1) (e.g. Van Vliet-Lanoë et al., 2004; Van Loon, 2009; Brandes and Winsemann, 2013; Gehrmann and Harding, 2018) similar to those caused by earthquakes.

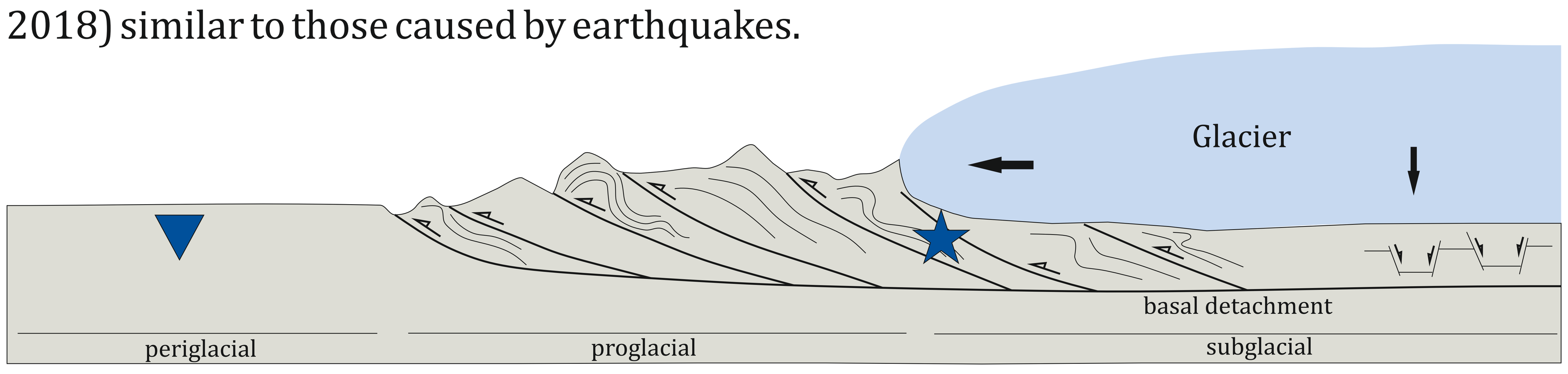
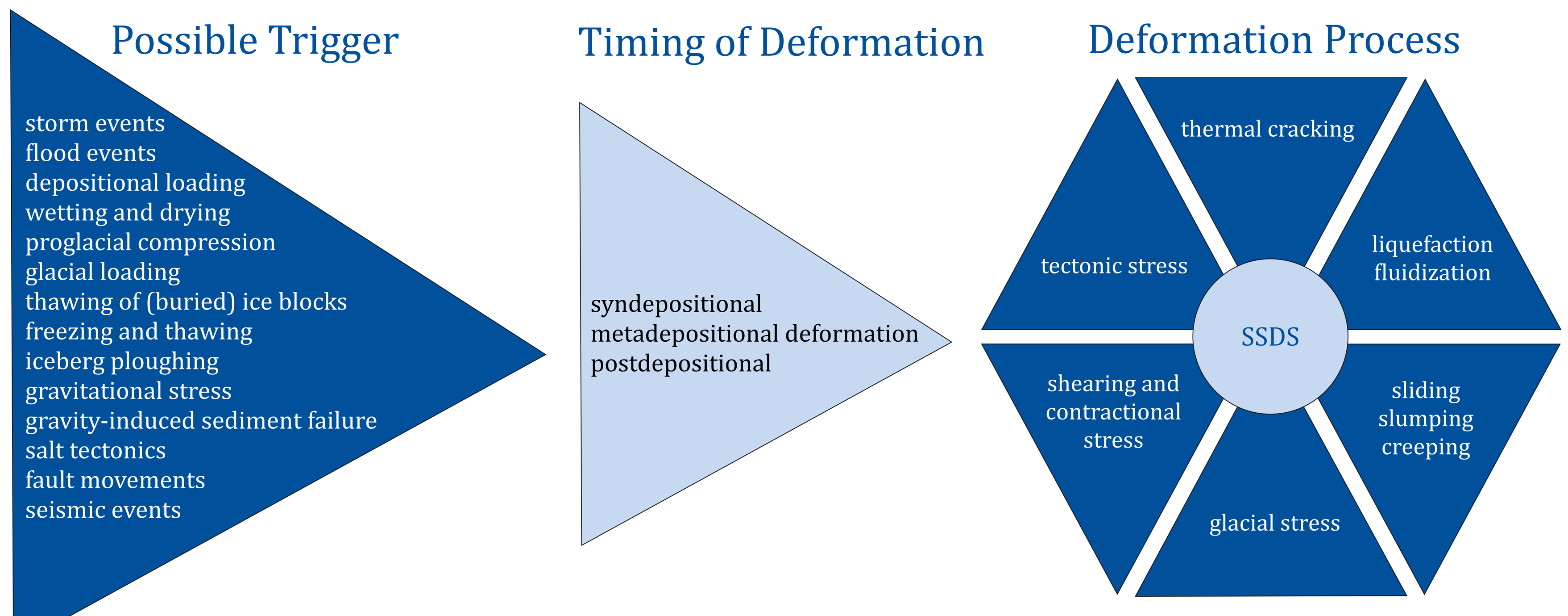


Fig. 1: Deformation structures that are related to a glaciotectonic complex (based on Aber and Ber, 2007). Typical SSDS formed subglacially and proglacially by glaciotectonic deformation and in the far field of the ice sheet in a periglacial environment (Müller et al. in press).

2. Potential and Limitations of the use of SSDS as Earthquake Indicator



- No diagnostic type of earthquake-induced SSDS exists
- There are several trigger processes that cause the formation of similar SSDS
- Earthquake-induced SSDS show the same deformation style as non-earthquake SSDS

3. Different styles of SSDS

Earthquakes can cause liquefaction and fluidization processes in susceptible sediments, such as fine- to medium-grained water-saturated sand, silt and mud with a loose grain packing. These SSDS include load casts, flame structures, ball-and-pillow structures (pseudonodules), convolute bedding (involutions), slide blocks (liquefaction speads), dish-and-pillar structures, clastic dykes, sand volcanoes and craters (Fig. 2). To unambiguously determin earthqaukes as the trigger mechanism it is nessesary to carefully evaluate the SSDS and the depositional system.

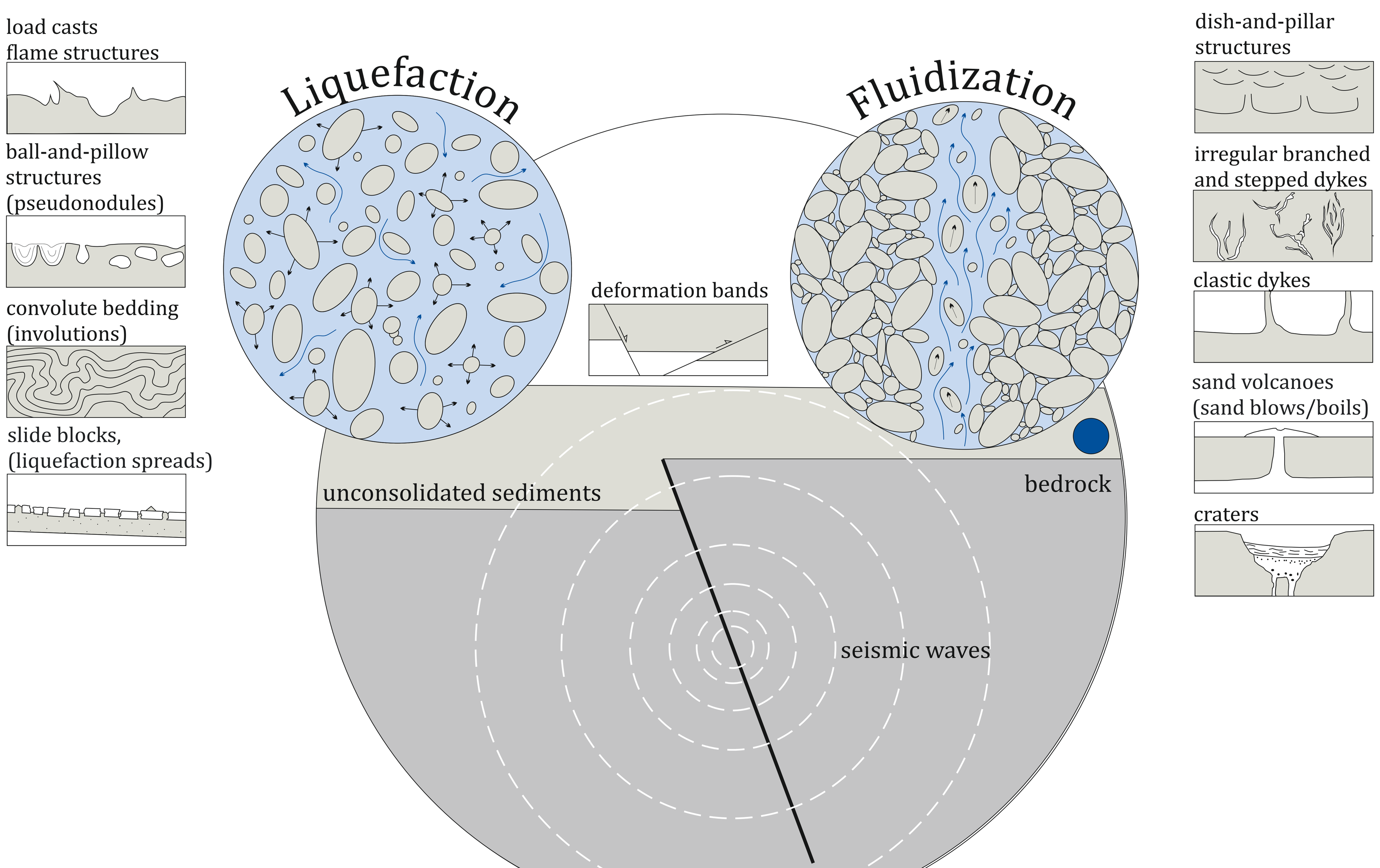


Fig. 2: Deformation structures that are related to neotectonic fault movement accompanied by an earthquake. The two main fluid escape mechanisms liquefaction and fluidization are based on Lowe (1975).

Table 1: Typical deformation structures that are related to periglacial, glaciotectonic and neotectonic processes (earthquakes). Note that different trigger processes cause similar deformation structures.

Typical SSDS	Trigger Process
Load casts, flame structures, ball-and-pillow structures (involutions), clastic dykes, sand volcanoes, craters, folds, thrusts, ice-wedge casts, deformation bands	Periglacial processes ▼
Load casts, flame structures, ball-and-pillow structures, clastic dykes, sand volcanoes, folds, thrusts, thrust-sheets, kettle holes, iceberg scours, deformation bands	Glaciotectonic processes ★
Load casts, flame structures, ball-and-pillow structures, intrusions, dish-and-pillar structures, clastic dykes, sand volcanoes, craters, slide blocks (liquefaction speads), folds, thrusts, deformation bands	Earthquakes / Neotectonic processes ●

4. Different Trigger Mechanisms and Related SSDS

Fig. 3: Deformation structures that developed in northern Germany due to different trigger processes. The different symbols show possible triggers that lead to similar structures. A) Deformation band in Middle Pleistocene sand caused by neotectonic fault movements; B) sand volcano in Late Pleistocene sediments caused by paleo-earthquakes; C) fold structures in a Middle Pleistocene subglacial shear zone ; D) fold structures in a Middle Pleistocene subglacial shear zone; E) conjugate deformation bands with normal displacement in Middle Pleistocene sand caused by proglacial deformation; F) reverse displaced deformation bands in Middle Pleistocene sand caused by an advancing ice sheet; G) ice-wedge cast in Middle Pleistocene sand caused by freezing and thawing; H) involutions in Middle Pleistocene sand caused by freezing and thawing.

5. The Solution - The Combination of Deformation Bands and SSDS

The inconclusive nature of SSDS requires a more robust indicator for neotectonic activity. The work of Cashman et al. (2007), Brandes and Tanner (2012) and Brandes et al. (2018a, b) showed that near-surface deformation bands in unconsolidated sediments are an indicator for neotectonic activity at basement faults. The occurence of deformation bands and SSDS are the most reliable indicator for paleo-earthquakes, if the deformation bands follow the strike of the nearby fault and the SSDS match some criteria. The deformation bands reflect the fault activity and the SSDS indicate the propagation of seismic waves (Müller et al., in press).

6. Criteria for Earthquake-related SSDS

Characteristic features of seismically-induced SSDS are:

- the occurrence close to major faults
- a large lateral extent, although high lateral variabilities of the deformation style, pattern, and bed thickness are possible, depending on the susceptibility of the sediments for liquefaction and/or fluidization processes
- the occurrence of deformation bands close to the tip line, where the fault displacement goes to zero.

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