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Part I

Introduction

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More Information

1

Glacially Triggered Faulting

A Historical Overview and Recent Developments

HOLGER STEFFEN, ODLEIV OLESEN AND RAIMO SUTINEN

ABSTRACT

Glacially triggered faulting, also called glacially induced faulting or postglacial faulting, describes fault movement caused by a combination of tectonic and glacially induced isostatic stresses. This type of faulting is mainly recognized in intraplate regions but is also proposed for some plate boundary areas. Stresses induced by the advance and retreat of an ice sheet are thought to be released during or after ice melting and to reactivate pre-existing faults. Past reactivations were probably accompanied by great-magnitude seismic events triggering hundreds of landslides and seismically induced soft-sediment deformation structures in the region surrounding the faults. Reliable field evidence for reactivated faults in and around many formerly glaciated areas has considerably increased the number of confirmed and probable glacially induced faults in recent years.

We provide a historical overview of dedicated geoscientific investigations from the early reports of this type of faulting until recent findings. Beforehand, we discuss the definition of glacially triggered faulting, suggest a revision of the classification criteria and update the grading criteria for glacially induced fault claims.

1.1 Introduction

Climatic variations have led to repeated glaciations on the Earth. Especially, the Pleistocene glaciations have left many visible traces on the Earth's surface in the form of moraines, striated bedrock, erratics, etc. The Earth's response to the load redistributions of water, ice and sediments on the surface is termed *glacial isostatic adjustment* (GIA), (Wu & Peltier, 1982). Due to the nature of GIA several present-day observations can be related to the last glaciation, which peaked between 26 ka BP and 18 ka BP (Clark et al., 2009). The most prominent process is the ongoing land uplift of formerly glaciated areas such as Fennoscandia, North America and Patagonia.

A generally less appreciated GIA effect is crustal stress release that occurs during and after deglaciation and that can reactivate pre-existing faults and weakness zones through earthquakes. The shaking from these earthquakes can cause landslides and soft-sediment deformation structures (SSDS) (Fenton, 1999; Munier & Fenton, 2004; Olesen et al., 2004; Lund, 2015). Meanwhile, a wealth of such observations is available from around the world, which will be discussed in Chapters 11–21 of this book. Research focused until very recently on Northern Europe, i.e. Lapland, and eastern North America, but stress release due to GIA is now suggested in and around other formerly and presently glaciated areas as well (Brandes et al., 2015). Some studies additionally discuss fault reactivation during the advance of an ice sheet (Munier & Fenton, 2004; Brandes et al., 2011; Pisarska-Jamroży et al., 2018).

Several terms have been used to describe GIA-related stress release in the literature (see e.g. Fenton, 1999; Lund & Näslund, 2009). Perhaps the most common term is *postglacial faulting*, and the reactivated faults are consequently called *postglacial faults* (PGFs). This term might have similarities with, but is not connected to, the term *postglacial rebound* (PGR), a term generally used until the late 1970s to describe the land uplift after the last glaciation. However, the word *postglacial* in PGF does constrain events to the time period after the glaciation.

Peltier and Andrews (1976) introduced the term GIA, which encompasses PGR but also effects prior to deglaciation (i.e. during glaciation) and any consequent processes such as geoidal, rotational and sea-level changes as well as any corresponding effects due to stress changes. Hence, postglacial faulting is also encompassed by the nowadays widely accepted term ‘GIA’. Fenton (1999) considered the term ‘postglacial faulting’ unsatisfactory because it implies a temporal constraint and omits the fault genesis. He suggested that the terms *glacio-isostatic faulting* or *glacial rebound faulting* to be more suitable for faulting due to GIA. Nonetheless, postglacial faulting was still used in the literature but understood in a much broader temporal sense, e.g. also applicable to faulting occurring during glacial advance. Lund and Näslund (2009) introduced the term *glacially induced faulting* and correspondingly *glacially induced fault* (GIF) for the reactivated fault. Especially the latter term, GIF, has been increasingly used in the last decade to describe the faults although the ‘classic term’ PGF has been retained by many researchers, especially when referring to the prominent faults in Northern Europe (Figure 1.1). Another term that was discussed among the community is *glacially triggered faulting* (GTF) and thus *glacially triggered fault*. The term arose because ‘induced’ was interpreted by some researchers as meaning either new fault generation (rather than fault reactivation) or faulting associated with human activity, such as anthropogenic earthquakes. For others, GTF is simply the same as glacially induced faulting.

In this book the reader will find that all terms except glacially triggered fault have been used, depending on the taste of the authors. The interchangeable terms glacially triggered faulting, glacially induced faulting and postglacial faulting refer to the mechanism, whereas glacially induced fault and postglacial fault refer to the reactivated fault. Nonetheless, we encourage use of glacially triggered faulting or GTF when referring to the mechanism and glacially induced fault or GIF for the reactivated fault.

Glacially triggered faulting should not be confused with glaciotectonics, which is mostly the near-surface deformation of sediments and sometimes bedrock as a direct consequence of ice movement and which sometimes shows similarities with potential GTF features such as faults and SSDS. We refer the reader to Chapter 4, by Müller et al., who discuss the differences of glaciotectonics and GTF in detail.

Next, we discuss classification criteria for a GIF. This is followed by a brief history of major findings on GTF and the latest developments.

Figure 1.1 Oblique aerial photograph (SE view, taken from Olesen et al., 2004) of the fault scarp developed along the Máze Fault System constituting the central part of the Stuoragurra Fault Complex in Norway. The fault segment is located approximately 10 km to the NNE of the Masi settlement. Groundwater is leaking from the foot of the escarpment (lower right). (A black and white version of this figure will appear in some formats. For the colour version, please refer to the plate section.)

1.2 Classification Criteria for a Glacially Induced Fault

Given the heterogeneous structure of Earth's lithosphere, it is necessary to define criteria for correctly identifying a GIF and distinguishing it from the vast number of other faults around the globe. Such criteria were introduced by Mohr (1986) and have been modified and expanded by Fenton (1991, 1994). The six original criteria of Fenton (1991), briefly summarized, were as follows: (1) a fault must be continuous with a prominent disruption of pre-existing geological units; (2) its scarp face should not be affected by ice or meltwater; (3) it is not generated due to differential erosion; (4) it must displace late Quaternary/Holocene sediments or morphological features (e.g. shorelines); (5) it is not generated due to differential compaction; and (6) it should be trenched to ensure fault activity and determine erosional influence. Features 1 and 4 categorize the geological structure; features 2, 3 and 5 exclude other processes; and the last is a rather technical note on investigation methods. The latter was removed by Fenton (1994), who established seven criteria (e.g. Fenton, 1999; Munier & Fenton, 2004) and which we repeat verbatim, except for the addition of 'F' to the numbering, for clarity in the discussion to come:

F1. Faults should have demonstrable movement since the disappearance of the last ice sheet within the area of concern.

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Excerpt
More Information

F2. The fault should offset glacial and late-glacial deposits, glacial surfaces or other glacial geomorphic features. Preferably, it should be demonstrated that the fault displaces immediately postglacial stratigraphy and/or geomorphic features, though it need not cut younger features.
F3. Fault scarp faces and rupture planes expressed in bedrock should show no signs of glacial modification, such as striations or ice-plucking. Limited glacial modification, however, may be present on scarps that are late-glacial or inter-glacial in age.
F4. Surface ruptures must be continuous over a distance of at least 1 km, with consistent slip and a displacement/length ratio (D/L) of less than 0.001.
F5. Scarps in superficial material must be shown to be the result of faulting and not due to the effects of differential compaction, collapse due to ice melt, or deposition over pre-existing scarps.
F6. Care must be taken with bedrock scarps controlled by banding, bedding, or schistosity to show that they are not the result of differential erosion, ice-plucking, or meltwater erosion.
F7. In areas of moderate to high relief, the possibility of scarps being the result of having been created by deep-seated slumping driven by gravitational instability must be disproved.

Muir Wood (1993), in work contemporary to Fenton’s, provides five classification criteria in the form of a checklist. They can be briefly summarized, following Smith et al. (2014), that:

M1. a displaced sediment layer must have been formerly continuous;
M2. this sediment offset must be directly related to a fault;
M3. the ratio of displacement to length should be less than 1:1,000;
M4. the displacement should be consistent along the fault; and
M5. the movement should have occurred synchronously along the fault.

These can be considered as a more specific refinement of F1, F2 and F4 criteria listed earlier. The M1–M5 checklist has been applied in several dedicated studies, see e.g. Olesen et al. (2004), Smith et al. (2014) and Brooks and Adams (2020). Olesen et al. (2004) merged the M1–M5 checklist with a revised form of the F1–F7 criteria.

As research progresses, new findings warrant a discussion of the criteria, most notably criteria M3 (which is equivalent to F4) and M5. Therefore, we introduce revised classification criteria for GIFs. These are modified from the criteria listed earlier and for easier application expressed as a checklist like that of Olesen et al. (2004). We comment on each criterion and thereafter discuss previous criteria that should no longer be considered definitive.

The herein revised classification criteria are as follows:

1. **Disruption of a formerly continuous geological feature**: There is either an offset of an originally continuous surface or of sediment layer(s) which can be seen on the surface in an outcrop or in seismic reflection profiles, and/or there is an internal disturbance of a sediment, e.g. in the form of soft-sediment deformation structures (SSDS).

   Comment: This criterion revises, combines and extends F2 and M1. Previously, the disruption of a sediment unit was generally thought to be by a fault or fault scarp (F1, F2 and M1). However, SSDS also can be generated due to glacially triggered earthquakes along GIFs (e.g. Munier & Fenton, 2004; Müller et al., see Chapter 4), and thus should be added. The age of the sediment (see F1 and F2, e.g. ‘since the last ice sheet’, ‘glacial’ or ‘postglacial’) is of lesser importance because previous glaciations could have led to GIFs, and under certain conditions faults can be reactivated during ice advance (see Steffen et al., Chapter 2). Smith et al. (see Chapter 12), also hypothesize that some recognized GIFs were reactivated by glaciations that occurred prior to the most recent one.

2. **Relation to a fault that shows demonstrable offset**: A fault with noticeable offset can be connected to the disrupted feature (fault, fault scarp, SSDS, etc.). This fault is the GIF.

   Comment: We merge F1 and M2 and rephrase.
3. **Consistent displacement**: There is a reasonably consistent amount of slip along the length of the GIF.

   Comment: This is M4 and parts of F4. This criterion can be easily applied to GIFs with surface exposures. For faults with only indirect evidence of reactivation, e.g. with SSDS, this must be verified with appropriate methods (trenching, geophysical techniques); see e.g. Beckel et al., in Chapter 7, and Gestermann and Plenefisch, in Chapter 6.
4. **Relation to a formerly glaciated area**: The disturbed feature is found within or near to a formerly glaciated area.

   Comment: As clearly indicated by its name a GIF can be found within a formerly glaciated area. However, the GIA process also affects the region surrounding the ice sheet, most notably the peripheral bulge area. This area extends a few hundred kilometres around the ice sheet and is affected by glacially induced stress changes (Wu et al., Chapter 22). GIFs can thus occur in such a peripheral region, e.g. the Osning Thrust in Germany (Figure 1.2) as suggested by Brandes et al. (2015). Therefore, we suggest adding this criterion to highlight that GIFs are not limited to the formerly glaciated area. Earlier criteria assumed that GIFs were only to be found within the formerly glaciated area. In other words, the ‘area of concern’ of criterion F1 is extended by understanding the physics of GIA.
5. **Convincing exclusion of trigger mechanisms other than GIA**: As other processes are also able to reactivate faults or generate features that can mimic GIFs, those processes must be meticulously excluded in order to clearly confirm a GIF as such. Hence, investigation must convincingly demonstrate that there are:
   - no signs of gravity sliding as the driving mechanism for fault activity in areas of sufficient relief;
   - no signs of glacial modifications of fault scarps (especially those in metamorphic rocks controlled by schistosity, banding or bedding) implying glacial erosion (differential erosion or ice-plucking) was the cause;
   - no signs of glaciotectonics;
   - no signs of collapse due to melting of buried ice, differential compaction or deposition over a pre-existing erosional scarp resulting in an apparent offset in overburden;
   - in case of SSDS, no signs of other processes, e.g. mass movements, landslides, groundwater-level fluctuations, hydrostatic pressure changes related to lake drainage, water-wave or tsunami passage.

   Comment: These are reformulated criteria F3, F5, F6 and F7 (among others), mainly following the criteria list in Olesen et al. (2004). They are combined into a single criterion to provide a checklist. The last point of this criterion concerning SSDS has

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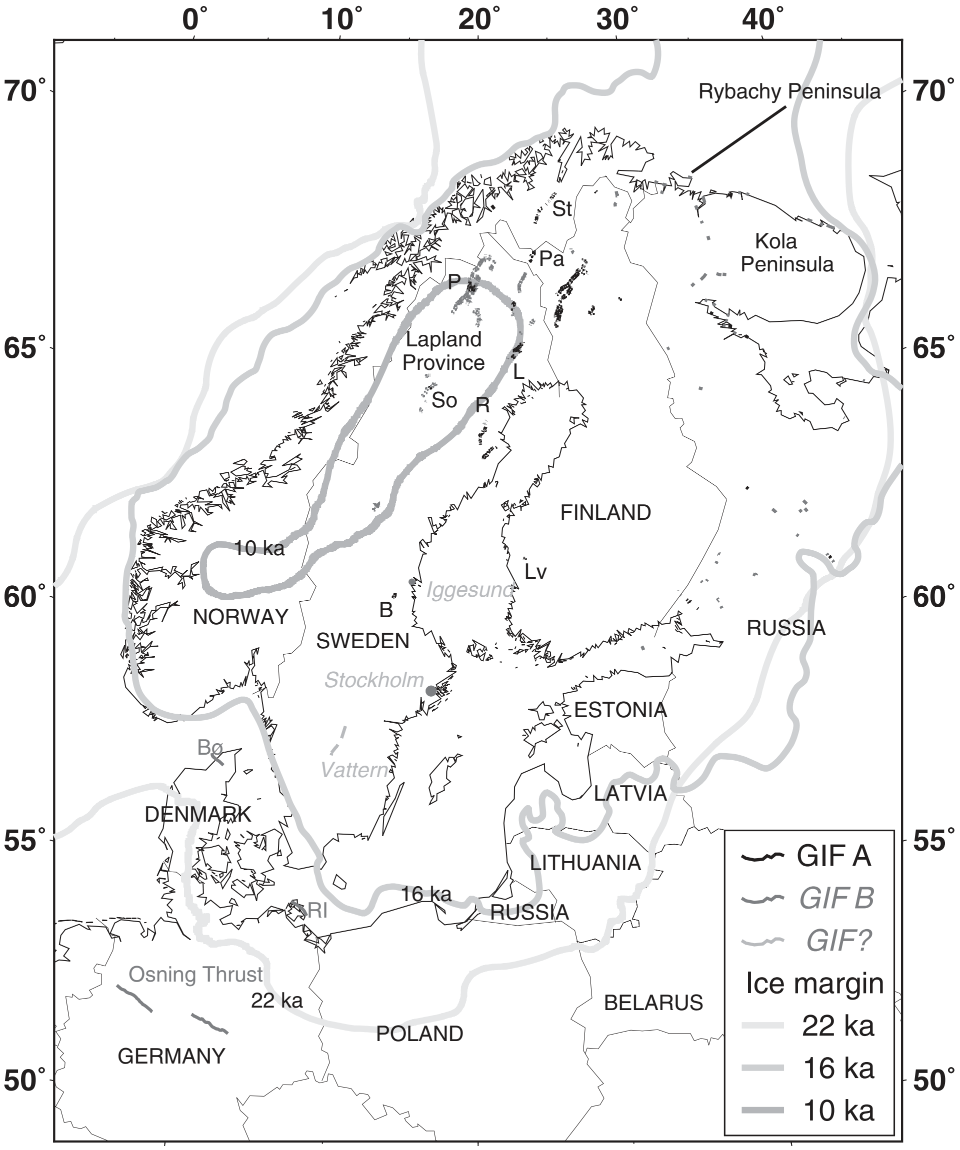

Figure 1.2 Glacially induced faults (GIFs, black lines and dots, uncertainty ‘A’ in Munier et al., 2020), probable GIFs (dark grey lines, uncertainty ‘B’ in Munier et al., 2020), suggested GIFs (light grey lines, uncertainty ‘C’ in Munier et al., 2020) and selected locations of suggested palaeoseismicity (light grey dots) in Northern and Central Europe. Ice limits from DATED-1 (Hughes et al., 2016). B – Bollnäs, Bø – Børglum, L – Lansjärv, Lv – Lauhavuori, P – Pärvie, Pa – Palojärvi, R – Röjnoret, RI – Rügen Island, So – Sorsele, St – Stuoragurra.

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More Information

been added because these structures are a common feature in the recent literature linked to glacially triggered earthquakes.

These five criteria must all be fulfilled for a fault to qualify as an (almost) certain GIF. There is no longer an age constraint, so GIFs are not limited to just the most recent glaciation and the times shortly before and after local deglaciation. Appropriate investigation methods must be ensured, of course, so that especially criterion 5 is convincingly fulfilled.

We suggest that two previously used criteria, M3 (= F4) and M5, be removed from the list of required criteria, but they might be useful as additional considerations:

1. **Displacement ratio**: The ratio of (usually vertical) displacement to overall length of the fault normally should be less than 1:1,000. For most GIFs this ratio is between 1:1,000 and 1:10,000.

   Comment: This is criterion M3, which can be used for surficial faults like the prominent GIFs in northern Fennoscandia. However, Muir Wood (1993) and Fenton (1994) already noted that this is not a necessary requirement, e.g. because mechanical behavior of some fault materials hampers the development of prominent fault scarps. The Lansjärv Fault in Sweden (Figure 1.2) has a ratio higher than 1:1,000 (Smith et al., 2014) and is thus an exception. This criterion would also limit the term GIF to structures that can be clearly identified on the surface. However, erosional processes and human activity, among other events, in and near formerly glaciated areas, especially those areas around the edge of the former ice sheets where the ice retreated 10,000 years earlier, may have buried, removed or leveled (parts of) surface traces of GIFs (see Sandersen & Sutinen, Chapter 3). Brooks and Adams (2020), for example, argue that the surficial fault traces of the 1989 Ungava earthquake in Canada (average surface offset of 0.8 m; Adams et al., 1991) are likely no longer visible today. Consequently, this criterion appears too strict.
2. **Synchronous displacement**: Reactivation of the fault affected the entire fault.

   Comment: This is M5. It was originally listed to allow an estimation of earthquake magnitude (Raymond Munier, personal communication, 2020). The criterion is also rather strict and was omitted by Olesen et al. (2004). Recent dating results by Olesen et al. (see Chapter 11) show that each of the three systems of the Stuoragurra Fault Complex was reactivated at different times.

Muir Wood (1993) introduced a grading scale for qualifying an observation as neotectonics in view of all information and any uncertainties. This scale is also applied to the GIF database of this book (Munier et al., 2020), but the wording of the scale is slightly altered: the five grades are kept, but neotectonics is replaced with GIF:

A. Almost certainly a GIF
B. Probably a GIF
C. Possibly a GIF
D. Probably not a GIF
E. Very unlikely a GIF

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Excerpt
More Information

This scale has been used recently by Brooks and Adams (2020) to classify Eastern Canadian GIF claims. The ‘classic’ postglacial faults in Northern Europe are usually classified as A. Many claims, especially at the edge of and outside the former ice sheet, are currently of grade B or C, mainly because they are not yet fully investigated and thus do not fulfill all classification criteria. Some earlier claims in the literature are classified as D or E when newer investigations could not support the initial claim; see e.g. Olesen et al. (2004). It is therefore fully possible that many currently B- or C-graded claims will receive a D or E after additional investigations in the future or will no longer be listed as GIF. For tracking of claims, we suggest removed claims be documented (ones which can be considered ‘F. Not a GIF’) together with a rationale for their removal. In turn, a small fraction of D- and E-graded faults may be elevated to A or B after more investigation.

1.3 Brief Historical Overview until the Early 2000s

Munier and Fenton (2004) provided the only previous history of global GTF research. Their review included peer-reviewed publications and limited-distribution reports as well as conference abstracts and personal communications. Some regional overviews were compiled for the Northern European faults (see corresponding Chapters 11–14 for references) and for a few other areas, for example, by Firth and Stewart (2000) for the British Isles and by Fenton (1994) for Eastern Canada and the Eastern United States, here updating work by Oliver et al. (1970) and Adams (1981). The work by Fenton (1994), for example, lists 173 publications. Clearly, our review cannot address all previous studies. In the following, we limit ourselves to the most important contributions, although even those might be different for other researchers. More information can be found though in this book’s chapters. Section 1.4 summarizes the developments of the last decade that gave rise to this book.

In the history of GTF research one must distinguish between (i) studies that discuss GTF and use one of the terms (mainly postglacial faulting) mentioned above, (ii) studies that discuss GTF but do not name it as such and (iii) studies that use the term postglacial faulting or similar to describe another process. Fenton (1994) points to Mather (1843) as an early describer of a postglacial faulting feature, which is not named as such. The term was used by Matthew (1894) for the first time. Then, in the late nineteenth/early twentieth century, GTF was widely recognized in investigations of postglacial geomorphic features in Eastern Canada and the Northeastern United States (Munier & Fenton, 2004). However, most of those features have very small offsets. Also, in Europe the term ‘postglacial faulting’ was used for small features (e.g. Brøgger, 1884; Reusch, 1888; Munthe, 1905), interestingly, far away from the Lapland Province with its prominent, but then-undiscovered, GIFs.

1.3.1 History in Lapland

Tanner (1930) noticed a 10-metre offset in raised shorelines along northern Rybachy (Fisher) Peninsula north of the Kola Peninsula (Figure 1.2) that could be related to fault