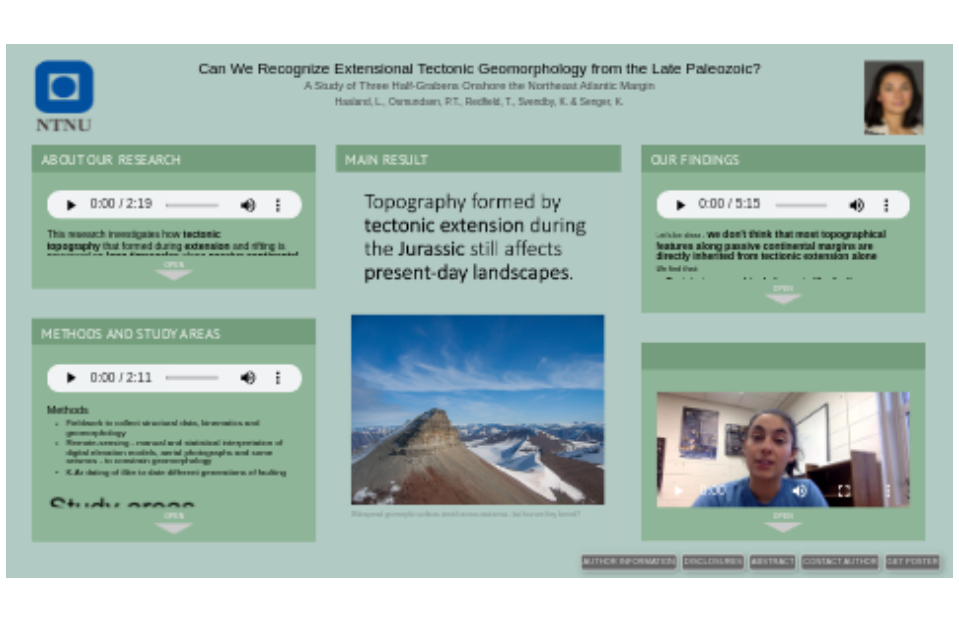
Can We Recognize Extensional Tectonic Geomorphology from the Late Paleozoic?



A Study of Three Half-Grabens Onshore the Northeast Atlantic Margin

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ABOUT OUR RESEARCH

This research investigates how **tectonic topography** that formed during **extension** and rifting is preserved on **long timescales** along **passive continental margins**.

We study topography in and around three half-graben basins (structures that record tectonic extension) to figure out:

1) Can we still recognize **relict landscape elements from rifting** along passive continental margins?

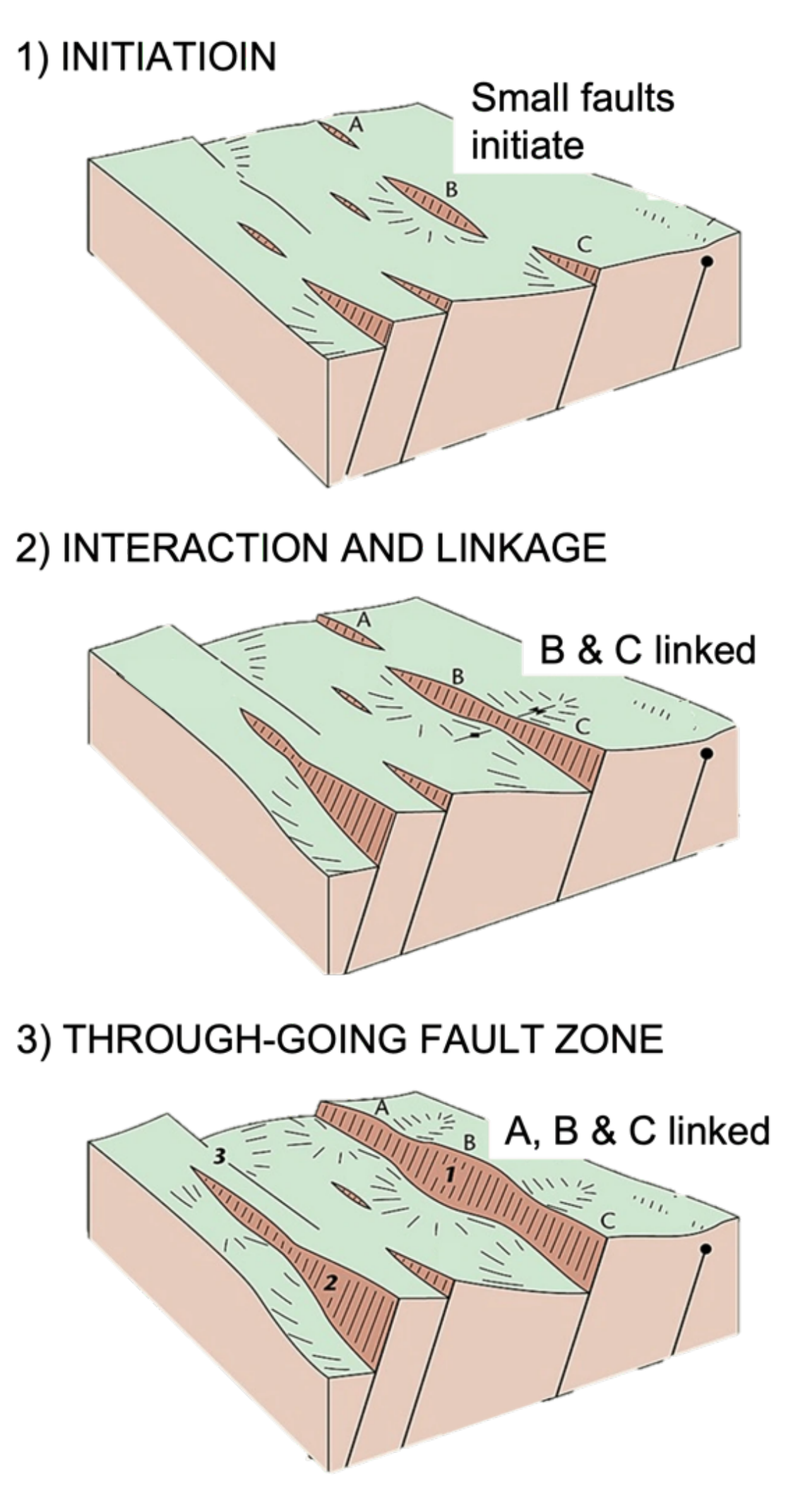
2) How do **rift-related features influence the present-day geomorphology** along passive continental margins?

Interested in some more background? Keep on reading

The formation and evolution of certain landscape elements in Scandinavia have been a topic of much debate. Some researchers interpret landscapes to be the result of crustal evolution during rifting, while others find that landscapes are first and foremost a product of the last glaciations.

Though we know a lot about how tectonic landscapes initially form, we don't know much about how they are preserved over time. We use half-graben basins, known to record tectonic extension, as field sites. This allows us to study individual landscape elements to assess their formation and evolution, and possible association to extensional tectonic events.

Models that describe the formation and evolution of tectonic topography in areas that are currently undergoing tectonic extension are useful to us because they predict which landscape elements we would expect to find if topography is preserved. The main model that we use is the Gawthorpe & Leeder (2008) three-stage description of normal fault and half-graben development:



A three-stage development of normal faults and half-graben basins in actively extending regions. Modified from Gawthorpe & Leeder (2008).

A number of topographical features are associated with the development of half-graben basins, importantly:

- A steep fault scarp with an uplifted footwall and downthrown hanging wall
- A less steep scarp in the hanging wall
- Closely spaced drainage with small catchment areas in the footwall as opposed to more widely spaced drainage and larger catchment areas in the hanging wall

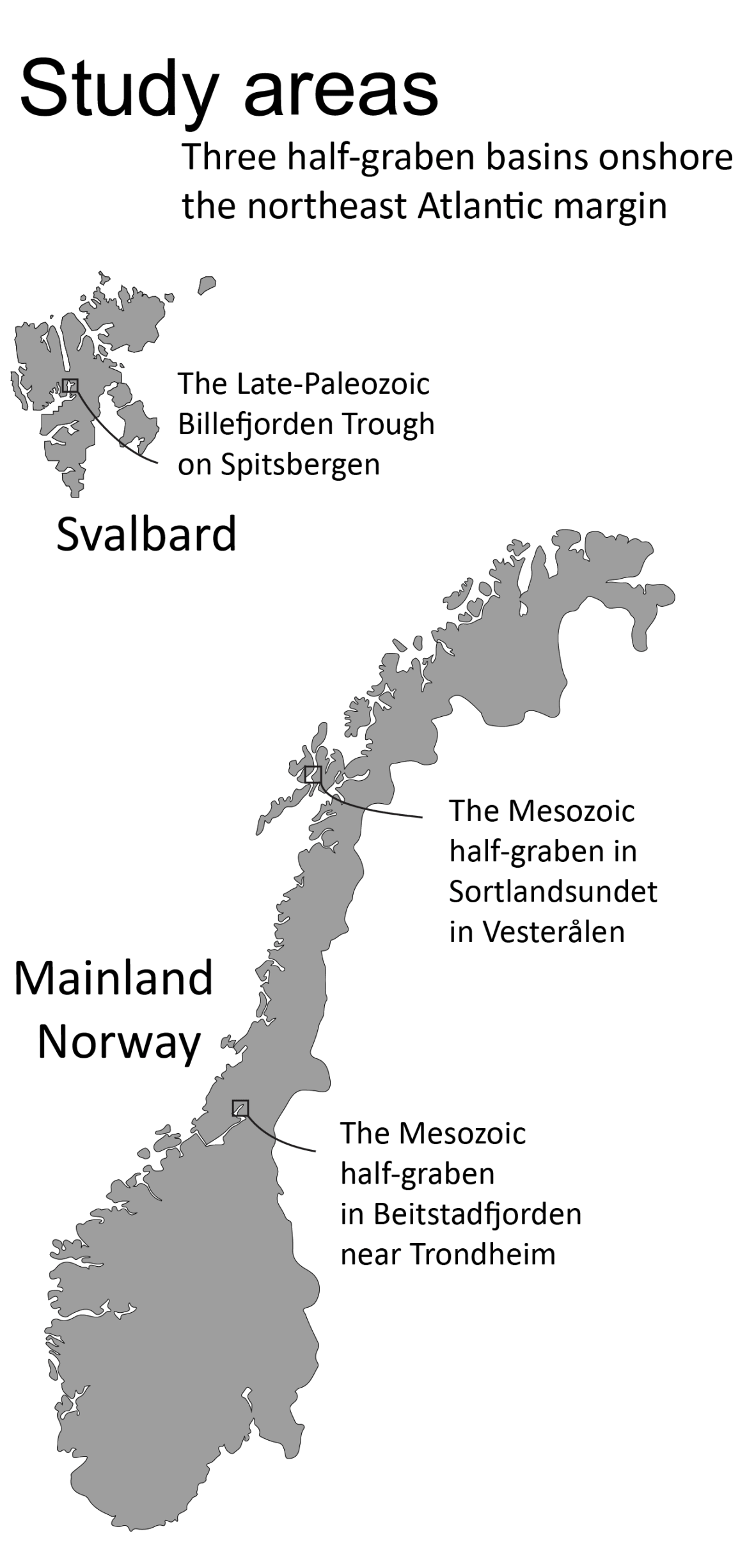
This study poses the question:

Are extensional features such as the ones described above still recognizable in the present-day landscapes of Scandinavia?

METHODS AND STUDY AREAS

Methods

- Fieldwork to collect structural data, kinematics and geomorphology
- Remote-sensing - manual and statistical interpretation of digital elevation models, aerial photographs and some seismcs - to constrain geomorphology
- K-Ar dating of illite to date different generations of faulting

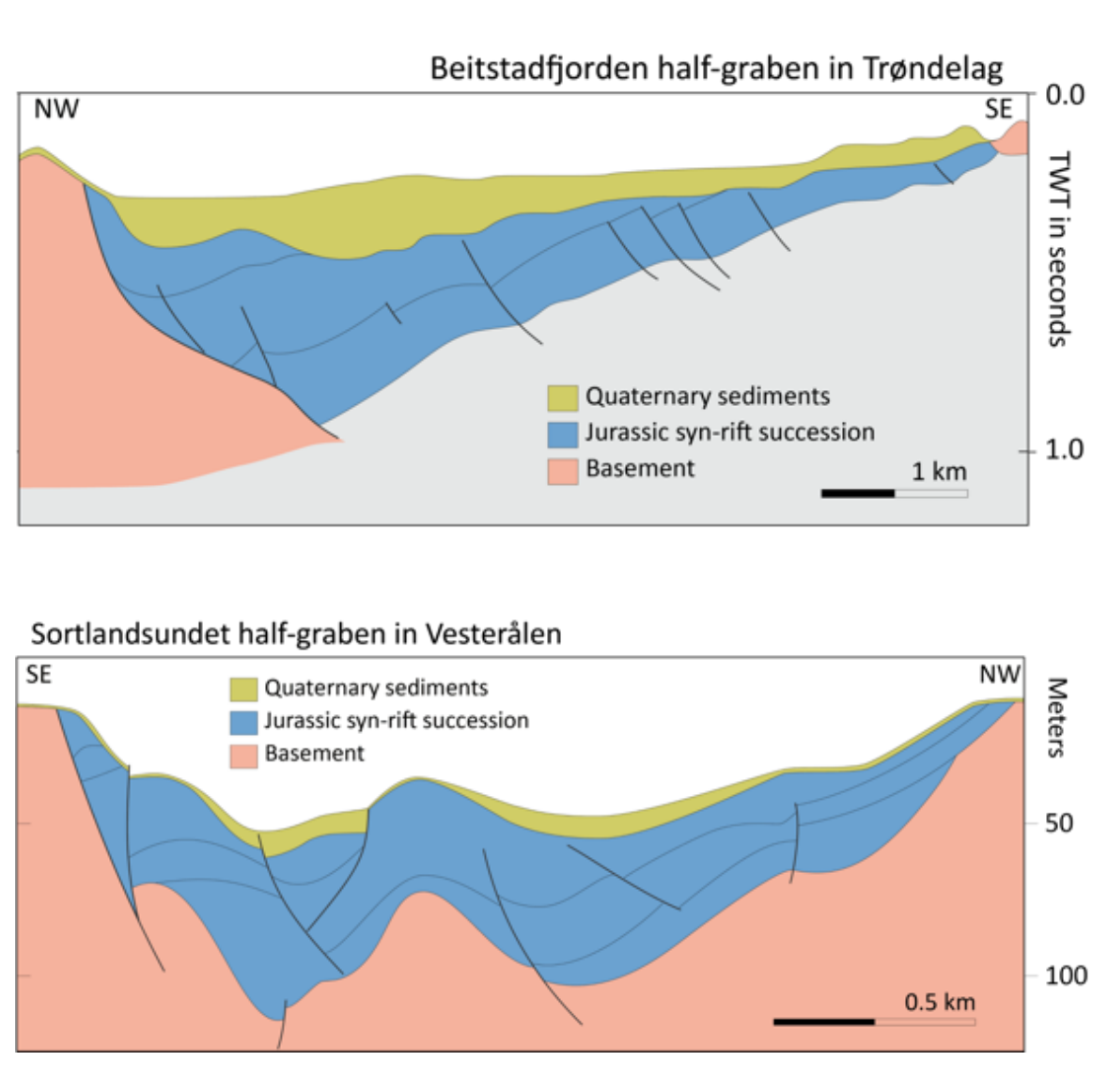

Study areas
Three half-graben basins onshore the northeast Atlantic margin
The Late-Paleozoic Billefjorden Trough on Spitsbergen
Svalbard
The Mesozoic half-graben in Sortlandsundet in Vesterålen
Mainland Norway
The Mesozoic half-graben in Beitstadfjorden near Trondheim

The Billefjorden Trough on Svalbard is Late Carboniferous in age, and has the entire basin stratigraphy exposed onshore. Additionally, there is a stratigraphic record preserved covering both the hanging wall and the footwall.

The two half-grabens onshore mainland Norway are Jurassic in age, and submerged in fjords. In these field sites, basin morphology and stratigraphy can only be studied in seismic sections (see below). The surrounding topography is quite well-exposed, and is used (with caution!) as a proxy for the morphology of the top basement.

As the three basins are not directly comparable in age, the study is based on the deformational *processes* involved in forming landscapes, and does not necessarily focus on correlating the basin-forming events in time between the three study areas.

As the two basins onshore mainland Norway do not have a stratigraphic record preserved, it is difficult to determine which processes happened when. It is useful to be able to compare morphologies to the basin on Svalbard for this purpose.

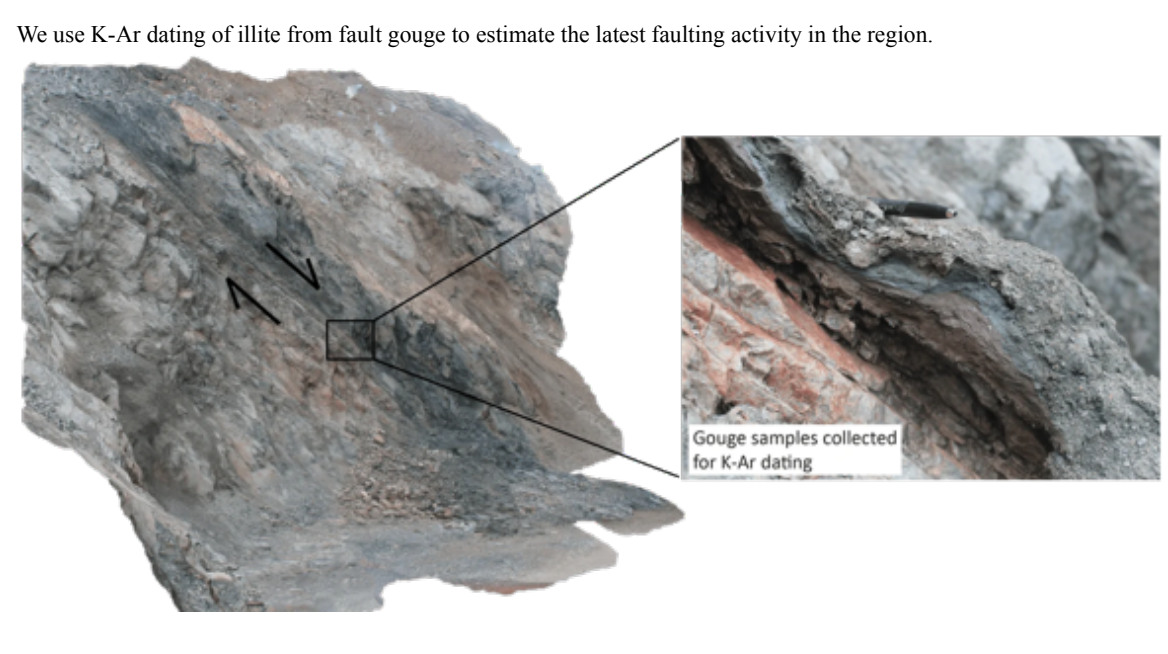

Beitstadfjorden half-graben in Trøndelag
NW
SE
0.0
TWT in seconds
1.0
Quaternary sediments
Jurassic syn-rift succession
Basement
1 km
Sortlandsundet half-graben in Vesterålen
SE
NW
Quaternary sediments
Jurassic syn-rift succession
Basement
Meters
50
100
0.5 km

Seismic sections of the two half-graben basins onshore mainland Norway. These are the best interpretations we have of basin morphology and stratigraphy of the submerged basins.

Timing still becomes an issue.

When were the basin-forming faults active? This important to know in order to constrain tectonic topography that possibly relates to the basin-forming events.

We use K-Ar dating of illite from fault gouge to estimate the latest faulting activity in the region.



3D-model of normal fault exposed in a quarry near the Sortlandsundet half-graben in Vesterålen (see location marked Q in photo of fault scarp in results section). Inset is a close-up photo of the fault gouge that we sampled for K-Ar dating of illite.

MAIN RESULT

Topography formed by **tectonic extension** during the **Jurassic** still affects **present-day landscapes.**

Widespread geomorphic surfaces stretch across vast areas - but how are they formed?

OUR FINDINGS

Let's be clear - **we don't think that most topographical features along passive continental margins are directly inherited from tectionic extension alone**

We find that:

1. **Certain topographical elements like fault scarps may be directly inherited from the initial rifting process**. Fault scarps vary in appearance, and are more prominent if the faulting was reactivated at a later stage
2. The most common way that topography is inherited from tectonic extension is through the formation of **weakness zones**, that later **reactivate**. This **rejuvenates tectonic topography** from earlier phases of deformation
3. The topographic expression in a region is also heavily dependent on other factors, such as **pre-rift tectonics, and post-rift tectonics and erosion, importantly including glacial activity**.

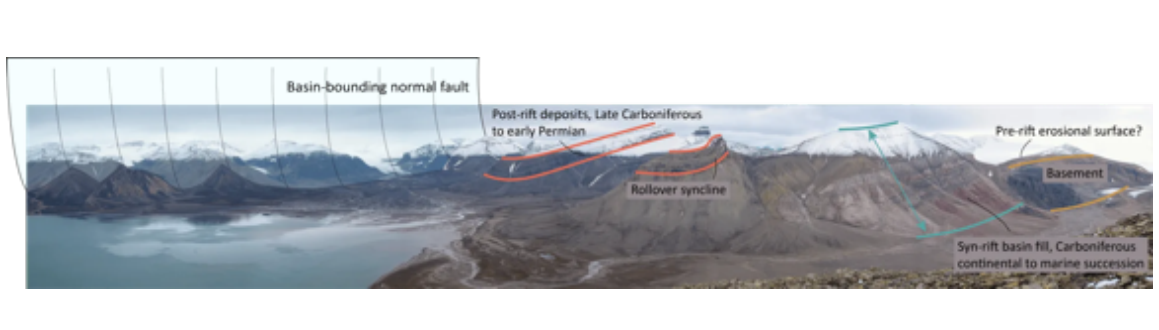
Scroll for more details.

Topography in the three study areas is important.

i) Topographical **scarps** are prominent in all three areas, and are thought to be directly inherited from the basin-forming extension:

Photo taken along-strike of the fault scarp in Beitstadfjorden in mainland Norway. The half-graben basin is located in the fjord on the right-hand side of the photo.

Photo of the fault scarp in Vesterålen in mainland Norway. The half graben basin lies in the fjord in the foreground. Q marks the quarry depicted in the 3D-model in the methods section. Modified from Osmundsen et al. (2010).


Basin-bounding normal fault
Post-rift deposits, Late Carboniferous to early Permian
Rollover syncline
Pre-rift erosional surface?
Basement
Syn-rift basin fill, Carboniferous continental to marine succession

Interpretation of the half-graben in Billefjorden. Notice the topographical scarp that is created by the basin-bounding normal fault in the background of the picture. Parts of the half-graben basin are in the fjord in front of the basin-bounding normal fault, but the basin stratigraphy is also exposed onshore in the right-hand side of the photo.

ii) In Vesterålen, we see landscape features that seem to be associated with extensional topography:

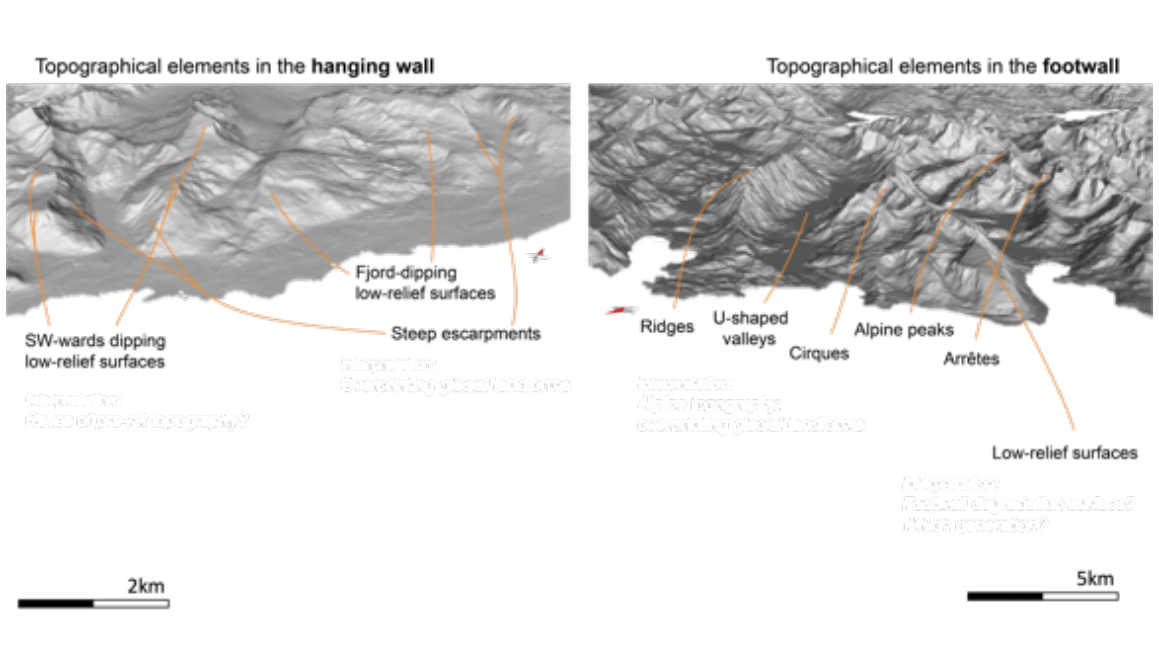
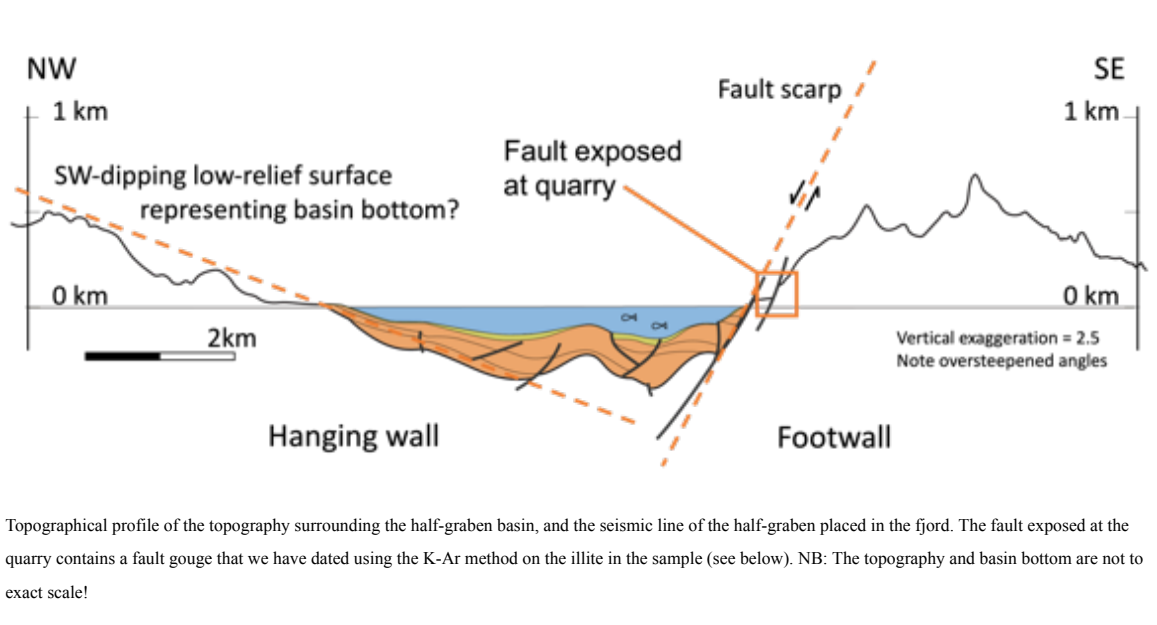

Topographical elements in the hanging wall
Fjord-dipping low-relief surfaces
SW-wards dipping low-relief surfaces
Steep escarpments
2km
Topographical elements in the footwall
Ridges
U-shaped valleys
Cirques
Alpine peaks
Arrêtes
Low-relief surfaces
5km

Figure showing topographical differences between the footwall and hanging wall of the half-graben basin in Vesterålen. Notice also that the incision pattern in the hanging wall shows much larger areas without incision compared to the footwall.

The relative **difference in topography** in the hanging wall and footwall sides of the half-graben basin indicate that the footwall is uplifted compared to the hanging wall. Additionally, the hanging wall has larger areas that **lack incision**, indicating that drainage patterns in the hanging wall might have been more widely spaced as they formed, compared to in the footwall. Glacial erosion has later exploited the initial drainage channels, exaggerating the incision in the footwall and obsuring some of the potential narrowly spaced incision pattern that might have existed.

We also see that the footwall scarp is much steeper than the topography in the hanging wall. The topography in the hanging wall, used as a proxy for top basement, coincides well with the basin bottom that we interpret from seismics:


NW
1 km
SW-dipping low-relief surface representing basin bottom?
0 km
2km
Hanging wall
Fault exposed at quarry
Fault scarp
SE
1 km
0 km
Vertical exaggeration = 2.5
Note oversteepened angles
Footwall

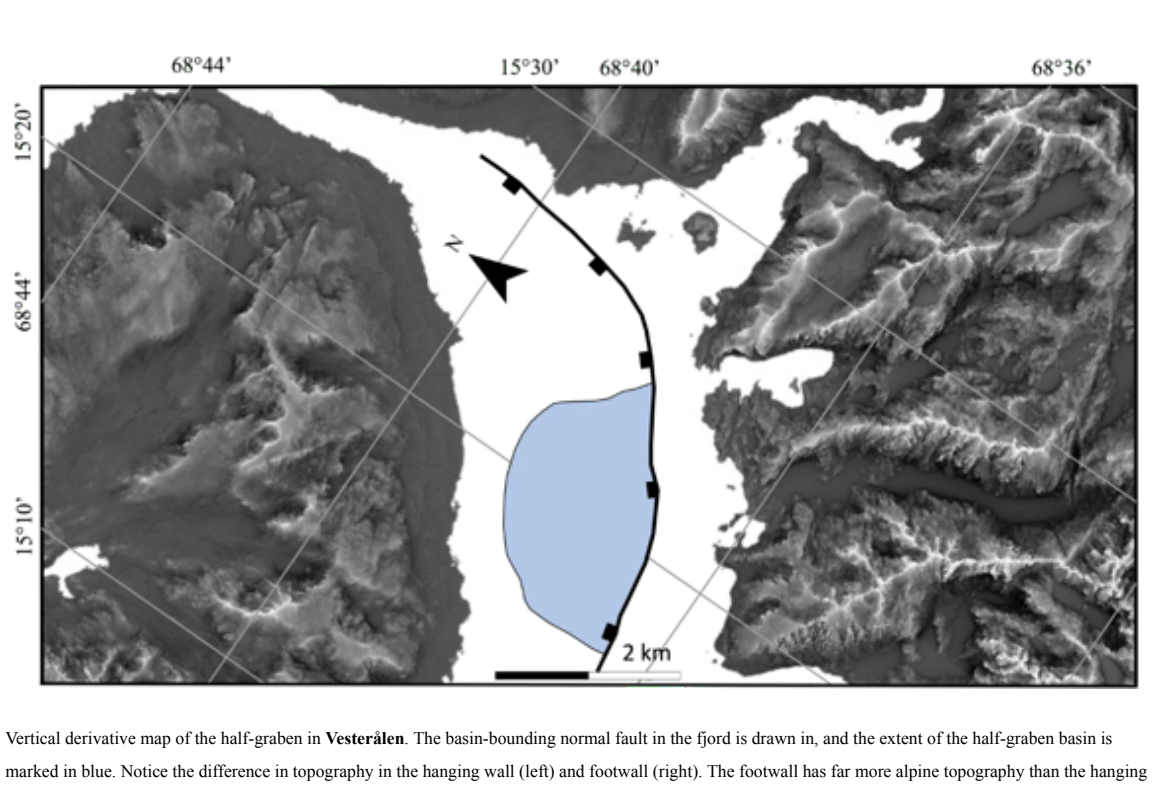
Topographical profile of the topography surrounding the half-graben basin, and the seismic line of the half-graben placed in the fjord. The fault exposed at the quarry contains a fault gouge that we have dated using the K-Ar method on the illite in the sample (see below). NB: The topography and basin bottom are not to exact scale!

By comparing photos of the topography in the hanging wall and footwall, we see a similar trend. The hanging wall displays a gentler topography consisting of rolling hills and the occasional steeper scarp. The footwall has highly uplifted, alpine topography.

Photo of the footwall topography, which is uplifted to approximately 1 km and shows an alpine expression. In the bottom middle of the photo we also see the quarry that exposes a normal fault (a description of it is in the methods-section).

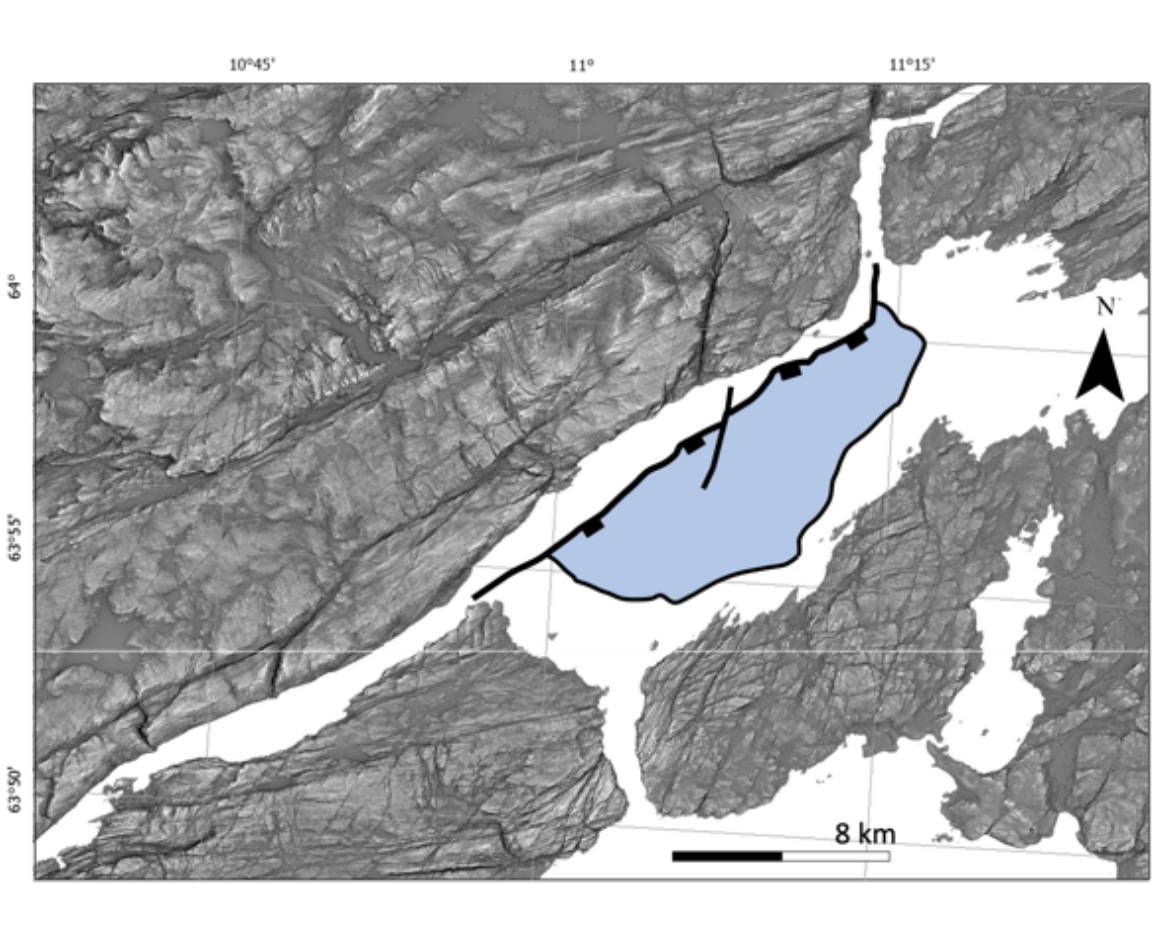
Photo of the hanging wall topography, which is around 0.3-0.5 km in elevation. This landscape has a much more subdued expression compared to the hanging wall.

Maps of the area show a similar trend. The map below is a *vertical derivative map*, a map based on the digital elevation model. Areas that have a large *change in elevation*, e.g., ridges and arêtes, show up in lighter colors.



Vertical derivative map of the half-graben in **Vesterålen**. The basin-bounding normal fault in the fjord is drawn in, and the extent of the half-graben basin is marked in blue. Notice the difference in topography in the hanging wall (left) and footwall (right). The footwall has far more alpine topography than the hanging wall. This indicates more recent uplift of the footwall.

iii) We do not see the same expression in the Beitstadfjorden area, where topography on either side of the basin is quite similar:



Vertical derivative map of the half-graben in **Beitstadfjorden**. The basin-bounding normal fault in the fjord is drawn in, and the extent of the half-graben basin is marked in blue. Notice that the topography on either side of the basin seems fairly similar.

So the Vesterålen basin might have topography inherited from tectonic extension, while the Beitstadfjorden half-graben does not seem to have as much extensional influence. Why is that?

Also, it seems unlikely that Jurassic topography is still preserved in the form of sharp peaks and ridges in Vesterålen. Could the tectonic topography be younger, but still reflect extensional tectonic activity?

Yes, it could.

There are indications that the basin-bounding normal fault in Vesterålen was **reactivated** at a much later stage than in Beitstadfjorden. New fault displacement may **rejuvenate the topography** in the region, making it appear similar to topography in actively extending regions.

In other words, we conclude that the zones of weakness formed during Jurassic extension get reactivated, **rejuvenating topography** - indicating an influence on present-day landscapes from Jurassic extension in Vesterålen.

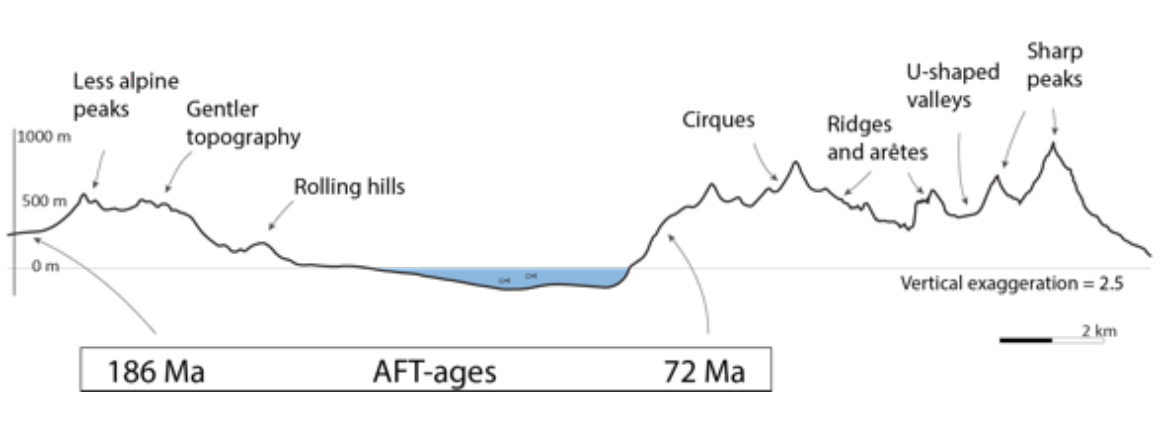
So **when was the normal fault in Vesterålen active**?

We have sampled fault gouge from a normal fault exposed in Vesterålen, and are still waiting for results. In the mean time, we have other indications that the fault in Vesterålen was active long after the Jurassic:

A 2013 study by Corine Davids et al. finds fault activity in the **Cretaceous, and likely even later**, using K-Ar dating of illite.

A 2010 paper by Hendriks et al. finds that the footwall uplift in Vesterålen took place during the **latest Cretaceous and likely later**, using apatite fission-track dating to date uplift.

Evidence for reactivation in Vesterålen:



This topographic profile shows distribution of landscape elements and apatite fission-track ages (AFT-ages) for two locations onshore the haging wall (left) and the footwall (right). Ages are from Hendriks et al. (2010).

The **contrast in apatite fission-track ages** (AFT-ages) indicate that the youngest sample was exhumed from a deeper depth, at a later time, by **footwall uplift**. The fission-track lengths indicate that the uplift was probably distributed over many events by slow or periodic exhumation. The conclusion then becomes that **the fault was active during the latest Cretaceous, and likely well into the Cenozoic**.

We also see that the topography on either side of the basin indicate more recent uplift in the footwall than in the hanging wall. Uplifted and alpine topography dominates the footwall, while the hanging wall has gentler topography.

Did reactivation happen in Beitstadfjorden to the same extent?

No, not that we are aware of.

Let's take a look at our conclusions.

It seems that tectonic topography is only directly inherited in some cases, like **fault scarps** that also make up a topographical scarp. However, topography is **indirectly inherited** through zones of weakness created during Jurassic extension, that later accommodate **reactivated extension**. This leaves us with landscapes similar to those that must have formed during Jurassic extension.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639172482/agu-fm2021/26-31-56-C1-74-89-48-2E-93-51-11-88-06-89-A8-66/Video/Video3_u40zq3.mp4

Thoughts, comments or questions are much appreciated!

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You can also reach me at lin.haaland@gmail.com

DISCLOSURES

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ABSTRACT

In this study we investigate how landscapes are inherited from continental rifting on long timescales. Areas that are currently undergoing extension typically have topographical features and drainage patterns that are easy to recognize. How these topographical rift features evolve on long timescales, however, is poorly understood.

Recent work from onshore parts of the northeast Atlantic margin suggests that some present-day landforms are inherited from late Paleozoic, Mesozoic and Early Cenozoic rifting and opening of the North Atlantic Ocean. These relict landscapes are difficult to recognize, as the topography is reworked by post-rift Cenozoic uplift and erosion, as well as repeated Quaternary glaciations. For that reason, interpretations of these landscapes vary considerably. However, some of these relict rift features are demonstrably preserved in half-grabens, as sedimentary basins with well-established ages.

Our research studies the topography around three half-grabens in Norway and on Svalbard, and aims to quantify landscape inheritance from rifting and margin formation. To do so, we use structural and geomorphological field observations, and remote sensing such as digital elevation model analyses and seismic images. We classify landscapes in detail, systematically reviewing present-day landscape distributions in order to distinguish extensional tectonic landforms from other geomorphological features.

Preliminary results find that certain present-day landforms along the northeast Atlantic Ocean are relics from rifting from as far back as the late Paleozoic. This is expressed by, among other things, major topographic contrasts between footwall and hanging wall in all three half-grabens. This means higher topographical elevations and deeper incision in the footwalls compared to the hanging walls. Additionally, the three study areas have very different landscapes, suggesting that their individual post-rift landscape evolutions were very different from each other. These differences seem to be influenced by the degree of glacial incision, the degree of erosional exploitation of pre-rift structures, and possible Late-Cretaceous or younger reactivation of basin-bounding normal faults.

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