# Paper 6

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# Seismotectonics of Skagerrak

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## Abstract

The seismotectonics of the western Skagerrak Sea between Norway and Denmark have not been well resolved due to large uncertainties in earthquake locations. The newly installed SNART station in southern Norway and the combination of Norwegian and Danish data provide more reliable earthquake locations, which are combined with new findings from seismic data to reveal clues about the origin of earthquake activity. The relocated earthquakes fall in two main groups, one associated with the Sorgenfri-Tronquist Zone (STZ) and the other striking N-S in a band between 6.5-7°E, between the STZ and 57°N. Reinterpretation of old seismic data crossing the N-S alignment of earthquakes shows that the event locations coincide with a new structure, named the Langust fault zone, which appears to be of more recent age than the neighboring Hummer, Krabbe, Kreps and Holmsland Fault Zones. The Langust fault zone is believed to be the origin of the N-S aligned earthquake activity. Furthermore, gravity and magnetic anomaly data indicate that this zone may be related to deep-seated crustal structures. The regional stress orientation with maximum horizontal compression in the NW-SE direction agrees well with observed normal, oblique normal and left-lateral strike-slip fault mechanisms of earthquakes in the region.

## Introduction

The Skagerrak Sea is located between southern Norway and northwestern Jutland, Denmark, connecting the North Sea to the Kattegat Sea further east. This area has long been known to be one of the most seismically active areas in Denmark (Lehmann, 1956; Gregersen, 1979; Gregersen, 1996), which is generally a region of low seismicity. Due to the offshore location of most of the events in the boarder zone between two seismic networks (the Norwegian and the Danish National Networks), location uncertainties have been large, and it is still not clear which structures are the origins of the Skagerrak earthquakes. The seismicity in the region has previously been studied by Gregersen (1979), who recognizes a general trend of events striking perpendicular to the coast of northwest Jutland. He concludes that the events seem to locate close to the base of the crust at approximately 30-40 km depth. In later studies, Gregersen et al. (1996a, 1996b) find no direct correlation to geologically known faults in the area. However, they recognize that the earthquakes occur along the central axis of the Norwegian-Danish basin where Mesozoic and pre-Upper Permian faults are present. Characteristic of both of these studies are the limited datasets available at the times of publication, both in terms of number of recorded events and station configuration.

In the present study, we relocate earthquakes in Skagerrak to obtain new information about their relation to tectonics. This is done by constraining hypocenter depths and velocity model based on the best records from both Norwegian and Danish stations. Since 2003, the station SNART has been in operation in southern Norway providing high-quality records of the Skagerrak earthquakes. Detailed investigations based on this station help constraining the relocation of older events.

The improved locations are compared to the regional tectonics including new interpretations of preexisting seismic sections in the region and to gravity and magnetic anomaly data. This joining of independent dataset provides important new clues about the origin of the Skagerrak seismicity.

## Tectonic setting

The Skagerrak sea is largely covered by sedimentary rocks of the same type as found in the hydrocarbon provinces of the North Sea. This implies a potential for hydrocarbon resources in the Skagerrak, which has motivated numerous studies aimed at studying the geological and tectonic evolution in this region (e.g. Lie and Husebye, 1993; Lie and Husebye, 1994; Longva and Thorsnes, 1997; Lie and Andersson, 1998). Main focus of both these local and more regional (e.g. Thybo, 1997; Scheck-Wenderoth and Lamarche, 2005) studies has been at the shallower parts of the crust, and limited information is available about deeper-lying structures.

The Skagerrak is located in a tectonically complex area (Figure 1), which has been formed through numerous events since Cambrian. The oldest rocks in the area are pre-Cambrian gneisses, which by the beginning of Paleozoic had been uplifted and eroded to a plane surface. Sediment deposition on this surface started during Cambrian. The

Caledonian Orogeny during early Paleozoic caused slight deformation, faulting, uplift and erosion (Longva and Thorsnes, 1997). This was followed by early Permian rifting causing intrusion of melted rock through volcanic activity. The following postrift thermal subsidence started during the early Permian and continued during the late Permian and Mesozoic in NW-SE oriented basin structures such as the Norwegian-Danish, German and Polish Basins (comprising the Northern and Southern Permian Basins). During the late Permian and Mesozoic, superposed extensional tectonics created NS oriented graben structures such as the Central, Horn and Glückstadt grabens. During Late Cretaceous to Early Cenozoic, a phase of inversion dominated, followed by renewed subsidence during the Cenozoic (Scheck-Wenderoth and Lamarche, 2005). As a consequence of this tectonic evolution, the area is today dominated by NW-SE oriented basins and younger NS oriented graben structures. The Skagerrak Sea covers part of the Norwegian-Danish Basin. Another dominating tectonic feature is the Sorgenfri-Tornquist Zone (STZ) striking through northern Denmark from the Skagerrak Sea to Bornholm in the SE. This is the northwesternmost segment of the Tornquist Zone (TZ), a fault zone extending from the Black Sea to the Skagerrak, which has been active at least since Late Carboneferous (Berthelsen, 1998; Erlström et al., 1997; Ziegler, 1990). Whereas the southeastern Tornquist-Tesseire Zone (TTZ) segment of the TZ marks the boundary between the Precambrian Baltic Shield and the younger western Europe, the STZ is an intracontinental fault zone within Baltica, separating the stable parts of the Baltic Shield from the weaker southwestern margin (Scheck-Wenderoth and Lamarche, 2005). The STZ underwent transtensional deformation during the Mesozoic, which transformed into transpression due to the Alpine compressional stresses during the late Cretaceous-early

Tertiary, causing an inversion of the movement on the STZ (Thybo, 1997; Lie and Andersson, 1998). The STZ is associated with a significant change in thickness of the crystalline crust, which is thinner to the southwest of the zone as illustrated in Figure 2 (Thybo, 1997; Lie and Andersson, 1998).

Other dominant tectonic features in NW Europe are the Caledonian Thrust Front striking NW-SE through southern Fennoscandia and continuing across the North Sea through the British Isles and the Variscan Thrust Front further south in Europe.

Figure 1 shows the main tectonic features of the region surrounding Skagerrak. The Permo-Triassic Øygaarden fault zone extends for more than 300 km along the west coast of Norway striking N-S. The STZ is bounded by normal faults, of which the most significant are the Børglum Fault and the Fjerritslev Fault. To the south of the STZ are several NS striking fault systems; the Hummer, Krabbe and Kreps and Holmsland fault zones. An onshore continuation of these NS oriented systems is the Mandal-Ustaoset lineament striking NS through southern Norway. Another dominating feature on land is the Bamble fault in southeastern Norway. Eastern Norway is dominated by the Permian Oslo Graben which continues off-shore as the Skagerrak Graben in eastern Skagerrak.

The present study focuses on the western part of Skagerrak, where the STZ strikes through. Previous studies have indicated that the seismicity in the region is not associated with the STZ, as it is the case further southwest in the Kattegat (Gregersen et al., 1996a; Gregersen et al., 1996b).

There has only been few focal mechanisms published for the western Skagerrak area, and the basis for stress inversions is scarce. However, published estimates of the orientation of maximum horizontal compression are in general agreement, varying between WNW-ESE (Hicks, 1996; Hicks et al., 2000), NW-SE (Gregersen, 1992) and NNW-SSE (Reinecker et al., 2005). Available earthquake focal mechanisms show strike-slip, normal or oblique normal faulting with fault planes in agreement with the published stress orientations (Bungum et al., 1991; Gregersen and Arvidsson, 1992; Dehls et al., 2000).

Several authors have compiled Moho depth data for the general region around the STZ based on seismic data (Thybo, 1997; Lie and Andersson, 1998; Scheck-Wenderoth and Lamarche, 2005). For the study area in Skagerrak, Moho depth estimates vary between 23-30 km.

## Seismicity in Skagerrak

Figure 1 also shows the seismicity of the area based on data from the Norwegian National Seismic Network (NNSN). Activity is observed in two areas off the west coast of Norway, one associated with the Viking Graben and the other closer to the coast. Further south is an active region in western Skagerrak, which is the target of the present study, in addition to a group of events in the Skagerrak graben. This activity is extending northwards through the Oslo Graben but is less pronounced in this part. In the Kattegat sea, a relatively high level of activity is associated with the STZ.

The offshore location of the study area in combination with the low magnitude of the earthquakes makes exact earthquake location a challenging task. Especially estimation of event depths is associated with large uncertainty. The high-quality data from the NNSN station SNART, available since summer 2003, provide new possibilities for detailed investigations of event depths in the area. Therefore events, which are well recorded on the SNART station, have been used to constrain the depths of the Skagerrak earthquakes. Following, events over a longer time span have been fixed at the estimated depth and relocated, providing more reliable epicenters.

A total of 10 events with data from SNART were used for estimating the depth of earthquakes in Skagerrak. Waveform modeling was attempted using the WKBJ program (Chapman et al., 1988). However, the Pn, Pg and PmP phases arrive almost simultaneously making benefit from this modeling limited. Generally, the best fit to data was obtained with a depth of 20 ± 5 km, depending on the velocity model used.

A more stable estimate of event depth was obtained through studying the variation of rms vs. depth in the locations. Again, there was a trade-off between moho depth in the velocity model and event depth, but this trade-off was limited significantly by including both Pn/Sn and Pg/Sg phases in the event locations. Two velocity models were tested, as shown in Table 1. Model A is the one used for routine location of earthquakes for the NNSN, model B is a modified version with Moho lifted to 25 km depth. Model B is probably a better representation of the 1D crustal structure below Skagerrak. However, the waveforms are recorded on land where the crust is thicker, and Model A therefore seems to provide a better average model for the traveled wave path. The error in depth as expressed by the root mean square (rms) of the travel times of the P and S waves, was tested for both models for the 10 earthquakes. Model A gave the lowest absolute rms values and the rms minima were more well defined indicating that this model gives the most reliable locations. Generally it was observed, that lowering the Moho also lowered the event locations. In all cases, there was a significant increase in rms when locating the events below moho, and we conclude that the majority of earthquakes in Skagerrak occur above Moho in the lower half of the crust. Figure 3 shows a number of rms vs. depth profiles obtained using velocity model A. It is seen in this figure that the depths are still associated with significant uncertainties, but generally, the best depth estimates are in the interval 13-23 km though shallower depths for some events cannot be excluded.

Based on the above results, it was decided to fix the events at a depth in the range between 10-25 km. All earthquakes in the time period 1985-2005 in the western Skagerrak area were relocated with depths fixed at 10, 15, 20 and 25 km and the average rms for all locations was extracted for each case. Lowest average rms was obtained when fixing at 15 km, and this was chosen as our best estimate of event depth. Figure 4 shows the relocated earthquakes on top of the main tectonic features. Only stations at a distance of less than 350 km were included in the locations.

The seismicity distribution in Figure 4 shows a N-S alignment of events in a band between 6.5-7°E. At 57°N this seismicity dies out towards south, but there is a slight tendency of an eastward continuation towards NW Jutland. In addition to the NS oriented seismic activity, several events are located along the southern edge of the STZ in Skagerrak.

The relocation has lead to a more focused picture of the seismicity, indicating that the location accuracy has improved. The N-S alignment of events is stronger and with less spread than was the case before relocation. An interesting feature to observe is the apparent alignment of events in a NW direction from the shoulder of Jutland towards Skagerrak, which can be seen in Figure 2. This alignment becomes much less clear after relocation, indicating that it may be an artifact due to location errors. After relocation, some of the events move closer to the N-S oriented group of events. However there still seems to be a cluster of events close to the coast of Jutland but with less tendency of lineation. The average rms of the locations is reduced from 1.245s before relocation to 0.945 s after. This, however, is also affected by the reduced number of stations used in the relocation due to the distance constraint. To estimate the uncertainty in the locations, two events were relocated 10 times using individual sets of phase picks. The two events were chosen so that one was recorded on the SNART station and the other was not, this to also see the effect of the station on the uncertainties. The spread in the locations for the 10 sets of phase picks indicated an uncertainty of ca. 15 km in the locations before installation of the SNART station. Including data from SNART improved the location accuracy to ca. 10 km. Comparing these uncertainties to the dimensions of the event clusters described above, it can be concluded that the alignments are real, and not a just consequence of location uncertainty.

## Seismotectonic interpretation

The two main groups of earthquakes observed after relocation (Figure 4) are the EW trending group of events associated with the STZ and the NS trending group of events between 6.5-7°E. The second group of events locates in a region with no previously known faults and does not seem to be associated with the neighboring Kreps and Holmsland fault zones. In order to study the origin of these events in more detail, old seismic profiles were reinterpreted for the region. An example of an EW trending profile is shown in Figure 5. The Kreps and Holmsland fault zones are clearly visible extending to reflector TR (Top Rotliegendes). In addition to these, a much younger structure (i.e. younger than reflector MU (Base Miocene Unconformity)) breaks the central part of the profile. This structure is a previously unknown small graben structure, which we suggest to name the Langust fault zone. The extent of the fault zone is shown in Figure 2b. Looking in more detail at the uppermost part of the profile (Figure 5b) we see that the fault zone is recent. It is clear that reflectors TP (Top Paleocene) and MU are cut, and we believe that it is also cutting through the Quaternary sediments, as opposed to the Hummer, Krabbe, Kreps and Holmsland fault zones, which show no activity above reflector TR (Figure 5a). The depth extent of the Langust fault zone is uncertain, but it is expected to continue at larger depth than where it disappears into the noise in the profiles. Figure 6 shows a profile almost parallel to the one in Figure 5. Here it is clear that the zone crosses the Top Rotliegendes reflector (TR). We believe that the N-S oriented earthquake activity in the western Skagerrak is associated with the Langust fault zone.

The locations of the events correlate well with the location of the fault zone, and the seismic profiles show recent activity as the fault cuts through the recent sediments.

Figure 7 shows a comparison of the relocated earthquakes to gravity and magnetic anomaly data from the region (Olesen et al., 1997; Skilbrei et al., 2000). In both dataset there is a distinct anomaly trending SSW from southern Norway, coinciding with the location of the Langust fault zone. This indicates the significance this structure may have at a crustal scale.

Looking at the seismic profiles in Figures 5 and 6, it is clear that the Langust fault zone is a graben structure with the central part of the zone sinking relative to the surroundings. Because of this, we expect the earthquakes occurring in the zone to have normal or oblique-normal mechanisms. The general stress orientation in the region with NW-SE compression makes left-lateral strike-slip rupture the most likely fault mechanism. These considerations are in good agreement with the observed normal, oblique normal and strike-slip mechanisms (Bungum et al., 1991; Gregersen and Arvidsson, 1992; Dehls et al., 2000).

Figure 8 shows a profile crossing the STZ. We believe that the EW oriented activity along the STZ is due to earthquakes of preferably normal mechanisms along the fault structures in the zone. The seismicity along the STZ shows an anomaly where the Langust faule zone crosses the STZ. Figure 8 illustrates how the Quarternary deposits are offset at this position.

## Conclusions

In the present study, earthquake location data have been combined with seismic data to reveal new clues about the origin of earthquake activity. The following conclusions can be drawn about the seismotectonics of western Skagerrak:

- Earthquake activity is concentrated in the crust, most likely around 10-20 km depth.
- The epicentre distribution reveals two active zones; one associated with the E-W oriented STZ and the other striking N-S in a band between 6.5-7°E, between the STZ and 57°N.
- The events in the STZ are expected to be associated with the Fjerritslev Fault or smaller normal fault structures in the zone.
- Seismic profiles across the area of the N-S oriented activity reveal a previously unknown graben structure, which is proposed named the Langust fault zone. This structure is more recent than the neighbouring Hummer, Krabbe, Kreps and Holmsland Fault Zones, and is expected to be the origin of present-day earthquake activity.
- The relation of the Langust fault zone to possible crustal-scale structures is confirmed by gravity and magnetic anomaly data.

- The geometry of the Langust fault zone and the regional stress orientation poses normal, oblique-normal and left-lateral strike-slip faulting as the most probable mechanisms for these earthquakes.
- The seismicity along the STZ shows an anomaly where the N-S trending Langust fault zone meets the E-W trending STZ.

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## Tables

Table 1. Velocity models tested for event location.

| $V_p$ km/s | Depth, top of layer Model A / km | Depth, top of layer Model B / km |
|---|---|---|
| 6.2 | 0 | 0 |
| 6.6 | 12 | 12 |
| 7.1 | 23 | 20 |
| 8.05 | 31 | 33 |
| 8.25 | 50 | 50 |
| 8.5 | 80 | 80 |

**Figures**

Figure 1: Main tectonic features in Skagerrak and surrounding areas plotted on the Top Rotliegendes map. Blue colors indicate deep areas, red indicates shallow areas. The seismicity, as located by the NNSN, is overlaid. The study area is marked with a gray square. Abbreviations: BF: Bamble Fault, BøF: Børglum Fault, CTF: Caledonean Thrust Front, CG: Central Graben, FF: Fjerritslev Fault, HFZ: Hummer Fault Zone, HG: Horn Graben, HoFZ: Holmsland Fault Zone, KaFZ: Krabbe Fault Zone, KeFZ: Kreps Fault Zone, MUL: Mandal-Ustaoset Lineament, NDB: Norwegian-Danish Basin, OG: Oslo Graben, SG: Skagerrak Graben, STZ: Sorgenfri-Tornquist Zone, VG: Viking Graben, VTF: Variscan Thrust Front, ØF: Øygaarden Fault.

Figure 2: a) Deep seismic profile (profile A in Figure 2b) showing how the Sorgenfri-Tornquist Zone marks a clear boundary between the thick crust of the Baltic Shield and the thinner crust underlying the Norwegian-Danish Basin. Vertical scale is two-way-time in seconds. b) Index map of seismic profiles presented in this paper on the Top Rotliegendes map. Profile A: Figure 2a, profile B: Figure 5, profile C: Figure 6, profile D: Figure 7. The white structure shows the extent of the Langust fault zone.

Figure 3: RMS vs. depth profiles for 10 well-recorded events in Skagerrak. Locations are based on velocity model A of Table 1.

Figure 4: Relocated earthquakes in the western Skagerrak area, plotted on top of the main tectonic features. The locations of the MUD and SNART stations are indicated as green triangles.

Figure 5: E-W oriented seismic profile crossing the Langust fault zone. a) Overview including the Kreps, Langust and Holmsland fault zones, b) zoom on the upper central part of the profile, showing the Langust fault zone. The index map shows the location of the profile and the extent of the Langust fault zone. Letters indicate the reflectors described in the text. The vertical scale is depth in kilometers. Abbreviations: TR: Top Rotliegendes; TP: Top Paleocene; MU: Base Miocene Unconformity; KeFZ: Kreps Fault Zone, LFZ: Langust fault zone, HoFZ: Holmsland Fault Zone.

Figure 6: E-W oriented seismic profile crossing the Langust fault zone. Note the clear offset of the marked Top Rotliegendes reflector (TR). The index map shows the location of the profile and the extent of the Langust fault zone. The vertical scale is depth in kilometers.

Figure 7: Comparison of a) gravity anomaly and b) magnetic anomaly data for the Skagerrak region to c) relocated seismicity.

Figure 8: Seismic profile crossing the STZ in western Skagerrak. The index map shows the location of the profile. The vertical scale is depth in kilometers.

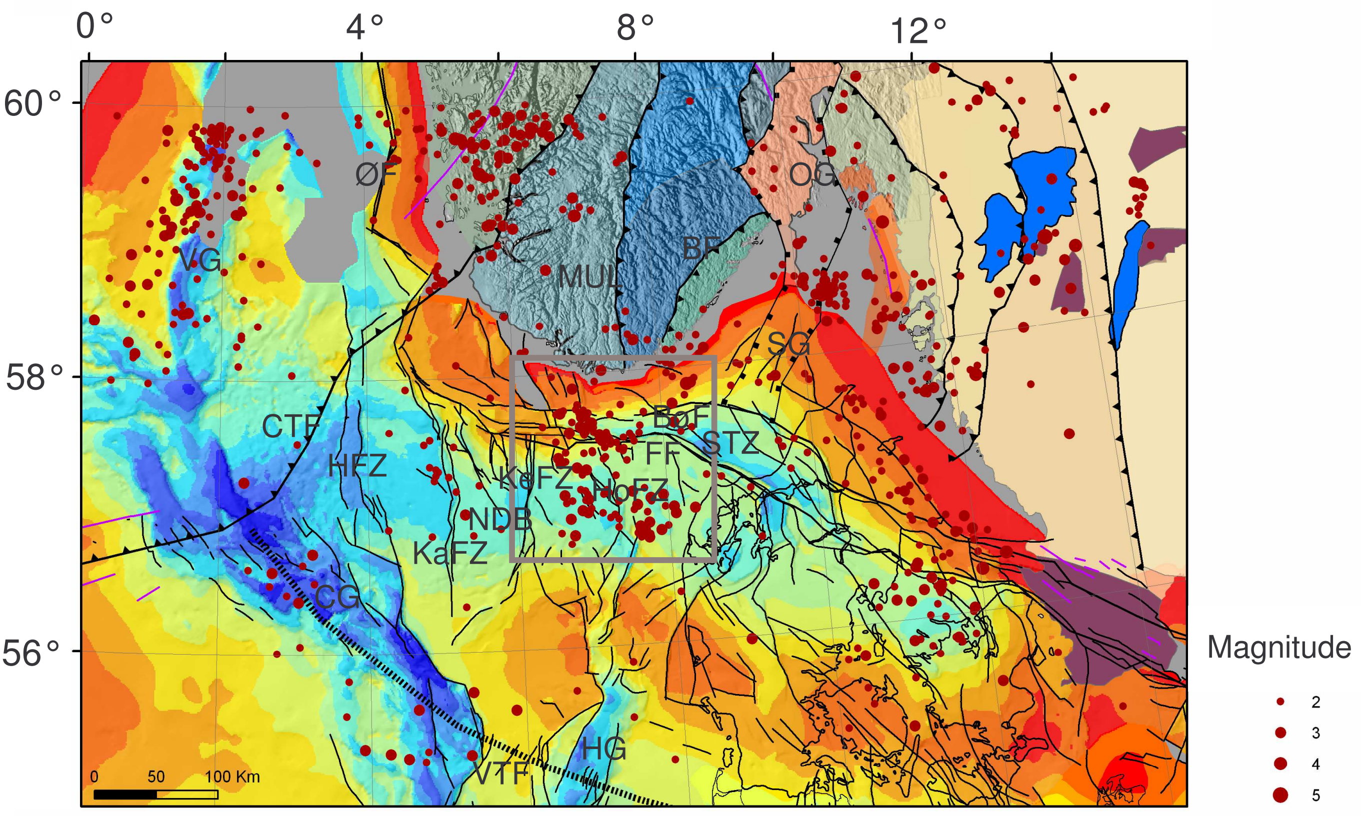
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Figure 1

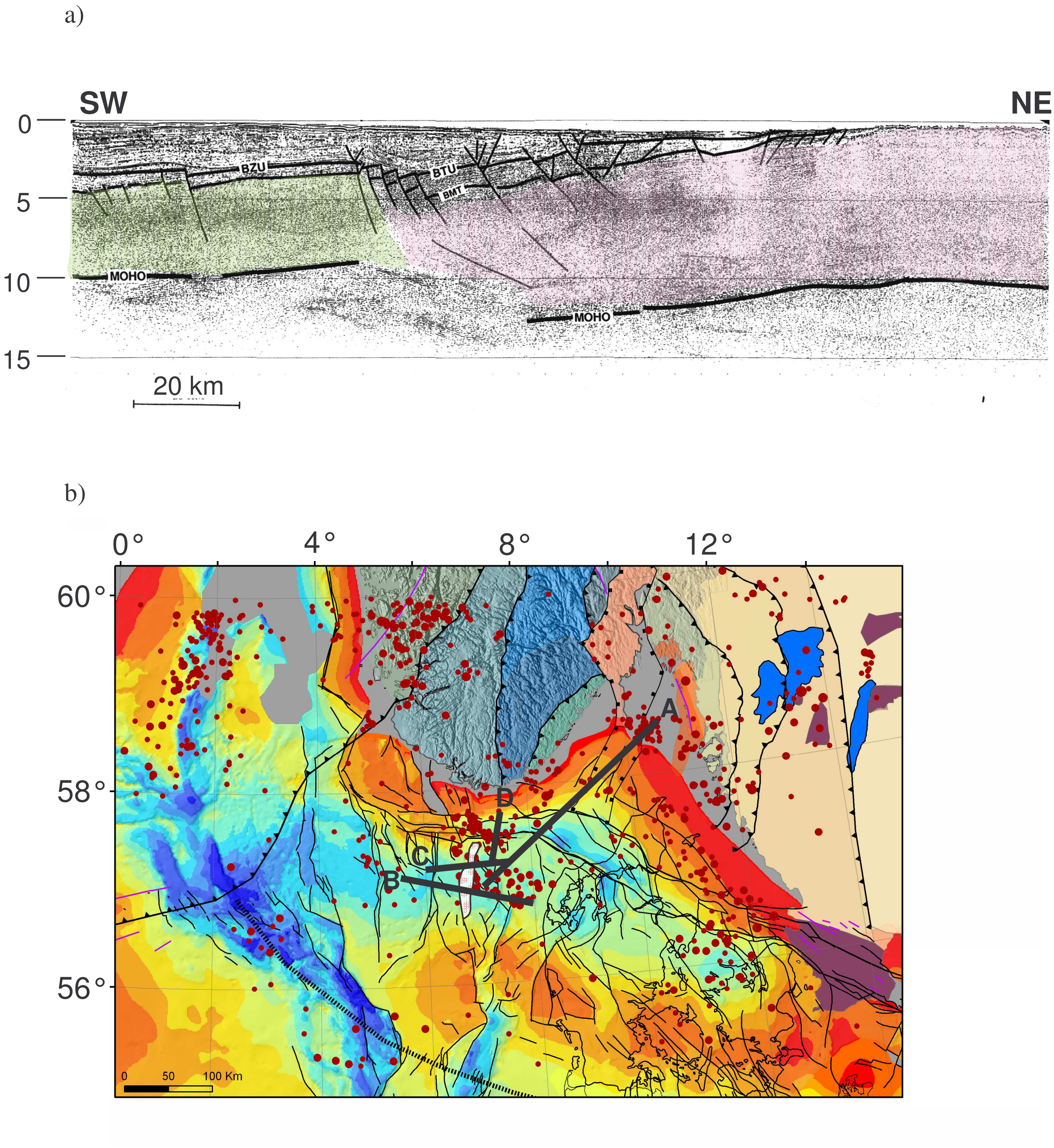
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Figure 2

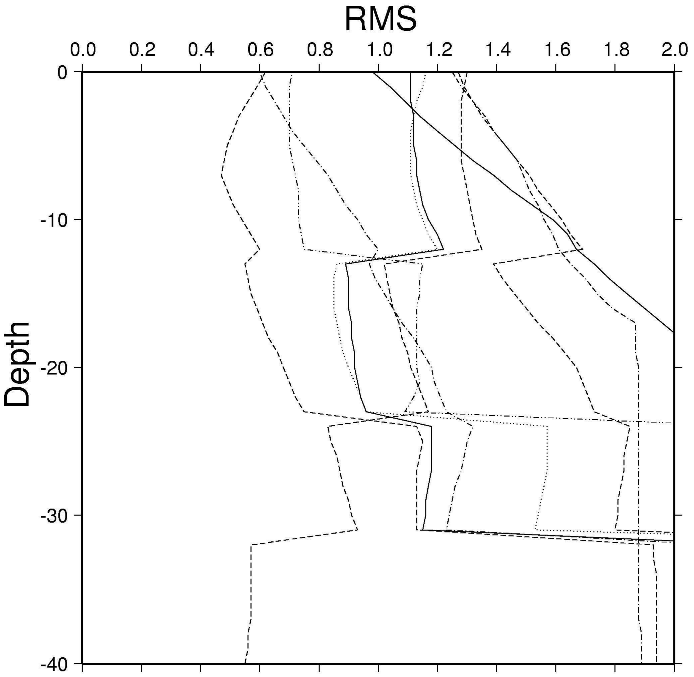

Figure 3

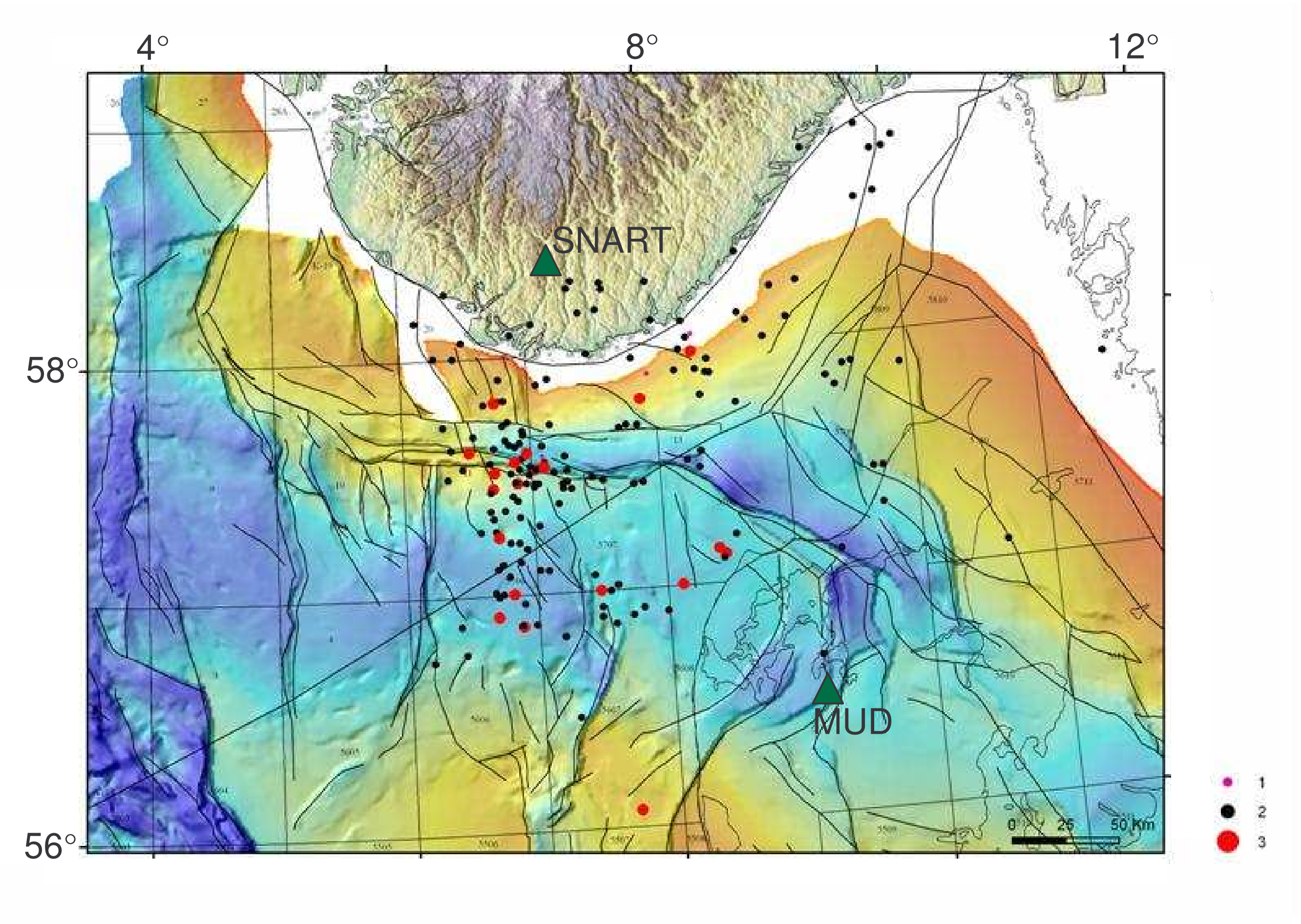

Figure 4

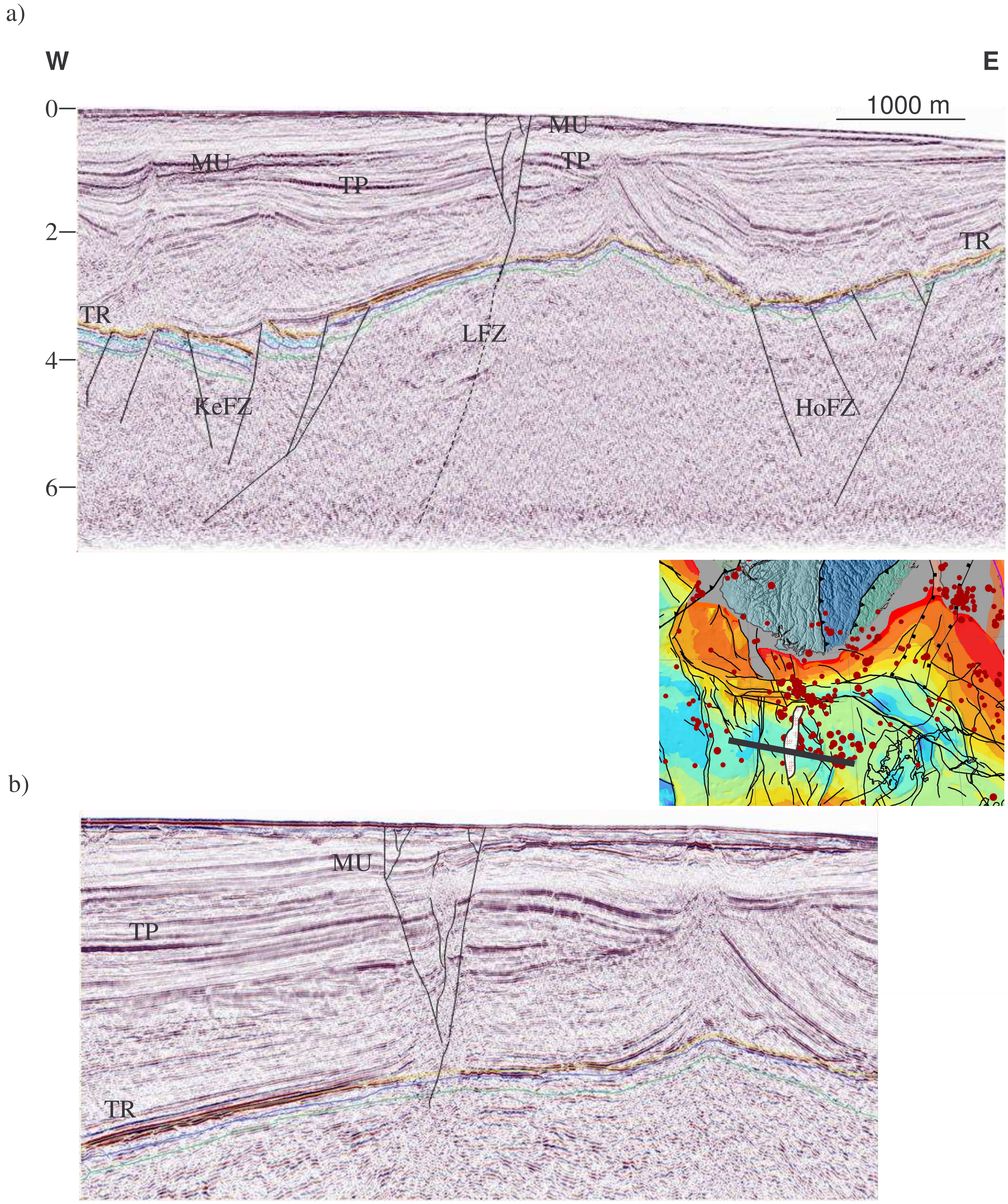

Figure 5

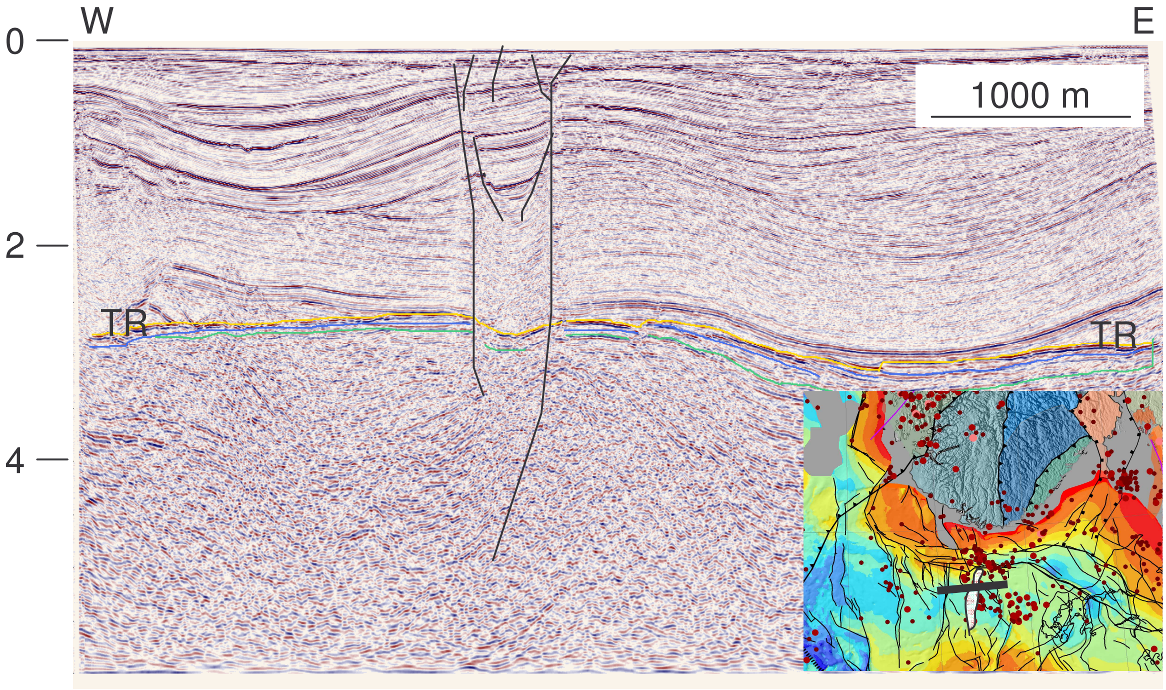

Figure 6.

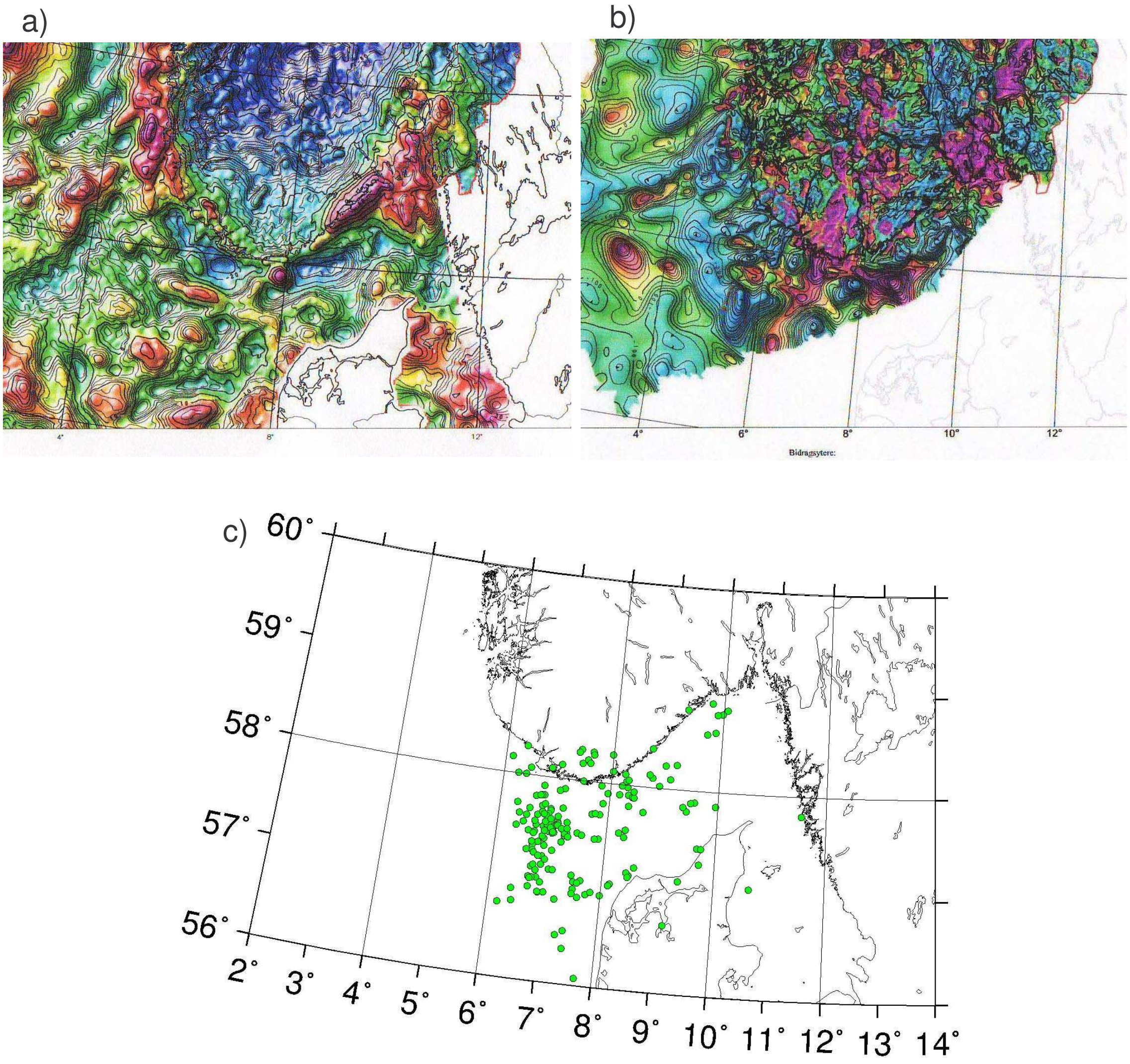
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Figure 7

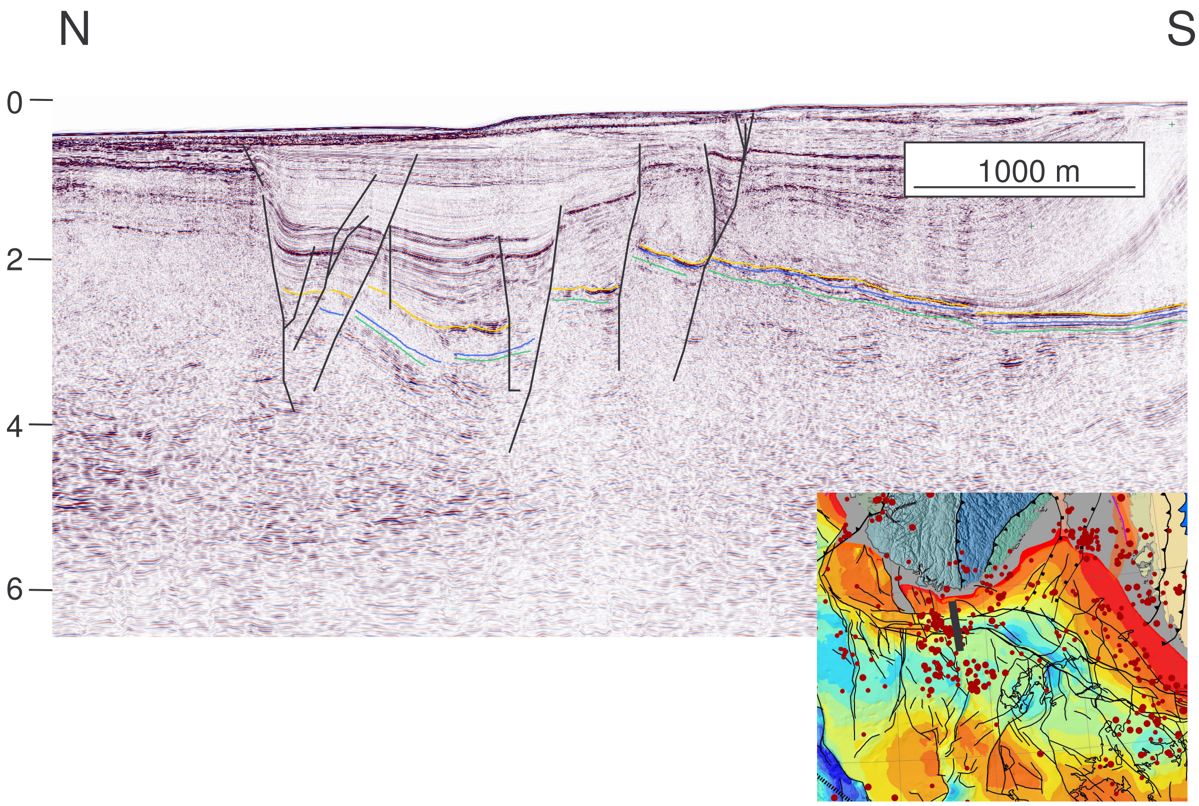

Figure 8