Oblique reactivation of lithosphere-scale lineaments controls rift physiography – The upper crustal expression of the Sorgenfrei-Tornquist Zone, offshore southern Norway

Thomas B. Phillips; Christopher A-L. Jackson; Rebecca E. Bell; Oliver B. Duffy

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Reviewer 2 – Patricia Cadenas

We thank Dr Cadenas for her insightful and thorough review, which we believe will greatly improve the overall manuscript. Following the overall positive nature of the review (see below), we append detailed responses to each of the queries and comments raised. Changes to the overall manuscript can be found in the attached tracked-changes document.

Original review

The manuscript presents a detailed analysis of the geometry and the kinematic evolution of major structures controlling the geometry of the Farsund Basin, offshore southern Norway. The study relies on the interpretation of borehole-constrained 3D and 2D seismic reflection data, the development of isochron and thickness maps of key stratigraphic horizons, and the development of throw-length and backstripped profiles for the major interpreted structures. The authors recognize major N-S and E-W upper crustal fault populations that they relate in depth to the Sorgenfrei-Tornquist lithospheric lineation. From the tectono-stratigraphic and the structural analysis, the authors document a polyphase activity of these faults which were reactivated in a broad range of tectonic styles during successive stages governed by a distinctive stress field. Based on all these observations, the authors discuss the evolution and the role of long-lived pre-existing structures during subsequent rift events and debate the main geodynamic implications into the regional tectonic framework. The study is well-supported by the available data and the methods and the workflow used are appropriate for this investigation.

Overall, the manuscript is well written and follows a clear layout; the title reflects the content of the paper and the abstract provides a complete summary of the work. The text explanations are well supported by the figures, which are of a high quality. I find this study very interesting and insightful due not only to the scientific background but also because of the methodology; the work drove to major conclusions that allows advances in the understanding of the studied area. The multiphase activity and the structural link between different fault systems in the Farsund Basin and the discovering of a previously undocumented Early Jurassic period of sinistral strike-slip activity are the most significant findings. In a more general sense, this work provides new insights to comprehend the constraints imposed by inherited lithospheric structures on the development of upper crustal faults during subsequent rift events, depending on the regional stress field. I would therefore highly recommend this manuscript to be published at Solid Earth.

However, I find that including some additional information and some minor modifications, in addition to other reviewers and readers comments, can improve the readability and the high quality of the manuscript.

In the abstract, I would propose presenting the interpreted link between the upper crustal faults and the STZ after addressing the detailed analysis of the upper crustal faults, which is the basis of the

study. Thus, I would move information from lines 17-18 to line 28, just before denoting the inferred evolution of the STZ from the analysis of upper crustal faults.

We agree with this comment from the reviewer. We have changed the structure of the abstract so that the analysis of the upper crustal fault populations is first introduced and then linked to the lithosphere-scale STZ (Line 17-34).

Line 89, figure 1a and c? and Line 90, figure 1a and c (Varnes Graben not in figure 1c).

We have made the required changes to the references to this figure. A label for the Varnes Graben has been included into Figure 1c.

I would put the regional geological history as section 2.1. I think it could be helpful to contextualize the evolution of the STZ.

We agree with this comment and as such now establish the framework of the regional geological history, before placing the STZ into this context. (Line 100-141)

I would define a section: 2.2) The Farsund Basin and I would move the STZ to a section 2.3. I think that a section dealing with the structure and the tectonic evolution of the Farsund Basin would be neccessary to set up the context of this work. I would move lines 164 to 169 to this section and I would include in this 2.2 section an explanation about the geometry of the main faults controlling the architecture of the Farsund Basin (i.e., including the information now in lines 212 to 215, line 220; if these structures were defined by previous works, what is known about these structures from these works?, what is the length of these structures?, explained now in sub-section 4.2, supported by the detailed structural map provided in figure 1c, in case this map was developed from the integration of previous maps). I think this could be helpful to follow the detailed analysis of the upper crustal fault population provided later by the authors.

Having carefully considered this suggestion, we disagree that the Farsund Basin should have its own sub-section in the Geological background section of the paper. Although the approximate geometry and existence of the basin has been defined previously by other authors, the detailed geometry and kinematics of the faults are new to this study (ie the individual faults have never been described in detail before or their properties including length characterised- this is new to our study). We therefore feel detailed mapping of the geometry of the basin forms a fundamental part of the new results presented in this study (and this information should be presented in the Results section rather than Geological Background), and are vital in linking the basin to the deeper lineament.

Line 98, the Carpathian orogenic front and the Ronne Graben are not labelled in figure 1a.

These super-regional structures are currently not shown on this figure, as we mainly focus on the northwestern component of the Tornquist zone (i.e. the Sorgenfrei-Tornquist Zone). References to more regional studies have been included to highlight the more regional structures (Line 146-147) (although we do not feel these super-regional structures are directly relevant to our study).

Lines 108 and 109, Palaeozoic terranes belonging to Central and Western Europe, figure 1D. This cannot clearly be inferred from the figure.

This sentence has now been clarified, and the figure reference removed (Line 158).

Line 114, Tornquist Fan is not labelled in the referenced Figure 1A.

We have removed the figure reference from this section (Line 164). The location of this more regional structure is not of importance to this study, although some information is added to the caption of Figure 1

I would move line 119 to 122 to line 116, after explaining that the STZ is defined as a change in lithospheric thickness. Then, I would explain the expression of this structure at shallow crustal levels.

We agree with the reviewer and have reorganised this section such that the evidence showing that at upper-crustal levels the STZ resides within Baltica (Line 166-169) comes before the definition of the STZ at these upper crustal levels (Line 170).

Line 125, "the STZ acted?",

The phrase "acts as" has been changed to "represents" (Line 178)

Line 165, Central Graben is not labelled in Figure 1A.

Reference to the Central Graben has been removed (Line 133)

Lines 170 to 173, this information could be more suitable for a discussion.

We feel that this section provides evidence for the basin being linked to a pre-existing structure, a key platform which later interpretations are based on. Therefore, we believe this information should come at this point in the paper.

In the data section, I think it would be necessary indicating some information about the boreholes and the seismic data (date of acquisition, acquired by oil companies, acquisition and processing parameters,. . .). Or providing a reference in case this information has been provided in another publication.

Additional information regarding the processing and acquisition information of the seismic surveys used in this study has been made available in a table in the supplementary material (Line 191-192).

I find useful adding some references to support the description of the quality of the seismic records (e.g. line 184).

Figure references have since been added to this section to visually support these textual descriptions (Line 196)

I would define a section 3.2) Methodology, including the information from line 185 to line 205. I would remove the section quantitative fault analysis (if this section is preserved, I would define a previous section in the same level, explaining the seismo-stratigraphic and structural seismic interpretation, supported by the figures displaying interpreted seismic profiles, borehole analysis and isochron and thickness maps; this information is now explaining in the section dealing with the available dataset). I would be convenient to introduce in this section what figures support each method (e.g., figure 3 after (. . .) isochrons between them (. . .) in line 190, figure 7 and 8 for the throw-length and backstripping techniques,...).

We have added an additional section (now section 3.2) that details the seismic interpretation and the generation of the isochrons (Line 205-298). Figure references have been changed where appropriate, but we have ensured that the figures are introduced in the order they appear are in the text.

Do the intrinsic geometric uncertainties in time domain and the spatial variations of velocity values affect throw measurements? It would be convenient adding in the methodology section some lines to further explain this limitations.

Because the overlying sedimentary sections are relatively homogeneous along-strike of the fault we expect there to be little lateral variation in overburden velocity (and thus extracted fault throws in the deeper section), we argue that, although absolute values (in metres) may vary, the overall throw patterns (in two-way time) underpinning our key interpretation and conclusions will remain. In addition, the faults are roughly at the same depth from east to west, thus burial related changes in velocity are also not expected to greatly effect depth conversions. To further support our interpretations, we undertook spot depth conversions (Line 200-201), with the appropriate depth measurements cited in the text (e.g. Line 268, Line 351, Line 499).

Lines 207 to 210, section 4.1 should be explained before section 4.2.

Sentence order in this section has now been changed (Line 244-248).

I would suggest the definition of a section 4.1 dealing with the stratigraphic architecture and the supported by the figures showing the interpreted seismic profiles. I would explain in this section the main interpreted key horizons, the main units, and its seismic expression (the paragraph included now lines 237 to 240, paragraph between lines 271 and 274). I think that some seismic to well ties should be displayed in the figures to support time constraints of the major seismic horizons for the entire seismo-stratigraphic sequence. In the same way, the authors provide in most cases depth estimations for some horizons, faults displacements and surfaces, so any seismic to well ties and velocity models developed from the checkshots should be displayed to support this information. For instance, Figure 1B is of a very good quality and it has not been referred and explained within the text. I think this figure should not be part of the "tectonic setting" figures. For sure, seismic to well ties and seismo-stratigraphic analysis has been a really important part of the analysis. This is a time-consuming and toughful work but of a great interest to support the analysis of the tectonic evolution. The crustal-scale faulting analysis provided by the authors now as section 4.1 can be included in this section. I think it could be suitable providing a description about the seismic imaging and interpretation of the main faults (if the faults are introduced in the tectonic setting, the authors can describe straighforward these faults using the seismic interpretation (depth, dip, fault links. . . as it has been interpreted on the seismic profiles). I would suggest to keep the regional description based on isochron maps in section 4.2.

We cannot generate seismic-well ties due to a lack of well-log data in the key wells. Checkshot data from multiple wells within and outside of the immediate area of interest are used for the depth conversion; this is now explained in the methodology section (Line 199-202). As mentioned in response to a previous comment, we feel that the detailed description of the faults should not be included in the regional setting section as this is new data generated in this study.

Line 215, Varnes Graben is not labelled in Figure 1c.

Label has been added

Line 216, the Fjerritslev North and South merge with the Farsund Fault between 6 and 8 s (TWT)?

Sentence has been clarified. (Line 259-260)

Line 225-228, the Moho-related reflectivity across the Fjerritslev Fault system can be inferred in Figure S2 provided as supplementary material. Where is this profile located?. Has this feature been

observed on several seismic profiles and/or previously proposed by noted references? (if this is the case this should be explained in the setting and overcome in the discussion to debate the link between the upper crustal faults and the STZ as deduced from this study and what has been previously proposed). Do the link between the STZ and the upper crustal faults is deduced from the lack of Moho reflections beneath the Farsund Basin, from the offset of Moho reflections by the Fjerritslev Fault System and from the distinctive trend of the upper crustal faults within the Farsund Basin when compared with the trend of the structure delineating the North Sea rift?

Location has been provided for Figure S2. Less emphasis will be placed on the possible linkage shown in Figure 2, as the interpretation at depth on this seismic section is highly uncertain. Instead, we now highlight the evidence for a geometric link between sub-crustal and upper crustal components, comparing this to proposals in different areas from other papers (i.e. Deeks and Thomas 1995) (Line 271-282).

Line 256-257, the authors suggest that the Fjerritslev North and South faults merge south of the 3D dataset as indicated by 2D seismic data. A figure displaying a 2D seismic line should be provided as a reference to support this interpretation?

Unfortunately, due to a lack of 3D seismic reflection data and suitably orientated 2D seismic profiles imaging faults, we can only currently speculate on this relationship. This is now made clear in the manuscript (Line 306-307). We suggest a relationship based on regional mapping and 2D seismic sections located further south of the 3D seismic volume, where a single fault is present. Furthermore, the phrasing of this sentence has been changed. Based on their map-view geometry, we infer the N-S striking faults merge southwards; however, this cannot be proven due to a lack of 3D seismic data and only few 2D lines in this area.

Line 260, HF2 is not labelled in the isochron maps showing the structure of the supra-salt levels.

HF2 has since been labelled on Figure 6

Line 304, the NS1 and NS2 faults are not labelled in figure 6b.

Labels have been added to the figure.

Line 322, although slip=fault activity??

“Slip” has been changed to “fault activity” (Line 372).

Lines 332 to 334, for the methodology section? After explaining the main developed isochron maps and before explaining the throw-length and backstripping profiles?.

This information has now been incorporated into the methodology section (Line 213-215).

I would suggest including a discussion section dealing with polyphase fault activity. I find the kinematic evolution of these faults described in section 6 from direct observations very suitable. However, some other aspects as the discrete Triassic activity along some segments of E-W faults (included between lines 368 and 389) or the geometric evolution of these faults during the Late Jurassic-Early Cretaceous oblique reactivation (lines 431 to 440, 445 to 447, 452 to 457 and 478 to 484) are discussed together with the previous interpretations and theoretical concepts so I find that these parts could be more appropriate for a discussion section.

Additional information has been incorporated into the first discussion section related to the polyphase fault activity, including the correlation between pre-existing faults and cross-cutting relay ramps, where pre-existing faults may segment the later-formed faults (Line 579-584). However, we

believe that some of the information referred to in the reviewers comment (e.g. “Line 431-440 etc.” (now at 483-486)) is of fundamental importance to interpretations, and therefore do not belong in the discussion section.

Line 397, Figure 10c?

This reference has now been changed to Fig. 10c and 11

Line 482, the eastern part of the Fjerritslev South Fault?

No, this refers to the western segment of the fault. Information regarding the segmentation of the fault has been added to Figure 12.

Line 625-630, do the authors mean that the STZ accommodated most of the deformation allowing the preservation of the cratonic lithosphere of Baltica almost undeformed?

Yes, this is what was meant. This sentence has been altered to make this point clearer (Line 689-690).

Figure 1 It would be useful including the meaning of STZ, TTZ and RFH in the figure caption of figure 1A.

The definitions of these abbreviations have been included in the Figure caption.

The rectangle delineating the extend of figure 1C seems to be too large taking into account the intersection of Fjerritslev Faults.

This has been changed.

Figure 1B is not cited and explained in the text.

This figure has now been cited in the seismic interpretation section of the methodology (Line 207-209

Figure 1C does not have a north arrow;

Changed

It would be useful including boreholes in Figure 1C together with the 2D seismic profiles. What is the red dot in figure 1c? a well location?.

The only available borehole in the area is currently shown in Figure 1c by the red dot. The definition of the red dot is further explained in the figure caption along with the figure inset.

The fault network across the Farsund Basin showed in Figure 1c. Taking into account some references provided in the text, I suppose that it comes from previous studies, but was this map developed from previous studies or was this map developed relying on seismic interpretions made in this study? If the fault trends come from previous studies, these references should be added in the figure caption. If the map was developed during this study it is a new outcome and it should be included in other figure to support the analysis of upper crustal faults.

This fault map has been created through interpretations made in this study, rather than compiled from previous works. Therefore, this forms a major result of this study, the origin of this fault map is now stated in the caption. Regional faults are based on the NPD fault maps; this is now stated in the figure caption.

Figures 2,4,5,9,10 and 14

Salt diapirs should be labelled or included in the legend.

Salt has been added to the captions or the figures of the seismic sections where appropriate

2D seismic lines: this should be included in the figure caption.

Changed

The inset map should include the scale; the maps are too small and the seismic lines displayed in white are difficult to see against the grey background.

Rough scale is included in the inset maps. Colour of the seismic lines has been changed to make them stand out more.

Figure 3, 6 and 12

Isochron maps showing thickness variations and associated faults for the main interpreted horizons; A) Triassic; B) Jurassic; C) Lower Cretaceous.

It could be useful adding latitudes and longitudes labels and using them as a reference to describe some of the observed features within the text.

The main features have been identified based on fault segments currently. The labelling of these different fault segments has been made clearer on the maps.

It should also useful adding some key contour values.

Contour interval has been included in the caption.

Figure 15

It could be useful adding fault names.

Fault names have been added to Figure 15c, as this panel represents the present day fault network.