RESEARCH ARTICLE

REVISED

Impact of sub-basalt thrust systems on the Faroe continental shelf for the late Paleoproterozoic–Cenozoic tectonic evolution of the margin.

[version 2; peer review: 2 approved]

Jean-Baptiste P. Koehl[1,2], David W. Jolley[3], Alexander L. Peace[4], Jhon M. Muñoz-Barrera[5,6], Gillian R. Foulger[7]

[1]Earth and Planetary Sciences, McGill University Faculty of Science, Montreal, Québec, H3A 0E8, Canada
[2]Geosciences, University of Oslo, Oslo, Oslo, 0371, Norway
[3]Geology and Geophysics, University of Aberdeen School of Geosciences, Aberdeen, Scotland, AB24 3UE, UK
[4]School of Earth, Environment and Society, McMaster University School of Earth Environment & Society, Hamilton, Ontario, L8S 4L8, Canada
[5]National Agency of Hydrocarbon, Bogota, Cundinamarca, 111321, Colombia
[6]Earth Science, University of Bergen, Bergen, Hordaland, 5007, Norway
[7]Earth Sciences, Durham University Department of Earth Sciences, Durham, England, DH1 3LE, UK

v2 **First published:** 13 Aug 2024, **4**:181
https://doi.org/10.12688/openreseurope.18284.1
Latest published: 07 Dec 2024, **4**:181
https://doi.org/10.12688/openreseurope.18284.2

Abstract

Background

The Faroe margin in the northeastern Atlantic is segmented by margin-orthogonal, WNW–ESE-striking lineaments extending several hundred kilometers out to the continent–ocean transition. Despite several earlier studies speculating that these features are the product of reactivation of pre-Cenozoic basement-seated structures at depth, the thick Cenozoic volcano-sedimentary sequences deposited along the margin mask the underburden, thus rendering the identification and interpretation of such structures and resolving the pre-Cenozoic history of the area challenging. The present study documents for the first time the existence of margin-orthogonal basement-seated thrust systems and describes their detailed geometry, kinematics, and tectonic evolution.

Methods

We interpreted basement-seated tectonic structures on seismic reflection data from TGS on the Faroe Platform and the Wyville–Thomson and Munkagrunnur ridges using the newly

Open Peer Review

Approval Status ✓ ✓

	1	2
version 2 (revision) 07 Dec 2024	✓ view	✓ view
version 1 13 Aug 2024	? view	? view

1. **Martyn Stoker**, The University of Adelaide, Adelaide, Australia

2. **Piotr Krzywiec**, Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Any reports and responses or comments on the article can be found at the end of the article.

established seismic facies of major thrust systems.

Results

The data show that the Wyville–Thomson Ridge, Munkagrunnur Ridge, and Faroe Platform are cored by WNW–ESE-striking thrust systems hundreds of kilometers long and 30–50 km wide, showing dominantly top-SSW kinematics. The thrusts were reworked into NE–SW-striking folds during the Caledonian Orogeny and controlled the formation of Caledonian thrusts, which in turn controlled the formation of post-Caledonian faults. The pre-Caledonian nature of the WNW–ESE-striking thrusts and their geometry and kinematics suggest a relationship with late Paleoproterozoic Laxfordian shear zones onshore northern Scotland and the continuation of the coeval Nagssugtoqidian Orogen in southeastern Greenland, the Ammassalik Belt. The thrust systems also align with the Tornquist Zone in eastern Europe and the North Sea, thus suggesting either that they controlled the formation of the Tornquist Zone or a possibly much longer (Paleoproterozoic?) tectonic history for the Tornquist Zone.

Conclusions

The Faroe Island margin is crosscut by late Paleoproterozoic Laxfordian–Nagssugtoqidian thrust systems, which controlled further tectonic development of the margin.

Plain language summary

The Faroe Islands and nearby areas were covered by thick lava flows in the Cenozoic (< 65 million years ago) during the opening of the North Atlantic Ocean. Thus far, the strong seismic signal of the lavas made the study of deeper and older rock units and tectonic structures (> 65 million years old) challenging. In the present work, we describe newly identified, hundred of km long and tens of km wide systems of old cracks in the Earth's crust in the subsurface around the Faroe Islands. The cracks trend parallel to the Greenland–Iceland–Faroe Ridge and are probably part of an 1.8 billion year old system, which continues onshore northern Scotland and has counterparts in southeastern Greenland formed during the collision of two or more tectonic plates. The newly identified structures controlled the formation of contractional structures formed during the collision of Greenland with Europe ca. 425 million years ago and of subsequent extensional structures. In addition, the present work suggests that the Greenland–Iceland–Faroe Ridge partly consists of ≥ 1.8 million years old continental crust instead of < 65 million years old oceanic crust as previously suggested. This has implications for our understanding of plate tectonics and Earth's internal dynamics.

The present study shows a new method to investigate the old tectonic history of entire regions using seismic reflection data, in the hope that it will be used more widely by the scientific community in the future to identify and study similar structures worldwide, for example when evaluating earthquake risk and exploring for natural resources such as white and orange hydrogen.

Keywords
Plate tectonics, fault, shear zone, thrust, orogen, Laxfordian Orogen, Ammassalik Belt, Nagssugtoqidian Orogen, late Paleoproterozoic, Neoproterozoic, Caledonian Orogen, inheritance, Orogenic Bridge Theory, Greenland-Iceland-Faroe Ridge, Seaward-Dipping Reflectors,

Corresponding author: Jean-Baptiste P. Koehl (jeanbaptiste.koehl@gmail.com)

Author roles: Koehl JBP: Conceptualization, Data Curation, Formal Analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Jolley DW**: Formal Analysis, Investigation, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Peace AL**: Formal Analysis, Investigation, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Muñoz-Barrera JM**: Formal Analysis, Investigation, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing; **Foulger GR**: Formal Analysis, Investigation, Validation, Visualization, Writing – Original Draft Preparation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101023439 (Impact of Timanian faults on Arctic Tectonics [ArcTec]).
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

How to cite this article: Koehl JBP, Jolley DW, Peace AL *et al.* **Impact of sub-basalt thrust systems on the Faroe continental shelf for the late Paleoproterozoic–Cenozoic tectonic evolution of the margin. [version 2; peer review: 2 approved]** Open Research Europe 2024, **4**:181 https://doi.org/10.12688/openreseurope.18284.2

First published: 13 Aug 2024, **4**:181 https://doi.org/10.12688/openreseurope.18284.1

REVISED **Amendments from Version 1**

Added several paragraphs and a new Figure 6 about the implications of a continental nature of the crust at the Greenland–Iceland–Faroe Ridge and detailing the development of a potential orogenic bridge and several paragraphs about the implications of the studied structures on the post-Caledonian evolution of the margin upon suggestion of Prof. Martyn Stoker. Also extensively modified and added highly relevant details the discussion about a possible relationship of the studied structures around the Faroe Islands and the Tornquist Zone in eastern Europe based on the comments and suggested references by Prof. Krzywiec. Also modified Figure 1a–c to better illustrate the location and geometry of the Tornquist Zone's fault segments.

Any further responses from the reviewers can be found at the end of the article

Introduction

The Faroe Islands lie along the northwestern part of the European continental shelf (Figure 1a), which was rifted away from its conjugate counterpart in southeastern Greenland in the Cenozoic, after repeated extensional events had affected the margin. These include Devonian collapse, Permian–Triassic, Cretaceous, and early Cenozoic events (Bird *et al.*, 2016; Coward *et al.*, 1989; Jolley *et al.*, 2021; Wilson *et al.*, 2010). A major outstanding issue with the pre-Cenozoic geology of the area is the difficulty in imaging rock units below the thick lava flows (Ólavsdóttir *et al.*, 2016) and the lack of studies showing the seismic character of metamorphosed basement rocks. For this study, we benefitted from reprocessed 2D seismic reflection data from TGS (survey OF95RE11) and from several recent studies focusing on local- (a few hundreds of meters high and wide) to regional-scale structures (up to hundreds of kilometers long, tens of kilometers thick) within metamorphosed basement rocks (Koehl, 2020; Koehl, 2021; Koehl, 2024a; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl & Stokmo, 2024).

Previously, late Paleocene–Miocene compression related to anomalous ridge-push along the extinct Ægir Ridge (Boldreel & Andersen, 1993; Boldreel & Andersen, 1998) and/or (Precambrian?) preexisting structures and transfer zones (Johnson *et al.*, 2005; Kimbell *et al.*, 2005), or early Paleocene rifting (Ziska & Varming, 2008) were proposed as causes for the formation of margin-oblique to margin-orthogonal structural elements such as the Wyville–Thomson, Ymir, and Munkagrunnur ridges and the Faroe Platform. However, the nature of the rocks (metamorphosed basement rocks or inverted sedimentary basin) at the core of these structural highs was thus far uncertain and the transition between these structures poorly understood (Ólavsdóttir *et al.*, 2016). The present study reveals the nature of the rocks within these highs and proposes a much older origin and tectonic history, explaining both previously inferred Cenozoic contractional reactivation and inherited basement-seated transfer zones at these margin-oblique/orthogonal structural elements. Our findings also invalidate an early Paleocene rift-related origin for these structures.

The present study extends the interpretation of old (Paleoproterozoic) orogenic belts and continental crust farther offshore. Hence, it has direct implications for the orogenic bridge theory proposed by Koehl and Foulger (2024) and for plate tectonics in general. For example, it suggests that tectonic plates are less mobile over time than previously suggested. It also has implications for regional correlations of old (Paleoproterozoic) orogens and fold-and-thrust belts. Major implications also include the use of seismic reflection imaging to map contractional ductile shear zones and thrust systems, which is now proven at various margins and will, hopefully, be widely used in the coming years.

Geological setting

Wyville–Thomson and Ymir ridges

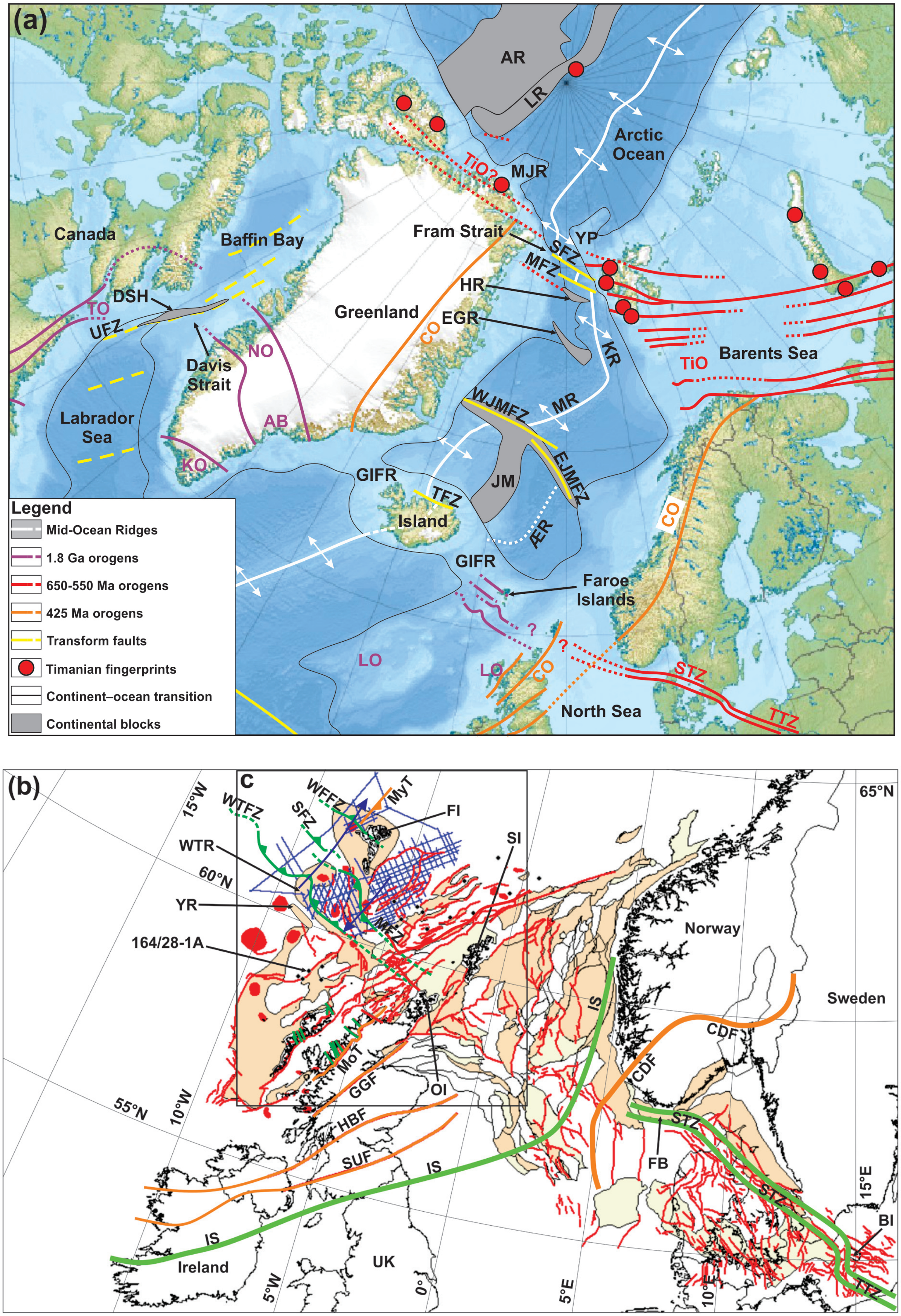
The Wyville–Thomson and Ymir ridges are elongate, respectively 30–50 km and < 10 km wide, WNW–ESE-striking high southwest of the Faroe Islands (Figure 1b). The ridges are capped by Paleogene lava flows and Cenozoic sedimentary deposits, which thin over the ridges, and are onlapped by (Cretaceous?) sedimentary rocks underlying the Paleocene lavas (e.g., Johnson *et al.*, 2005, their figure 6). Notably, previous studies showed that Eocene sedimentary units are folded, whereas Oligocene sedimentary successions onlap the ridges. These lines of evidence were used to suggest that both ridges were topographic highs during most of the Cenozoic. Previously proposed formation mechanisms include the reactivation of WNW–ESE-striking transfer faults and/or various episodes of post-breakup contraction, including in the late Eocene–mid Oligocene (Boldreel & Andersen, 1993; Boldreel & Andersen, 1998; Johnson *et al.*, 2005; Kimbell *et al.*, 2005; Kimbell *et al.*, 2016; Smallwood, 2008; Waddams & Cordingley, 1999). Boldreel and Andersen (1993) proposed that the ridges initiated from the inversion of an extensional fault, whereas Kimbell *et al.* (2005) suggested that the ridges are part of a Cenozoic ramp-anticline complex.

Munkagrunnur Ridge

The Munkagrunnur Ridge is a N–S-trending topographic high south of the Faroe Islands, which bends into a NW–SE trend towards the Wyville–Thomson Ridge in the south and bounds the Faroe–Shetland Basin in the east (Figure 1c). Formation involving several stages of Cenozoic (e.g., late Eocene–mid Oligocene) post-breakup contraction was proposed previously, i.e., similar to the Wyville–Thomson and Ymir ridges (Johnson *et al.*, 2005; Smallwood, 2008; Stoker *et al.*, 2015). Detailed sequence stratigraphic investigations even suggested repeated (up to eight discrete, < 1 Myr) episodes of tectonic uplift of the ridge during the mid-Eocene (Ólavsdóttir *et al.*, 2010). An origin of the ridge as a drape fold between two synclines has also been considered (Stoker *et al.*, 2015).

Faroe platform

The Faroe Platform is a structural high located at the northwestern edge of the European continental shelf encompassing the Faroe Islands. It consists of 20–46 km of continental crust (Funck *et al.*, 2017; Richardson *et al.*, 1998; Figure 1c). Despite its shallow character, the 3–9 km thick cover of Paleogene lava


(a)
AR
LR
Arctic
Ocean
TiO?
MJR
Canada
Baffin Bay
Fram Strait
YP
SFZ
MFZ
HR
DSH
TO
UFZ
Greenland
EGR
CO
Davis
Strait
NO
KR
TiO
Barents Sea
Labrador
Sea
AB
WJMFZ
MR
EJMFZ
KO
GIFR
TFZ
JM
Island
ÆR
CO
Legend
Mid-Ocean Ridges
1.8 Ga orogens
650-550 Ma orogens
425 Ma orogens
Transform faults
Timanian fingerprints
Continent–ocean transition
Continental blocks
GIFR
Faroe
Islands
?
?
LO
LO
CO
STZ
North Sea
TTZ
(b)
c
WFFZ
MyT
WTFZ
SFZ
FI
15°W
SI
65°N
WTR
60°N
YR
MFZ
164/28-1A
Norway
Sweden
IS
CDF
CDF
MoT
GGF
OI
55°N
10°W
HBF
STZ
SUF
FB
IS
15°E
STZ
BI
IS
Ireland
UK
5°W
0°
5°E
10°E
TTZ

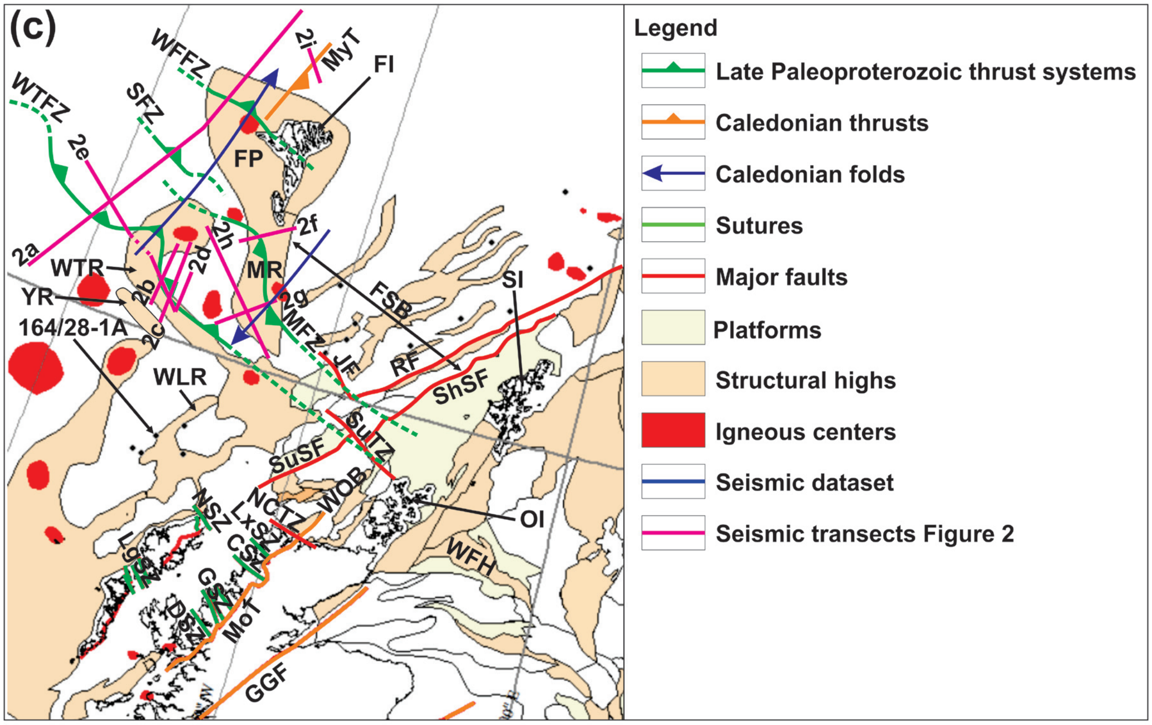
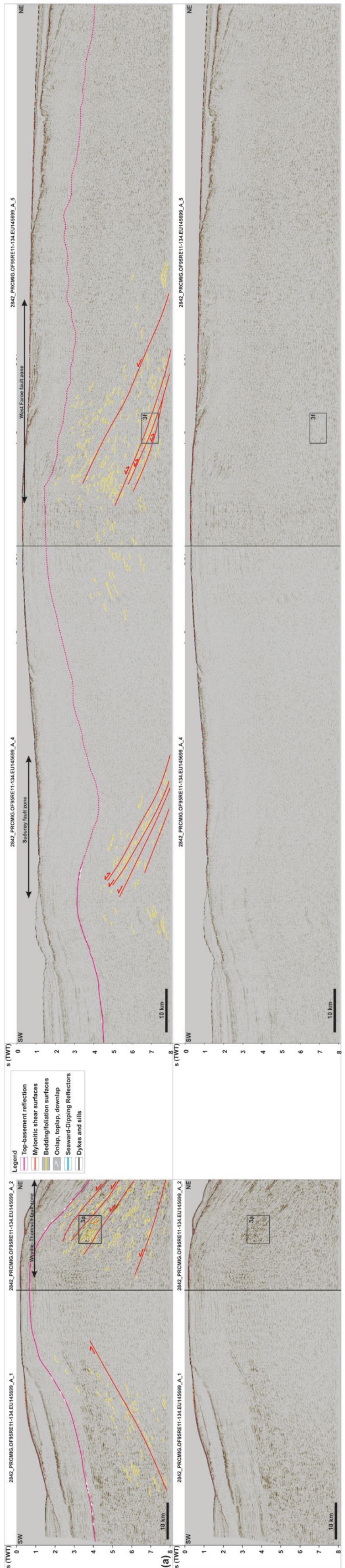


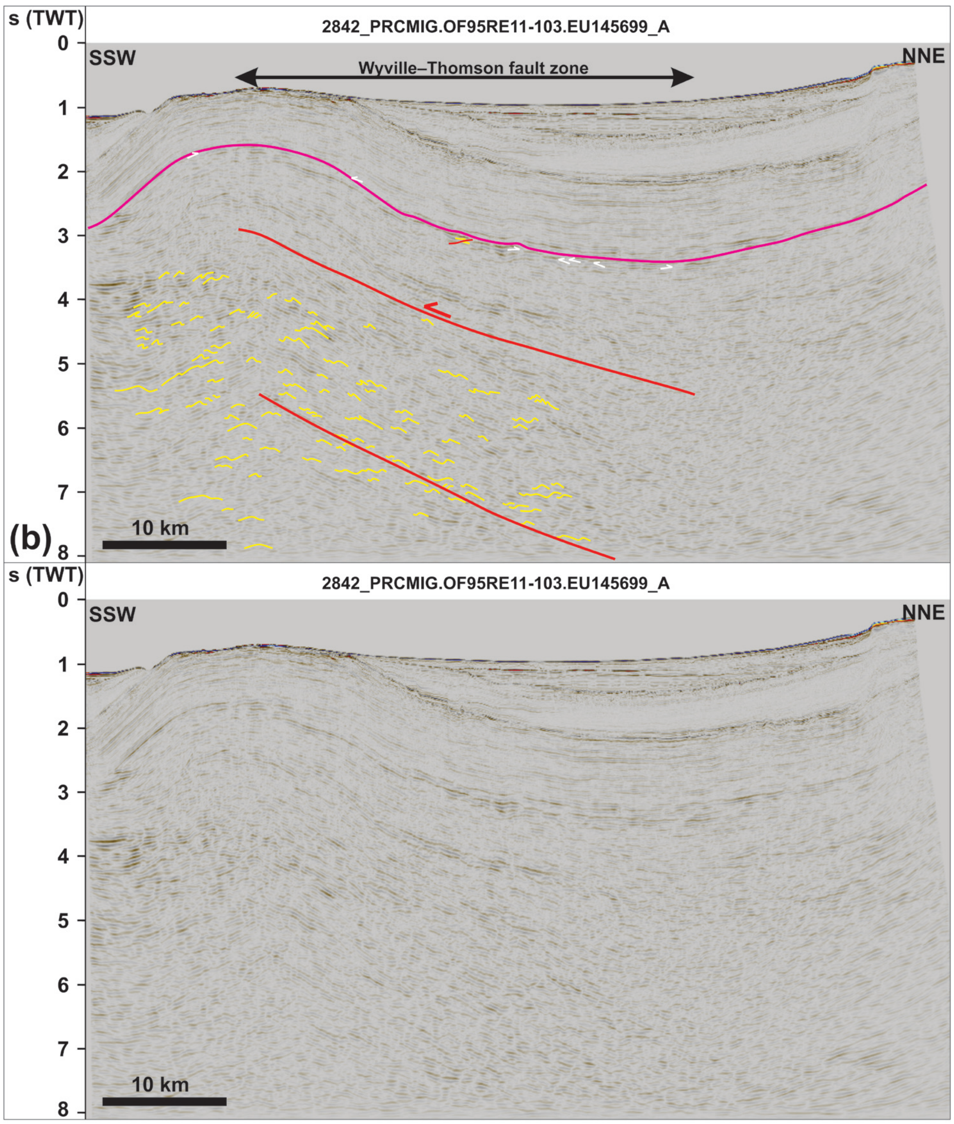
Figure 1. (**a**) Regional map of the Northeast Atlantic Ocean and main structural elements. Notice the alignment of the Tornquist Zone with the major (late Paleoproterozoic?) thrust systems discussed in the present study. Basemap is the International Bathymetric Chart of the Arctic Ocean (Jakobsson *et al.*, 2012). Abbreviations: AB: Ammassalik Belt; AR: Alpha–Mendeleev Ridge; ÆR: Ægir Ridge; CO: Caledonian Orogen; DSH: Davis Strait High; EGR: East Greenland Ridge; EJMFZ: East Jan Mayen Fault Zone; GIFR: Greenland–Iceland–Faroe Ridge; HR: Hovgård Ridge; JM: Jan Mayen Microcontinent Complex; KO: Ketilidian Orogen; KR: Knipovich Ridge; LO: Laxfordian Orogen; LR: Lomonosov Ridge; MFZ: Molloy Fault Zone; MJR: Morris Jesup Rise; MR: Mohns Ridge; NO: Nagssugtoqidian Orogen; SFZ: Spitsbergen Fault Zone; STZ: Sorgenfrei–Tornquist Zone; TFZ: Tjörnes Fault Zone; TiO: Timanian Orogen; TO: Torngat Orogen; TTZ: Teisseyre–Tornquist Zone; WJMFZ: West Jan Mayen Fault Zone; YP: Yermak Plateau. (**b**) Structural map of the continental shelf in Scandinavia, the North Sea, the UK, and the Faroe Islands showing the outline of major structures, basins, and highs in the region. Abbreviations: CDF: Caledonian Deformation Front; FB: Farsund Basin; FI: Faroe Islands; GGF: Great Glen Fault; HBF: Highland Boundary Fault; IS: Iapetus Suture; MFZ: Munkagrunnur fault zone; MoT: Moine Thrust; MyT: Mykines thrust; OI: Orkney Islands; SI: Shetland Islands; STZ: Sorgenfrei–Tornquist Zone; SUF: Southern Upland Fault; TTZ: Teisseyre–Tornquist Zone; UK: United Kingdom; WFFZ: West Faroe fault zone; WTFZ: Wyville–Thomson fault zone; WTR: Wyville–Thomson Ridge; YR: Ymir Ridge. (**c**) Zoom in the study area off the Faroe Islands. The location of (**c**) is shown as a black frame in (**b**). Major sutures, fault zones onshore the UK, and deformation fronts are from Pharaoh (1999). The geometry and location of the Sorgenfrei–Tornquist Zone and Teisseyre–Tornquist Zone are from Mazur *et al.* (2015), Phillips *et al.* (2018), and Ponikowska *et al.* (2024). Basins and highs in the northern UK, Shetland Island, and Faroe Island regions are from Johnson *et al.* (2005), Wilson *et al.* (2010), Bird *et al.* (2016), and Jolley *et al.* (2021), from the Norwegian Offshore Directorate and De Luca *et al.* (2023) for the North Sea, and from Vejbæk and Andersen (2002) and Gregersen *et al.* (2022) for the southeastern North Sea and southern Baltic Sea. Paleoproterozoic shear zones onshore northern Scotland are from Coward and Park (1987) and Bergh *et al.* (2012). Abbreviations: CSZ: Canisp Shear Zone; DSZ: Diabaig Shear Zone; FI: Faroe Islands; FP: Faroe Platform; FSB: Faroe–Shetland Basin; GGF: Great Glen Fault; GSZ: Gairloch Shear Zone; JF: Judd Fault; LgSZ: Langavat Shear Zone; LxSZ: Laxford Shear Zone; MFZ: Munkagrunnur fault zone; MR: Munkagrunnur Ridge; NCTZ: North Coast Transfer Zone; NSZ: Ness Shear Zone; MoT: Moine Thrust; MyT: Mykines thrust; OI: Orkney Islands; RF: Rona Fault; SFZ: Suðurøy fault zone; ShSF: Sheltand–Spine Fault; SI: Shetland Islands; SuTZ: Sula Transfer Zone; SuSF: Sula–Sgier Fault; WFFZ: West Faroe fault zone; WFH: West Fladen High; WLR: West Lewis Ridge; WOB: West Orkney Basin; WTFZ: Wyville–Thomson fault zone; WTR: Wyville–Thomson Ridge; YR: Ymir Ridge.

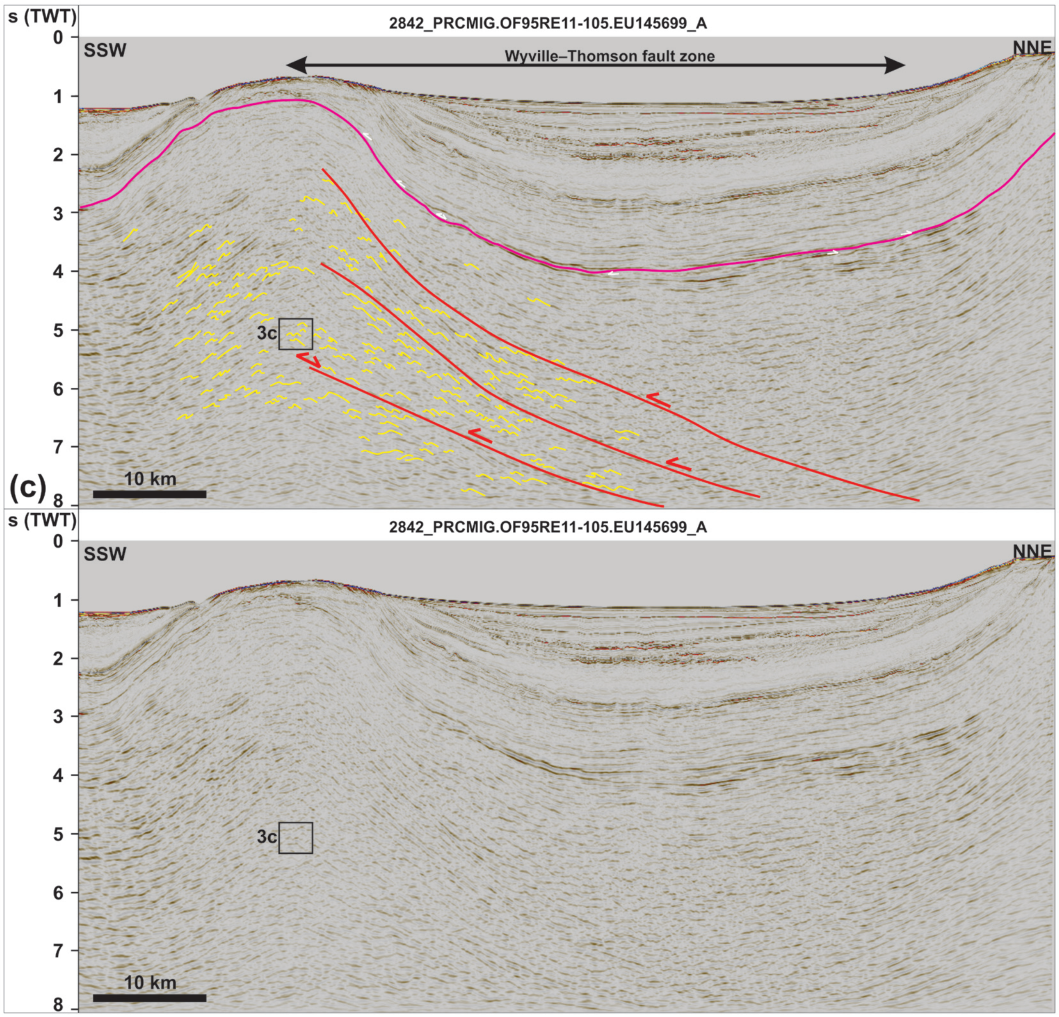
flows and sedimentary rocks, which crop out on the seabed and on the Faroe Islands, have thus far made it difficult to resolve the pre-rift evolution of the platform (Ólavsdóttir *et al.*, 2016; Ólavsdóttir *et al.*, 2021; Richardson *et al.*, 1998). Nevertheless, forward gravity modelling suggests that the lava flows are underlain by two sedimentary basins (Ólavsdóttir *et al.*, 2021).

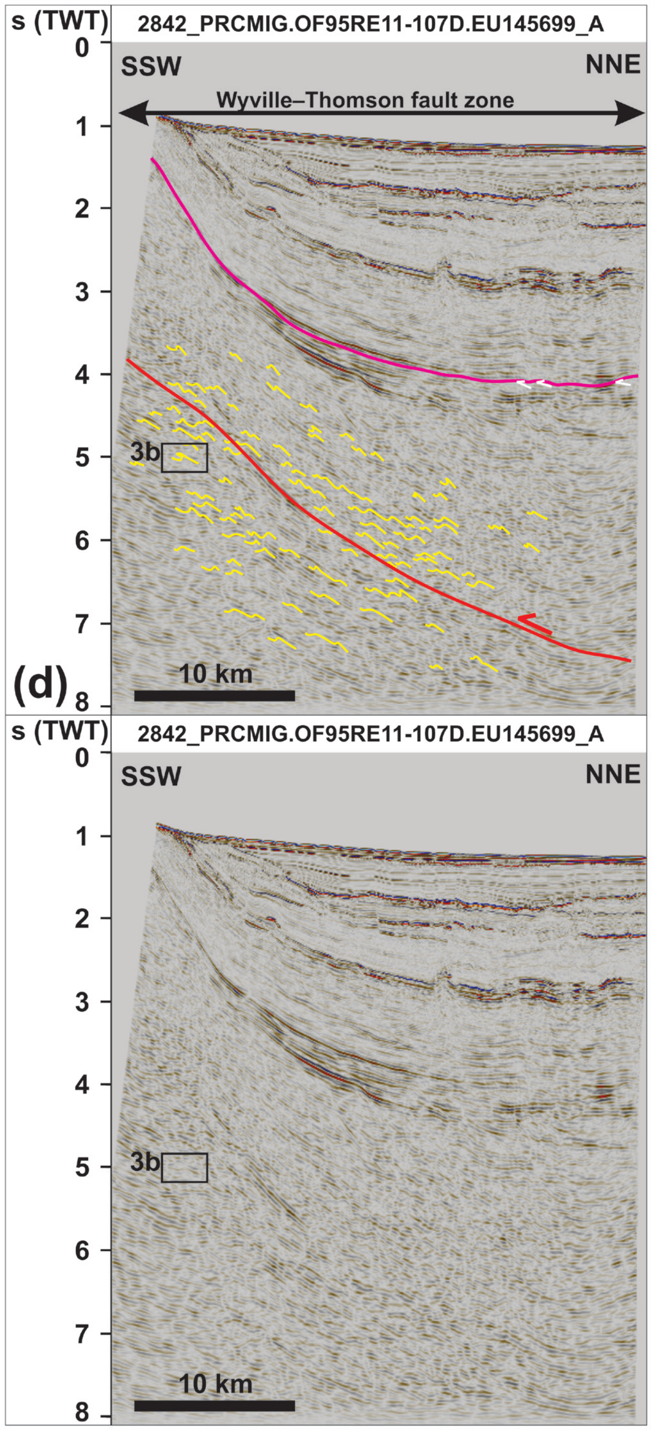
Methods

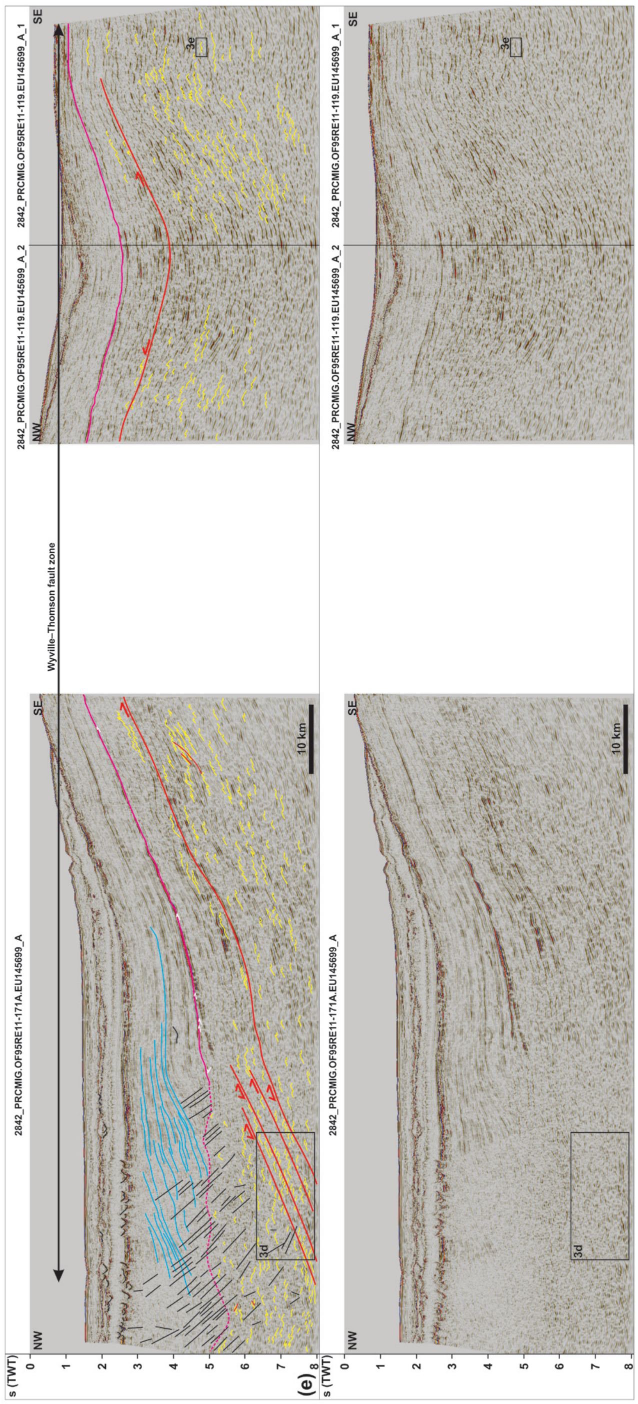
We used seismic reflection data from TGS to interpret basement-seated contractional ductile shear zones and thrust systems around the Faroe Islands (survey OF95RE11). Our interpretation is based on the previous detailed description of the internal geometry of thrust systems by Koehl *et al.* (2022; 2023a), Koehl (2024a), and Koehl and Stokmo (2024). Mylonitic thrusts were interpreted using previous works by Christensen (1965), Fountain *et al.* (1984), and Hurich *et al.* (1985). In addition, we used modern examples of mylonitic thrusts in metamorphosed basement rocks on seismic data to refine our interpretation (e.g., Fazlikhani *et al.*, 2017; Hedin *et al.*, 2016; Koehl *et al.*, 2018; Phillips *et al.*, 2016). High-resolution versions of the data (Figure 2a–i) are available on DataverseNO (https://doi.org/10.18710/780M9P).

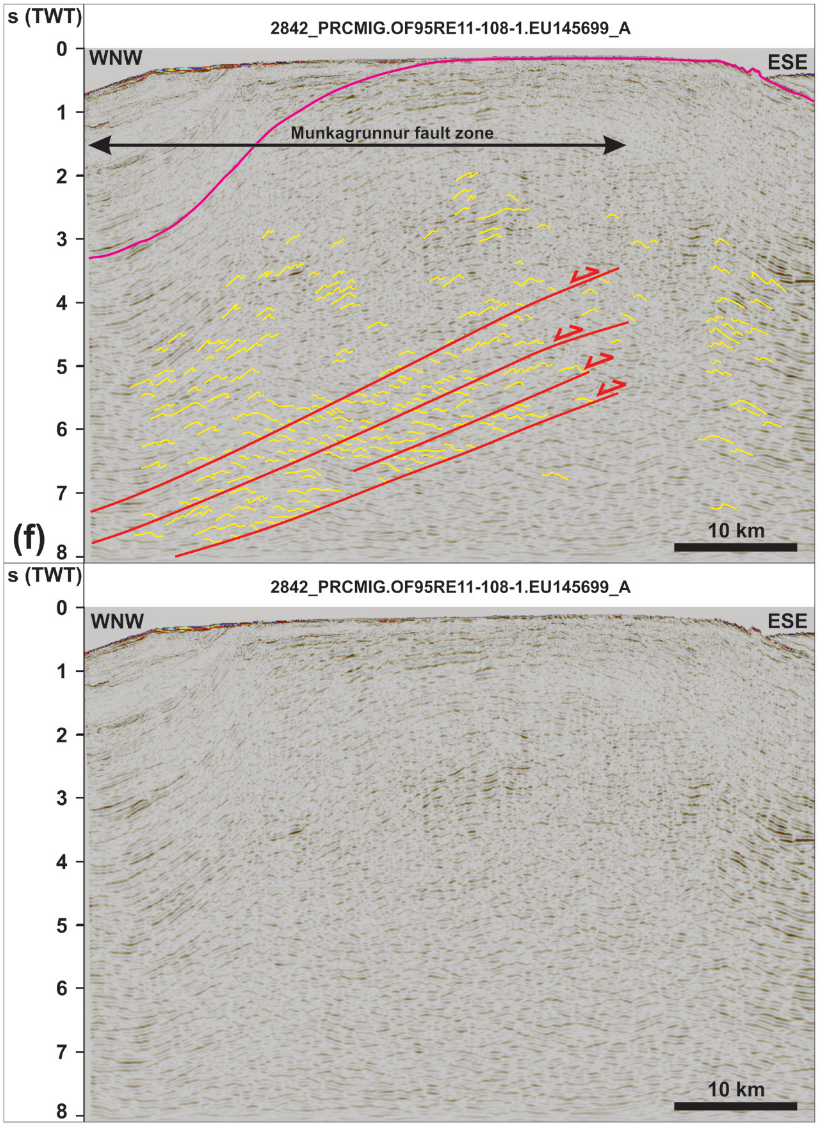

Legend
Top-basement reflection
Mylonitic shear surfaces
Bedding/foliation surfaces
Onlap, toplap, downlap
Seaward-Dipping Reflectors
Dykes and sills
s (TWT)
SW
NE
10 km
(a)
2842_PRCMG.OF9SRE11-134.EU145699_A_1
2842_PRCMG.OF9SRE11-134.EU145699_A_2
2842_PRCMG.OF9SRE11-134.EU145699_A_4
2842_PRCMG.OF9SRE11-134.EU145699_A_5
Sudbury fault zone
West Farne fault zone

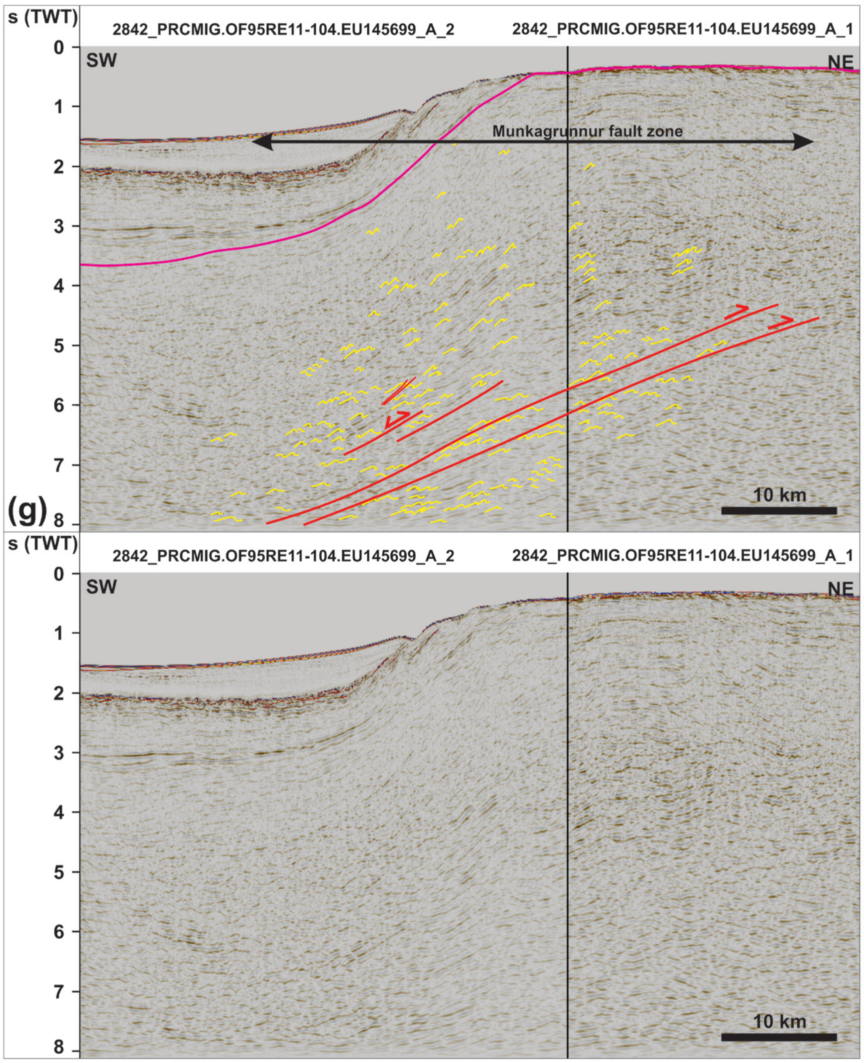

s (TWT)
2842_PRCMIG.OF95RE11-103.EU145699_A
0
1
2
3
4
5
6
7
8
SSW
NNE
Wyville–Thomson fault zone
10 km
(b)
s (TWT)
2842_PRCMIG.OF95RE11-103.EU145699_A
0
1
2
3
4
5
6
7
8
SSW
NNE
10 km

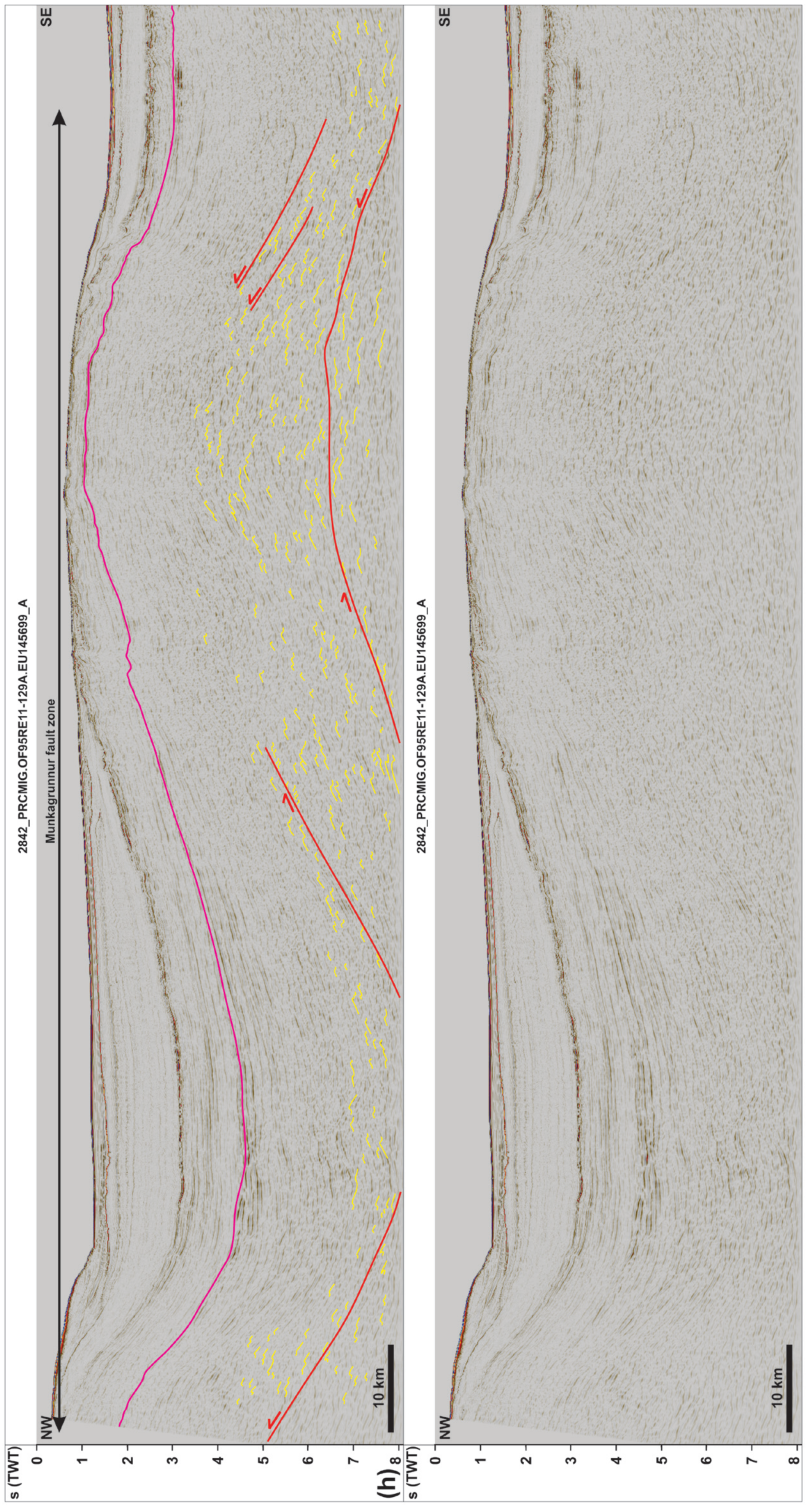

s (TWT)
2842_PRCMIG.OF95RE11-105.EU145699_A
SSW
NNE
Wyville–Thomson fault zone
3c
(c)
10 km
0
1
2
3
4
5
6
7
8
s (TWT)
2842_PRCMIG.OF95RE11-105.EU145699_A
SSW
NNE
3c
10 km


s (TWT)
2842_PRCMIG.OF95RE11-107D.EU145699_A
SSW
NNE
Wyville–Thomson fault zone
0
1
2
3
4
5
6
7
8
3b
10 km
(d)
s (TWT)
2842_PRCMIG.OF95RE11-107D.EU145699_A
SSW
NNE
0
1
2
3
4
5
6
7
8
3b
10 km


2842_PRCMIG.OF95RE11-171A.EU145699_A
2842_PRCMIG.OF95RE11-119.EU145699_A_2
2842_PRCMIG.OF95RE11-119.EU145699_A_1
Wyville–Thomson fault zone
s (TWT)
(e)
NW
SE
10 km
3d
3e


s (TWT)
2842_PRCMIG.OF95RE11-108-1.EU145699_A
WNW
ESE
Munkagrunnur fault zone
10 km
(f)
s (TWT)
2842_PRCMIG.OF95RE11-108-1.EU145699_A
WNW
ESE
10 km


s (TWT)
2842_PRCMIG.OF95RE11-104.EU145699_A_2
2842_PRCMIG.OF95RE11-104.EU145699_A_1
0
1
2
3
4
5
6
7
8
SW
NE
Munkagrunnur fault zone
10 km
(g)
s (TWT)
2842_PRCMIG.OF95RE11-104.EU145699_A_2
2842_PRCMIG.OF95RE11-104.EU145699_A_1
0
1
2
3
4
5
6
7
8
SW
NE
10 km


2842_PRCMIG.OF95RE11-129A.EU145699_A
Munkagrunnur fault zone
NW
SE
10 km
s (TWT)
(h)
2842_PRCMIG.OF95RE11-129A.EU145699_A
NW
SE
10 km
s (TWT)

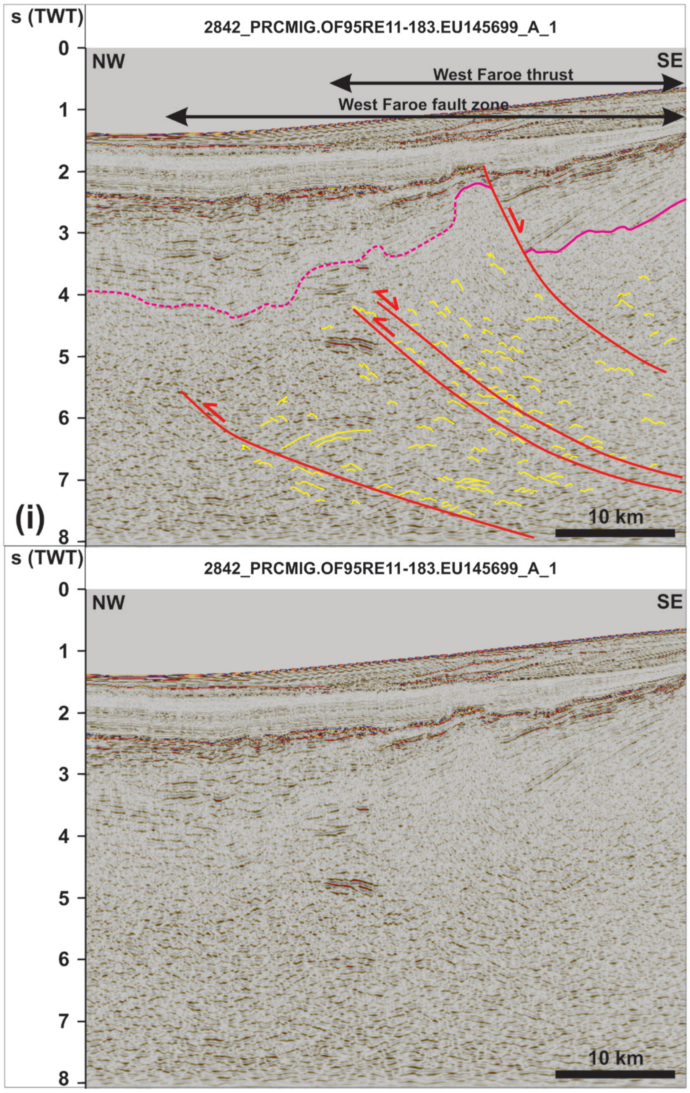


Figure 2. Seismic reflection data off the Faroe Island continental shelf. See Figure 1c for location. Data courtesy of TGS. (**a**) NNE–SSW-trending seismic transect west of the Faroe Islands showing the occurrence of major NNE-dipping, top-SSW thrust systems below Cenozoic lavas off the Faroe Islands. The thrust systems consist of major mylonitic shear surfaces (red lines) and of tightly folded bedding or foliation surfaces (yellow lines). Relatively small (kilometer to hundreds of meters wide) features of interest include asymmetric (up to isoclinal recumbent) folds, duplexes, and antiformal thrust stacks. The vergence of asymmetric fold structures (and mylonitic shear surfaces) is opposite on either side of major ridges and highs, e.g., at Wyville–Thomson Ridge, suggesting limited amounts of movement. There are Z-shaped reflections in the lower part of the Suðurøy and West Faroe fault zones suggesting extensional reactivation of the fault zones. (**b**), (**c**) and (**d**) NE–SW-trending seismic transects showing the continuation of the top-SSW Wyville–Thomson fault zone at Wyville–Thomson Ridge. (**e**) WNW–ESE-trending seismic section along the Wyville–Thomson Ridge showing tens of kilometers wide, open, NNE–SSW-striking macrofolds deforming the top-SSW Wyville–Thomson fault zone. The opposite sense of shear is indicated by asymmetric folds and minor brittle thrusts on either limbs of the macrofolds, which suggests limited amount of tectonic displacement. In the northwest, the section displays gently northwest-dipping, moderate-amplitude reflections (blue lines), curving-downward reflections (black lines), and southeast-dipping disruption surfaces (black lines) interpreted respectively as SDRs, saucer-shaped sills, and dykes and sills. The later crosscut the folded Wyville–Thomson fault zone. The Wyville–Thomson fault zone and related asymmetric folds extend below and northwest of the SDRs suggesting that the Iceland–Faroe Ridge consists (at least partly) of continental crust. (**f**) ENE–WSW-trending seismic section at the Munkagrunnur Ridge showing asymmetric folds indicating top-east kinematics along the Munkagrunnur fault zone. The Z-shaped reflections suggest extensional reworking of the fault zone. (**g**) NE–SW-trending seismic transect at Munkagrunnur Ridge showing the dominance of top-NNE kinematic indicators (e.g., NNE-verging folds and top-NNE minor brittle thrusts) along the Munkagrunnur fault zone. (**h**) NW–SE-trending transect along the Munkagrunnur Ridge showing the reworking of the Munkagrunnur fault zone by a tens of kilometers wide, NNE–SSW-striking, SSW-plunging macrofold with opposite sense of shear on either flanks. (**i**) Folded portion of the West Faroe fault zone that was overprinted by a top-northwest Caledonian thrust. The listric, post-Caledonian, brittle, normal fault, which offsets the Top-basement reflection by ca. 1 second (TWT) merges with the top-northwest thrust at depth suggesting it formed along preexisting zones of weakness in the crust.

The data frequency (c. 40 Hz; Nicholson, 2012 her figure 1) and seismic velocity within Paleoproterozoic metamorphosed basement rocks (overall 6200–6400 m.s^{-1}, i.e., c. 6300 m.s^{-1}; Bamford, 1979; Luckett & Baptie, 2015; Watson & Dunning, 1979 their figures 4, 10, and 11) and in mylonites (up to 6700 m.s^{-1}; e.g., Kästner *et al.*, 2020 their table 2) indicate that the vertical resolution of the seismic data (1/4 of the wavelength) is c. 39 m (6300/40/4). In places, the vertical resolution of seismic data may be as good as 1/32 of the wavelength (Kallweit & Wood, 1982; Li & Zhu, 2000), i.e., up to c. 5 m in the present case (6300/40/32). The horizontal resolution of the data at depth is a function of depth and the wavelength (Geldart & Sheriff, 2004) and is c. 627 m at a 5000 m depth ($(5000 \times (6300/40/2))^{1/2}$). Since the studied asymmetric folds within major shear zones and thrust systems are generally > 500 meters wide and > 150 meters thick, they are well within the vertical and horizontal resolution of the seismic dataset even at high depth (> 5000 m). Noteworthy, the horizontal resolution of the data at a depth of 2900 m (termination of well 164/28-1A) is c. 478 m ($(2900 \times (6300/40/2))^{1/2}$). See Supplement 5 in Koehl (2024b) attached to the interpretation in Koehl and Stokmo (2024) for more information on the resolvability of the targeted intra-shear-zone structures such as hundreds-of-meter- to kilometer-scale asymmetric folds on seismic reflection data.

Structures in overlying post-Caledonian sedimentary and igneous rocks only mildly (if at all) rework the studied pre-Cretaceous structures and, thus, have little impact on the geometry of the studied structures. Post-Caledonian structures were therefore not investigated, except where they showed a clear relationship with the studied basement-seated structures (e.g., merging, truncating, and/or reworking).

Our interpretation was tied to exploration wells 164/28-1A west of the West Lewis Ridge (Figure 1c), which terminated at a depth of c. 2900 m in Cretaceous sedimentary successions (see Jolley *et al.,* 2021, their figure 19 for the tie). The well also penetrated a c. 400 meters thick volcanoclastic succession including hyaloclastite and lava flows (Jolley *et al.*, 2021). The main Top-basement unconformity was interpreted as a major unconformity with onlap of Cretaceous sedimentary rocks onto the Wyville–Thomson Ridge throughout the study area.

We used Petrel 2021.3 to interpret seismic reflection data, and CorelDraw 2017 to design the figures. Alternative open-source software are OpendTect and GIMP respectively.

Results

Observations

Wyville–Thomson Ridge. Basement rocks at the WNW–ESE-striking Wyville–Thomson Ridge present several types of structures below the Top-basement unconformity, all of which are characteristic of major contractional shear zones and thrust systems. These include mylonitic shear surfaces (e.g., Fountain *et al.*, 1984; Hurich *et al.*, 1985; Phillips *et al.*, 2016; Reeve *et al.*, 2013), asymmetric folds (e.g., Koehl, 2024a; Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl & Stokmo, 2024), duplexes (e.g., Koehl, 2021; Koehl, 2024a; Koehl *et al.*, 2022; Koehl *et al.*, 2023b; Koehl & Stokmo, 2024), and minor brittle thrusts (e.g., Brewer *et al.*, 1980; Brewer *et al.*, 1981; Koehl, 2021; Koehl *et al.*, 2022; Koehl *et al.*, 2023b; Koehl & Stokmo, 2024; O'Connor, 1992; Shaw *et al.*, 1999). These are further described below.

In NE–SW-trending cross section, basement rocks at the Wyville–Thomson Ridge consist of numerous undulating, upward-convex, low- to moderate-amplitude seismic reflections with an undulation wavelength of a few hundred meters to a few kilometers (Figure 2a–i). Most of the undulating reflections are asymmetric and typically show a long, gently-dipping edge and a short, steeply-dipping edge (Figure 2a–d and Figure 3a). In places, these asymmetric reflections display a tight hinge zone with parallel edges (Figure 3b). A few undulating upward-convex reflections are symmetric and are found at the center of the ridge (Figure 3c).

On the northeastern flank of the Wyville–Thomson Ridge, numerous asymmetric reflections lean towards the south-southwest, i.e., showing a long, gently-NNE-dipping edge and a short, steeply-SSW-dipping edge (Figure 2a–d and Figure 3a–b). Subsidiary undulating reflections on the south-western flank of the ridge show opposite characteristics with a long, gently-SSW-dipping southwestern edge and a short, steeply-NNE-dipping northeastern edge (Figure 2a–c).

In places, some asymmetric undulating reflections are arranged in packages separated by planar, 2–8 seconds (TWT) deep, gently-NNE-dipping, moderate- (in places high-) amplitude disruption surfaces (Figure 2a–i). These disruption surfaces are traced for tens of kilometers in cross section and for at least 150 km along the strike of the Wyville–Thomson Ridge (Figure 1c and Figure 4a). In addition, minor, a few hundred meters to a few kilometers, high-angle disruption surfaces mildly offset asymmetric reflections in a reverse fashion (Figure 3a).

In NW–SE-trending along-strike section, the major, hundreds of kilometers long disruption surfaces are folded into up to 100 km wide, NE–SW-striking open folds (Figure 2e). These NE–SW-striking folds are confirmed by the depth map (i.e., map-view geometry) of the main disruption surface, which also shows that these major open folds plunge moderately to the north-northeast, displaying dome- and trough-shaped geometries (Figure 4a).

In the northwest, NW–SE-trending sections show a series of thick, moderate-amplitude, gently-northwest-dipping reflections between 3 and 5 seconds (TWT; see blue lines in Figure 2e), which have been previously interpreted as Seaward-Dipping Reflectors (SDRs; Davison *et al.*, 2010; Parson *et al.*, 1988; Smythe, 1983; Spence *et al.*, 1989). Farther northwest, these are truncated by numerous, moderately- to steeply-southeast-dipping disruption surfaces within low- to moderate-amplitude rock units (see planar black lines in Figure 2e). These disruption surfaces are observed up to

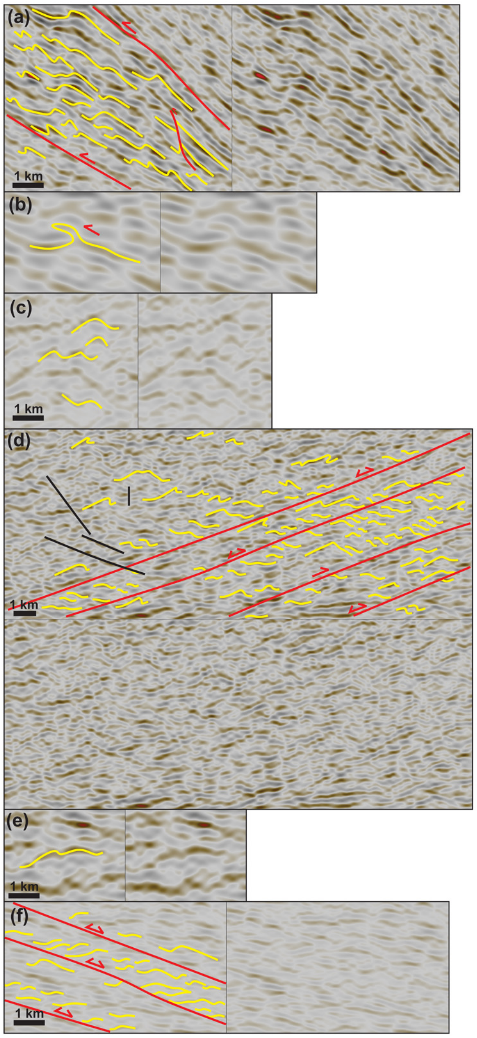


Figure 3. Zoom in specific structures on seismic reflection data. See Figure 2 for legend. All figure insets show interpreted data on the left-hand side and uninterpreted data on the right-hand side, except for (**d**), which shows interpreted data up and uninterpreted data down. Data courtesy of TGS. (**a**) Forward-dipping duplexes (see Koehl, 2021 for definition) consisting of SSW-verging asymmetric folds, minor top-SSW brittle thrusts, and antiformal stacks (yellow lines) bounded upwards and downwards by major mylonitic shear surfaces (red lines) along the Wyville–Thomson fault zone. All the structures consistently indicate top-SSW kinematics. See location in Figure 2a. (**b**) Isoclinal recumbent fold indicating top-SSW kinematics along the Wyville–Thomson fault zone. See location in Figure 2d. (**c**) Symmetric folds within the core of the Wyville–Thomson Ridge suggesting limited movement. See location in Figure 2c. (**d**) Southwest-verging asymmetric folds and down-northwest extensional duplexes suggesting extensional reactivation of folded WNW–ESE-striking (late Paleoproterozoic) thrust systems. The folded and reactivated/overprinted thrust systems are crosscut by southeast-dipping (Cenozoic) sills and dykes (black lines). See location in Figure 2d. (**e**) Symmetric folds within the core of NNE–SSW-striking (Caledonian) macrofolds along strike the Wyville–Thomson fault zone. See location in Figure 2e. (**f**) Z-shaped reflections within WNW–ESE-striking thrust systems. The SSW-verging asymmetric folds (up) are juxtaposed with Z-shaped extensional duplexes across (down) a major NNE-dipping mylonitic shear surface (red line) suggesting down-NNE extensional reactivation of top-SSW thrust systems. See location in Figure 2a.

a depth of 7.5 seconds (TWT) and terminate below a layer of high-amplitude, flat-lying sedimentary strata crosscut by multiple high-amplitude, U-shaped reflections at a depth of 2.5–3 seconds (TWT) interpreted as saucer-shaped sills (see U-shaped black lines in Figure 2e).

At a depth ≥ 6 seconds (TWT) below the moderately- to steeply-southeast-dipping disruption surfaces and gently-northwest-dipping SDRs, upward-convex reflections similar to those within the Wyville–Thomson Ridge are arranged in packages of dominantly southeast-leaning and locally Z-shaped reflections separated by gently-northwest-dipping disruption surfaces (Figure 3d). Locally, the upward-convex reflections display intermediate geometries between Z-shaped and southeast-leaning (Figure 3d).

Munkagrunnur Ridge. South of the Faroe Islands along the western flank of the Munkagrunnur Ridge (Figure 1c), the data shows that basement rocks are dominated by a few hundred meters to a few kilometers wide, asymmetric reflections leaning to the east (Figure 2f). Farther south, the reflections lean to the north-northeast (Figure 2g). Similarly, a major, 4–8 seconds (TWT) deep disruption surface is observed in the area and displays a comparable, c. 70° map-view change in orientation, i.e., bending from a west-dipping geometry in the north, just south of the Faroe Islands, to a SSW-dipping geometry at the southern tip of the Munkagrunnur Ridge (Figure 1c).

In NW–SE-striking sections, the major disruption surface appears folded into a major, ≥ 70 km wide, southwest-plunging antiform, and undulating reflections are dominantly symmetrical within the Munkagrunnur Ridge (Figure 2h), i.e., similar to the disruption surfaces and undulating reflection within the Wyville–Thomson Ridge (Figure 2e and Figure 3e).

Faroe Platform. West and southwest of the Faroe Islands, basement rocks show asymmetric reflections in NE–SW-trending cross sections comparable to those at Wyville–Thomson Ridge (Figure 2a). Additional features of interest are packages of Z-shaped reflections separated by planar, NNE-dipping disruption surfaces (Figure 3d and f) and 30–40 km wide macrofolds of the Top-basement reflection similar to that observed at the Wyville–Thomson Ridge (Figure 2a). In map view, the main disruption surfaces appears mildly folded into a ≥ 50 km wide, NNE-plunging antiform similar to that observed at the Wyville–Thomson Ridge (Figure 4a).

On the southeastern limb of this major NNE-plunging fold, asymmetric, undulating, low- to moderate-amplitude reflections lean to the northwest and disruption surfaces dip gently to moderately to the southeast (Figure 2i), i.e., similarly to asymmetric undulating reflections and disruption surfaces in the southeastern limb of the major NNE-plunging antiform at Wyville–Thomson Ridge (Figure 2e). In addition, the southeast-dipping disruption surfaces on the Faroe Platform deepen from a c. 2.0–4.0 seconds (TWT) depth in the southwest to a c. 4.25–7.25 seconds (TWT) depth in the northeast, i.e., following the attitude of the NNE-plunging antiform on the Faroe Platform (Figure 4a–b).

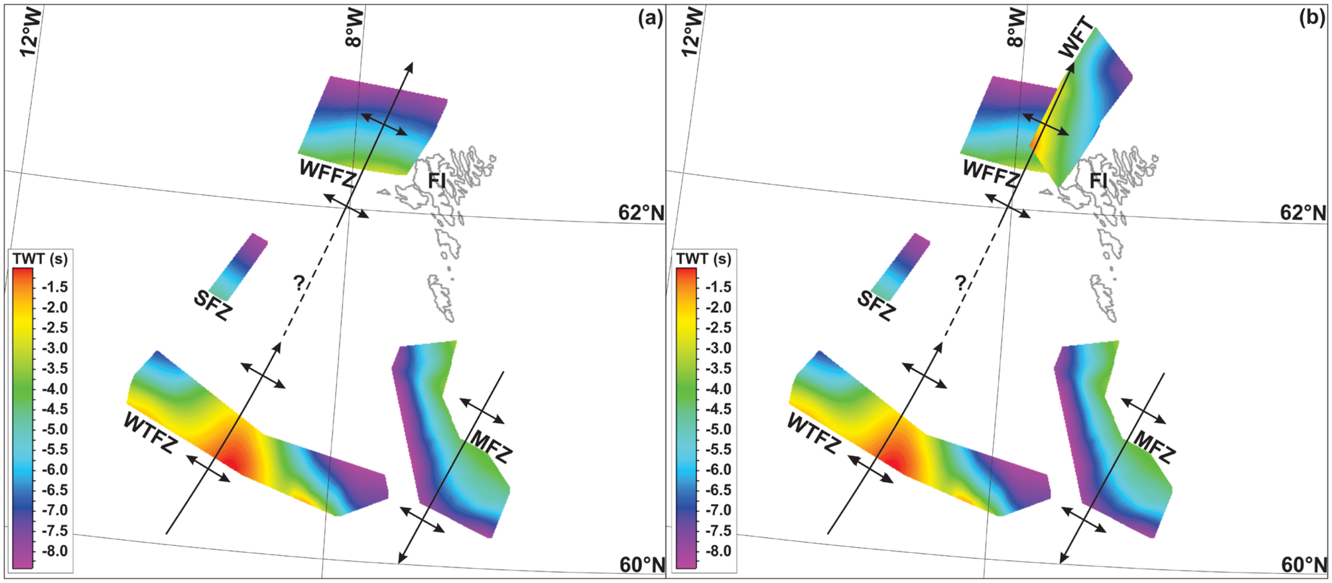


Figure 4. Time (TWT) maps of the WNW–ESE-striking thrust systems off the Faroe Islands without (**a**) and with (**b**) Caledonian thrusts (West Faroe thrust). There is apparent folding of the thrust systems into tens of kilometers wide, NNE–SSW-striking, dominantly NNE- and subsidiarily SSW-plunging macrofolds and the formation of Caledonian thrusts along the limbs of the Caledonian macrofolds. Abbreviations: FI: Faroe Islands; MFZ: Munkagrunnur fault zone; SFZ: Suðurøy fault zone; WFFZ: West Faroe fault zone; WFT: West Faroe thrust; WTFZ: Wyville–Thomson fault zone.

North of the Faroe Islands, a major, high-angle, southeast-dipping, listric disruption surface bounds thickened wedges of post-Caledonian sedimentary rocks against metamorphosed basement rocks consisting of northwest-leaning asymmetric reflections and crosscut by moderately- to gently-southeast-dipping disruption surfaces (Figure 2i). In the upper part, the high-angle disruption surface offsets discrete reflections by c. 0.1 second (TWT) in a normal fashion (Figure 2i). At depth, the high-angle disruption surface dips moderately to gently and parallels major southeast-dipping disruption surfaces within basement rocks (Figure 2i).

Interpretation

Magmatic features. In the northwest, the moderately southeast-dipping disruption surfaces crosscutting the SDRs and terminating below the saucer-shaped sills do not show any offset of the truncated features (Figure 2e). A tectonic origin is therefore unlikely. Given their occurrence below a system of saucer-shaped sills and absence farther southeast and their planar and gently- to moderately-dipping geometry (Figure 2e), they are interpreted as a magmatic feeder system of sills and dykes related to the rifting of the northeastern Atlantic.

WNW–ESE-striking thrust systems. Asymmetric undulating reflections occur as packages consistently displaying a long and a short limb (e.g., long northeastern and short southwestern limb on the northeastern flank of Wyville–Thomson Ridge; Figure 2a) and are in places crosscut and offset by minor, reverse, high-angle disruption surfaces (Figure 2a and Figure 3a) and by major, moderately dipping disruption surfaces (Figure 2a–d). These features are typical of major thrust systems, both in the field (Bell & Hammond, 1984; Fossen & Holst, 1995; Nabavi and Fossen, 2021 their figure 2f; Platt, 1983) and on seismic data (e.g., Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl, 2024a; Koehl & Stokmo, 2024; Figure 2a–i and Figure 3a–f). Thus, the asymmetric reflections are interpreted as folded (bedding? foliation?) surfaces indicating the sense of shear and direction of tectonic transport within metamorphosed basement rocks, and minor, high-angle and major moderately-dipping disruption surfaces as brittle thrusts and contractional mylonitic shear zones within major thrust systems respectively (Fountain *et al.*, 1984; Hurich *et al.*, 1985; Koehl *et al.*, 2022; Phillips *et al.*, 2016). Major thrust systems in the study area include the NNE-dipping Wyville–Thomson, Suðurøy, and West Faroe fault zones, and the SSW-dipping Munkagrunnur fault zone (Figure 1b–c and Figure 2a and g).

In places, asymmetric reflections show limbs with the same dip direction and/or parallel to one another, thus suggesting recumbent to isoclinal geometries (Figure 3b). In addition, in places, asymmetric folds are arranged in packages (Figure 3a) separated by major WNW–ESE-striking mylonitic shear zones (Figure 2a–i and Figure 4a). These packages of asymmetric folds are interpreted as contractional, forward-dipping duplexes (see Koehl, 2021 for definition), some of which possibly evolved into antiformal thrust stacks (Figure 3a; Boyer & Elliott, 1982).

Overall in the study area, asymmetric folds indicate a dominant top-SSW (Figure 5a) and subsidiary top-NNE transport directions in NE–SW-striking cross section (Figure 2a–i and

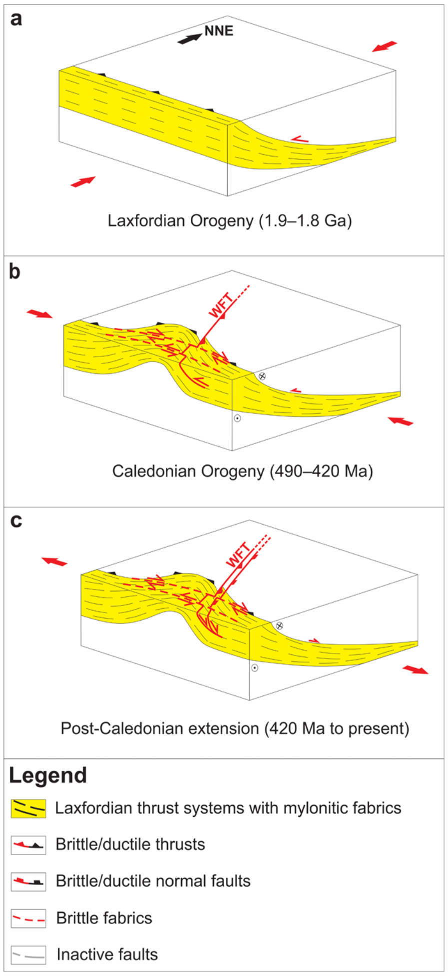


Figure 5. (**a**) Formation of mylonitic, WNW–ESE-striking (dominantly top-SSW) thrust systems during the late Paleoproterozoic Laxfordian (–Nagssugtoqidian) Orogen. (**b**) Reworking of the thrust systems into tens to hundreds of kilometers wide, NNE–SSW-striking macrofolds during the Caledonian Orogeny and formation of NNE–SSW-striking mylonitic Caledonian thrusts and shear zones (e.g., West Faroe thrust – WFT) on the limbs of folded Paleoproterozoic thrust systems. (**c**) Post-Caledonian (i.e., Devonian–Permian and possibly Mesozoic–Cenozoic) reactivation and overprinting of Laxfordian thrust systems, including formation of listric brittle normal faults merging with Caledonian and folded Paleoproterozoic thrust systems at depth. Note that the mapped thrust systems were probably reactivated/overprinted during late Neoproterozoic and potentially Cenozoic contractional events.

Figure 3a–f). More specifically, at Wyville–Thomson Ridge and on the Faroe Platform (Figure 1c), asymmetric folds are SSW-verging in the northeastern and NNE-verging in the southwestern flanks of major, open, 30–40 km wide, WNW–ESE-striking macrofolds, which affect the Top-basement reflection and overlying Mesozoic–early Cenozoic volcanosedimentary successions (Figure 2a–c). The opposite kinematics of the asymmetric folds suggest that they may have formed as parasitic folds. Together with the occurrence of symmetric folds within the hinge of the WNW–ESE-striking macrofolds (Figure 2a–c and Figure 3c), this suggests an overall limited amount of tectonic movement (probably up to a few tens of km).

NE–SW-striking Caledonian folds and thrusts. In NW–SE-trending along-strike section, the WNW–ESE-striking thrust systems and mylonitic shear zones are folded into open, up to 100 km wide, NE–SW-striking macrofolds that also involve both basement and Mesozoic–early Cenozoic volcanosedimentary successions (Figure 2e and Figure 5b). This is illustrated for example by the switch in dominant structural strike at the Munkagrunnur Ridge, i.e., top-east folds and shear zones in the west and top-NNE in the south (Figure 2f–g). These macrofolds include possible southeast- and northwest-verging asymmetric (parasitic?) folds and associated duplexes and minor brittle thrusts (Figure 2e) and their initiation must postdate the formation of WNW–ESE-striking thrust systems. Similarly to WNW–ESE-oriented structures, asymmetric folds on the limbs of, NE–SW-striking macrofolds also show opposite vergence (top-southeast and top-northwest; Figure 2e), thus also limiting tectonic movements to possibly a few tens of km.

North of the Faroe Islands, the northwest-leaning asymmetric folds and related gently- to moderately-southeast-dipping disruption surfaces suggest the occurrence of a shallow (up to 2.0 seconds TWT) top-northwest shear zone in basement rocks (Figure 2i and Figure 5b). The shallow character and northeastward deepening geometry of the shear zone, i.e., mimicking the attitude of the underlying, WNW–ESE-striking West Faroe fault zone at depth (i.e., southeast-dipping because folded into a NNE-plunging macrofold) suggests that the West Faroe fault zone controlled the formation of the top-northwest shear zone (Figure 2i, Figure 4a–b, and Figure 5b).

The top-northwest sense of shear indicated by the northwest-verging folds is comparable to that of the Moine Thrust in northern Scotland (Coward, 1980; Coward, 1990; Coward *et al.*, 1980; McClay & Coward, 1980; Ramsay, 1969; Soper & Wilkinson, 1975) and in adjacent offshore areas (e.g., Bird *et al.*, 2016). In addition, the seismic geometry of the top-northwest shear zones are similar to that of the Moine Thrust (Bird *et al.*, 2016). This suggests that the top-northwest shear zone and related asymmetric folds and macrofolds (Figure 2e and Figure 3e) initiated during the Caledonian Orogeny (Figure 5b). We name this fault the West Faroe Thrust.

Post-Caledonian normal faults and reactivation. The high-angle disruption north of the Faroe Islands offsets post-Caledonian sedimentary successions in a normal fashion and is therefore interpreted as a normal fault. The fault merges with the top-northwest West Faroe Thrust at depth (Figure 2i and Figure 5c). A similar relationship was documented along the offshore continuation of the Moine Thrust in the West Orkney Basin, where post-Caledonian (Devonian–Permian) brittle normal faults merge at depth with the Moine Thrust (Bird *et al.*, 2016). In addition, folded portions of the WNW–ESE-striking thrust systems west of the Faroe Islands (e.g., Wyville–Thomson fault zone below the SDRs) show Z-shaped reflections within duplex structures (Figure 2e). These indicate that folded portions of WNW–ESE-striking thrust systems were inverted during post-Caledonian extension (Figure 3d and f), and that Caledonian and pre-Caledonian structures controlled the formation of subsequent post-Caledonian normal faults in the study area (Figure 5c).

Discussion

Timing of formation of WNW–ESE-striking thrust systems

The inversion of WNW–ESE-striking thrust systems and related structures (Figure 2a and e and Figure 3d and f) and their controlling relationship over Caledonian folds and thrusts and post-Caledonian normal faults (Figure 2i and Figure 4a–b) imply a pre-Caledonian origin for WNW–ESE-structures. Their strike possibly indicates that they formed during an episode of NE–SW-oriented contraction. Here, we review possible origins for the WNW–ESE-striking thrust systems off the Faroe Islands.

Late Paleoproterozoic origin. The 240 km wide, WNW–ESE-striking Ammassalik Belt in southeastern Greenland is the southeastern continuation of the late Paleoproterozoic Nagssugtoqidian Orogen in western Greenland (Bridgewater & Myers, 1979; Chadwick & Vasudev, 1989; Chadwick *et al.*, 1989; van Gool *et al.*, 2002; van Gool *et al.*, 2005). The belt consists dominantly of steeply-dipping, strike-slip (dominantly sinistral), E–W-striking shear zones, which are crosscut by gently dipping, top-SSW shear zones and nappe stacks, which formed in the Paleoproterozoic under greenschist facies conditions (Bridgewater & Myers, 1979; Chadwick & Vasudev, 1989; Chadwick *et al.*, 1989; Kalsbeek *et al.*, 1993). The regional strike and kinematics of structures in the Ammassalik Belt are comparable to those of the WNW–ESE-striking thrust systems off the Faroe Islands (Figure 2a–i, Figure 4a, and Figure 5a).

Smaller scale similarities include mylonitic fabrics (with sharp boundaries between intensely deformed and little deformed material) and imbricate structures, which are common both within the gently NNE-dipping shear zones of the Ammassalik Belt (Bridgewater & Myers, 1979) and within the major thrust systems west and southwest of the Faroe Islands (e.g., asymmetric folds and duplexes separated by mylonitic thrust surfaces; Figure 2a–i). In addition, fold structures within shear zones in southeastern Greenland are of comparable size (hundred to a few hundreds of meters width and height) and geometry (south- to SSW-verging asymmetric, up to isoclinal; Chadwick & Vasudev, 1989, e.g., their figures 9 and 13) to those observed within the thrust systems in the study area (Figure 2a–i). Moreover, the broad occurrences of sheared basic dykes within the shear zones at the Ammassalik Belt (Bridgewater & Myers, 1979) may very well be present in the study area too and help enhance the acoustic impedance contrast allowing the imaging of the intra-thrust shear fabrics on the interpreted seismic reflection data (e.g., amplitude contrast between the mylonitic shear zones and asymmetric folds).

In northern Scotland, Paleoproterozoic structures in the Lewisian Complex include WNW–ESE-striking, amphibolite-facies, mylonitic shear zones formed during the Laxfordian Orogeny, such as the several kilometer-wide, > tens of kilometers long Laxford (or Tarbet), Canisp (or Stoer), Gairloch, Diabaig, Ness, and Langavat shear zones (Attfield, 1987; Beach, 1974; Coward *et al.*, 1980; Coward & Park, 1987; Evans, 1965). These are also tightly folded into WNW–ESE-elongated, dome-shaped anticlines in the same way as the WNW–ESE-striking thrust systems on the Faroe Island continental shelf, which were reworked by NE–SW-striking Caledonian folds (Figure 2a–i and Figure 4a). In addition, the double vergence of contractional structures off the Faroe Islands, i.e., (dominantly) top-SSW and (subsidiarily) top-NNE transport direction (Figure 1b–c and Figure 2a–i), is consistent with the alternating top-SSW and top-NNE vergence of folds and shear zones onshore northern Scotland (e.g., top-NNE Laxford Shear Zone and top-SSW Diabaig Shear Zone; Figure 1c; Beach, 1974; Coward *et al.*, 1980; Coward & Park, 1987). Furthermore, some Laxfordian shear zones in northern Scotland also show top-SSW tectonic transport, e.g., Diabaig Shear Zone (Beach, 1974; Coward *et al.*, 1980). Although most Laxfordian shear zones in northern Scotland display steep, subvertical geometries and evidence of (dominantly dextral) strike-slip movements (Coward & Park, 1987), these may reflect Caledonian reactivation/overprinting due to NW-SE-oriented Caledonian contraction and/or portions of Paleoproterozoic shear zones that were folded during the Caledonian Orogeny similarly to the thrust systems off the Faroe Islands rather than exotic terranes or inliers (e.g., Friend *et al.*, 2008; Storey *et al.*, 2010; Figure 5b).

The strong similarities (e.g., strike, transport direction, fold and shear zone geometries, mylonitic fabrics) of structures in the Paleoproterozoic Ammassalik Belt in southeastern Greenland and coeval Laxfordian shear zones in northern Scotland with the mapped thrust systems off the Faroe Islands suggest that they are all part of the same (Laxfordian–Nagssugtoqidian) orogen. We therefore propose that the WNW–ESE-striking thrust systems west and southwest of the Faroe Islands formed during the late Paleoproterozoic (Figure 5a).

Considering the occurrence of WNW–ESE-striking Inverian (ca. 2.49–2.48 Ga) shear zones in northern Scotland, which are crosscut by parallel Laxfordian shear zones (e.g., Attfield, 1987; Coward & Park, 1987), it is possible that the observed offshore thrust systems initiated during the Inverian Orogeny. However, more data and further work are needed to test this hypothesis. A late Paleoproterozoic age (ca. 1.8 Ga) for the presented thrust systems is therefore considered as a minimum age.

We note that the proposed relationship with late Paleoproterozoic Laxfordian–Nagssugtoqidian (and/or Inverian?) belts do not preclude a link of the mapped thrust systems with the Tornquist Zone and related fault segment, the Teisseyre–Tornquist Zone (Krzywiec *et al.* 2022; Mazur *et al.*, 2015) and Sorgenfrei–Teisseyre Zone (Phillips *et al.*, 2018; Ponikowska *et al.*, 2024).

This would either mean that the Tornquist Zone formed along inherited late Paleoproterozoic thrusts, or that it had already been formed in the late Paleoproterozoic. The latter is possible considering the WNW–ESE strike of major late Paleoproterozoic Svecokarelian–Svecofennian structures in southern Baltica (Bergh *et al.*, 2012; Nordgulen & Saintot, 2008; Saintot *et al.*, 2011), i.e., parallel to the Tornquist Zone (Abramovitz *et al.*, 1999; Cotte *et al.*, 2002; Coward, 1990; Graversen, 2009; Hossein Shomali *et al.*, 2006; Narkiewicz *et al.*, 2015; Pegrum, 1984; Phillips *et al.*, 2018), and the proximity (< 100 km) of the southernmost Svecokarelian–Svecofennian structures in surface outcrops to the Sorgenfrei–Tornquist Zone in southeastern Sweden (Saintot *et al.*, 2011). In addition, southern Baltica was also the locus of the late Paleoproterozoic Transscandinavian Igneous Belt, which also consists of WNW–ESE-striking structures in southernmost Sweden and Denmark, e.g., possibly late Paleoproterozoic WNW–ESE-striking gneissic fabrics on the island of Bornholm (Johansson *et al.*, 2015), i.e., in the vicinity of the Sorgenfrei–Tornquist Zone.

Late Neoproterozoic origin. A possible event is the late Neoproterozoic episode of deformation recorded by amphibolite-facies, top-west movements along the east-dipping Barnhill Shear Zone in northwestern Scotland (Storey *et al.*, 2004) and in the Walls Metamorphic Series in the Shetland Islands (Walker *et al.*, 2020). Although the N–S strike and top-west kinematics of the Barnhill Shear Zone differs from that of the major WNW–ESE-striking thrust systems west and southwest of the Faroe Islands, they may reflect folding of the shear zone during the Caledonian Orogeny as observed for the thrust systems in the study area (Figure 2e, Figure 4a, and Figure 5b).

In eastern Europe, late Neoproterozoic deformation was recorded southwest of the WNW–ESE-striking Teisseyre–Tornquist Zone (Belka *et al.*, 2003; Narkiewicz & Petecki, 2017; Zelazniewicz *et al.,* 2009). In addition, the imaginary prolongation of the Sorgenfrei–Tornquist Zone to the west-northwest lines up with the Wyville–Thomson fault zone (Figure 1a–b). However, late Neoproterozoic deformation along the Teisseyre–Tornquist Zone is only preserved in exotic Gondwanan terranes in the southwest, and, thus far, the Tornquist Zone was only traced as far as the southern North Sea, where it controlled the formation and geometry of a series of WNW–ESE-striking, post-Caledonian rift basins (e.g., E–W-striking Farsund Basin; Figure 1b) and associated normal faults when it was reactivated as a major strike-slip fault (Pegrum, 1984; Phillips *et al.*, 2018). More work is therefore needed to further examine this potential relationship.

Another fold-and-thrust belt that displays similar characteristics as those in the study area is the Timanian Orogen in northern Baltica. The Timanides are characterized by tens of km wide, tens of km thick, thousands of km long, dominantly top-SSW thrust systems, which extend from northwestern Russia to northern Norway, Svalbard and the western Barents Sea (Koehl *et al.*, 2022; Koehl *et al.*, 2023a; Koehl *et al.*, 2023b; Koehl, 2024a; Koehl & Stokmo, 2024; Olovyanishnikov *et al.*, 2000; Siedlecka & Siedlecki, 1967). However, the Timanian Orogen is located some distance (c. one thousand km) from the study area.

Thus, although a late Neoproterozoic origin is possible for the interpreted thrust systems, a formation during the late Paleoproterozoic is more probable. It is therefore probable that the Barnhill Shear Zone in northern Scotland represents (or formed along) a folded portion of an inherited late Paleoproterozoic thrust system. This suggests that late Neoproterozoic deformation reactivated and/or overprinted preexisting late Paleoproterozoic orogens and related structures.

Mid-Cenozoic origin. The positive relief at the location of major WNW–ESE- and NE–SW-striking macrofolds and thrust systems suggests recent activity along both structural trends. This is also suggested by the occurrence of multiple, high-angle, shallow (1.5–4.0 seconds TWT) reverse faults at the Wyville–Thomson and Ymir ridges (Boldreel & Andersen, 1993 their figures 4 and 5, Boldreel & Andersen, 1998 their figures 4 and 5; Johnson *et al.*, 2005 their figure 6; Kimbell *et al.*, 2016 their figure 2c; Stoker *et al.*, 2015; Jolley *et al.*, 2021; see Figure 1b–c for location). However, we did not find any convincing evidence of Cenozoic brittle reverse faulting within the Wyville–Thomson Ridge as suggested in Boldreel and Andersen (1993; 1998) and Kimbell *et al.* (2005; ramp-anticline complex).

The onlap of Cenozoic (Paleogene) volcanic lava flows and sedimentary rocks (e.g., Boldreel & Andersen, 1993 their figures 4 and 5, Boldreel & Andersen, 1998 their figures 4 and 5; Johnson *et al.*, 2005 their figure 6; Kimbell *et al.*, 2016 their figure 2c; Jolley *et al.*, 2021) onto metamorphosed and intensely folded basement rocks at depth (present study; Figure 3a–f) may suggest some contraction-related uplift during Cenozoic times. However, it must be noted that this may simply suggest the existence of paleotopography rather than contraction and uplift, and that lava flows do not behave like sediments and thickness variations and onlap features of lava flow successions therefore do not necessarily have the same geological implications as for sedimentary successions. Notably, the impact of existing topography on the thickness of lava flows significantly differs from that on sediments (e.g., Ganci *et al.*, 2018; Rizo, 2018; Richardson & Karlstrom, 2019). It is therefore possible that Paleogene lava flows in the study area mimic existing paleotopography onto which they were emplaced (e.g., lava flow sequence thickness variations in Jolley *et al.*, 2021).

In addition, the existence of topographic relief at present seafloor along both WNW–ESE- and NE–SW-striking macrofolds and thrust systems and the lack of ongoing tectonic contraction suggests that most (if not all) of present-day topography was partly inherited, possibly from the mid-Paleozoic Caledonian Orogeny (present study) and/or partly related to isostatic adjustments (Smallwood, 2008). Magmatic-underplating-related uplift in the Faroe–UK region during the Cenozoic was ruled out (Smallwood, 2008). Together with the absence of pervasive contractional deformation structures within Cenozoic volcanosedimentary successions (i.e., not as pervasive as suggested by Boldreel & Andersen, 1993; Boldreel & Andersen, 1998; Johnson *et al.*, 2005;

Kimbell *et al.*, 2016; and Stoker *et al.*, 2015; Figure 2a–i), this indicates that Cenozoic contraction/transpression was, at most, mild if any. Thus, a Cenozoic origin for the observed WNW–ESE-striking thrust systems and related structures in metamorphosed basement rocks at depth (e.g., asymmetric folds, duplexes, mylonitic shear zones) can be ruled out (Figure 2a–i and Figure 3a–f).

Nevertheless, it is possible that some Cenozoic contractional structures are present in the study area (e.g., Ymir Ridge; Boldreel & Andersen, 1993; Boldreel & Andersen, 1998; Johnson *et al.*, 2005; Kimbell *et al.*, 2016), the strike of which matches that of the interpreted WNW–ESE-striking thrust systems (Figure 1b–c, Figure 2a–i, and Figure 4a), and that some of the topography at the structural highs in the study area is Cenozoic (e.g., Stoker *et al.*, 2005; Stoker *et al.*, 2013). Thus, the proposed late Paleoproterozoic thrust systems and their Caledonian overprints (Figure 5a–b) may have been mildly reactivated/overprinted during Cenozoic contraction/transpression.

By contrast, there is no evidence for extensional reactivation at Wyville–Thomson Ridge (Figure 2a–i). Hence, we may safely dismiss the presumed influence of an early Paleocene rifting event (Ziska & Varming, 2008) in shaping the ridge and related structures, and an origin of the ridge along an inverted normal fault (Boldreel & Andersen, 1993).

Influence on NW–SE-striking post-Caledonian transfer zones and tectonosedimentary evolution

The interpreted WNW–ESE-striking thrust systems align with post-Caledonian transfer zones on the continental shelf, e.g., the Wyville–Thomson fault zone aligns with the Sula Transfer Zone in the southeast (Bird *et al.*, 2016) and the southeastward prolongation of the Munkagrunnur fault zone coincides with the Judd Fault (also Judd Transfer Zone; Lamers & Carmichael, 1999; Stoker *et al.*, 2018; Sørensen, 2003; Figure 1c). The NW–SE-striking Sula transfer zone supposedly accommodates a switch of polarity of the main post-Caledonian, Devonian–Triassic normal faults, e.g., between the southeast-dipping Sula–Sgier Fault in the southwest and the northwest-dipping Shetland Spine Fault in the northeast (Bird *et al.*, 2016; Figure 1c). Basement-seated thrust systems represent outstanding, (at least) hundreds of kilometers long, tens of kilometers wide, possibly tens of kilometers thick zones of weakness in the crust (Figure 1a–c, Figure 2a–i, and Figure 4a) and it is therefore probable that they have had a considerable impact on the formation and evolution of subsequent structures. In the present case that is on accommodating switches of polarity of post-Caledonian faults as transfer zones (Figure 5c). It is therefore proposed that the interpreted, WNW–ESE-striking, late Paleoproterozoic thrust systems continue southeast of the Faroe Islands, where they may be located at shallower crustal level and directly controlled the formation and evolution of the post-Caledonian transfer zones, as previously speculated by Kimbell *et al.* (2005). This is further supported by the occurrence of multiple NW–SE-striking transfer zones in northern Scotland (e.g., North Coast Transfer Zone), the Faroe Islands, and between the Faroe Islands and the Shetland Islands (Bird *et al.*, 2016; Kimbell *et al.*, 2005; Lamers & Carmichael, 1999; Moy & Imber, 2009; Rumph *et al.*, 1993; Stoker *et al.*, 2018; Sørensen, 2003; Wilson *et al.*, 2010; Figure 1c), thus suggesting the existence of widespread WNW–ESE-striking fabrics in basement rocks in the region (Figure 5c).

An interesting feature is the rectangular basin shape created by the NNE-dipping Judd Fault and Rona Fault at the southern edge of the Faroe–Shetland Basin. The former parallels the studied potential late Paleoproterozoic thrust systems, whereas the latter parallels Caledonian structures such as the Moine Thrust (Figure 1b–c). It is therefore possible that the rectangular basin geometry is controlled by the two preexisting structural trends at depth.

Previous works have suggested various episodes of post-Caledonian uplift and erosion and rifting in the northeastern Atlantic region, including coeval contraction and extension at times (e.g., Dean *et al.*, 1999; Lamers & Carmichael, 1999; Stoker, 2016; Stoker *et al.*, 2017; Stoker *et al.*, 2018). It is of course possible that the late Paleoproterozoic thrust systems described herein were mildly reactivated and/or overprinted during these events. However, this is not clear from the data analyzed. As suggested by Dean *et al.* (1999) and Stoker (2016), a possible explanation is that the studied WNW–ESE-striking thrust systems were reactivated as strike-slip faults, which may explain the possibly occasionally coeval timing of contraction and extension along the margin. This would however be challenging to identify if the structures were only mildly reactivated/overprinted. Nevertheless, there should probably be clues such as high-angle to sub-vertical disruption surfaces reflecting truncation of the structures by recent strike-slip faults. This is not obvious from the data analyzed. More detailed work should therefore be performed in the Faroe–Shetland Basin area, where the relative abundance of exploration wells and seismic reflection data (including 3D data) would provide a more reliable tie between tectonic movements and sedimentary deposition along specific structures. A serious limitation might be the lack of deep seismic reflection data and poor seismic imaging below the Cenozoic volcanic successions in this area, thus impeding the correlation of shallow post-Caledonian brittle faults and sedimentary strata with deep, basement-seated structures.

The lack or mild character of post-Caledonian reactivation/overprinting of the studied WNW–ESE-striking late Paleoproterozoic thrust systems is in line with observations along the potentially related Tornquist Zone. For example, Phanerozoic sedimentary strata above the Teisseyre–Tornquist Zone are generally not disturbed by post-Caledonian tectonic events, dipping gently to the southwest (Mazur *et al.*, 2015). Nonetheless, the Tornquist Zone and shows evidence of mild Late Cretaceous–early Cenozoic contraction (e.g., Ponikowska *et al.*, 2024), i.e., possibly similar to the study structures. Other potential episodes of mild reactivation along the Teisseyre–Tornquist Zone include Devonian–Mississippian extension, Variscan contraction in the Pennsylvanian, and

Permian–Triassic extension (Krzywiec *et al.*, 2022), the former and latter of which coincide with well-established extensional events in the study area off the Faroe Islands and northern Scotland.

Implications for the Orogenic Bridge Theory and breakup in the northeastern Atlantic

The data suggest that late Paleoproterozoic thrust systems west of the Faroe Islands continue below the SDRs at the Iceland–Faroe Ridge, i.e., past the presumed continent–ocean transition (Figure 2e). This suggests that the Iceland–Faroe Ridge consists (at least partly) of thinned, orogenic, continental crust (Figure 2e and Figure 3d), thus supporting recent works (e.g., Foulger *et al.*, 2020; Foulger *et al.*, 2021).

The present results also support the Orogenic Bridge Theory, a recent concept which states that rifting style is controlled by preexisting orogens (Koehl & Foulger, 2024). Rift-parallel orogens facilitate breakup, whereas rift-orthogonal orogens delay or impede breakup and localize the formation of major transform faults (Koehl & Foulger, 2024). This concept and inconsistencies around the nature of the crust offshore (Darbyshire *et al.*, 1998; Foulger, 2006; Foulger *et al.*, 2003; Foulger *et al.*, 2020; Foulger *et al.*, 2021; Menke *et al*., 1995) were used to suggested the existence of elongate ribbons of (hyper-) extended orogenic crust between continents at the location of preexisting, rift-orthogonal orogens, e.g., at the late Paleoproterozoic Laxfordian–Nagssugtoqidian Orogen at the Greenland–Iceland–Faroe Ridge (Koehl & Foulger, 2024). The formation of major transform faults along preexisting, rift-orthogonal, orogenic structures would explain the reworking of late Paleoproterozoic Laxfordian shear zones in northern Scotland into subvertical strike-slip structures (Figure 5c).

The WNW–ESE-striking Laxfordian orogen (thickened continental crust) and related structures at the Faroe margin and their counterparts in southeastern Greenland were unsuitably oriented to accommodate thinning of the crust during rifting of the northeastern Atlantic because the main structures strike parallel to the extension direction. In addition, their low-angle geometry was unsuitable to accommodate transform faulting. Thus, a significant delay should be expected for continental breakup at the Greenland–Iceland–Faroe Ridge compared with adjacent areas along the rift axis.

Plume activity may very well be responsible for the intense magmatism recorded at the conjugate margin pair (southeastern Greenland and Faroe Islands) and in Iceland (Dahl-Jensen *et al.*, 1997; Geoffroy *et al.*, 2022; Jolley *et al.*, 2021; Layfield *et al.*, 2023; Millett *et al.*, 2016; Walker *et al.*, 2022). However, should the studied late Paleoproterozoic structures extend farther offshore than what is presented in Figure 2e, the anomalously thick character of the crust under the Greenland–Iceland–Faroe Ridge may then be explained by the existence of a (continuous?) rift-orthogonal ribbon (i.e., continuous orogenic bridge; Koehl & Foulger, 2024; Figure 6a–d) or by several isolated blocks of continental crust entrapped by extensive magmatism (e.g., rifted oceanic magmatic plateau; Coffin & Eldholm, 1992; Rime *et al.*, 2024) or by several microcontinents similar to the Jan Mayen Microcontinent Complex and all rifted from one another and separated by regular, Penrose-like oceanic crust (e.g., Blischke *et al.*, 2016; Bott, 1985; Johnson & Heezen, 1967). Since the thickness of the Greenland–Iceland–Faroe Ridge is consistently higher than 20 km from southeastern Greenland to the Faroe shelf, a scenario with several microcontinents separated by Penrose-like oceanic crust is unlikely. Ongoing work using seismic reflection data within the Greenland–Iceland–Faroe Ridge suggests that the late Paleoproterozoic structures described in the present study extend at least to eastern Iceland (Koehl *et al.*, 2025) and, thus, that the Greenland–Iceland–Faroe Ridge may be a continuous orogenic bridge (Figure 6a–d; Koehl & Foulger, 2024), potentially developing into a rifted oceanic magmatic plateau (e.g., Rime *et al.*, 2024), i.e., the early phase towards its evolution to a ruptured orogenic bridge.

A continuous ribbon of continental crust between southeastern Greenland, Iceland, and the Faroe Islands is compatible with seafloor spreading at the Reykjanes Ridge and Kolbeinsey Ridge and with plume magmatism. The orogenic bridge may have formed during the late Paleoproterozoic Laxfordian–Nagssugtoqidian Orogeny (Figure 6a) and was then reworked and tightened during NW–SE-oriented Caledonian contraction (Figure 6b). The crust was then thinned during several ensuing episodes of extension, e.g., late–post-orogenic collapse in the Devonian and Permian–Triassic and Jurassic–Cretaceous rifting (Figure 6c). While relatively thinner crust northeast and southwest of Iceland was broken up, highly thickened orogenic crust at the Greenland–Iceland–Faroe Ridge is still being thinned and stretching together with seafloor spreading at the adjacent Reykjanes and Kolbeinsey ridges (Figure 6d; Koehl & Foulger, 2024).

This potentially has major implications for offshore areas where the nature of the crust is disputed, e.g., Mozambique Ridge (König & Jokat, 2010; Ryzhova *et al.*, 2022), Madagascar Ridge (Jacques *et al.*, 2019; O'Connor *et al.*, 2019; Sato *et al.*, 2022), Rio Grande Ridge (Hoyer *et al.*, 2022; Ventura Santos *et al.*, 2019), Walvis Ridge (Fromm *et al.*, 2017a; Fromm *et al.*, 2017b; Hoyer *et al.*, 2022), Mauritius Islands (Torsvik *et al.*, 2013), and the Chagos–Laccadive Ridge (Ajay *et al.*, 2010; Nair *et al.*, 2013). Notably, the present study shows a new way to map very old and deep orogenic systems using high-resolution seismic reflection data. The technique presented here may be used to track the offshore continuation of major preexisting orogenic structures into contested continental blocks, e.g., of the East African–Antarctica Orogen (Abdelsalam *et al.,* 1998; Armistead, 2019; Bauer & Siemes, 2004; Boger *et al.*, 2015; Collins *et al.*, 2000; Collins *et al.*, 2012; De Waele *et al.*, 2011; Fritz *et al.*, 2013; Golynski & Jacobs, 2001; Hamimi *et al.*, 2022; Jacobs, 1999; Johnson, 2014; Key *et al.*, 1989; Mosley, 1993; Quick & Bosch, 1990; Ruppel *et al.*, 2015; Shackleton, 1996; Stern & Kröner, 1993) in the Madagascar and Mozambique ridges and Kuunga Orogen (Axelsson *et al.*, 2020; Bingen *et al.*, 2009; Brandt *et al.*, 2014; Collins *et al.*, 2003;

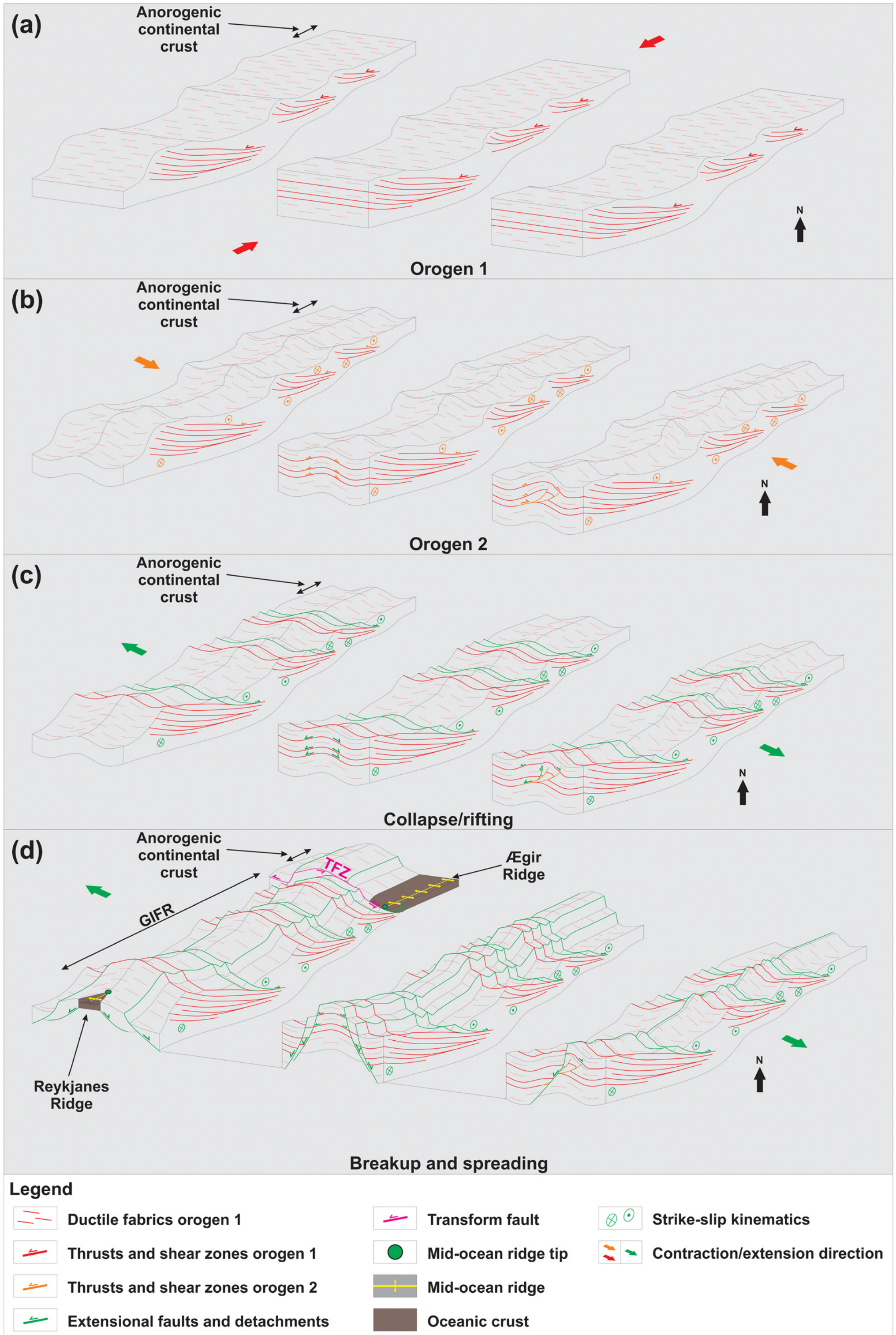


Figure 6. Model showing the development of an orogenic bridge at the Greenland–Iceland–Faroe Ridge through (**a**–**b**) two orogeneses perpendicular to one another ((**a**) WNW–ESE-striking Laxofordian–Nagssugtoqidian Orogen and (**b**) NE–SW-striking Caledonian Orogen), (**c**) repeated extension along extensional faults and detachments and inherited orogenic structures, e.g., in the Devonian, Permian–Triassic, and Jurassic–Cretaceous, and (**d**) breakup along inherited, reactivated and/or overprinted orogenic structures in the Cenozoic. Note that any number of additional orogeneses and/or extensional collapse/rifting may be added in between these events. Abbreviations: GIFR: Greenland–Iceland–Faroe Ridge; TFZ: Tjörnes fault zone.

Dharmapriya *et al.*, 2015; Ghosh *et al.*, 2004; He *et al.*, 2018; Hirayama *et al.*, 2020; Sacchi *et al.*, 2000; Srinivasan & Rajeshdurai, 2010; Tucker *et al.*, 2007; Viola *et al.*, 2008) in the Rio Grande, Walvis, and Laccadive–Chagos ridges.

It has also potential applications for the definition of the term "terrane" and for the tectonics of presumed terranes in onshore areas, e.g., in the northern UK, which were thus far thought to have been separated by oceanic domains prior to being accreted during major orogenic events. For example, the Hebridean Craton in northern Scotland is believed to have been accreted to Avalonia during the Grampian and Caledonian orogenies (Holdsworth *et al.*, 2012; Watson & Dunning, 1979). The possible relationship of the studied late Paleoproterozoic thrust systems with the Tornquist Zone challenges this paradigm by suggesting that the two cratons as well as Baltica may have been one and the same at least since the late Paleoproterozoic. The various terranes would thus reflect the strong heterogeneities in rock types and deformation intensity (including metamorphic grade and structure types) at various crustal levels within a single craton.

Conclusions

1) The continental shelf off the Faroe Islands is crosscut by pre-Caledonian, tens of km wide, (at least) hundreds of km long, WNW–ESE-striking, dominantly top-SSW, pre-Caledonian thrust systems.

2) The dominant top-SSW kinematics of the WNW–ESE-striking thrust systems off the Faroe Islands suggest affinities with Paleoproterozoic orogens, e.g., the Ammassalik Belt in southeastern Greenland and the contemporaneous Svecokarelian–Svecofennian Orogen in Scandinavia, and with the Tornquist Zone in eastern Europe and the southern North Sea.

3) During the Caledonian Orogeny, the thrust systems were reworked into open, NE–SW-striking folds and controlled the formation of Caledonian thrusts and shear zones analogous to the Moine Thrust.

4) The late Paleoproterozoic thrust systems were possibly reactivated and/or overprinted during late Neoproterozoic and/or various episodes of post-Caledonian extension and contraction (transpression?). However, post-Caledonian reactivation/overprinting (if any) was of limited intensity.

5) The present work supports the Orogenic Bridge Theory by supporting the theory that the Greenland–Iceland–Faroe Ridge consists, at least partly, of thinned orogenic continental crust.

Ethical approval and consent

Ethical approval and consent were not required.

Data availability

Underlying data

The data were provided by TGS (https://www.tgs.com/ in the methods chapter of the manuscript). The data are private and subject to a data privacy agreement (cannot be shared, published, or showed without consent of TGS). Yet, TGS allowed us access to the data and gave us permission to publish the data (Academic License Agreement number NA0509-366). Any interested party may thus contact TGS directly with a research project proposal and be granted access to the data. Access to the data is free of charge for academic research purposes.

Extended data

DataverseNO: extended data for "Impact of sub-basalt thrust systems on the Faroe continental shelf for the late Paleoproterozoic–Cenozoic tectonic evolution of the margin", doi.org/10.18710/780M9P, 2024.

The project contains the following extended data:

-00_ReadMe.txt

-Figure_2a.jpg

-Figure_2b.jpg

-Figure_2c.jpg

-Figure_2d.jpg

-Figure_2e.jpg

-Figure_2f.jpg

-Figure_2g.jpg

-Figure_2h.jpg

-Figure_2i.jpg

The data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Acknowledgements

The authors thank TGS for access to and permission to publish seismic reflection data in the Faroe Island continental shelf.

References

Abdelsalam MG, Stern RJ, Copeland P, *et al.*: **The neoproterozoic keraf suture in NE sudan: sinistral transpression along the eastern margin of West Gondwana.** *J Geol.* 1998; **106**(2): 133–147.
Publisher Full Text

Abramovitz T, Landes M, Thybo H, *et al.*: **Crustal velocity structure across the tornquist and Iapetus Suture Zones — a comparison based on MONA LISA and VARNET data.** *Tectonophysics.* 1999; **314**(1–3): 69–82.
Publisher Full Text

Ajay KK, Chaubey AK, Krishna KS, *et al.*: **Seaward dipping reflectors along the SW continental margin of India: evidence for volcanic passive margin.** *J Earth Syst Sci.* 2010; **119**(6): 803–813.
Publisher Full Text

Armistead SE: **Tectonic evolution of Madagascar over three billion years of Earth's history**. Ph.D. Thesis. University of Adelaide, Adelaide, Australia, 2019; 230.
Reference Source

Attfield P: **The structural history of the canisp shear zone.** In: *Evolution of the Lewisian and Comparable Precambrian and High Grade Terrains.* edited: Park, R. G. and Tarney, J., Geological Society Special Publication, 1987; **27**: 165–173.
Publisher Full Text

Axelsson E, Mezger K, Ewing T: **The kuunga orogeny in the eastern ghats belt: evidence from geochronology of biotite, amphibole and rutile, and implications for the assembly of Gondwana.** *Precambrian Res.* 2020; **347**: 105805.
Publisher Full Text

Bamford D: **Seismic constraints on the deep geology of the Caledonides of northern Britain.** In: *The Caledonides of the British Isles — reviewed.* edited by: Harris, A.L., Holland, C. H. and Leake, B. E., Geological Society, London, Special Publication, 1979; **8**: 93–96.
Publisher Full Text

Bauer W, Siemes H: **Kinematics and geothermometry of mylonitic shear zones in the Orvinfjella central Dronning Maud Land, east Antarctica.** *Geol Jahrb.* 2004; **B96**: 391–425.

Beach A: **The measurement and significance of displacements on Laxfordian shear zones, North-West Scotland.** *Proc Geol Assoc.* 1974; **85**(1): 13–21.
Publisher Full Text

Belka Z, Valverde-Vaquero P, Dörr W, *et al.*: **Accretion of first Gondwana-derived terranes at the margin of Baltica.** In: *Palaeozoic Amalgamation of Central Europe.* edited by: Winchester, J. A., Pharaoh, T. C. and Verniers, J., Geological Society, London, Special Publications, 2003; **201**: 19–36.
Publisher Full Text

Bell TH, Hammond RL: **On the internal geometry of mylonite zones.** *J Geol.* 1984; **92**(6): 667–686.
Publisher Full Text

Bergh SG, Corfu F, Myhre PI, *et al.*: **Waas the precambrian basement of Western Troms and Lofoten-Vesterålen in Northern Norway linked to the Lewisian of Scotland? A comparison of crustal components, tectonic evolution and amalgamation history.** In: *Tectonics - Recent Advances.* edited by Sharkov, E., InTech, 2012.
Publisher Full Text

Bingen B, Jacobs J, Viola G, *et al.*: **Geochronology of the Precambrian crust in the Mozambique belt in NE Mozambique, and implications for Gondwana assembly.** *Precambrian Res.* 2009; **170**(3–4): 231–255.
Publisher Full Text

Bird PC, Cartwright JA, Davies TL: **Basement reactivation in the development of rift basins: an example of reactivated Caledonide structures in the West Orkney Basin.** *J Geol Soc London.* 2016; **172**(1): 77–82.
Publisher Full Text

Blischke A, Gaina C, Hopper JR, *et al.*: **The Jan Mayen microcontinent: an update of its architecture, structural development and role during the transition from the Ægir Ridge to the mid-oceanic Kolbeinsey Ridge.** In: *The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution.* edited by: Péron-Pinvidic G, Hopper JR, Stoker MS, Gaina C, Doornenbal JC, Funck T and Árting UE, Geological Society, London, Special Publications, 2016; **447**: 299–337.
Publisher Full Text

Boger SD, Hirdes W, Ferreira CAM, *et al.*: **The 580-520 Ma Gondwana suture of Madagascar and its continuation into Antarctica and Africa.** *Gondwana Res.* 2015; **28**(3): 1048–1060.
Publisher Full Text

Boldreel LO, Andersen MS: **Late Paleocene to Miocene compression in the Faeroe-Rockall area.** In: *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference.* edited by Parker, J. R Geological Society, London, 1993; 1025–1034.
Publisher Full Text

Boldreel LO, Andersen MS: **Tertiary compressional structures on the Faroe-Rockall Plateau in relation to northeast Atlantic ridge-push and Alpine foreland stresses.** *Tectonophysics.* 1998; **300**(1–4): 13–28.
Publisher Full Text

Bott MHP: **Plate tectonic evolution of the Icelandic transverse ridge and adjacent regions.** *J Geophys Res.* 1985; **90**(B12): 9953–9960.
Publisher Full Text

Boyer SE, Elliott D: **Thrust systems.** *AAPG Bulletin.* 1982; **669**(9): 1196–1230.
Publisher Full Text

Brandt S, Raith MM, Schenk V, *et al.*: **Crustal evolution of the Southern Granulite Terrane, south India: new geochronological and geochemical data for felsic orthogneisses and granites.** *Precambrian Res.* 2014; **246**: 91–122.
Publisher Full Text

Brewer JA, Cook FA, Brown LD, *et al.*: **COCORP seismic reflection profiling across thrust faults**. Geological Society, London, Special Publications, 1981; **9**: 501–511.
Publisher Full Text

Brewer JA, Smithson SB, Oliver JE, *et al.*: **The Laramide Orogeny: evidence from COCORP deep crustal seismic profiles in the Wind River Mountains, Wyoming.** *Tectonophysics.* 1980; **62**(3–4): 165–189.
Publisher Full Text

Bridgewater D, Myers JS: **Outline of the Nagssugtoqidian mobile belt of East Greenland.** *Rapport Grønlands Geologisks Undersøkelse.* 1979; **89**: 9–18.
Publisher Full Text

Chadwick B, Dawes PR, Escher JC, *et al.*: **The Proterozoic mobile belt in the Ammassalik region, south-east Greenland (Ammassalik mobile belt): an introduction and re-appraisal.** *Rapport Grønlands Geologisks Undersøkelse.* 1989; **146**: 5–12.
Publisher Full Text

Chadwick B, Vasudev VN: **Some observations on the structure of the early Proterozoic, Ammassalik mobile belt in the Ammassalik region, South-East Greenland.** *Rapport Grønlands Geologisks Undersøkelse.* 1989; **146**: 29–40.
Publisher Full Text

Christensen NI: **Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars.** *J Geophys Res.* 1965; **70**(24): 6147–6164.
Publisher Full Text

Coffin MF, Eldholm O: **Volcanism and continental break-up: a global compilation of large igneous provinces.** In: *Magmatism and the Causes of Continental Break-up.* edited by: Storey BC, Alabaster T and Pankhurst RJ, Geological Society, London, Special Publication, 1992; **68**: 17–30.
Publisher Full Text

Collins AS, Johnson S, Fitzsimons IW, *et al.*: **Neoproterozoic deformation in central Madagascar: a structural section through part of the east African Orogen.** In: *Proterozoic East Gondwana: Supercontinent Assembly and Breakup.* edited by Yoshida, M., Windley, B. F. and Dasgupta, S., Geological Society, London, Special Publications, 2003; **206**: 363–379.
Publisher Full Text

Collins AS, Kinny PD, Razakamanaja T: **Depositional age, provenance and metamorphic age of metasedimentary rocks from southern Madagascar.** *Gondwana Res.* 2012; **21**(2–3): 353–361.
Publisher Full Text

Collins AS, Razakamanaja T, Windley BF: **Neoproterozoic extensional detachment in central Madagascar: implications for the collapse of the East African Orogen.** *Geol Mag.* 2000; **137**(1): 39–51.
Publisher Full Text

Cotte N, Pedersen HA, TOR Working Group: **Sharp contrast in lithospheric structure across the Sorgenfrei-Tornquist Zone as inferred by Rayleigh wave analysis of TOR1 project data.** *Tectonophysics.* 2002; **360**(1–4): 75–88.
Publisher Full Text

Coward MP: **The Caledonian thrust and shear zones of N.W. Scotland.** *J Struct Geol.* 1980; **2**(1–2): 11–17.
Publisher Full Text

Coward MP: **The Precambrian, Caledonian and Variscan framework to NW Europe.** In: *Tectonic Events Responsible for Britain's Oil and Gas Reserves.* edited by: Hardman, R. F. P. and Brooks, J., Geological Society, London, Special Publications, 1990; **55**: 1–34.
Publisher Full Text

Coward MP, Enfield MA, Fischer MW: **Devonian basins of northern scotland: extension and inversion related to late caledonian – variscan tectonics.** In: *Inversion Tectonics.* edited by: Cooper, M. A. and Williams, G. D., Geological Society, London, Special Publications, 1989; **44**: 275–308.
Publisher Full Text

Coward MP, Kim JH, Parke J: **A correlation of Lewisian structures and their displacement across the lower thrusts of the Moine Thrust zone, NW Scotland.** *Proceedings of the Geologists' Association.* 1980; **91**(4): 327–337.
Publisher Full Text

Coward MP, Park RG: **The role of mid-crustal shear zones in the early Proterozoic evolution of the Lewisian.** In: *Evolution of the Lewisian and Comparable Precambrian and High Grade Terrains.* edited by: Park, R. G. and Tarney, J., Geological Society Special Publication, 1987; **27**: 127–138.
Publisher Full Text

Dahl-Jensen T, Holbrook WS, Hopper JR, *et al.*: **Seismic investigation of the East Greenland volcanic rifted margin.** *Geology Greenland Surv Bull.* 1997; **176**: 50–54.
Publisher Full Text

Darbyshire FA, Bjarnason IT, White RS, *et al.*: **Crustal structure above the Iceland mantle plume imaged by the ICEMELT refraction profile.** *Geophys J Int.* 1998; **135**(3): 1131–1149.
Publisher Full Text

Davison I, Stasiuk S, Nuttall P, *et al.*: **Sub-basalt hydrocarbon prospectivity in the Rockall, Faroe–Shetland and Møre basins, NE altantic.** In: *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference.* edited by: Vining, B. A. and Pickering, S. C., Geological Society, London, 2010; **7**: 1025–1032.
Publisher Full Text

De Luca M, Mancinelli P, Patruno S, *et al.*: **Iapetus ocean serpentinites and mesozoic intra-platform basins revealed by gravity and magnetic**

across the greater east shetland platform (Northern North Sea, UK). *Tectonophysics.* 2023; **862**: 229980.
Publisher Full Text

De Waele B, Thomas RJ, Macey PH, *et al.*: **Provenance and tectonic significance of the palaeoproterozoic metasedimentary successions of central and northern Madagascar.** *Precambrian Res.* 2011; **189**(1–2): 18–42.
Publisher Full Text

Dean K, McLachlan K, Chambers A: **Rifting and the development of the Faeroe-Shetland Basin.** In: *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference.* edited by Fleet AJ and Boldy SAR, Geological Society, London, Petroleum Geology Conference Series, 1999; **5**(1): 533–544.
Publisher Full Text

Dharmapriya PL, Malaviarachchi SPK, Santosh M, *et al.*: **Late-neoproterozoic ultrahigh-temperature metamorphism in the highland complex, Sri Lanka.** *Precambrian Res.* 2015; **271**: 311–333.
Publisher Full Text

Evans CR: **Geochronology of the Lewisian basement near Lochinver, Sutherland.** *Nature.* 1965; **207**: 54–56.
Publisher Full Text

Fazlikhani H, Fossen H, Gawthorpe RL, *et al.*: **Basement structure and its influence on the structural configuration of the northern north sea rift.** *Tectonics.* 2017; **36**(6): 1151–1177.
Publisher Full Text

Fossen H, Holst TB: **Northwest-verging folds and the northwestward movement of the Caledonian jotun nappe, Norway.** *J Struct Geol.* 1995; **17**(1): 3–15.
Publisher Full Text

Foulger GR: **Older crust underlies Iceland.** *Geophys J Int.* 2006; **165**(2): 672–676.
Publisher Full Text

Foulger GR, Du Z, Julian BR: **Icelandic-type crust.** *Geophys J Int.* 2003; **155**(2): 567–590.
Publisher Full Text

Foulger GR, Doré T, Emeleus CH, *et al.*: **The Iceland microcontinent and a continental Greenland–Iceland–Faroe ridge.** *Earth-Sci Rev.* 2020; **206**: 102926.
Publisher Full Text

Foulger GR, Gernigon L, Geoffroy L: **Icelandia.** In: *In the Footsteps of Warren Hamilton: New Ideas in Earth Science.* edited by: Foulger, G. A., Hamilton, L. C., Jurdy, D. M., Stein, C. A., Howard, K. A. and Stein, S., Geological Scoiety of America, Special Paper. 2021; **553**. : 1–12.
Publisher Full Text

Fountain DM, Hurich CA, Smithson SB: **Seismic reflectivity of Mylonite zones in the crust.** *Geology.* 1984; **12**(4): 195–198.
Publisher Full Text

Friend CRL, Strachan RA, Kinny PD: **U–Pb zircon dating of basement inliers within the moine supergroup, Scottish Caledonides: implications of archaean protolith ages.** *J Geol Soc.* London. 2008; **165**(4): 807–815.
Publisher Full Text

Fritz H, Abdelsalam M, Ali KA, *et al.*: **Orogen styles in the East African Orogen: a review of the Neoproterozoic to Cambrian tectonic evolution.** *J Afr Earth Sci.* 2013; **86**: 65–106.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Fromm T, Jokat W, Behrmann JH: **Interaction between a hotspot and a fracture zone: the crustal structure of Walvis Ridge at 6° E.** *Tectonophysics.* 2017a; **716**: 108–120.
Publisher Full Text

Fromm T, Jokat W, Ryberg T, *et al.*: **The onset of Walvis Ridge: pume influence at the continental margin.** *Tectonophysics.* 2017b; **716**: 90–107.
Publisher Full Text

Funck T, Geissler WH, Kimbell GS, *et al.*: **Moho and basement depth in the NE Atlantic Ocean based on seismic refraction data and receiver functions.** In: *The NE Atlantic Region: A Reapraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution.* Geological Society, London, Special Publications. 2017; **447**: 207–231.
Publisher Full Text

Ganci G, Cappello A, Bilotta G, *et al.*: **Mapping volcanic deposits of the 2011–2015 Etna eruptive events using satellite remote sensing.** *Front earth Sci.* 2018; **6**: 83.
Publisher Full Text

Geldart LP, Sheriff RE: **Problems in exploration seismology and their solutions**. *Society of Exploration Geophysicists, Geophysical References Series*. 2004; **14**: 181–220.
Publisher Full Text

Geoffroy L, Gernigon L, Foulger GR: **Linear magnetic anomalies and the limits of oceanic crust in oceans.** In: *In the Footsteps of Warren B.* Hamilton: New Ideas in Earth Science. edited by: Foulger, G. R., Hamilton, L. C., Jurdy, D. M., Stein, C. A., Howard, K. A. and Stein, S. Geological Society of America Special Paper, 2022; 553.
Publisher Full Text

Ghosh JG, de Wit MJ, Zartman RE: **Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies.** *Tectonics.* 2004; **23**(3): TC3006.
Publisher Full Text

Golynski A, Jacobs J: **Grenville-Age versus Pan-African magnetic anomaly imprints in Western Dronning Maud Land, East Antarctica.** *J Geol.* 2001; **109**(1): 136–142.
Publisher Full Text

Graversen O: **Structural analysis of superosed fault systems of the Bornholm horst block, Tornquist Zone, Denmark.** *Bulleting Geol Soc Denmark.* 2009; **57**: 25–49.
Publisher Full Text

Gregersen U, Hjelm L, Vosgerau H, *et al.*: **Seismic data and interpretation to mature potential geological storage of CO_2.** GEUS Report, 2022/26. 2022; 1–165.
Publisher Full Text

Hamimi Z, Hagag W, Fritz H, *et al.*: **The tectonic map and structural provinces of the late Neoproterozoic Egyptian Nubian Shield: implications for crustal growth of the Arabian–Nubian Shield (East African Orogen).** *Front Earth Sci.* 2022; **10**: 921521.
Publisher Full Text

He XF, Hand M, Santosh M, *et al.*: **Long-lived metamorphic *P–T–t* evolution of the highland complex, Sri Lanka: insights from mafic granulites.** *Precambrian Res.* 2018; **316**: 227–243.
Publisher Full Text

Hedin P, Almqvist B, Berthet T, *et al.*: **3D reflection seismic imaging at the 2.5 km deep COSC-1 scientific borehole, central Scandinavian Caledonides.** *Tectonophysics.* 2016; **689**: 40–55.
Publisher Full Text

Hirayama E, Tsunogae T, Malaviarachchi SPK, *et al.*: **Prolonged Neoproterozoic high-grade metamorphism of the Wanni Complex, Sri Lanka: new insights from petrology, phase equilibria modelling, and zircon U-Pb geochronology of partially melted cordierite gneiss from Walpita.** *Geol J.* 2020; **55**: 6147–6168.
Publisher Full Text

Holdsworth RE, Woodcock NH, Strachan RA: **Geological framework of Britain and Ireland.** In: *Geological History of Britain and Ireland*. edited by: Woodcock, N. and Strachan, R. 2012; 19–39.
Publisher Full Text

Hossein Shomali Z, Roberts RG, Pedersen LB, *et al.*: **Lithospheric structure of the tornquist zone resolved by nonlinear P and S teleseismic tomography along the TOR Array.** *Tectonophysics.* 2006; **416**(1–4): 133–149.
Publisher Full Text

Hoyer PA, Haase KM, Regelous M, *et al.*: **Mantle plume and rift-related volcanism during the evolution of the Rio Grande rise.** *Commun Earth Environ.* 2022; **3**: 18.
Publisher Full Text

Hurich CA, Smithson SB, Fountain DM, *et al.*: **Seismic evidence of mylonite reflectivity and deep structure in the Kettle dome metamorphic core complex, Washington.** *Geology.* 1985; **13**(8): 577–580.
Publisher Full Text

Jacobs J: **Neoproterozoic/Lower Palaeozoic events in Central Dronning Maud Land (East Antarctica).** *Gondwana Res.* 1999; **2**(3): 473–480.
Publisher Full Text

Jacques G, Hauff F, Hoernle K, *et al.*: **Nature and origin of the Mozambique Ridge, SW Indian Ocean.** *Chem Geol.* 2019; **507**: 9–22.
Publisher Full Text

Jakobsson M, Mayer L, Coackley B, *et al.*: **The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0.** *Geophys Res Lett.* 2012; **39**(12): L12609.
Publisher Full Text

Johansson Å, Andersen T, Simonsen SL: **Hafnium isotope characteristics of late palaeoproterozoic magmatic rocks from Blekinge, Southeast Sweden: possible correlation of small-scale Hf and Nd isotope variations in zircon and whole rocks.** *GFF.* 2015; **137**(1): 74–82.
Publisher Full Text

Johnson GL, Heezen BC: **Morphology and evolution of the Norwegian-Greenland Sea.** *Deep-Sea Res Oceanogr Abstr.* 1967; **14**(6): 755–771.
Publisher Full Text

Johnson H, Ritchie JD, Hitchen K, *et al.*: **Aspects of the cenozoic deformational history of the Northeast Faroe-Shetland Basin, Wyville-Thomson and Hatton Bank areas.** In: *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference*. edited by: Doré, A. G. and Vinning, B.A. Geological Society, London, 2005; 993–1007.
Publisher Full Text

Johnson PR: **An expanding Arabian-Nubian shield geochronologic and isotopic dataset: defining limits and confirming the tectonic setting of a neoproterozoic accretionary orogen.** *Open Geol J.* 2014; **8**: 3–33.
Publisher Full Text

Jolley DW, Millett JM, Schofield N, *et al.*: **Stratigraphy of volcanic rock successions of the North Atlantic rifted margin: the offshore record of the Faroe-Shetland and Rockall basins.** *Earth Environ Sci Trans R Soc Edinb.* 2021; **112**(2): 61–88.
Publisher Full Text

Kallweit RS, Wood LC: **The limits of resolution of zero-phase wavelets.** *Geophysics.* 1982; **47**(7): 977–1131.
Publisher Full Text

Kalsbeek F, Austrheim H, Bridgewater D, *et al.*: **Geochronology of archaean and proterozoic events in the Ammassalik area, South-East Greenland, and**

comparisons with the Lewisian of Scotland and the Nagssugtoqidian of West Greenland. *Precambrian Res.* 1993; **62**(3): 239–270.
Publisher Full Text

Kästner F, Pierdominici S, Elger J, *et al.*: **Correlation of core and downhole seismic velocities in high-pressure metamorphic rocks: a case study for the COSC-1 borehole, Sweden.** *Solid Earth.* 2020; **11**(2): 607–626.
Publisher Full Text

Key RM, Charsley TJ, Hackman BD, *et al.*: **Superimposed upper proterozoic collision-controlled orogenies in the Mozambique Orogenic belt of Kenya.** *Precambrian Res.* 1989; **44**(3–4): 197–225.
Publisher Full Text

Kimbell GS, Ritchie JD, Johnson H, *et al.*: **Controls on the structure and evolution of the NE atlantic margin revealed by regional potential field imaging and 3D modelling**. In: *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference*. edited by: Doré, A. G. and Vinning, B.A. Geological Society, London, 2005; **6**: 933–945.
Publisher Full Text

Kimbell GS, Stewart MA, Gradmann S, *et al.*: **Controls on the location of compressional deformation on the NW European margin**. In: *The NE Atlantic Region: A Reapraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution, Geological Society*. London, Special Publications, 2016; **447**: 249–278.
Publisher Full Text

Koehl JBP: **Impact of timanian thrusts on the phanerozoic tectonic history of Svalbard**. Keynote Lecture, EGU General Assembly, May 3rd–8th, Vienna, Austria, 2020.
Publisher Full Text

Koehl JBP: **Early cenozoic eurekan strain partitioning and decoupling in central spitsbergen, Svalbard.** *Solid Earth.* 2021; **12**(5): 1025–1049.
Publisher Full Text

Koehl JBP: **The myth of the De Geer Zone [version 1; peer review: 1 approved with reservations, 1 not approved].** *Open Res Europe.* 2024a awaiting peer review; **4**: 1.
Publisher Full Text

Koehl JBP: **Extended data for "Caledonian reactivation and reworking of timanian thrust systems and implications for latest mesoproterozoic to mid-paleozoic tectonics and magmatism in northern Baltica"**. 2024b.
Publisher Full Text

Koehl JBP, Allaart L, Noormets R: **Devonian-Carboniferous extension and Eurekan inversion along an inherited WNW-ESE-striking fault system in billefjorden, Svalbard [version 1; peer review: 1 approved, 2 not approved].** *Open Res Eur*. 2023b; **3**: 124.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Koehl JBP, Bergh SG, Henningsen T, *et al.*: **Middle to late Devonian—Carboniferous collapse basins on the finnmark platform and in the southwesternmost Nordkapp basin, SW barents sea.** *Solid Earth.* 2018; **9**(2): 341–372.
Publisher Full Text

Koehl JBP, Foulger GR: **The orogenic bridge theory: towards a predicting tool for past and future plate tectonics [version 1; peer review: 1 approved with reservations, 3 not approved].** *Open Res Europe.* 2024 awaiting peer review; **4**: 76.
Publisher Full Text

Koehl JBP, Foulger GR, Peace AL: **The Greenland-Iceland-Faroe Orogenic Bridge**. Tectonic Studies Group, Annual Meeting, 7–9th January, British Geological Survey, Nottingham, UK, 2025.
Publisher Full Text

Koehl JBP, Magee C, Anell I: **Impact of timanian thrust systems and their implications for late neoproterozoic-phanerozoic tectonic evolution of the northern barents sea and Svalbard.** *Solid Earth.* 2022; **13**(1): 85–115.
Publisher Full Text

Koehl JBP, Polonio I, Rojo-Moraleda LA: **Timanian fold-and-thrust belt and caledonian overprint in the selis ridge imaged by new 3D seismic attributes and spectral decomposition.** *Tektonika.* 2023a; **1**(1): 76–100.
Publisher Full Text

Koehl JBP, Stokmo EMB: **Caledonian reactivation and reworking of timanian thrust systems and implications for latest mesoproterozoic-mid Paleozoic tectonics and magmatism in northern Norway and the southern barents sea [version 1; peer review: 1 approved with reservations, 1 not approved].** *Open Res Europe.* 2024 awaiting peer review; **4**: 30.
Publisher Full Text

König M, Jokat W: **Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data.** *Geophys J Int.* 2010; **180**(1): 158–180.
Publisher Full Text

Krzywiec P, Kufrasa M, Poprawa P, *et al.*: **Together but separate: decoupled Variscan (late Carboniferous) and Alpine (Late Cretaceous-Paleogene) inversion tectonics in NW Poland.** *Solid Earth.* 2022; **13**(3): 639–658.
Publisher Full Text

Lamers E, Carmichael S: **The Paleocene deepwater sandstone play West of Shetland.** In: *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference.* edited by Fleet AJ and Boldy SAR, Geological Society, London, Petroleum Geology Conference Series. 1999; **5**(1): 645–659.
Publisher Full Text

Layfield LK, Schofield N, Watson D, *et al.*: **3D Seismic reflection evidence for lower crustal intrusions beneath the Faroe-Shetland Basin, NE Atlantic Margin.** *J Geol Soc.* 2023; **180**(5).
Publisher Full Text

Li QC, Zhu GM: **Singularity detection of the thin bed seismic signals with wavelet transform.** *Acta Seimol Sin.* 2000; **13**(1): 61–66.
Publisher Full Text

Luckett R, Baptie B: **Local earthquake tomography of Scotland.** *Geophys J Int.* 2015; **200**(3): 1538–1554.
Publisher Full Text

Mazur S, Mikolajczak M, Krzywiec P, *et al.*: **Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica?** *Tectonics.* 2015; **34**(12): 2465–2477.
Publisher Full Text

McClay KR, Coward MP: **The Moine Thrust zone: an overview**. Geological Society, London, Special Publications, 1980; **9**: 241–260.
Publisher Full Text

Menke W, Brandsdóttir B, Einarsson P, *et al.*: **Reinterpretation of the RRISP-77 Iceland shear-wave profiles.** *Geophys J Int.* 1995; **126**(1): 166–172.
Publisher Full Text

Millett JM, Hole MJ, Jolley DW, *et al.*: **Frontier exploration and the North Atlantic Igneous Province: new insights from a 2.6km offshore volcanic sequence in the NE Faroe-Shetland Basin.** *J Geol Soc.* 2016; **173**(2): 320–336.
Publisher Full Text

Mosley PN: **Geological evolution of the late Proterozoic "Mozambique Belt" of Kenya.** *Tectonophysics.* 1993; **221**(2): 223–250.
Publisher Full Text

Moy DJ, Imber J: **A critical analysis of the structure and tectonic significance of rift-oblique lineaments ('transfer zones') in the Mesozoic-Cenozoic succession of the Faroe-Shetland Basin, NE Atlantic margin.** *J Geol Soc London.* 2009; **166**: 831–844.
Publisher Full Text

Nabavi ST, Fossen H: **Fold geometry and folding - a review.** *Earth-Sci Rev.* 2021; **222**: 103812.
Publisher Full Text

Nair N, Arnand SP, Rajaram M: **Tectonic framework of Laccadive Ridge in Western Continental Margin of India.** *Mar Geol.* 2013; **346**: 79–90.
Publisher Full Text

Narkiewicz M, Maksym A, Malinowski M, *et al.*: **Transcurrent nature of the Teisseyre-Tornquist Zone in Central Europe: results of the POLCRUST-01 deep reflection seismic profile.** *Int J Earth Sci.* 2015; **104**: 775–796.
Publisher Full Text

Narkiewicz M, Petecki Z: **Basement structure of the Paleozoic Platform in Poland.** *Geol Q.* 2017; **61**(2): 502–520.
Publisher Full Text

Nicholson A: **Seismic data re-processing offshore Faroes April 2011-January 2012.** *TGS Final Report.* OF9495RE11, 2012; **624**: 1–75.

Nordgulen Ø, Saintot A: **The character and kinematics of deformation zones (ductile shear zones, fracture zones and fault zones) at Forsmark - report from phase 3**. Swedish Nuclear Fuel and Waste Management Co, Stockholm, Sweden, P-07-111, 2008.

Ólavsdóttir J, Boldreel LO, Andersen MS: **Development of a shelf margin delta due to uplift of Munkagrunnur Ridge at the margin of Faroe-Shetland Basin: a seismic sequence stratigraphic study.** *Petrol Geosci.* 2010; **16**: 91–103.
Publisher Full Text

Ólavsdóttir J, Eidesgaard ÓR, Stoker MS: **The stratigraphy and structure of the Faroese continental margin.** In: *The NE Atlantic Region: A Reapraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution.* edited by: Péron-Pinvidic, G., Hopper, J. R., toker, M. S., Gaina, C., Doornenbal, J. C., Funck, T. And Árting, U. E., Geological Society, London, Special Publications, London, Special Publications, 2016; **447**: 1–10.
Publisher Full Text

Ólavsdóttir J, Stoker MS, Riishuus MS, *et al.*: **Discovery of two sub-volcanic basins below the North Atlantic Igneous Province (NAIP), Faroe Platform, NE Atlantic Ocean.** *Tectonics.* 2021; **40**(4): e2020TC006589.
Publisher Full Text

Olovyanishnikov VG, Roberts D, Siedlecka A: **Tectonics and sedimentation of the meso- to neoproterozoic Timan-Varanger Belt along the Northeastern Margin of Baltica.** *Polarforschung.* 2000; **68**: 267–274.
Reference Source

O'Connor RM: **Thrust faulting near Oamaru from seismic reflection profiles.** *New Zeal J Geol Geop.* 1992; **35**(2): 243–247.
Publisher Full Text

O'Connor JM, Jokat W, Regelous M, *et al.*: **Superplume mantle tracked isotopically the length of Africa from the Indian Ocean to the Red Sea.** *Nat Commun.* 2019; **10**(1): 5493.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Parson LM, the ODP Leg 104 Scientific Party: **Dipping reflector styles in the NE Atlantic Ocean**. In: *Early Tertiary Volcanism and the Opening of the NE Atlantic*. edited by: Morton, A. C., Parson, L. M., Geological Society, Special Publication, 1988; **39**: 57–68.

Pegrum RM: **The extension of the Tornquist zone in the Norwegian North Sea.** *Norsk Geol Tidsskr.* 1984; **64**: 39–68.
Reference Source

Pharaoh TC: **Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): a review.** *Tectonophysics.* 1999; **314**(1–3): 17–41.
Publisher Full Text

Phillips T, Jackson CAL, Bell RE, *et al.*: **Reactivation of intrabasement structures during rifting: a case study from offshore Southern Norway.** *J Struct Geol.* 2016; **91**: 54–73.
Publisher Full Text

Phillips TB, Jackson CAL, Bell RE, *et al.*: **Oblique reactivation of lithosphere-scale lineaments controls rift physiography – the upper-crustal expression of the Sorgenfrei–Tornquist Zone, offshore Southern Norway.** *Solid Earth.* 2018; **9**(2): 403–429.
Publisher Full Text

Platt JP: **Progressive refolding in ductile shear zones.** *J Struct Geol.* 1983; **5**(6): 619–622.
Publisher Full Text

Ponikowska M, Stovba SM, Mazur S, *et al.*: **Crustal-scale pop-up structure at the junction of two continental-scale deformation zones in the Southern Baltic sea.** *Tectonic.* 2024; **43**(4): e2023TC008066.
Publisher Full Text

Quick JE, Bosch PS: **Geologic map of the wadi khadra area, kingdom of Saudi Arabia.** USGS, OF 90–316, scale:1:50 000. 1990.
Reference Source

Ramsay JG: **The measurement of strain and displacement in orogenic belts.** In: *Time and Place in Orogeny*. Geological Society, London, Special Publications, 1969; **3**: 43–79.
Publisher Full Text

Reeve MT, Bell RE, Jackson CAL: **Origin and significance of intra-basement seismic reflections offshore Western Norway.** *J Geol Soc, London.* 2013; **171**: 1–4.
Publisher Full Text

Richardson KR, Smallwood JR, White RS, *et al.*: **Crustal structure beneath the Faroe Islands and the Faroe–Iceland Ridge.** *Tectonophysics.* 1998; **300**(1–4): 159–180.
Publisher Full Text

Richardson P, Karlstrom L: **The multi-scale influence of topography on lava flow morphology.** *Bulleting Volcanol.* 2019; **81**(4): 21.
Publisher Full Text

Rime V, Keir D, Phethean J, *et al.*: **Central Afar: an analogue for oceanic plateau development.** *Geology.* 2024; **52**(11): 819–824.
Publisher Full Text

Rizo SR: **Quantifying the effect of topographic slope on Lava Flow Thickness: a first step to improve lava flow volume estimation methods.** Master's Thesis, University of South Florida, *USF Tampa Graduate Theses and Dissertations*. 2018.
Reference Source

Rumph B, Reaves M, Orange VG, *et al.*: **Structuring and transfer zones in the Faeroe Basin in a regional tectonic context.** In: *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference.* edited by: Parker, J. R., Geological Society, London. 1993; **4**: 999–1009.
Publisher Full Text

Ruppel AS, Läufer A, Jacobs J, *et al.*: **The Main Shear Zone in Sør Rondane, East Antarctica: implications for the late-Pan-African tectonic evolution of Dronning Maud Land.** *Tectonics.* 2015; **34**(6): 1290–1305.
Publisher Full Text

Ryzhova DA, Kosnyreva MV, Dubinin EP, *et al.*: **The structure Tectonosphere of the Mozambique and Madagascar ridges by geophysical data.** *Moscow Univ Geol Bull.* 2022; **77**(1): 18–27.
Publisher Full Text

Sacchi R, Cadoppi P, Costa M: **Pan-African reactivation of the Lurio segment of the Kibaran belt system: a reappraisal from recent age determinations in Northern Mozambique.** *J Afr Earth Sci.* 2000; **30**(3): 629–639.
Publisher Full Text

Saintot A, Stephens MB, Viola G, *et al.*: **Brittle tectonic evolution and paleostress field reconstruction in the southwestern part of the Fennoscandian Shield, Forsmark, Sweden.** *Tectonics.* 2011; **30**(4): TC4002.
Publisher Full Text

Sato T, Nogi Y, Sato H, *et al.*: **A new tectonic model between the Madagascar Ridge and Del Cano Rise in the Indian Ocean.** *J Geol Res: Solid Earth.* 2022; **127**(1): e2021JB021743.
Publisher Full Text

Shackleton RM: **The final collision zone between East and West Gondwana: where is it?** *J Afr Earth Sci.* 1996; **23**(3): 271–287.
Publisher Full Text

Shaw JH, Bilotti F, Brennan PA: **Patterns of imbricate thrusting.** *GSA Bulletin.* 1999; **111**(8): 1140–1154.
Publisher Full Text

Siedlecka A, Siedlecki S: **Some new aspects of the geology of Varanger Peninsula (Northern Norway).** *Nor geol unders.* 1967; **247**: 288–306.
Reference Source

Smallwood JR: **Uplift, compression and the Cenozoic Faroe-Shetland sediment budget**. In: *The Nature and Origin of Compression in Passive Margins*. edited by: Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R. and Ritchie, J. D., Geological Society, London, Special Publications, 2008; **306**: 137–152.
Publisher Full Text

Smythe DK: **Faeroe-Shetland escarpment and continental Margin North of the Faeroes**. In: *Structures and Development of the Greenland-Scotland Ridge*. edited by: Bott, M. H. P., Saxov, S., Talwani M. and Thiede, J., Nato Conference Series, Springer, Boston, Massachusetts, USA, 1983; **8**: 109–119.
Publisher Full Text

Soper NJ, Wilkinson P: **The Moine Thrust and Moine Nappe at Loch Eriboll Sutherland.** *Scott J Geol.* 1975; **11**: 339–359.
Publisher Full Text

Sørensen AB: **Cenozoic basin development and stratigraphy of the Faroes area.** *Petroleum Geoscience.* 2003; **9**(3): 189–207.
Publisher Full Text

Spence GD, White RS, Westbrook GK, *et al.*: **The Hatton Bank continental margin—I. shallow structure from two-ship expanding spread seismic profiles.** *Geophys J R Astron Soc.* 1989; **96**(2): 273–294.
Publisher Full Text

Srinivasan V, Rajeshdurai P: **The Suruli shear zone and regional scale folding pattern in Madurai block of Southern Granulite Terrain, South India.** *J Earth Syst Sci.* 2010; **119**(2): 147–160.
Publisher Full Text

Stern RJ, Kröner A: **Late Precambrian crustal evolution in NE Sudan: isotopic and geochronologic constraints.** *J Geol.* 1993; **101**(5): 555–574.
Publisher Full Text

Stoker M: **Cretaceous tectonostratigraphy of the Faroe-Shetland region.** *Scott J Geol.* 2016; **52**(1): 19–41.
Publisher Full Text

Stoker M, Holford S, Hillis R: **A rift-to-drift record of vertical crustal motions in the Faroe-Shetland Basin, NW European margin: establishing constraints on NE Atlantic evolution.** *J Geol Soc.* 2018; **175**(2): 263–274.
Publisher Full Text

Stoker M, Hoult R, Nielsen T, *et al.*: **Sedimentary and oceanographic responses to early Neogene compression on the NW European margin.** *Mar Pet Geol.* 2005; **22**(9–10): 1031–1044.
Publisher Full Text

Stoker M, Leslie A, Smith K: **A record of Eocene (Stronsay Group) sedimentation in BGS borehole 99/3, offshore NW Britain: Implications for early post-break-up development of the Faroe-Shetland Basin.** *Scott J Geol.* 2013; **49**(2): 133–148.
Publisher Full Text

Stoker MS, Smith K, Kimbell GS, *et al.*: **Dynamic evolution of the Faroe-Shetland region, energy and marine geoscience programme commisioned report, CR/15/001**. Brittish Geological Survey, Edinburgh, UK, 2015; 95.
Reference Source

Stoker M, Stewart M, Shannon P, *et al.*: **An overview of the Upper Palaeozoic-Mesozoic stratigraphy of the NE Atlantic region**. Geological Society, London, Special Publications, 2017; **447**(1): 11–68.
Publisher Full Text

Storey CD, Brewer TS, Parrish RR: **Late-Proterozoic tectonics in northwest Scotland: one contractional orogeny or several?** *Precambrian Res.* 2004; **134**(3–4): 227–247.
Publisher Full Text

Storey CD, Brewer TS, Anckiewicz R, *et al.*: **Multiple high-pressure metamorphic events and crustal telescoping in the NW Highlands of Scotland.** *J Geol Soc.* 2010; **167**: 455–468.
Publisher Full Text

Torsvik TH, Amundsen H, Hartz EH, *et al.*: **A Precambrian microcontinent in the Indian ocean.** *Nat Geosci.* 2013; **6**: 223–227.
Reference Source

Tucker RD, Kusky TM, Buchwaldt R, *et al.*: **Neoproterozoic nappes and superposed folding of the itremo group, West-Central Madagascar.** *Gondwana Res.* 2007; **12**(4): 356–379.
Publisher Full Text

Van Gool JAM, Connelly JN, Marker M, *et al.*: **The Nagssugtoqidian Orogen of West Greenland: tectonic evolution and regional correlations from a West Greenland perspective.** *Can J Earth Sci.* 2002; **39**(5): 665–686.
Publisher Full Text

Van Gool JAM, Garde AA, Larsen LM: **Correlation of Precambrian geology in labrador and Southern Greenland**. geological survey of denmark and Greenland report, 2004/29. 2005; 1–30.
Reference Source

Vejbæk OV, Andersen C: **Post mid-Cretaceous inversion tectonics in the Danish Central Graben - regionally synchronous tectonic events?** *Bull Geol Soc Den.* 2002; **49**(2): 129–144.
Reference Source

Ventura Santos R, Ganade CE, Lacasse CM, *et al.*: **Dating Gondwanan continental crust at the Rio Grande Rise, South Atlantic.** *Terra Nova.* 2019; **31**(5): 424–429.
Publisher Full Text

Viola G, Henderson IHC, Bingen B, *et al.*: **Growth and collapse of a deeply eroded orogen: insights from structural, geophysical, and**

geochronological constraints on the Pan-African evolution of NE Mozambique. *Tectonics.* 2008; **27**(5): TC5009.
Publisher Full Text

Waddams P, Cordingley T: **The regional geology and exploration potential of the NE Rockall Basin**. In: *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. edited by: Fleet, A. J. and Boldy, S. A., Geological Society, London, 1999; **5**: 379–390.
Publisher Full Text

Walker S, Bird AF, Thirlwall MF, *et al.*: **Caledonian and Pre-Caledonian orogenic events in Shetland, Scotland: evidence from garnet Lu-Hf and Sm-Nd geochronology**. In: *Pannotia to Pangaea: Neoproterozoic and Paleozoic Orogenic Cycles in the Circum-Atlantic Region*. Geological Society, London, Special Publications, 2020; **503**: 305–331.
Publisher Full Text

Walker F, Schofield N, Millett J, *et al.*: **Paleogene volcanic rocks in the northern Faroe-Shetland Basin and Møre Marginal High: understanding lava field stratigraphy.** In: *Cross-Border Themes in Petroleum Geology II: Atlantic Margin and Barents Sea.* edited by: Chiarella D, Archer SG, Howell JA, Jackson CAL, Kombrink H and Patruno S. Geological Society, London, Special Publications, 2022; **495**: 199–235.
Publisher Full Text

Watson F, Dunning FW: **Basement-cover relations in the British Caledonides**. In: *The Caledonides of the British Isles — reviewed*. edited by: Harris, A.L., Holland, C. H. and Leake, B. E., Geological Society, London, Special Publication, 1979; **8**: 67–91.
Publisher Full Text

Wilson RW, Holdsworth RE, Wild LE, *et al.*: **Basement-influenced rifting and basin developments: a reapraisal of post-Caledonian faulting patterns from the North Coast Transfer Zone, Scotland**. In: *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*. edited by: Law R. D., Butler, R. W., Holdsworth, R. E., Krabbendam, M. and Strachan, R. A., Geological Society, London, Special Publications, 2010; **335**: 795–826.
Publisher Full Text

Zelazniewicz A, Bula Z, Fanning M, *et al.*: **More evidence on Neoproterozoic terranes in Southern Poland and Southeastern Romania.** *Geologicla Quarterly.* 2009; **53**(1): 93–124.
Reference Source

Ziska H, Varming T: **Palaeogene evolution of the Ymir and Wyville Thomson ridges, European North Atlantic margin**. In: *The Nature and Origin of Compression in Passive Margins*. edited by: Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R. And Ritchie, J. D., Geological Society, London, Special Publications, 2008; **306**: 153–168.
Publisher Full Text

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 2

Reviewer Report 13 December 2024

https://doi.org/10.21956/openreseurope.20606.r48255

✔ **Martyn Stoker**
The University of Adelaide, Adelaide, South Australia, Australia

I am very satisfied with the author responses to my queries and suggestions. Thus, I am happy to approve the revised version 2 of the paper.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Tectonostratigraphy of passive continental margins

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 13 December 2024

https://doi.org/10.21956/openreseurope.20606.r48256

✔ **Piotr Krzywiec**
Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Authors addressed all the issues I raised in my review and this paper might be, in my opinion, indexed in its final form. I still have however one last suggestion: information on the Teisseyre-Tornquist Zone and the Sorgenfrei-Tornquist Zone has been added but Authors decided to retain in their text also Tornquist Zone. I suggest to drop this term altogether, as such geological unit simply does not function in geological literature. TTZ and STZ are very different in terms of their crustal structure and geological history and they should not be treated as two segments of one, longer and broader, tectonic zone. Having only TTZ and STZ mentioned in the text would not hamper final impact of this paper; on the other hand, removing Tornquist Zone would result in clearer and more focused text that would be better understood by readers from this part of Europe.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 14 November 2024

https://doi.org/10.21956/openreseurope.19761.r43687

?

Piotr Krzywiec
Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

This is interesting paper dealing with enigmatic structures within the basement of the Faroe–Shetland region.

Authors used seismic data in order to propose system of compressional Precambrian deformation with some implications also for more recent, Phanerozoic history. Seismic imaging is, at such large depths and often beneath lava flows, not perfect and leaves quite a lot of room for speculations, but presented interpretation and models seem to viable.

Paper is generally well written, properly illustrated, but there are some flaws (of different calibre) that require additional attention from the Authors:

(1). Authors use term “Tornquist Zone” to describe zone of deformation known from S Scandinavia, Poland, and W Ukraine – however, there is no single Tornquist Zone, instead two regional tectonic zones are distinguished: Teisseyre-Tornquist Zone in Poland and W Ukraine, and Sorgenfrei-Tornquist Zone in S Scandinavia (cf. Mazur et al., 2015, Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica? Tectonics, refer 1, and Ponikowska et al., 2024, Crustal-Scale Pop-Up Structure at the Junction of Two Continental-Scale Deformation Zones in the Southern Baltic Sea, Tectonics, refer 2, for current views on TTZ and STZ).

These zones have different crustal characteristics and different geological histories. Also, their location is different than what is shown on Fig. 1.

Taking this into account, text on comparison of structures mapped in broad Faroe–Shetland region and the "Tornquist Zone" needs to be modified, quite substantially in my opinion.

(2) page 2: Authors claim that they used "newly established methodology" while in "Methods" chapter fairly standard workflow of seismic reflection data interpretation is described, it would be good to explicitly describe new / novel aspect of seismic interpretation applied in this study

(3) page 2: instead "strong seismic signal of the lavas" use " strong attenuation of seismic energy by lavas" or something along those lines

(3) link from age 6 https://doi.org/10.18710/780M9P does not work

(4) page 16: Authors claim that " Structures in overlying post-Caledonian sedimentary and igneous rocks are irrelevant to the present study" - this is a bit puzzling as in this paper there are numerous references to the post-Caledonian events, this should be rephrased and better clarified

(5) page 16: it would be good to add figure with well tie instead of reference to other papers; also, location of wells used in this study should be shown on the map

(6) page 22: fairly well seismically documented example of post-Caledonian multiple reactivation along the TTZ could be found in Krzywiec et al. 2022, Together but separate: decoupled Variscan (late Carboniferous) and Alpine (Late Cretaceous–Paleogene) inversion tectonics in NW Poland, Solid Earth, refer 3

References

1. Mazur S, Mikolajczak M, Krzywiec P, Malinowski M, et al.: Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica?. *Tectonics*. 2015; **34** (12): 2465-2477 Publisher Full Text
2. Ponikowska M, Stovba S, Mazur S, Malinowski M, et al.: Crustal-Scale Pop-Up Structure at the Junction of Two Continental-Scale Deformation Zones in the Southern Baltic Sea. *Tectonics*. 2024; **43** (4). Publisher Full Text
3. Krzywiec P, Kufrasa M, Poprawa P, Mazur S, et al.: Together but separate: decoupled Variscan (late Carboniferous) and Alpine (Late Cretaceous–Paleogene) inversion tectonics in NW Poland. *Solid Earth*. 2022; **13** (3): 639-658 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Partly

If applicable, is the statistical analysis and its interpretation appropriate?

Not applicable

Are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Nov 2024

Jean-Baptiste Koehl

Dear Prof. Krzywiec, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments. **Comments by the reviewer**
Comment 1: (1). Authors use term "Tornquist Zone" to describe zone of deformation known from S Scandinavia, Poland, and W Ukraine – however, there is no single Tornquist Zone, instead two regional tectonic zones are distinguished: Teisseyre-Tornquist Zone in Poland and W Ukraine, and SorgenfreiTornquist Zone in S Scandinavia (cf. Mazur et al., 2015, Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica? Tectonics, refer 1, and Ponikowska et al., 2024, Crustal-Scale Pop-Up Structure at the Junction of Two Continental-Scale Deformation Zones in the Southern Baltic Sea, Tectonics, refer 2, for current views on TTZ and STZ). These zones have different crustal characteristics and different geological histories. Also, their location is different than what is shown on Fig. 1. Taking this into account, text on comparison of structures mapped in broad Faroe–Shetland region and the "Tornquist Zone" needs to be modified, quite substantially in my opinion.
Response: Agreed. The authors of the present manuscript concede that the location, geometry, and name of the various segments of the Tornquist Zone are not are accurate as they should be. Some specific details on the tectonic evolution of the Tornquist Zone and its various segments are indeed relevant to include to the present manuscript and the authors of the present manuscript thank the reviewer for calling the attention to the work by Mazur et al. (2015), Krzywiec et al. (2022), and Ponikowska et al. (2024). The authors of the present manuscript also concede that a scenario in which a post-Paleoproterozoic Tornquist Zone is controlled by late Paleoproterozoic fabrics and structures should be discussed in the present manuscript. Changes: Redesigned Figure 1a–b with the correct location and geometry of the various segments of the Tornquist Zone, the Sorgenfrei–Tornquist and Teisseyre–Tornquist zones. In addition, added "The geometry and location of the Sorgenfrei–Tornquist Zone and Teisseyre–Tornquist Zone are from Phillips *et al.* (2018), Krzywiec *et al.* (2022), and Ponikowska *et al.* (2024)." and related abbreviations to the caption of Figure 1b. Also separated the abbreviations for Figure 1b and Figure 1c in the figure caption. Rewrote the last two sentences of the Abstract into "The thrust systems also align with the Tornquist Zone in eastern Europe and the North Sea, thus suggesting either that they controlled the formation of the Tornquist Zone or a possibly much longer (Paleoproterozoic?) tectonic history for the Tornquist Zone. Conclusions The Faroe Island

margin is crosscut by late Paleoproterozoic Laxfordian–Nagssugtoqidian thrust systems, which controlled further tectonic development of the margin" to account for the case scenario in which the Tornquist Zone formed along preexisting Paleoproterozoic thrust systems. Rewrote the sixth paragraph in the "Late Paleoproterozoic origin" sub-section into "We note that the proposed relationship with late Paleoproterozoic Laxfordian–Nagssugtoqidian (and/or Inverian?) belts do not preclude a link of the mapped thrust systems with the Tornquist Zone and related fault segment, the Teisseyre–Tornquist Zone (Mazur *et al.*, 2015; Krzywiec *et al.* 2022) and Sorgenfrei–Teisseyre Zone (Phillips *et al.*, 2018; Ponikowska *et al.*, 2024). This would either mean that the Tornquist Zone formed along inherited late Paleoproterozoic thrusts, or that it had already been formed in the late Paleoproterozoic. The latter is possible considering the WNW–ESE strike of major late Paleoproterozoic Svecokarelian–Svecofennian structures in southern Baltica (Bergh *et al.*, 2012; Nordgulen & Saintot, 2008; Saintot *et al.*, 2011), i.e., parallel to the Tornquist Zone (Abramovitz *et al.*, 1999; Cotte *et al.*, 2002; Coward, 1990; Graversen, 2009; Hossein Shomali *et al.*, 2006; Narkiewicz *et al.*, 2015; Pegrum, 1984; Phillips *et al.*, 2018), and the proximity (< 100 km) of the southernmost Svecokarelian–Svecofennian structures in surface outcrops to the Sorgenfrei–Tornquist Zone in southeastern Sweden (Saintot *et al.*, 2011). In addition, southern Baltica was also the locus of the late Paleoproterozoic Transscandinavian Igneous Belt, which also consists of WNW–ESE-striking structures in southernmost Sweden and Denmark, e.g., possibly late Paleoproterozoic WNW–ESE-striking gneissic fabrics on the island of Bornholm (Johansson *et al.*, 2015), i.e., in the vicinity of the Sorgenfrei–Tornquist Zone." and the second paragraph in the "Late Neoproterozoic origin" sub-section into "In eastern Europe, late Neoproterozoic deformation was recorded southwest of the WNW–ESE-striking Teisseyre–Tornquist Zone (Belka *et al.*, 2003; Narkiewicz & Petecki, 2017; Zelazniewicz *et al.* 2009). In addition, the imaginary prolongation of the Sorgenfrei–Tornquist Zone to the west-northwest lines up with the Wyville–Thomson fault zone (Figure 1a–b). However, late Neoproterozoic deformation along the Teisseyre–Tornquist Zone is only preserved in exotic Gondwanan terranes in the southwest, and, thus far, the Tornquist Zone was only traced as far as the southern North Sea, where it controlled the formation and geometry of a series of WNW–ESE-striking, post-Caledonian rift basins (e.g., E–W-striking Farsund Basin; Figure 1b) and associated normal faults when it was reactivated as a major strike-slip fault (Pegrum, 1984; Phillips *et al.*, 2018). More work is therefore needed to further examine this potential relationship.". Also added reference to Mazur et al. (2015), Krzywiec et al. (2022), and Ponikowska et al. (2024) to the reference list. Finally, added another paragraph at the end of the "Influence on NW–SE-striking post-Caledonian transfer zones and tectonosedimentary evolution" section: "The lack or mild character of post-Caledonian reactivation/overprinting of the studied WNW–ESE-striking late Paleoproterozoic thrust systems is in line with observations along the potentially related Tornquist Zone. For example, Phanerozoic sedimentary strata above the Teisseyre–Tornquist Zone are generally not disturbed by post-Caledonian tectonic events, dipping gently to the southwest (Mazur *et al.*, 2015). Nonetheless, the Tornquist Zone and shows evidence of mild Late Cretaceous–early Cenozoic contraction (e.g., Ponikowska *etal.*, 2024), i.e., possibly similar to the study structures." to further illustrate the resemblance of the tectonic evolution of the Tornquist Zone and the studied structures off the Faroe Islands.

Comment 2: (2) page 2: Authors claim that they used "newly established methodology" while

in “Methods” chapter fairly standard workflow of seismic reflection data interpretation is described, it would be good to explicitly describe new / novel aspect of seismic interpretation applied in this study.
Response: Agreed. The sentence is poorly phrased and this is not a new methodology and the newly established facies/character of major, mylonitic thrust systems on seismic reflection data. Changes: Rewrote the end of the sentence into “using the newly established seismic facies of major thrust systems”. Also shortened the abstract to 300 words.

Comment 3: (3) page 2: instead “strong seismic signal of the lavas” use “ strong attenuation of seismic energy by lavas” or something along those lines.
Response: Agreed. Changes: Rewrote the targeted phrase in the plain language summary into “strong attenuation of seismic energy by lavas”.

Comment 4: (3) link from age 6 https://doi.org/10.18710/780M9P does not work.
Response: Agreed. The main author of the present manuscript presents his apologies to the reviewer. The dataset, though ready to be published, was never submitted. Changes: Submitted the dataset to the repository. It should now be accessible.

Comment 5: (4) page 16: Authors claim that “ Structures in overlying post-Caledonian sedimentary and igneous rocks are irrelevant to the present study” - this is a bit puzzling as in this paper there are numerous references to the post-Caledonian events, this should be rephrased and better clarified.
Response: Agreed. The sentence is poorly phrased. The authors of the present manuscript simply wanted to emphasize that the main structures investigated in the present study are pre-Caledonian (possibly late Paleoproterozoic) and Caledonian structures and were only mildly (if at all) reworked during post-Caledonian events. Post-Caledonian structures and tectonism therefore have little implications for the geometry of the studied structures. The authors of the present manuscript concede that this should be better specified. Changes: The paragraph was rewritten into “Structures in overlying post-Caledonian sedimentary and igneous rocks only mildly (if at all) rework the studied pre-Cretaceous structures and, thus, have little impact on the geometry of the studied structures. Post-Caledonian structures were therefore not investigated, except where they showed a clear relationship with the studied basement-seated structures (e.g., merging, truncating, and/or reworking).”.

Comment 6: (5) page 16: it would be good to add figure with well tie instead of reference to other papers; also, location of wells used in this study should be shown on the map
Response: Partly agreed. The well to which the interpretation was tied is displayed in Figure 1c. This was not specified in the text. However, the well tie was performed and published in a previous study (Jolley et al., 2021). The seismic reflection data used to tie to data are not part of the present study and require other permission/license, which are not covered by the present manuscript. Thus, the well tie and related seismic reflection data cannot be added to the present study. They are nevertheless available in figure 19 in Jolley et al. (2021). Changes: Added “(Figure 1c) in the fourth paragraph in the Method chapter.

Comment 7: (6) page 22: fairly well seismically documented example of post-Caledonian multiple reactivation along the TTZ could be found in Krzywiec et al. 2022, Together but separate: decoupled Variscan (late Carboniferous) and Alpine (Late Cretaceous–Paleogene)

inversion tectonics in NW Poland, Solid Earth, refer 3.
Response: Agreed.

See response to comment 1. Changes: See response to comment 1. Also added the following sentence at the end of the newly added paragraph in the "Influence on NW–SE-striking post-Caledonian transfer zones and tectonosedimentary evolution" section: "Other potential episodes of mild reactivation along the Teisseyre–Tornquist Zone include Devonian–Mississippian extension, Variscan contraction in the Pennsylvanian, and Permian–Triassic extension (Krzywiec et al., 2022), the former and latter of which coincide with well-established extensional events in the study area off the Faroe Islands and northern Scotland." to further specify potential resemblance in the tectonic evolution of the Faroe Islands and northern Scotland region with the Tornquist Zone in eastern Europe.

Competing Interests: No competing interests were disclosed.

Reviewer Report 04 September 2024

https://doi.org/10.21956/openreseurope.19761.r43656

?

Martyn Stoker
The University of Adelaide, Adelaide, South Australia, Australia

Review of Koehl et al. – Impact of sub-basalt thrust systems on the Faroe continental shelf for the late Paleoproterozoic–Cenozoic tectonic evolution of the margin

It has long been considered that the cross-cutting structural grain of the pre-Cenozoic basement of the Faroe–Shetland region reflects the interaction of long-lived NE- (Caledonian)and NW-trending (Precambrian) lineaments, which were periodically and variably reactivated throughout the breakup of Pangaea (cf. Ritchie et al. 2011 and references therein). However, this new article by Koehl et al. identifies and describes the character of these features – interpreted as late Paleoproterozoic margin-orthogonal thrust systems – as observed on seismic reflection data, arguably for the first time in this region, enabling a potential insight into the evolution of this structural framework.

The paper is very well written and presented, with the structural analysis greatly benefitting from the availability of reprocessed seismic reflection data. This allowed for the interpretation of the seismic character of the deep basement of the Faroe–Shetland region, including beneath the thick Cenozoic lava flows that characterise the Faroe Islands continental margin. Although seismic interpretation always carries a degree of ambiguity, the structural interpretation in this paper is backed up by a significant knowledge of the internal geometry of thrust systems thereby enabling the potential seismic recognition of key criteria, such as mylonitic shear surfaces, asymmetric folds and their vergence direction, duplexes, and minor brittle thrusts. Thus, at the very least, the paper provides an important model that should be considered and tested in any future studies in this region.

Comments

My main experience in the Faroe–Shetland region concerns its late Palaeozoic–Cenozoic tectonostratigraphic development (Stoker *et al*. 2017). Based on this, I have a couple of general comments for the authors to think about:

1. Whereas the authors' state (page 16, para 2) that 'Structures in the … post-Caledonian sedimentary and igneous rocks are irrelevant to the present study…', I would argue that the post-Caledonian rock record in the Faroe–Shetland region is entirely relevant when considering the formation/longevity of the basement structural system. Key observations from my studies include:
    - It is well established that the eastern and southern margin of the Faroe-Shetland Basin and its component sub-basins have been controlled by the NE-trending Rona Fault and the WNW-trending Judd Fault throughout its development (Lamers & Carmichael 1999; Stoker *et al*. 2018).
    - This basin configuration and its infill has been developing since at least the Jurassic (and possibly the Permo-Triassic) (Ritchie *et al*. 2011; Stoker *et al*. 2017).
    - The Cretaceous stratigraphic record of the Faroe-Shetland Basin reveals a sedimentary succession that is punctuated by episodes of uplift, erosion and contractional deformation that can be linked to a pattern of coeval extension and compression consistent with intra-plate strike-slip tectonism (Dean *et al.* 1999; Stoker 2016).
    - This tectonic instability continued throughout the Paleocene and Eocene development of the basin, spanning the breakup of the SE Greenland and Faroe–Shetland conjugate margins (Stoker *et al*. 2018).
    - The structural disposition of the Eocene sediments and the onlap pattern of the overlying Oligocene–Neogene succession indicates that the present-day deep-water bathymetry of the Faroe–Shetland region most probably developed in the late Palaeogene–Early Neogene interval (Stoker *et al*. 2005, 2013). Whether this is a result of contraction or loss of dynamic support following plate breakup remains unclear.

This history of basin development and sedimentation preserved in the Faroe-Shetland Basin is a clear record of episodic reactivation throughout the Mesozoic and Cenozoic of an existing underlying structural framework. Whereas I have offered explanations for the above observations in my own publications, I am intrigued to wonder how they might relate to this new model. Thus, I would ask the authors to consider the post-Caledonian stratigraphic record as one way of testing their model. Based on this tectonostratigraphic framework, it is obvious that any Mid-Cenozoic contraction that might be linked to their WNW–ESE-striking thrust system is just a response to episodic reactivation (as concluded in the paper). Perhaps the Discussion could be modified so that a subsection on 'post-Caledonian reactivation' highlights the significance of the NE- and NW-trending lineaments to tectonostratigraphic development. The current 'Mid-Cenozoic origin' text (page 21) might also form part of this subsection. Having said that, the abundance of inversion domes generated and episodically growing throughout the Cenozoic (Johnson *et al*. 2005; Ritchie *et al*. 2008) is noteworthy and clearly reflects a protracted phase of contraction/transpression either side of plate breakup. Perhaps this suggests that Cenozoic compression in the Faroe–Shetland region is more related to oceanic spreading. Any thoughts?

2. It would be useful to have a paragraph that considers the general implications of this model for the evolution of the NE Atlantic region in general, especially regarding plate breakup. Significantly, the authors mention that the Greenland-Iceland-Faroe Ridge partly consists of continental crust, which supports the Orogenic Bridge Theory. Thus, what impact does this model have on plate breakup in the NE Atlantic? What bearing (if any) does it have on the 'plates vs. plumes' controversy, which has been going on for several decades.

One minor detail: in the plain language summary, on the fourth line from the bottom, '1.8 million years' should read '1.8 billion years'.

Actions

I leave it up to the authors to consider whether or not to act on my suggestions. However, I do feel that their assessment that the post-Caledonian tectonostratigraphic framework is 'irrelevant' to this study leaves the Discussion unbalanced and lacking crucial information that has an important bearing on the 'Timing of Formation...' and the ensuing history of reactivation.

Nevertheless, I think that this is a very good paper with exciting consequences for better understanding the structural framework of the Faroe-Shetland continental margin.

Martyn Stoker
03-September-2024

References

1. DEAN K, McLACHLAN K, CHAMBERS A: Rifting and the development of the Faeroe-Shetland Basin. *Geological Society, London, Petroleum Geology Conference Series*. 1999; **5** (1): 533-544 Publisher Full Text
2. JOHNSON H, RITCHIE J, HITCHEN K, MCINROY D, et al.: Aspects of the Cenozoic deformational history of the Northeast Faroe–Shetland Basin, Wyville–Thomson Ridge and Hatton Bank areas. *Geological Society, London, Petroleum Geology Conference Series*. 2005; **6** (1): 993-1007 Publisher Full Text
3. LAMERS E, CARMICHAEL S: The Paleocene deepwater sandstone play West of Shetland. *Geological Society, London, Petroleum Geology Conference Series*. 1999; **5** (1): 645-659 Publisher Full Text
4. Ritchie J, Johnson H, Quinn M, Gatliff R: The effects of Cenozoic compression within the Faroe-Shetland Basin and adjacent areas. *Geological Society, London, Special Publications*. 2008; **306** (1): 121-136 Publisher Full Text
5. Ritchie J. D, Ziska H, Johnson H, Evans D: Geology of the Faroe–Shetland Basin and adjacent areas. British Geological Survey Research Report. *British Geological Survey Jarðfeingin*. 2011. Reference Source
6. Stoker M: Cretaceous tectonostratigraphy of the Faroe–Shetland region. *Scottish Journal of Geology*. 2016; **52** (1): 19-41 Publisher Full Text
7. Stoker M, Leslie A, Smith K: A record of Eocene (Stronsay Group) sedimentation in BGS borehole 99/3, offshore NW Britain: Implications for early post-break-up development of the Faroe–Shetland Basin. *Scottish Journal of Geology*. 2013; **49** (2): 133-148 Publisher Full Text
8. Stoker M, Holford S, Hillis R: A rift-to-drift record of vertical crustal motions in the Faroe–Shetland Basin, NW European margin: establishing constraints on NE Atlantic evolution. *Journal of the Geological Society*. 2018; **175** (2): 263-274 Publisher Full Text

9. Stoker M, Hoult R, Nielsen T, Hjelstuen B, et al.: Sedimentary and oceanographic responses to early Neogene compression on the NW European margin. *Marine and Petroleum Geology*. 2005; **22** (9-10): 1031-1044 Publisher Full Text
10. Stoker M, Stewart M, Shannon P, Bjerager M, et al.: An overview of the Upper Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region. *Geological Society, London, Special Publications*. 2017; **447** (1): 11-68 Publisher Full Text

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Tectonostratigraphy of passive continental margins

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 26 Nov 2024

Jean-Baptiste Koehl

Dear Prof. Stoker, thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

Comments by the reviewer
Comment 1: **1.** Whereas the authors' state (page 16, para 2) that 'Structures in the … post-Caledonian sedimentary and igneous rocks are irrelevant to the present study…', I would argue that the post Caledonian rock record in the Faroe–Shetland region is entirely relevant

when considering the formation/longevity of the basement structural system.
Response: Agreed. The sentence is poorly phrased. The authors of the present manuscript simply wanted to emphasize that the main structures investigated in the present study are pre-Caledonian (possibly late Paleoproterozoic) and Caledonian structures and were only mildly (if at all) reworked during post-Caledonian events. Post-Caledonian structures and tectonism therefore have little implications for the geometry of the studied structures. The authors of the present manuscript concede that this should be better specified.
Changes: The paragraph was rewritten into "Structures in overlying post-Caledonian sedimentary and igneous rocks only mildly (if at all) rework the studied pre-Cretaceous structures and, thus, have little impact on the geometry of the studied structures. Post-Caledonian structures were therefore not investigated, except where they showed a clear relationship with the studied basement-seated structures (e.g., merging, truncating, and/or reworking).".

Comment 2: Key observations from my studies include: It is well established that the eastern and southern margin of the Faroe-Shetland Basin and its component sub-basins have been controlled by the NE-trending Rona Fault and the WNW-trending Judd Fault throughout its development (Lamers & Carmichael 1999; Stoker et al. 2018).
Response: Agreed. The reviewer makes a compelling point about the WNW–ESE-striking Judd Fault, which coincides with the southeastward continuation of the Munkargrunnur fault zone.
Changes: Modified the title of the "Influence on NW–SE-striking post-Caledonian transfer zones" into "Influence on NW–SE-striking post-Caledonian transfer zones and tectonosedimentary evolution". Added the location of the Judd Transfer Zone in Figure 1b–c and related abbreviation to the figure caption. Added ") and the southeastward prolongation of the Munkagrunnur fault zone coincides with the Judd Fault (also Judd Transfer Zone; Lamers & Carmichael, 1999; Stoker *et al.*, 2018; Sørensen, 2003;" section and reference to Lamers and Carmichael (1999), Stoker *et al.* (2018), Sørensen (2003) later in the same paragraph. Also added one paragraph after the first paragraph "An interesting feature is the rectangular basin shape created by the NNE-dipping Judd Fault and Rona Fault at the southern edge of the Faroe–Shetland Basin. The former parallels the studied potential late Paleoproterozoic thrust systems, whereas the latter parallels Caledonian structures such as the Moine Thrust (Figure 1b–c). It is therefore possible that the rectangular basin geometry is controlled by the two preexisting structural trends at depth.".

Comment 3: This basin configuration and its infill has been developing since at least the Jurassic (and possibly the Permo-Triassic) (Ritchie et al. 2011; Stoker et al. 2017).
Response: The various episodes of post-Caledonian uplift and erosion and rifting suggested in Stoker et al. (2017) may of course have mildly reactivated the studied structures. The authors of the present manuscript concede that this should be better reflected in the present manuscript.
Changes: Added mention of Permian–Triassic and Jurassic–Cretaceous rifting in the "Implications for the Orogenic Bridge Theory and breakup of the northeastern Atlantic" section and the new Figure 6c and a third paragraph to the "Influence on NW–SE-striking post-Caledonian transfer zones and tectonosedimentary evolution" section: "Previous works have suggested various episodes of post-Caledonian uplift and erosion and rifting in the

northeastern Atlantic region, including coeval contraction and extension at times (e.g., Dean *et al.*, 1999; Lamers & Carmichael, 1999; Stoker, 2016; Stoker et al., 2017, 2018). It is of course possible that the late Paleoproterozoic thrust systems described herein were mildly reactivated and/or overprinted during these events. However, this is not clear from the data analyzed. As suggested by Dean et al. (1999) and Stoker (2016), a possible explanation is that the studied WNW–ESE-striking thrust systems were reactivated as strike-slip faults, which may explain the possibly occasionally coeval timing of contraction and extension along the margin. This would however be challenging to identify if the structures were only mildly reactivated/overprinted. Nevertheless, there should probably be clues such as high-angle to sub-vertical disruption surfaces reflecting truncation of the structures by recent strike-slip faults. This is locally the case in shallow sedimentary strata, e.g., at the Ymir Ridge (Boldreel and Andersen, 1993 their figures 4 and 5, Boldreel and Andersen, 1998 their figures 4 and 5; Johnson et al., 2005 their figure 6; Kimbell et al., 2016 their figure 2c; Stoker et al., 2015; Jolley et al., 2021). However, it is not obvious within pre-Cretaceous basement rocks from the data analyzed. More detailed work should therefore be performed in the Faroe–Shetland Basin area, where the relative abundance of exploration wells and seismic reflection data (including 3D data) would provide a more reliable tie between tectonic movements and sedimentary deposition along specific structures. A serious limitation might be the lack of deep seismic reflection data and poor seismic imaging below the Cenozoic volcanic successions in this area, thus impeding the correlation of shallow post-Caledonian brittle faults and sedimentary strata with deep, basement-seated structures."

Comment 4: The Cretaceous stratigraphic record of the Faroe-Shetland Basin reveals a sedimentary succession that is punctuated by episodes of uplift, erosion and contractional deformation that can be linked to a pattern of coeval extension and compression consistent with intraplate strike-slip tectonism (Dean et al. 1999; Stoker 2016).
Response: Agreed. See response to comment 3.
Changes: See response to comment 3.

Comment 5: This tectonic instability continued throughout the Paleocene and Eocene development of the basin, spanning the breakup of the SE Greenland and Faroe–Shetland conjugate margins (Stoker et al. 2018).
Response: See response to comment 3.
Changes: See response to comment 3.

Comment 6: The structural disposition of the Eocene sediments and the onlap pattern of the overlying Oligocene–Neogene succession indicates that the present-day deep-water bathymetry of the Faroe–Shetland region most probably developed in the late Palaeogene–Early Neogene interval (Stoker et al. 2005, 2013). Whether this is a result of contraction or loss of dynamic support following plate breakup remains unclear.
Response: Agreed. The authors of the present manuscript thank the reviewer for recommending valuable previous works on the tectonic evolution of the margin to include to the present study.
Changes: Added reference to Stoker et al. (2005, 2013) in the fourth paragraph of the "Mid-Cenozoic origin" sub-section and to the reference list.

Comment 7: This history of basin development and sedimentation preserved in the Faroe-

Shetland Basin is a clear record of episodic reactivation throughout the Mesozoic and Cenozoic of an existing underlying structural framework. Whereas I have offered explanations for the above observations in my own publications, I am intrigued to wonder how they might relate to this new model. Thus, I would ask the authors to consider the post-Caledonian stratigraphic record as one way of testing their model. Based on this tectonostratigraphic framework, it is obvious that any Mid-Cenozoic contraction that might be linked to their WNW–ESE-striking thrust system is just a response to episodic reactivation (as concluded in the paper). Perhaps the Discussion could be modified so that a subsection on 'post-Caledonian reactivation' highlights the significance of the NE- and NW-trending lineaments to tectonostratigraphic development. The current 'Mid-Cenozoic origin' text (page 21) might also form part of this subsection. Having said that, the abundance of inversion domes generated and episodically growing throughout the Cenozoic (Johnson et al. 2005; Ritchie et al. 2008) is noteworthy and clearly reflects a protracted phase of contraction/transpression either side of plate breakup. Perhaps this suggests that Cenozoic compression in the Faroe–Shetland region is more related to oceanic spreading. Any thoughts?
Response: Agreed. The manuscript does need to further expand on the potential impact of the studied late Paleoproterozoic structures on the post-Caledonian evolution of the margin. See responses to comments 1 to 6. The reviewer also raises a highly relevant question regarding the cause of Cenozoic contraction around the Faroe Islands. Considering the potential continental nature of the crust at the Greenland–Iceland–Faroe Ridge, then Cenozoic contraction may be related to extension of the orogenic crust there and to seafloor spreading at the Reykjanes and Kolbeinsey ridges. However, as mentioned in the present study, the phases of tectonism that contributed the most to shape the studied structures are the late Paleoproterozoic Laxfordian–Nagssugtoqidian Orogeny and mid-Paleozoic Caledonian Orogeny. Subsequent tectonic events had only a limited impact on these structures, if any at all. Thus, it is probable that most of the relief created by the studied structures was already established in the mid-Paleozoic.
Changes: See also responses to comments 1 to 6. Also added "possibly from the mid-Paleozoic Caledonian Orogeny" in the third paragraph in the "Mid-Cenozoic origin" sub-section, and rewrote the fourth point of the conclusion into "The late Paleoproterozoic thrust systems were possibly reactivated and/or overprinted during late Neoproterozoic and/or various episodes of post-Caledonian extension and contraction (transpression?). However, post-Caledonian reactivation/overprinting (if any) was of limited intensity.".

Comment 8: **2**. It would be useful to have a paragraph that considers the general implications of this model for the evolution of the NE Atlantic region in general, especially regarding plate breakup. Significantly, the authors mention that the Greenland-Iceland-Faroe Ridge partly consists of continental crust, which supports the Orogenic Bridge Theory. Thus, what impact does this model have on plate breakup in the NE Atlantic? What bearing (if any) does it have on the 'plates vs. plumes' controversy, which has been going on for several decades.
Response: Agreed. This is an excellent suggestion by the reviewer.
Changes: Added "The WNW–ESE-striking Laxfordian orogen (thickened continental crust) and related structures at the Faroe margin and their counterparts in southeastern Greenland were unsuitably oriented to accommodate thinning of the crust during rifting of the northeastern Atlantic because the main structures strike parallel to the extension

direction. In addition, their low-angle geometry was unsuitable to accommodate transform faulting. Thus, a significant delay should be expected for continental breakup at the Greenland–Iceland–Faroe Ridge compared with adjacent areas along the rift axis. Plume activity may very well be responsible for the intense magmatism recorded at the conjugate margin pair (southeastern Greenland and Faroe Islands) and in Iceland (Dahl-Jensen et al., 1997; Millett et al., 2015; Geoffroy et al., 2021; Jolley et al., 2021; Walker et al., 2022; Layfield et al., 2023). However, should the studied late Paleoproterozoic structures extend farther offshore than what is presented in Figure 2e, the anomalously thick character of the crust under the Greenland–Iceland–Faroe Ridge may then be explained by the existence of a (continuous?) rift-orthogonal ribbon (i.e., continuous orogenic bridge; Koehl and Foulger, 2024; Figure 6a–d) or by several isolated blocks of continental crust entrapped by extensive magmatism (e.g., rifted oceanic magmatic plateau; Coffin and Eldholm, 1992; Rime et al., 2024) or by several microcontinents similar to the Jan Mayen Microcontinent Complex and all rifted from one another and separated by regular, Penrose-like oceanic crust (e.g., Johnson and Heezen, 1967; Bott, 1985; Blischke et al., 2016). Since the thickness of the Greenland–Iceland–Faroe Ridge is consistently higher than 20 km from southeastern Greenland to the Faroe shelf, a scenario with several microcontinents separated by Penrose-like oceanic crust is unlikely. Ongoing work using seismic reflection data within the Greenland–Iceland–Faroe Ridge suggests that the late Paleoproterozoic structures described in the present study extend at least to eastern Iceland (Koehl et al., 2025) and, thus, that the Greenland–Iceland–Faroe Ridge may be a continuous orogenic bridge (Figure 6a–d; Koehl and Foulger, 2024), potentially developing into a rifted oceanic magmatic plateau (e.g., Rime et al., 2024), i.e., the early phase towards its evolution to a ruptured orogenic bridge. A continuous ribbon of continental crust between southeastern Greenland, Iceland, and the Faroe Islands is compatible with seafloor spreading at the Reykjanes Ridge and Kolbeinsey Ridge and with plume magmatism. The orogenic bridge may have formed during the late Paleoproterozoic Laxfordian–Nagssugtoqidian Orogeny (Figure 6a) and was then reworked and tightened during NW–SE-oriented Caledonian contraction (Figure 6b). The crust was then thinned during several ensuing episodes of extension, e.g., late–post-orogenic collapse in the Devonian and Permian–Triassic and Jurassic–Cretaceous rifting (Figure 6c). While relatively thinner crust northeast and southwest of Iceland was broken up, highly thickened orogenic crust at the Greenland–Iceland–Faroe Ridge is still being thinned and stretching together with seafloor spreading at the adjacent Reykjanes and Kolbeinsey ridges (Figure 6d; Koehl and Foulger, 2024).

For **Figure 6** please refer (https://s3-eu-west-1.amazonaws.com/openreseurope/linked/242354.18284_-_Figure_6_%28Comment_-_OREU%29.docx)

Figure 6 Model showing the development of an orogenic bridge at the Greenland–Iceland–Faroe Ridge through (a–b) two orogeneses perpendicular to one another ((a) WNW–ESE-striking Laxofordian–Nagssugtoqidian Orogen and (b) NE–SW-striking Caledonian Orogen), (c) repeated extension along extensional faults and detachments and inherited orogenic structures, e.g., in the Devonian, Permian–Triassic, and Jurassic–Cretaceous, and (d) breakup along inherited, reactivated and/or overprinted orogenic structures in the Cenozoic. Note that any number of additional orogeneses and/or extensional collapse/rifting may be added in between these events. Abbreviations: GIFR: Greenland–Iceland–Faroe Ridge; TFZ: Tjörnes fault zone.”. Also updated the title of the “Implications for the Orogenic Bridge Theory” section into “Implications for the Orogenic Bridge Theory and breakup in the northeastern Atlantic”. Furthermore, added a new Figure 6 detailing the development of an orogenic bridge at the Greenland–Iceland–Faroe Ridge.

Comment 9: One minor detail: in the plain language summary, on the fourth line from the bottom, ‘1.8 million years’ should read ‘1.8 billion years’.
Response: Agreed.
Changes: Replaced “million” by “billion” in the plain language summary.

Comment 10: Actions: I leave it up to the authors to consider whether or not to act on my suggestions. However, I do feel that their assessment that the post-Caledonian tectonostratigraphic framework is 'irrelevant' to this study leaves the Discussion unbalanced and lacking crucial information that has an important bearing on the 'Timing of Formation...' and the ensuing history of reactivation. Nevertheless, I think that this is a very good paper with exciting consequences for better understanding the structural framework of the Faroe-Shetland continental margin.
Response: The authors of the present manuscript present their apologies for the misunderstanding created by their phrasing of the methods chapter. The authors of the present manuscript did not imply that post-Caledonian tectonostratigraphic framework is irrelevant to the study of the margin. This was also righteously pointed out by Prof. Krzywiec (reviewer 2) and was corrected accordingly. See also response to comments 1 to 7 and to Prof. Krzywiec’s comment 5.
Changes: See response to comments 1 to 7 and to Prof. Krzywiec’s comment 5 (reviewer 2).

Competing Interests: No competing interests were disclosed.