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The North Sea rift basement records extensional collapse of the Caledonian orogen

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Our knowledge of crystalline basement rocks flooring continental rift basins, rifted margin deposits, and foreland basins is poor, yet important for understanding basin evolution, crustal heat production, petroleum maturation, and for offshore mineral exploration. Using the northern North Sea rift as an example, we demonstrate how modern broadband seismic data can be utilized to unravel basement lithology and structure at a previously unprecedented level of detail. In our case study, we have discovered a pre-rift Caledonian basement with a folded structural pattern very similar to Devonian collapse-related structures onshore Western Norway. The data indicate that the collapse-generated Caledonian infrastructure extends >100 km into the northern North Sea, defining a wide zone of Caledonian crust that turned hot and mobilized vertically by upright folding and detachment faulting during the post-collisional stage. This extensive post-orogenic thermally induced collapse makes the south Scandinavian Caledonides unique among Phanerozoic orogens.

Crystalline crustal rocks of the continents continue under continental rifts and passive margins, where they are buried under kilometer-thick packages of sedimentary rocks. These sedimentary packages dampen and obscure magnetic, gravimetric, and seismic signals, and most of the relatively few wells that are drilled into the basement only sample the upper few meters or tens of meters of crystalline rocks. Hence, in contrast to the sedimentary strata, which in places host large petroleum accumulations, the underlying crystalline basement is poorly known.

There is a growing academic interest in these buried portions of the continents. Offshore and buried basement conceal an important evolutionary record of stretched continental crust, as knowledge of these basement regions is essential for a complete understanding of tectonic processes, notably orogeny and rifting. For example, knowledge of pre-rift basement can help to understand the location, structure and geometry of rift systems. Furthermore, the amount of pre-rift extension taken up by the crust in rifts and passive margins is important for reconstructions of former (super) continents.

In this work, we show how modern reflection seismic data can reveal new aspects of buried basement, particularly in the shallower parts of passive margins and rifts. We utilize RGB blending of the spectral components of the seismic signal. While spectral decomposition techniques are widely used to extract information about sedimentary structures and architecture such as river channels in clastic deposits¹, our application to the basement itself is

new. Broadband 3D seismic data, where a wide range of frequencies are recorded, are particularly well suited for imaging buried basement. Naturally, shallowly buried crust is better imaged than deep crust, but features can be observed throughout the crust. In our case study, we use 3D broadband seismic data from the northern North Sea rift, focusing on the basement on the Norwegian (eastern) side, notably the rift shoulder offshore Western Norway (the Horda Platform) (Fig. 1). The data reveal large-scale folds and associated shear zones in the offshore basement, suggesting a more extensive collapse of the central Caledonian orogen than previously realized.

Results

Seismic imaging of basement

To explore buried crystalline crust, we make integrated use of seismic data in two different ways. The first approach is to explore the top basement unconformity, i.e., the interface between the rift basin deposits and the older and much more complexly deformed crystalline basement. The second approach is to map intra-basement reflectors below the top basement unconformity. Combining these two approaches is elevating our understanding of the buried North Sea rift basement to a new level of confidence and detail (Fig. 1).

Regarding the top basement unconformity, our detailed seismic mapping and use of spectral decomposition methods have revealed patterns of frequency variations that in part reflect the overburden and geomorphic

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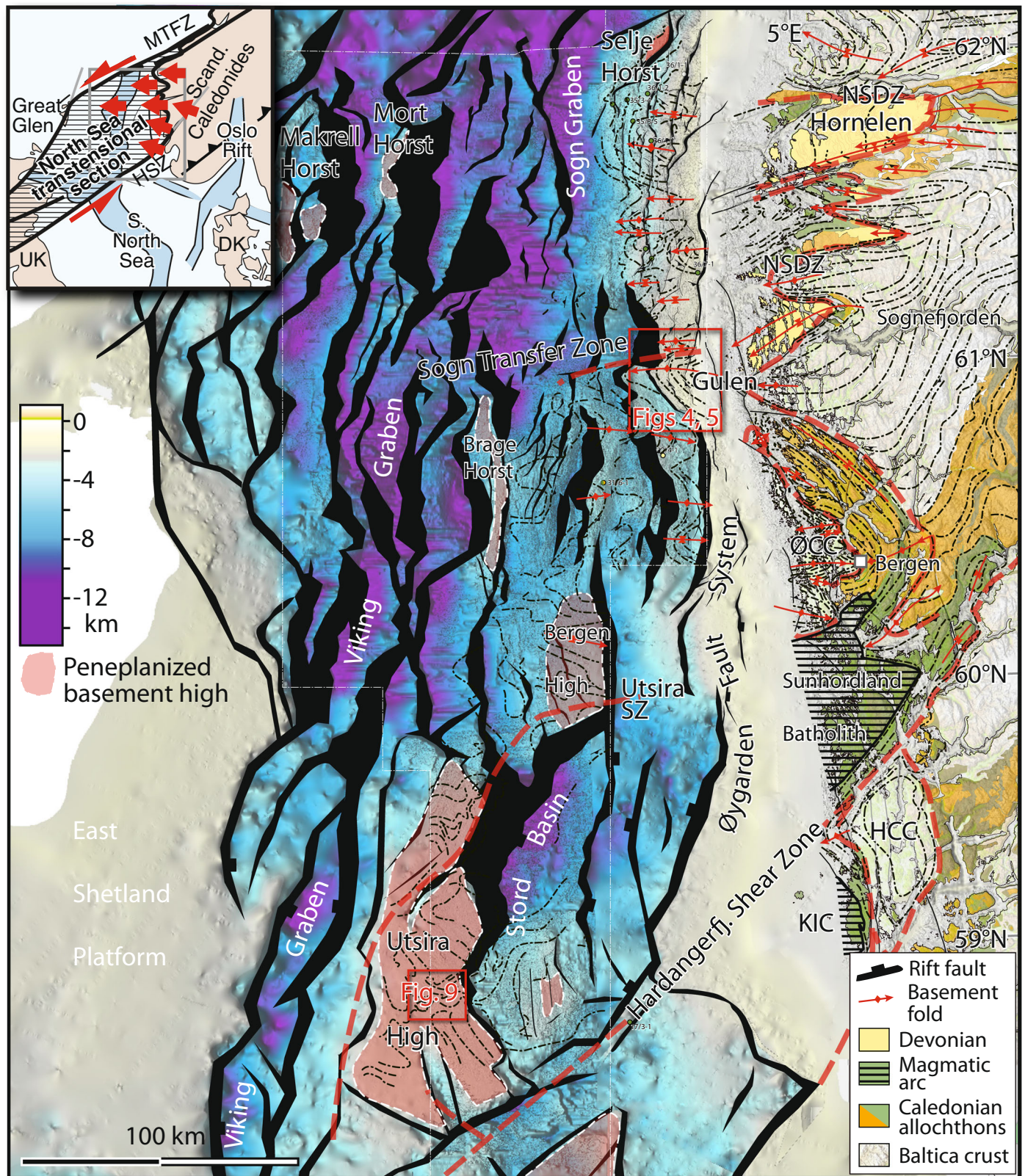
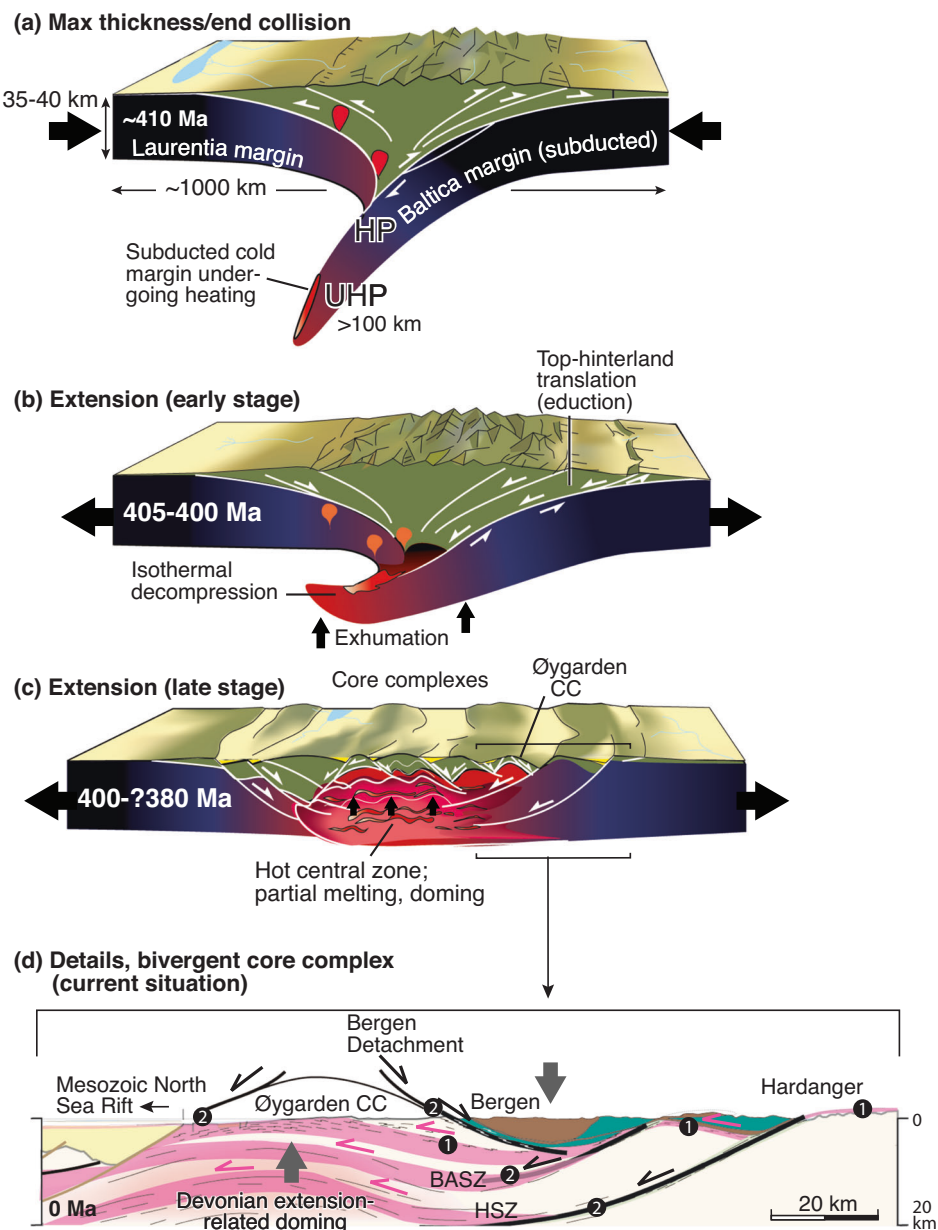


Fig. 1 | Geologic map of top crystalline basement in the northern North Sea and coastal Western Norway. Collapse basement folds indicated by red arrows. Some of these folds are mapped within the basement, below the top basement surface. Black faults are rift faults that postdate and offset the basement fold structures. Offshore highs with Mesozoic erosional surfaces (e.g., Utsira High) are marked. Onshore, green color indicates oceanic Caledonian allochthonous units while orange marks

continentally derived units. Inset map shows the regional setting with the Mesozoic rift overprinting the Devonian transensional regime that existed during the collapse of the Caledonian orogen. Red arrows on the inset map indicate Devonian extension directions. NSDZ is the Nordfjord–Sogn detachment zone that stretches from Gulen past Hornelen. ØCC is the Øygarden Core Complex, a Baltica basement window west of Bergen, and HCC is the Haugesund Core Complex.

Fig. 2 | Evolution of the Caledonian crust from end convergence (Early Devonian) to completely collapsed crust (Middle Devonian). **a** End continental subduction. **b** Early extensional stage with exhumation of the Baltica margin and uniform hinterland-directed transport of the orogenic wedge above the Baltican basement. **c** Advanced collapse stage, where the crust is heated and softened, promoting vertical movements in the form of doming and metamorphic core complex formation. **d** More detailed view of the Øygarden metamorphic core complex (CC) and its bivergent shear zone system (present-day erosion level). Pink zones indicate extension-related shear zones in the deeper basement, reworked by the Bergen Detachment. Black lines mark late-stage strain localization features, mostly ductile but with a late brittle stage. Note that the North Sea rift postdates this Devonian extensional deformation. (U)HP (ultra)high pressure, BASZ Bergen Arc Shear Zone, HSZ Hardangerfjord Shear Zone.



expressions such as channels eroded into the basement, and in part the basement with its variations in lithology, layering and structure. In places where a uniform sequence of sedimentary layers covers the top basement surface, the patterns appearing on blend images are largely related to the basement itself. Internally in crystalline crust underneath rift basins and continental margin deposits, reflectivity and frequency are typically low and seismic imaging poor. Nevertheless, with modern 3D-seismic broadband data, intra-basement packages of reflectors can be observed and mapped in three dimensions. Even though individual reflectors may not be continuous over large areas, reflectors at different depths and from different parts of the data cube can be combined to constrain the overall structural pattern of the crust. In our North Sea rift example (Fig. 1), we find abundant evidence of an extensively folded basement that obtained its final structure during the collapse of the Caledonian orogen.

Nature of onshore Caledonian crust

The onshore basement is dominated by the collapsed and exhumed Silurian–Early Devonian Caledonian orogen. The Caledonian collisional

event was relatively short (~20 million years) and initially cold, with deep (locally >100 km deep) subduction of a rigid Baltica margin. During the collision, a growing orogenic wedge of allochthonous crustal units developed² (Fig. 2a), consisting of continental nappes overlain by oceanic terranes often referred to as outboard terranes or the Upper Allochthon³.

After the collision of Baltica with Laurentia around 425–405 Ma (Fig. 2a), the subducted hinterland portion of the Baltica continental crust, now exposed along the coast of Western Norway (Fig. 1), was heated and then decompressed almost isothermally towards normal crustal depths (Figs. 2a, b)^{4,5}. Structural and kinematic data show that decompression and the related crustal thinning occurred in response to divergent motions between Laurentia and Baltica in the northern North Sea region⁶. This divergence allowed for tectonic stretching of the orogenic crust and tectonic transport of the orogenic wedge toward the hinterland⁷ (Fig. 2b). Ar⁴⁰–Ar³⁹ cooling ages from Baltica basement show that exhumation to middle to upper crustal depths continued through the Middle Devonian^{8,9} (Fig. 3). The youngest Ar⁴⁰–Ar³⁹ mica cooling ages (time of cooling through 450–400 °C) are reported from the most high-pressure coastal region north of the Middle

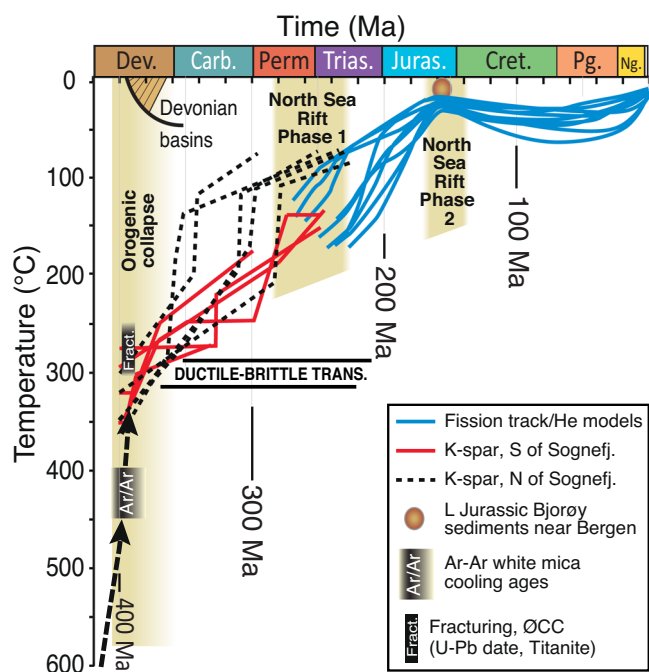


Fig. 3 | Temperature–time diagram showing cooling paths of the onshore basement in West Norway. Dashed paths: K-feldspar 40Ar/39Ar time–temperature models from the Nordfjord–Sogn detachment zone north of Sognefjorden¹⁸. Red paths: similar models of Baltica basement south of Sognefjorden⁹. Blue lines: time–temperature models based on fission track and (U–Th)/He data in the coastal area south of Sognefjorden⁴⁴. “Ar/Ar” box marks white mica cooling ages from the Baltica basement¹⁴. The U–Pb age of the oldest dated brittle fracture in the region (from the Øygarden Core Complex; ØCC) is indicated¹⁰. The ductile–brittle transition for normal granitic continental crust is shown (around 300 °C⁴⁵). The data show that the basement passed this rheologic transition in the Devonian, and that the late ductile upright folding discussed in this paper relates to Devonian extensional collapse.

Devonian Hornelen basin (Fig. 1) at around 380 Ma⁸. Farther south, Ar⁴⁰–Ar³⁹ mica ages cluster around 400 Ma, and brittle structures transecting the late upright folds in the Øygarden Core Complex (ØCC in Fig. 1) have been dated to the Lower to Middle Devonian (Fig. 3)¹⁰. Hence, different parts of the Caledonian crust entered brittle crustal levels at different times, earlier in the south and later in the north. By the time that rifting is initiated in the Permian, the crust is assumed to have reached normal thickness. The Permian basement surface is preserved in deeply downfaulted parts of the northern North Sea rift, while the basement in elevated parts of rotated fault blocks and along the rift flanks experienced some further Triassic to Early Jurassic erosion due to footwall uplift¹¹. The temperature–time paths shown in Fig. 3 show paths from the onshore coastal part of Fig. 1, while deep hanging walls to major offshore faults have preserved basement that reached the surface in the Permian.

Dating of migmatitic material in the Baltica crust shows that, during the initial rapid decompression (prior to the middle and upper crustal level cooling outlined in Fig. 3), exhumation was associated with partial melting^{12–14}. This must have turned the middle crust into a rheologically soft and gravitationally less dense layer, prone to ascend buoyantly to form upright folds or dome-like structures (Fig. 2c). Associated differential vertical movements occurred in concert with activity on extensional shear zones. Extensional shear zones developed already at the initial and intermediate stages of orogenic extensional collapse. While those early shear zones were hinterland-dipping (Fig. 2b), a change into a system of bivergent extensional shear zones occurred as collapse-related exhumation continued toward the brittle–ductile transition (Fig. 3)¹⁵. The result was a series of metamorphic core complexes that involved large-scale folding and

associated extensional shear zones with up to a hundred kilometers offset¹⁴ (Fig. 2c, d), all located in a vast region of sinistral Devonian transtension^{7,16}.

Onshore Norway, this orogenic collapse event created deformation that increased in intensity from the inland to the coastal rift flank, where a set of plunging upright folds formed during this post-orogenic extensional evolution, folding the main ductile extensional shear fabric. These folds are associated with several kilometer-thick ductile shear zones^{16,17}, locally with a brittle overprint¹⁸. The first-order folds have wavelengths of up to tens of kilometers and amplitudes of several kilometers, with Baltica crust occupying antiformal cores and with tectonically overlaying Caledonian allochthons and Devonian supradetachment basins in synformal positions. Regionally, the system of detachments and folds define an up to 100 km wide zone onshore, vanishing eastwards into the mainland. In the following we argue that this tectonic style extends far into the northern North Sea rift proper.

The offshore Gulen fold example

We here use an area in the northeastern part of the North Sea rift to demonstrate how modern seismic data and methodology can be utilized to reveal the nature of the buried basement. In this area, the seismic broadband survey extends close to the Norwegian coast and its coastal bedrock platform, with only a small gap between relevant onshore and offshore data^{11,19}. Our selected example is a seismically imaged antiform offshore Sognefjorden, here referred to as the offshore Gulen antiform, which can be linked to the adjacent onshore Gulen antiform²⁰. The basis for this correlation is its proximity to the onshore Gulen antiform, the way that its location matches the offshore projection of the onshore Gulen antiform, and the fact that both the onshore and offshore folds involve folding of a strong lithologic banding that offshore is identified by multiple subparallel seismic reflectors and onshore is a shear fabric related to the orogenic collapse. The offshore antiform is buried under 300–400 m of seawater and 1–2 km of Jurassic to Quaternary sediments, but still very well imaged at the top basement level in the spectral decomposition blends (Fig. 4).

Spectral decomposition blends, where RGB colors represent different frequency (or cycles/km for depth-converted data) bins, exhibit basement layers of different seismic properties and their large-scale fold pattern. The data also reveal second-order (parasitic) folds at the 0.1–1 km scale (Fig. 4d, also see Supplementary Fig. S1). The layering is strikingly similar to the gneissic layering observed onshore (Fig. 4b, c), but with a level of continuity that by far surpasses relevant onshore examples that are cluttered by vegetation, sedimentary cover, lakes, fjords, and human infrastructure. Different blend colors represent different parts of the seismic frequency (or cycles/km) spectrum and relate to variations in acoustic impedance between different basement layers and the unconformably overlying sandy Jurassic sedimentary strata. In the Gulen case, the cover is interpreted to be sandstone, so that the variations are mainly those within the basement, i.e., metamorphic rock layers or groups of layers with different seismic properties.

The visually impressive top basement blend images of the offshore Gulen antiform shown in Figs. 4a and 5 represent the subcrop pattern of the basement fold at the lower Jurassic paleotopographic denudation surface. The seismically defined layers that outline the fold on the blend images correspond to reflective layers dipping into the crystalline basement (Fig. 4b, d). While these reflectors represent basement heterogeneities, it is not straightforward to directly relate layers of specific frequency bins (colors) to specific lithologies, because the colors also depend on layer thickness, interference, tuning effects, noise, and other geophysical effects. However, a very similar looking onshore lithologic banding (Fig. 4c) suggests that the offshore blend features may relate to alternating granitic, gneissic (with biotite), and amphibolitic lithologies. Furthermore, information about bedrock properties can be deduced from variations in paleotopography. The brighter bands, which show up as around 200–350 m thick bands in the data (Fig. 4b), are locally seen to define paleotopographic ridges (see star in Fig. 5a, b). This indicates that they are more resistant to erosion than adjacent lithologies, as is the case also for onshore granitic layers.

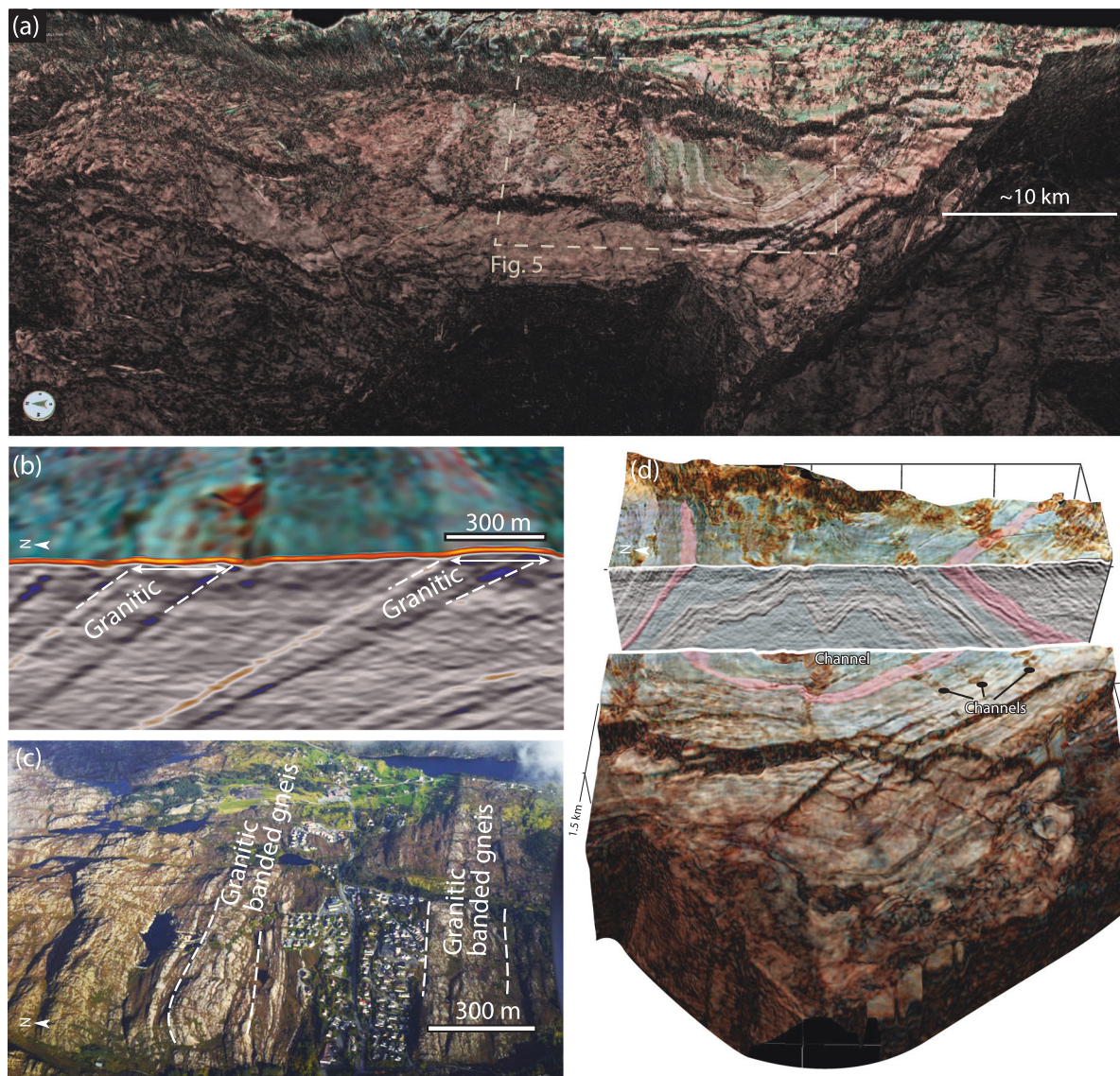


Fig. 4 | Images of the top basement surface offshore and onshore. **a** Top crystalline basement offshore W Norway, looking eastward toward the Norwegian coastal region. The variations in color and lightness reflect variations in lithology, and the lithologic banding defines a folded pattern. The image is an RGB blend, as explained in the text. **b** Detailed view of the blend (upper greenish part) and its relation to the vertical seismic reflection pattern (lower grayish part). Note positive relief, especially for the rightmost of the two annotated layers that we interpret as granitic.

Outstanding bands on the blend map correspond to well-defined seismic reflectors or reflector packages with widths of around 1–3 km, very similar to the onshore lithologic pattern in (c), which is an oblique aerial photo showing alternating granitic and more mafic gneissic layers onshore central Sotra (ØGC in Fig. 1). **d** Perspective view of the top crystalline basement surface showing the offshore Gulen antiform and the banded structure that is revealed by the RGB blend and the conventional seismic data.

Topography also correlates with the larger-scale fold structure, where a rougher (Fig. 5c, d) and slightly lower (Fig. 5b) topography is seen in the north (upper) part of Fig. 5a. The marked changes in terrane roughness likely relate to a change in lithology. Also, the more widely eroded core of the fold seems to consist of more easily erodible lithology. In this part a wider channel network is seen, focusing on narrower channels through the flat and, in terms of erosion, more resistant middle part of the fold.

The three-dimensional geometry of the fold was investigated by mapping out reflectors within the basement, as shown in Fig. 6. These reflectors are generated by rocks of different densities and/or sound velocities, which for typical onshore basement could represent mica-rich schist or gneiss, amphibolite and granitic layers. Seismic anisotropy caused by deformation fabrics characteristic of shear zones also create seismic reflections²¹. The seismic reflection pattern reveals a 20 km wide gentle to open upright west-plunging antiform, splitting westward into two slightly diverging hinges (Fig. 6a, arrows).

The offshore Gulen fold structure is defined by a series of parallel bands believed to represent different rock types. Onshore, this pattern is characteristic for strongly sheared or flattened basement, where originally non-parallel features (intrusive structures and tectonic fabrics) have been transposed into subparallel layers. Many Caledonian continental nappes show very strong fabrics and banding, as do the parts of the Baltica crust that have been involved in Caledonian collapse-related ductile flattening and shearing. The onshore Gulen fold is defined by a 3–5 km thick series of banded Baltica gneisses that were sheared during the Caledonian collapse shear zone (detachment zone)²². The offshore Gulen fold is also defined by sheared basement rocks, but it is possible that these basement rocks occupy a higher tectonostratigraphic level (continental allochthons). Hence the folded layers may represent an allochthonous continental unit, an interpretation favored in Fig. 7. The differently eroded basement rocks north of the offshore Gulen fold (Fig. 5) must represent a different unit, most likely higher (outboard) nappe units.

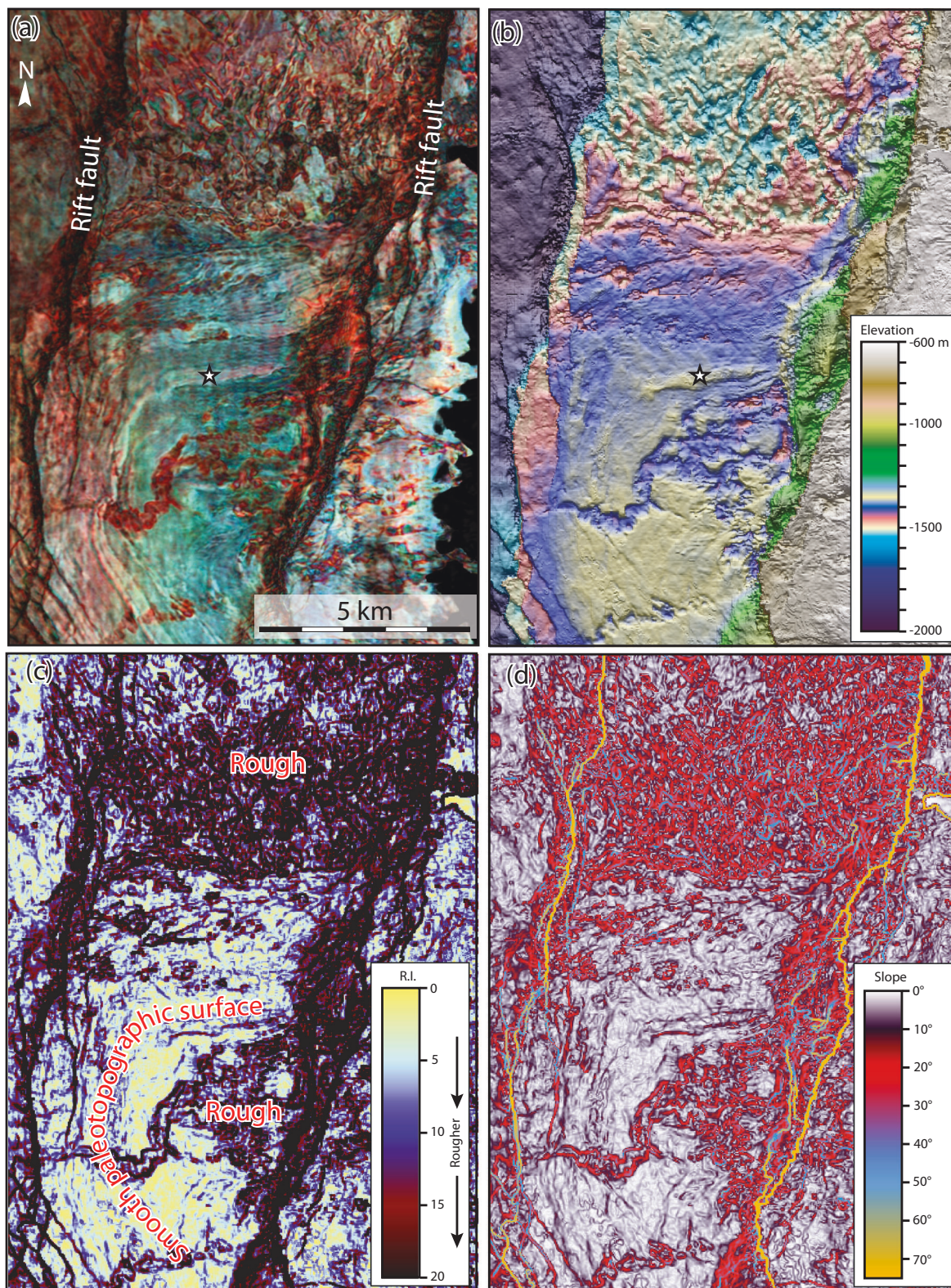


Fig. 5 | Vertical views of the eroded offshore Gulen antiform at the buried ~200 million years old top basement unconformity. a Blend image, showing folded layers at the top basement level, with erosional river channels that are carved up to 60 m into the basement. Two late rift faults cutting the fold are annotated. Star marks topographic ridge. **b** Elevation map colored to reveal the paleotopographic expression in the fold area. Note the rough area in the north and the narrowing of the

wide drainage system in the core of the fold toward the west. **c** Roughness index calculated from seismically mapped top basement surface shown in (b), showing a core and a northern part that is much rougher than the smooth layered middle part. **d** Slope map, showing variations in geomorphic expression and fluvial channels consistent with (a–c). See Figs. 1 and 4 for location.

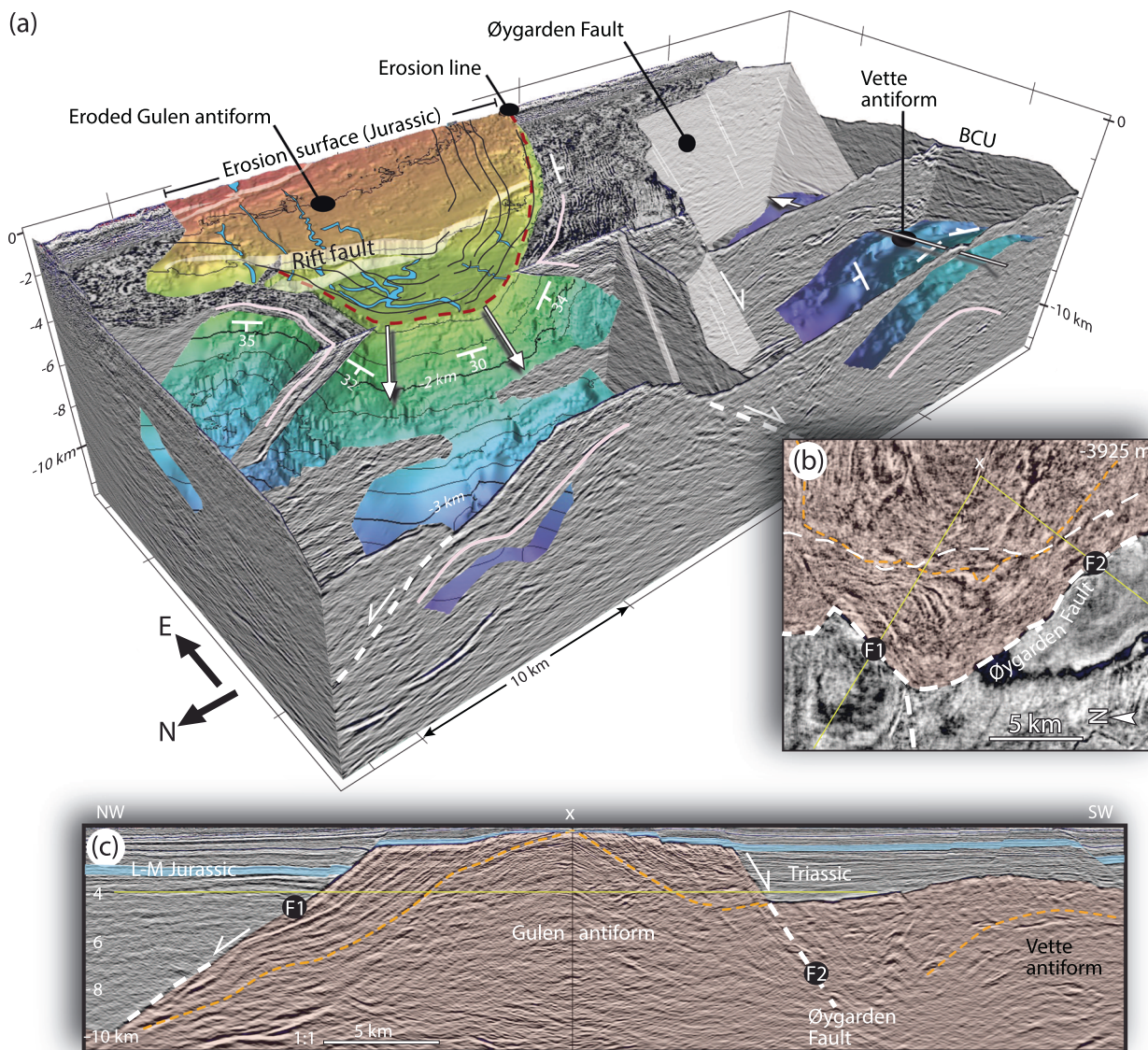


Fig. 6 | The west-plunging offshore Gulen and the east-plunging Vette basement antiforms. **a** 3D model, showing seismic sections through the offshore Gulen and Vette antiforms. Both folds are illustrated by an interpreted internal basement reflector (colored surfaces). The Gulen surface is truncated by the top basement unconformity. The two antiforms plunge in opposite directions (W and E, respectively). The erosion line for the mapped Gulen antiform reflector is shown as a dashed dark red line. Strike/dip symbols give the orientation of this surface at several locations, while arrows indicate fold hinges. Only seismic data below the base Cretaceous unconformity (BCU) is shown. **b** Deeper (−3925 m) horizontal slice through the Gulen Fold, showing how the Øygarden Fault is guided by the fold around the hinge zone. **c** Vertical section through the fold (yellow line in **b**). The Øygarden Fault cuts through the folded layers on the south side (F2) of the fold even

though being subparallel to the folded layers in map view (**b**). On the north side (F1) the fault is cutting the basement banding at a much lower angle, and locally exploiting this banding (upper part). Note that the reflectors along and above the orange dashed line in (**c**) represent Devonian mylonitic banding. Basement is given a red tint in (**b**) and (**c**). White dashed lines in all figures are fault traces. The Orange dashed line in (**b**) marks the intersection between the interpreted horizon in (**a**) and the horizontal slice in (**b**). The yellow line in (**b**) marks the location of the profile shown in (**c**). The yellow line in (**c**) marks the constant depth slice shown in (**b**). The location is approximately that annotated for Fig. 4 (see Fig. 1), but **a** is shifted slightly southward to cover the Vette antiform.

A regionally folded basement province

The offshore Gulen fold is only one of many large-scale folds that can be identified in the offshore seismic data cube. Although individual basement reflectors cannot be traced across the study area, the data as a whole reveal a uniform set of basement folds in the northern North Sea rift area east of the Viking–Sogn graben system with consistent orientation, geometry, wavelength, and amplitude. The fold pattern continues southwards, northwards, and westwards from the offshore Gulen antiform. This offshore fold pattern is outlined in Figs. 7 and 8 (also see Supplementary Figs. S2 and S3) and is very similar to the onshore fold pattern in both map view and cross-section. The onshore series of large upright E–W trending folds vanishes 50–100 km

inlands and gets more pronounced westward into the North Sea rift. They affect the major Devonian extensional shear zones and to a lesser extent also the associated supradetachment basins of Middle Devonian age, which occupy synformal positions in the fold system. As may be expected, the synform-antiform pattern seen onshore does not project cylindrically into the offshore area. Instead, a non-cylindrical pattern with dome-like geometries is revealed (Fig. 8), consistent with the general style of large-scale late folds both onshore and offshore. For example, the synclinal structure containing the Hornelen basin is replaced by a large antiformal structure (named Hornelen antiform in Fig. 8) and several shorter-wavelength folds to the south.

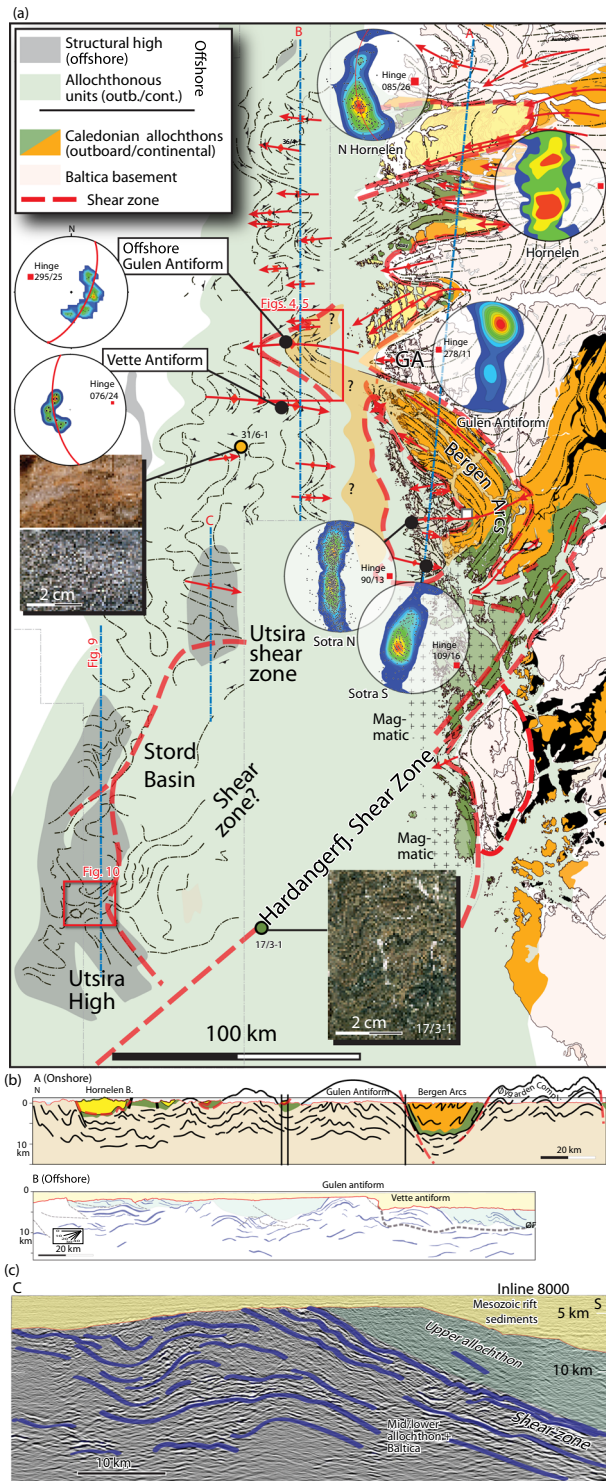


Fig. 7 | Geologic map and sections showing the regional onshore and offshore fold pattern. **a** Map showing main onshore units and onshore and offshore fold pattern. Offshore, the pattern shows the most dominant folds seen in the crust. Spherical projections, where red marks the highest and blue the lowest concentration of poles to gneissic banding/reflectors, show that the folds plunge gently both to the east and west, onshore and offshore. The western extent of the interpretation is limited by poor seismic resolution in the deepest parts of the rift. Core photos from two key wells are also shown. 31/6-1 shows granite and amphibolite (metagabbro) that is typical for both allochthonous units and Baltica basement. 17/3-1 shows greenschist typical for onshore Upper Allochthon (outboard) Caledonian units. **b** Two coast-parallel sections onshore (A) and offshore (B), where the latter is based on NVG seismic data (inline 9750). **c** Interpreted section through the Utsira shear zone (line C in a).

In more detail, an adjacent east-plunging antiform (the Vette antiform) is imaged in the downfaulted block south of the west-plunging offshore Gulen antiform. The two antiforms are similar in size, orientation and style, except for their opposite plunge directions (Fig. 6). The Vette antiform is about 25 km wide and its dipping lithologic layering has clearly influenced the top basement paleotopography (Fig. 8b), which in this area is of late Permian to early Triassic age²⁵. To the north and south of these two antiforms are wide synformal structures (e.g., the Solund synform in Fig. 8), containing a down-folded unit of lower seismic reflectivity. From onshore-offshore correlation, this tectonostratigraphically higher unit most likely represents the Caledonian Upper allochthon, overlaying more reflective Baltica continental crust. Although attempts to relate lithology to seismic facies have been made before^{24–26}, it is more convincingly expressed in the new broadband 3D seismic data. We found that coherency or semblance attributes (also called discontinuity calculations) are sometimes useful to separate different parts of the crust, as shown in Fig. 9. This profile clearly shows that the upper transparent part of the crust gradually thins northward. A similar eastward thickening across the Utsira High can be seen in E–W sections (Supplementary Fig. S5). However, we did not find evidence for a previously²⁶ postulated dome-shaped core complex geometry within the Utsira High basement itself.

The style of folding described above can be traced 50–100 km west of the present coastline (Fig. 7). Farther into the deeper central parts of the North Sea rift, the basement reflectivity becomes too low for internal structures to be mapped out. The fold pattern can also be traced southward into the Utsira High (Fig. 7). Vertically, the folded structural pattern can be traced into the middle crust, in a few places close to the base of the seismic data (20 km depth). Altogether, this information suggests that the onshore pattern of the folded basement extends more than 50–100 km westward into the rift interior and vertically into the middle crust.

The Ordovician–Silurian Utsira High basement

The Utsira High (Fig. 1) is a major N–S oriented intra-rift horst complex that was peneplanized after late Paleozoic to early Triassic rifting. The peneplanation exposed the crystalline basement to erosion, but some half-grabens with rotated Permian deposits are locally preserved. The Utsira High is special in that a number of wells have been drilled into the crystalline basement, thus providing valuable information about crustal lithology and age.

Most of the cores from the Utsira High wells show that the basement contains magmatic rocks of granitic to gabbroic composition, but also gneiss, dacite, schist, phyllite, and metasandstone are represented²⁷ (Supplementary Fig. S4). U–Pb dating of some of the magmatic rocks has yielded ages mostly ranging from 482–430 Ma^{28,29}. This covers the time interval of Ordovician–Silurian convergence and subduction of the Iapetus Ocean up to the time of Caledonian continental collision³⁰, and the dated igneous rocks can be correlated with the onshore Caledonian arc complex known as the Sunnhordland Batholith³¹ (Fig. 1). The two wells located between the Utsira High and the mainland to the east also appear to sample the Upper Allochthon (e.g., well 17/3-1 in Fig. 7), suggesting that Upper Allochthon units dominate the area between the Utsira High and the mainland. Like the offshore Gulen fold, the top basement surface is an angular unconformity against which different tilted lithologic units subcrop. Hence, frequency decomposition blends can be used to further explore variations in basement structure below the unconformity.

Frequency blends from the top basement exhibit a folded banding or foliation, although locally suppressed by a strong signal from the overlying Permian Zechstein limestone. Where visible, the fold pattern shows folded bands or units of different seismic properties, from 10 km thick down to seismic resolution (Fig. 10). The folds are of similar scale (wavelength) as those to the north, but their geometry and orientations seem more complex and variable. The example shown in Fig. 10 has the characteristics of a classical fold interference pattern³². Although particular attention has been paid to the granitic rocks sampled by Utsira High basement wells, our observations emphasize that the basement in the Utsira Horst is

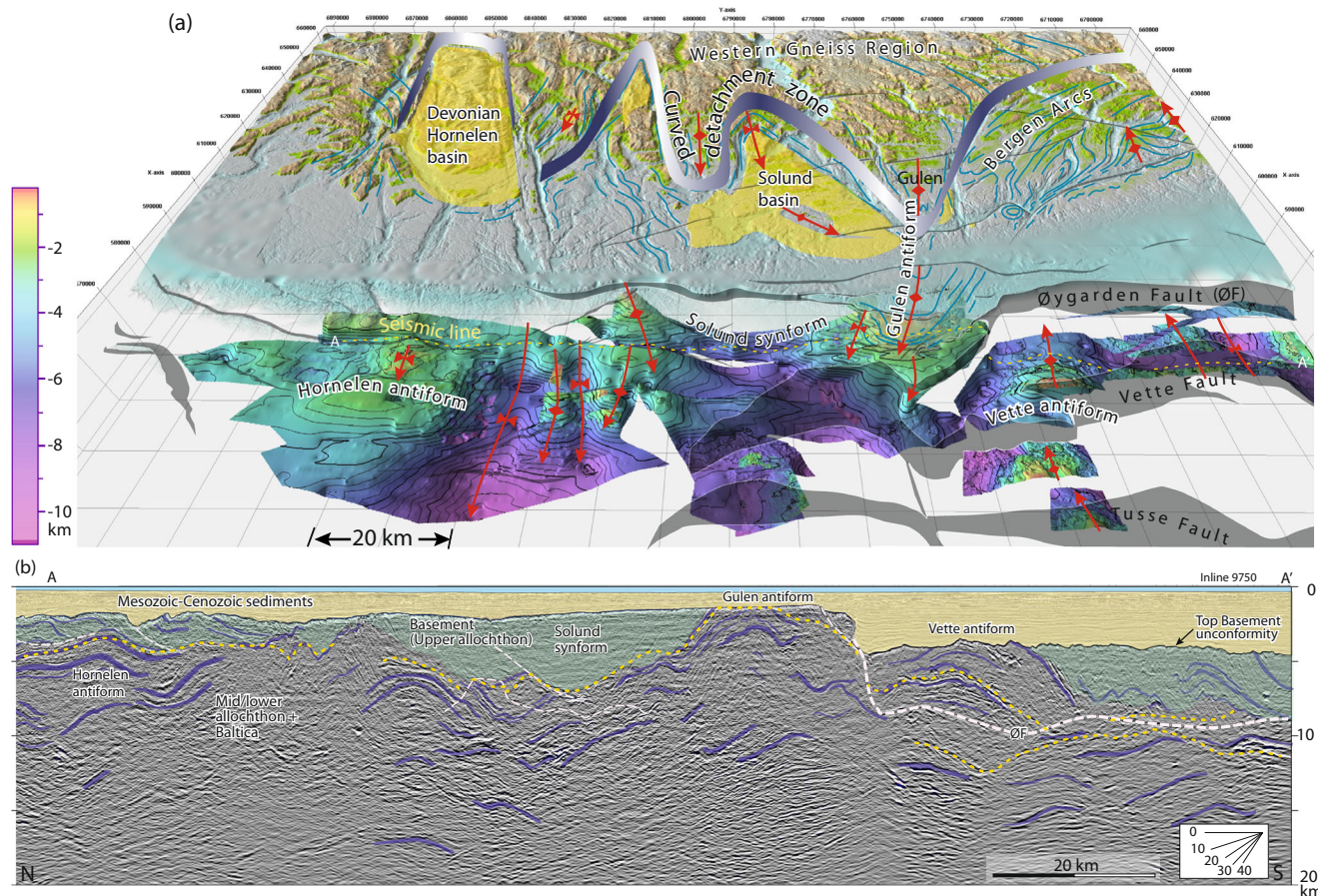


Fig. 8 | 3D visualization relating offshore curved detachment and Devonian supradetachment basins to the offshore fold pattern. a View toward the east, showing the position of Devonian basins (yellow) above the main onshore detachment zone. The offshore folded surface is indicated in (b) as a dashed yellow line. This is a rough interpretation meant to visualize the general offshore intra-basement

geometry and is located within the zone of sheared rocks in the upper part of the Baltica crust. The main faults are marked gray (transparent) at the top basement level. **b** N–S section through the basement, showing a general pattern of upright folds. The pale green tint suggests Upper Allochthon units. Note that the color scale applies to the folded surface in (a) only.

heterogeneous and deformed, dominated by rocks that were foliated and folded during and after the Caledonian collision. This observation agrees with onshore exposure of Upper Allochthonous units, where more or less homogeneous plutonic rocks occur together with well-foliated metamorphic rocks of plutonic, volcanic, and sedimentary origin. An onshore example of the heterogeneous Upper Allochthonous units from the NW side of the Hardangerfjord Shear Zone (Fig. 7) is presented as an inset in Fig. 10.

Discussion

The reflective nature of the sheared Baltica basement offshore defines a consistent pattern of upright folds and domes, while more complex fold patterns are locally revealed in the overlying volumes of Caledonian allochthons, for instance in the Utsira High basement. It seems clear that this characteristically folded and sheared onshore Caledonian crust extends at least 50–100 km westwards.

The offshore Gulen antiform can be traced downwards to a depth of around 12 km. Not all fold structures are traceable to this depth, but the general structural style revealed by the seismic data is that of upright folds down to 10–15 km depth, i.e., from the current top of the crystalline basement through the middle crust. Ductile folding of these basement rocks would, depending on the temperature gradient, require a burial depth of roughly 10 km. Hence, some 10 km of crust must have been removed between the time of collapse-related Middle Devonian folding and the Mesozoic. These folds must therefore have formed at 10–25 km depth in a collapsing Devonian crust.

Whereas the onshore folding and shear fabric patterns exposed by these units were considered to be the result of Caledonian collision and thrusting prior to our enhanced understanding of kinematic indicators in the early 1980s, later work^{14,33,34} has demonstrated that post-collisional extensional collapse sheared, folded and fundamentally redefined the structural pattern after the Silurian to early Devonian Caledonian history of collision and thrusting. The offshore data presented here show that the Devonian collapse of the Caledonian hinterland was much more wide-reaching than previously thought. The Devonian age of the folding is constrained onshore by a marked difference in fold strain between the basins and their substrate. Folds are more frequent and tighter in the underlying extensional shear zone, and together with detailed structural observations, this is taken as evidence that the large-scale upright folding of extensional detachment mylonites and Devonian basins developed progressively during the Devonian extensional and Devonian collapse history, starting before and continuing during deposition of the Middle Devonian basins, coeval with continued movement on the extensional shear zone system^{16,17}.

One of the more convincing offshore pre-rift basement shear zones is the Utsira Shear Zone³⁵ (Figs. 1 and 7c), which was exploited during rifting by the Utsira East Fault²⁴. An interesting aspect of this shear zone is its mostly southeasterly dip, opposite to most major onshore collapse shear zones (west to northwest dipping). An onshore parallel is the curved Bergen Detachment (Fig. 1), which initiated in the Middle Devonian at an advanced stage of the extensional collapse (Fig. 2d). The east-dipping Bergen Detachment reactivates the top-W extensional fabric in the basement with an opposite (down-E) sense of shear, and is associated with the exhumation

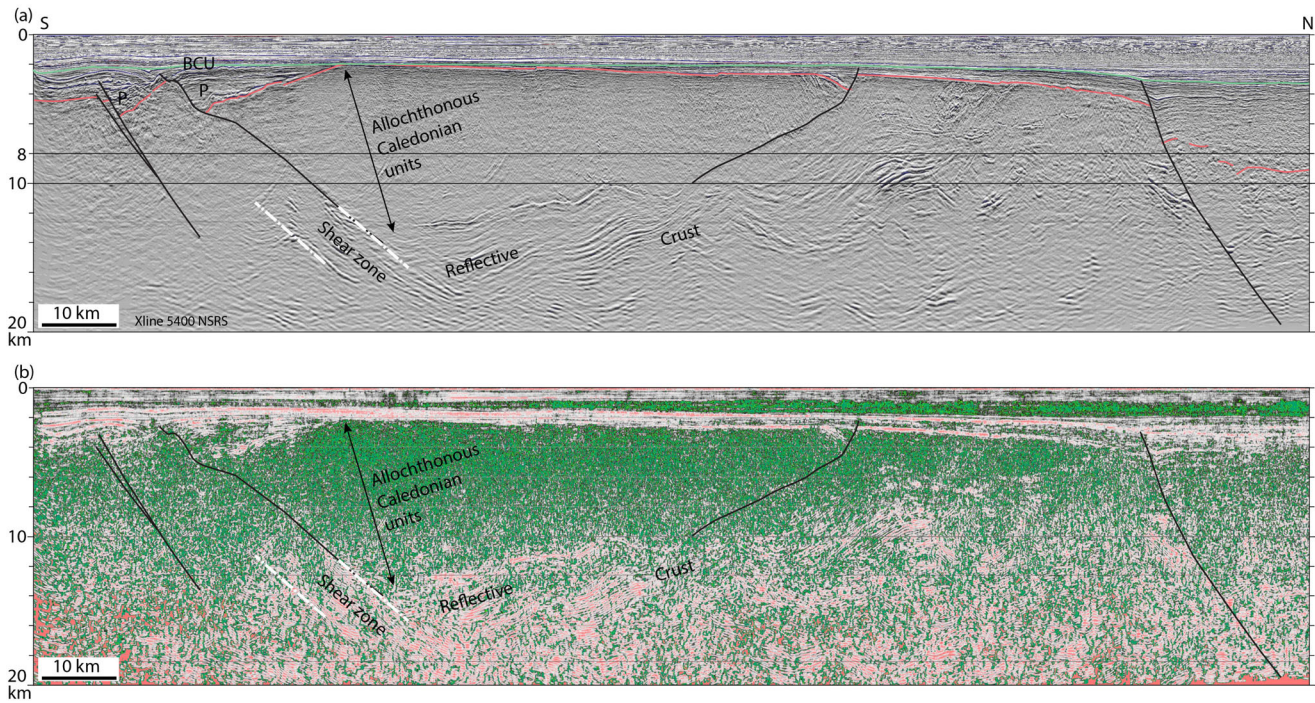


Fig. 9 | Coast-parallel seismic section illustrating contrasting types of basement. **a** South-dipping reflective crust interpreted as Baltica crust, possibly with Baltica-derived Caledonian nappes in the upper part, overlain by seismically more transparent units interpreted as Caledonian allochthonous units. **b** Same section through a coherency (semblance) cube, where coherency relates to the degree of similarity

between waveforms. Green color indicates high coherence, or low degree of lateral seismic waveform similarity, and characterizes the allochthonous units. Inline NVG5400 along the E margin of the Utsira High. See Fig. 7 for location. P Permian sedimentary rocks. BCU Base Cretaceous unconformity.

of the upwarping of the Øygarden Complex as a pre-rift core complex (Fig. 2d)¹⁵. These foreland-dipping shear zones mark the transition from hinterland-directed extensional displacement of Caledonian allochthonous units (Fig. 2b) to a stage of gravity-influenced vertical basement movements, formation of core complexes and associated development of foreland-dipping shear zones (Fig. 2c).

Offshore core complexes have been described farther north along the Norwegian rifted Atlantic margin, where they also have a Devonian origin, but locally continued to develop during the first stage of rifting in the late Paleozoic to Triassic³⁶. We do not see much evidence for this development in the northern North Sea. The large N–S trending Permo-Triassic faults mostly transect the Devonian basement structures, forming as relatively steep normal faults that rotated during rift-related crustal stretching³⁷ and cut the crust until they flatten and merge with the reflective pattern of the lower crust³⁸. Some rift-related brittle reactivation within low-angle Devonian extensional shear zones probably occurred, and low-angle rift-related faulting has been documented onshore within the wide and mostly ductile Nordfjord–Sogn detachment zone^{18,39,40}. However, the fold and shear zone pattern developed during Devonian extension¹⁷ was not significantly modified by this reactivation. This can be demonstrated for the Nordfjord–Sogn detachment zone, where Permian brittle reactivation created a new local detachment fault that cuts off the folded Devonian strata^{18,39}. Offshore, large Devonian crustal structures contributed to the formation of transfer zones or domain boundaries that define 100 km scale segmentation of the rift³⁵. Besides of the Hardangerfjord Shear Zone, which represents a major rift transfer zone immediately south of the study area (Fig. 1), the Gulen antiform is located at another such zone (the Sogn transfer zone; Fig. 1). This antiformal structure clearly caused deflection or termination of Permo-Triassic faults, e.g., the Øygarden Fault System (Figs. 1 and 8), as they attempted to follow the trend of the basement banding. The Utsira shear

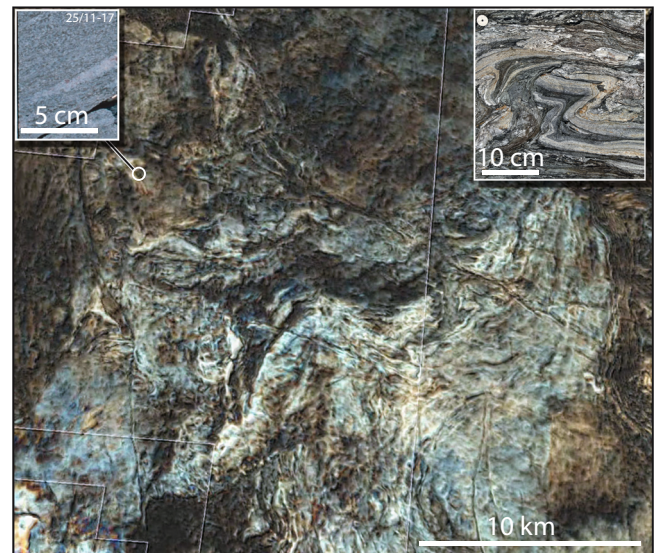


Fig. 10 | Top basement unconformity blend map from the Utsira High. Color differences reveal a folded structural pattern with first-order folds at the 10 km scale, but with many smaller higher-order folds. Hence these folds are similar in size to the offshore Gulen and related folds to the north, but with a more complex geometry. Upper left inset: Core photo from a basement well within the area, showing a deformed intermediate magmatic lithology (orthogneiss). Upper right inset: field photo (Nordheimsund, Hardanger) from the same tectonostratigraphic basement unit (Upper Allochthon), showing similarly varying lithology (dark mafic and light felsic layers) exposing a complex deformation pattern at the decimeter scale. See Fig. 1 or Fig. 7 for the location of the main image.

zone (Fig. 1) is another example, where the rift fault bounding the Stord basin seems to be controlled by the shear zone, particularly in the northern part where the Stord basin is at its deepest. These faults contributed to the rift structuring in the form of horst and graben structures, but there is no core complex development associated with this rift faulting. This difference between the North Sea rift and the rifted Atlantic margin farther north likely relates to their different orientations. The NE–SW trending Møre–Vøring margin runs subparallel to the Caledonian/Devonian structures, i.e., optimal for reactivation. The N–S trending North Sea, however, is highly oblique to many of the Devonian structures. In addition, the Atlantic rifted margin experienced higher amounts of extension than the failed North Sea rift.

The onset of buoyant Devonian doming can be explained in terms of decompression of the subducted Baltica crust, which during exhumation experienced a roughly isothermal decompression path to normal crustal depths². This decompression promoted partial melting and rheologic softening as the subducted crust re-entered normal crustal depths. In addition, fluids released from metamorphic reactions contribute to the increased buoyancy and rheologic weakening of the crust¹².

The Devonian extension of the Caledonian crust illustrated in Fig. 2 is interpreted to have occurred in an overall transtensional tectonic regime^{16,17} (Fig. 1, inset). Transtension can explain NE–SW to E–W trending upright folds^{16,41}, but the dome-shaped core complexes and associated bivergent shear zones call for thermally controlled basement buoyancy within this transtensional setting. We postulate that Baltica crust extends at least 75 km west of the current coastline underneath Caledonian allochthons, demonstrating the presence of a hot collapse-related crustal structure that is much wider than previously assumed. This interpretation implies a new type of orogen that supplement the traditional cold and hot orogens^{42,43}, namely a hybrid orogen that is cold throughout the collisional stage and then turning hot during its subsequent extensional collapse and exhumation stage. The results also suggest that strong orogenic collapse produces extensive low-angle structures that may not reactivate easily during later rifting. It is possible that this has contributed to the Atlantic Ocean not opening along the North Sea and the Caledonian suture, but west of the British Isles. The data and results presented here serve as an example of how basement buried below thick basin deposits now can be explored in terms of structure, morphology and lithology.

Methods

We have applied the spectral decomposition method to PSDM (pre-stack depth migration) broadband 3D seismic data owned by CGG (NVG NS legacy data cube), in addition to various attribute analyses of the data set. For the Utsira High, we used time-migrated 3D data owned by Aker BP. The spectral decomposition method transforms the reflection data into the frequency domain, or the similar cycles/km domain for the depth-converted data (we used both types of data), which generates a range of frequency cubes. Three band-restricted components of the seismic data were selected and blended into a single volume using an RGB color scheme, as specified in the caption to each blend image above. Color variations may reflect changes in layer thickness, lithology, velocity, or seismic anisotropy. Hence these variations may be difficult to explain in detail, but they reveal patterns that in the case of basement often can be assigned to the basement structure. Seismic interpretation was performed by means of Petrel software. Frequency domain blends were produced using GeoTeric software. Depth (elevation), dip and roughness maps shown in Fig. 5 were made in QGIS from the basement interpretation from CGG data in Petrel.

Data availability

Offshore seismic data are property of CGG (CGG.com) and AKER BP. Public seismic and well data available at <https://public-enterprise-search.dsif.dawlmknpdprd01.ienergycloud.solutions/search>. Well data used in this work are available at <https://factpages.sodir.no/en/wellbore/PageView/Exploration/All/4541>. Interpretations derived from CGG data are not public, except for the figures themselves as presented in this article.

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Author contributions

I.P. ignited the idea for this basement paper by presenting North Sea frequency blend images based on his own interpretations to the first author. H.F. expanded on the subject through seismic interpretation and blend image investigations, in collaboration with I.P. and M.S.B. C.C. contributed to the investigation and understanding of the post-Caledonian collapse history. H.F. wrote the paper and produced the figures, with some input from the other authors.

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Competing interests

The authors declare no competing interests.

Additional information

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