Rift kinematics preserved in deep-time erosional landscape below the northern North Sea

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ABSTRACT

Our understanding of continental rifting is largely derived from the stratigraphic record. This archive is, however, incomplete as it does not capture the geomorphic and erosional record of rifting. New 3D seismic reflection data reveals a Late Permian-Early Triassic landscape incised into the pre-rift basement of the northern North Sea. This landscape, which covers at least 542 km^2, preserves a drainage system bound by two major tectonic faults. A quantitative geomorphic analysis of the drainage system reveals 68 catchments, with channel steepness and knickpoint analysis of catchment-hosted paleo-rivers showing that the landscape preserved a >2

Myrs long period of transient tectonics. We interpret that this landscape records punctuated uplift of the footwall of a major rift-related normal fault at the onset of rifting. The landscape was preserved by a combination of relatively rapid subsidence in the hangingwall of a younger fault and burial by post-incision sediments. We show how and why erosional landscapes are preserved in the stratigraphic record, and how they can help us understand the tectono-stratigraphic evolution of ancient continental rifts.

INTRODUCTION

Tectonics, landscape evolution, and stratigraphy are closely coupled in active continental rifts (e.g. Cowie et al., 2000; Gawthorpe and Leeder, 2000). Growing normal faults influence the geometry of drainage networks and incision rates within upland catchments, which in turn controls the location, magnitude, and routing of sediment supply to neighbouring depocenters (Cowie et al., 2006; Whittaker et al., 2010). This coupling means that the transient erosional response of fluvial landscapes to rifting can be used to record the timescales, throw rates and kinematics of active faulting over a range of spatial scales (e.g. Kirby and Whipple, 2012; Whittaker and Boulton, 2012). In modern rifts, we can analyse digital elevation models (DEMs), together with independent tectonic and stratigraphic constraints, to estimate the patterns and rates of fault evolution (e.g. Pechlivanidou et al., 2018; Watkins et al., 2020; Quye-Sawyer et al., 2021), but in many ancient rifts similar rift-related paleo-landscapes are absent. Consequently, time-averaged patterns of faulting must be reconstructed indirectly from structural measurements and stratigraphic observations (e.g. Gawthorpe and Leeder, 2000, Kent et al., 2017). If paleo-landscapes can be found in the stratigraphic record of ancient rifts, they may reveal important new information about fault behaviour.

To our knowledge, the oldest palaeo-landscapes ever found are 55-58 Ma, seismically imaged drainage networks found of the coast of Scotland, UK, developed and preserved in response to Iceland plume-driven uplift and subsidence (Hartley et al., 2011; Stucky de Quay et al., 2017). Here, we present a new candidate for the oldest ever complete landscape yet described from the geological record, defined by an erosional surface carved into the Paleozoic basement of the northern North Sea rift, offshore Norway, imaged in 3D seismic reflection data (Text S1, S2 in the Data Repository). The surface covers at least c. 542 km^2 and reveals a drainage system that developed at the onset of Permian-Triassic rifting (~261±10 Ma; Fossen & Dunlap, 1999). A quantitative geomorphic analysis of the surface shows that this drainage system contains an exceptional record of the transient landscape response to incipient faulting, from which we deduce the history and timescales of rift-related normal faulting. Our work shows how paleo-surfaces imaged in 3D seismic reflection data can provide crucial insights into the tectono-stratigraphic evolution of ancient continental rifts.

GEOLOGICAL SETTING

The study area is located in the northern North Sea rift (Fig. 1A). An up to 12 km thick syn- and post-rift sedimentary succession was deposited on crystalline basement during and after Late Permian-Early Triassic and Middle Jurassic-Early Cretaceous rifting (Færseth, 1996; Bell et al., 2014; Maystrenko et al., 2017). In the Late Permian-Early Triassic, E-W extension led to the development of large (>100 km long) normal faults, such as the W-dipping Vette and Øygarden faults, which bound half-grabens and are the focus of this study (Fig. 1B). By the Triassic, these faults had developed large displacements (up to 4 km) and were associated with relatively high slip rates (0.1–0.15 mm/yr); however, the relative age of these faults remains unknown. The top of the basement in the footwall of the Vette Fault is capped by a distinct erosional surface (Fig. 1B), which we describe and analyse below. Upper Permian and Lower Triassic sequences capping this surface comprise alluvial and fluvial rocks (Evans, 2003).

METHODS

3D seismic interpretation

We use broadband 3D seismic reflection data to map the top of the acoustic basement at a spatial resolution of 12.5×18.5 m, revealing a landscape preserved in the footwall of the Vette Fault (Figs. 1, S1). The top of the acoustic basement is a high-amplitude reflection originating from the impedance contrast between sedimentary rocks (above) and crystalline basement (below). To analyse the geomorphology of this surface, we create a DEM by restoring it to its original geometry, removing the effects of subsequent burial, fault block rotation, and post-rift tilting (Text S3; Figs. S1, S2) (cf. Hartley et al., 2011; Stucky de Quay et al., 2017). We also map two seismically distinct, wedge-shaped Permian-Triassic units to understand the preservation of the landscape (Unit 1 showing medium-to-low amplitude, sub-horizontal layering and Unit 2; characterised by chaotic, discontinuous low amplitudes (e.g. Fig. 1B).

Geomorphic analysis

We perform a quantitative analysis of the restored DEM using TopoToolbox 2 (Schwanghart and Scherler, 2014) and recover stream networks and river long profiles using a D8 flow routing algorithm with a flow accumulation threshold of 0.25 km^2 (e.g. Whittaker and Boulton, 2012). As the derivation of a stream network requires a consistent hydrological surface, pits in the reconstructed DEM must be filled. Since this aims to remove erroneous elevation values, we use the seismic resolution (18 m) as the maximum filling depth. We provide full details on our workflow in the supplementary material (Figs. S3, S4). Because rivers and streams perturbed by tectonic uplift often show steep segments in their elevation profiles (e.g. Kirby and Whipple, 2012), we calculate the normalized channel steepness of the fluvial network (e.g. Schwanghart and Scherler, 2014) (Fig. 2B, Text S4).

To investigate any preserved transient landscape responses to normal faulting, we identify knickpoints in the palaeo-river long profiles of our stream network using the TopoToolbox 2 with a knickpoint finder tolerance 2.5 times the seismic resolution of our survey (45 m) (Text S5, Figs. S5, S6). This high tolerance assures that we extract only major knickpoints in the network (Fig. 2C, D, Figs. S5, S6). We measured the elevation of these knickpoints relative to the Vette Fault to a precision of ± 25 m, and their distance upstream with a precision of ± 100 m (Tab. S1). Knickpoint height relative to the fault was compared to geologic constraints on fault throw (c.f. Bell et al., 2014) and knickpoint locations were compared to palaeo-catchment drainage area. For knickpoints located upstream of the footwall-bounding Vette Fault, we estimate a potential timescale for their propagation upstream, assuming they started from the fault, using the propagation velocity, V, derived from a unit stream power erosion law (Tucker and Whipple, 2002) (Text S6) and data compilations upstream of modern active faults (Whittaker and Boulton, 2012; Kent et al., 2018).

RESULTS

Seismic and geomorphic expression of the palaeo-landscape

Our study area covers an area of ~542 km^2 and is located between the Vette and the Øygarden faults (Fig. 1). The surface is carved into basement rocks regionally consisting of Devonian sediments, Caledonian allochthons, and Proterozoic crust (Fazlikhani et al., 2017). In cross-section, the surface is highly irregular, showing relatively steep slopes (up to 15°) and moderate relief (<800 m) (Fig. 1B). This seismically defined morphology, combined with our subsequent geomorphic analysis (Fig. 2) and the depositional setting of the overlying, non-marine Triassic rocks filling and preserving the unconformity surface, are very strong evidence that the surface represents a subaerial landscape.

Our DEM analysis of the surface reveals an intricate 3D landscape showing a small fault-bounded mountain range with relief up to 800 m, cut by a dendritic fluvial network, from which individual catchments can be identified with exceptional clarity (Fig. 2A). Consequently, our results depict a possibly unique snapshot of an ancient footwall landscape, which based on the available age must have formed during slip accumulation on the Vette Fault.

Landscape response to active faulting at 250 Ma

We extracted 68 palaeo-catchments with drainage areas up to 60 km^2 from the DEM (Tab. S1). The longest trunk rivers are up to 20 km long. Many catchments show abrupt channel steepness index variations (Fig. 2B). For instance, high steepness index river segments (>50 m long) are mainly found in catchments that decrease in elevation and appear to drain westwards towards the Vette Fault, (Fig. 2B) (Tabs. S1, 2). Reconstructed palaeo-channel long profiles are *not* concave up, but show distinct convexities on a range of length scales (Fig. 3A). The channel geometries are remarkably similar to those observed in modern fluvial systems draining across active normal faults (c.f. Whittaker, 2012). Consequently the sharp variations in channel steepness suggest that the palaeo-landscape was not in a topographic steady state when preserved.

Numerous knickpoints are visible on many of the paleo-river long profiles; we extract those that pass our filtering threshold (Figs. 2C, 3A). Thirteen catchments have at least one significant knickpoint upstream of the Vette Fault and several have two (Tabs. S1, S2) (Fig. 3A). These knickpoints lie at distances between 0.44-10 km upstream of the Vette Fault, with elevations for the lower or single set of knickpoints varying between 45->300 m (Fig. 3B, C), considerably lower than the overall relief of the palaeo-landscape (Fig. 2). In terms of their size and scale, these catchments and knickpoints are comparable to modern fluvial systems crossing faults in Italy, Turkey, and Greece (Whittaker and Boulton, 2012; Whittaker and Walker, 2015; Roda-Boluda and Whittaker, 2017), where rivers have been shown to record changing fault slip rates over timescales of 1-5 million years.

When plotted along the strike of the Vette Fault, (Fig 3) knickpoint elevation for both sets of knickpoints relative to the fault is an order of magnitude smaller than the fault throw between 0-40 km along strike, with these values being comparable for the northern part of the fault. Knickpoint elevations are smallest 25-40 km along strike, which is where throw is presently greatest (Fig. 3). Given that knickpoint elevation, since formation, scales predictably with fault slip rate (c.f. Whittaker and Walker, 2015), we infer that along-strike changes in elevation define two paleo fault segments that were active early in the evolution of the Vette Fault. The upper set of knickpoints also have elevations that are considerably less than the geologic throw. Although there is some scatter, single knickpoints on paleo-catchments with bigger drainage areas are located predictably further upstream, ($L \sim A^{0.38\pm0.12}$) (Fig. S7) which is consistent with them forming at a similar time. Consequently, we interpret these knickpoints to capture the transient response of the footwall landscape to the early growth of the Vette Fault near the onset of rifting. The palaeo-landscape was subsequently buried in the hanging wall of the Øygarden Fault before the transient tectonic signal had a chance to propagate fully through the fluvial system.

DISCUSSION & CONCLUSIONS

Preserved landscape – transient tectonics

Our study reveals a subaerial drainage system carved into the footwall of the Vette Fault, northern North Sea Rift (Fig. 1). The overlying stratigraphy indicates that this landscape developed during Permian-Triassic rifting. Our geomorphic analysis of the system reveals that many catchments draining across the Vette Fault have high steepness indices (Fig. 2B), and that 13 of the 68 catchments have knickpoints, which are indicative of an increase in tectonic uplift rates (Fig. 2C) (*sensu* Hartley et al., 2011; Stucky de Quay et al., 2017). The seismically imaged paleo-rivers thus capture the landscape response to footwall uplift, generated by growth of the Vette Fault around 250 Ma. The presence of two sets of knickpoints reflects changing fault slip rates during the early evolution of the fault. This likely reflects throw rate increases driven by fault growth and perhaps linkage, evidenced by the fact that the lower set of knickpoints records two, presumably unlinked, paleo segments. This is the first time that the geomorphic response of catchments to active fault growth and interaction has been reconstructed and mapped in an ancient rift.

Duration of faulting and knickpoint migration

Once formed, knickpoints migrate upstream, as catchments progressively respond to the relative change in base level (Kirby and Whipple, 2012). We can thus use the duration of knickpoint migration upstream of the Vette Fault as a proxy for the time of fault activity. Knickpoint elevation upstream of interacting fault segments is known to scale with the relative difference in throw rates and the time since this has taken place (Whittaker & Boulton, 2012). The maximum elevation of the lower knickpoints is ~250 m. If we divide this by published time-averaged throw rates on the Vette Fault of 0.15 mm/yr (Bell et al., 2014) as a maximum, this would imply that the transient landscape represents a minimum of 1.7 Myrs, similar to faulted landscapes in Greece (e.g. Whittaker and Walker, 2015). Alternatively, if we calculate upstream migration of the knickpoints using bedrock erodibilities based on an average of a compilation of modern systems upstream of active faults with similar drainage areas and slip rates (see Methods) we obtain a preferred median landscape response time of 2.1 Mysr and extremes of a 1.1 to 10.1 Myrs; this suggests that the paleo-landscape records fault growth and interaction over periods >2 Myrs (Fig. 4C). Considering that dating of sedimentary rocks, fault rocks, and dykes suggest that Permian-Triassic rifting began between 261±10 (Fossen & Dunlap, 1999) and lasted tens of millions of years (Ravnås et al., 2000), our results indicate that the Vette Fault was only active for a fraction of this episode.

Landscape preservation – strain migration

Erosional landscapes, such as the one described here, are not usually preserved in the stratigraphic record, despite undoubtedly forming throughout the history of Earth. To understand its preservation, we reconstruct the tectono-stratigraphic context and evolution of the system through time (Fig. 4). The landscape developed at the onset of rifting in the northern North Sea, when the young Vette Fault initiated, and when Permian-Triassic strata (Unit 1) were being deposited in its immediate hanging wall (Fig. 4A). The knickpoints and overall landscape were created when segments of the Vette Fault were displacing paleo-streams and rivers (Fig. 2C). Subsequently, the drainage system was rapidly buried and preserved beneath Permian-Triassic strata (Unit 2) (Figs. 1B, 4B). This period lasted c. 2 Myrs. The rapid burial of the footwall of the Vette Fault, before the transient landscape had equilibrated, was likely driven by strain migration from fhe Vette Fault to the Øygarden Fault, with the hanging wall of the former producing subsidence that outpaced footwall uplift on the Vette Fault.

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FIGURES

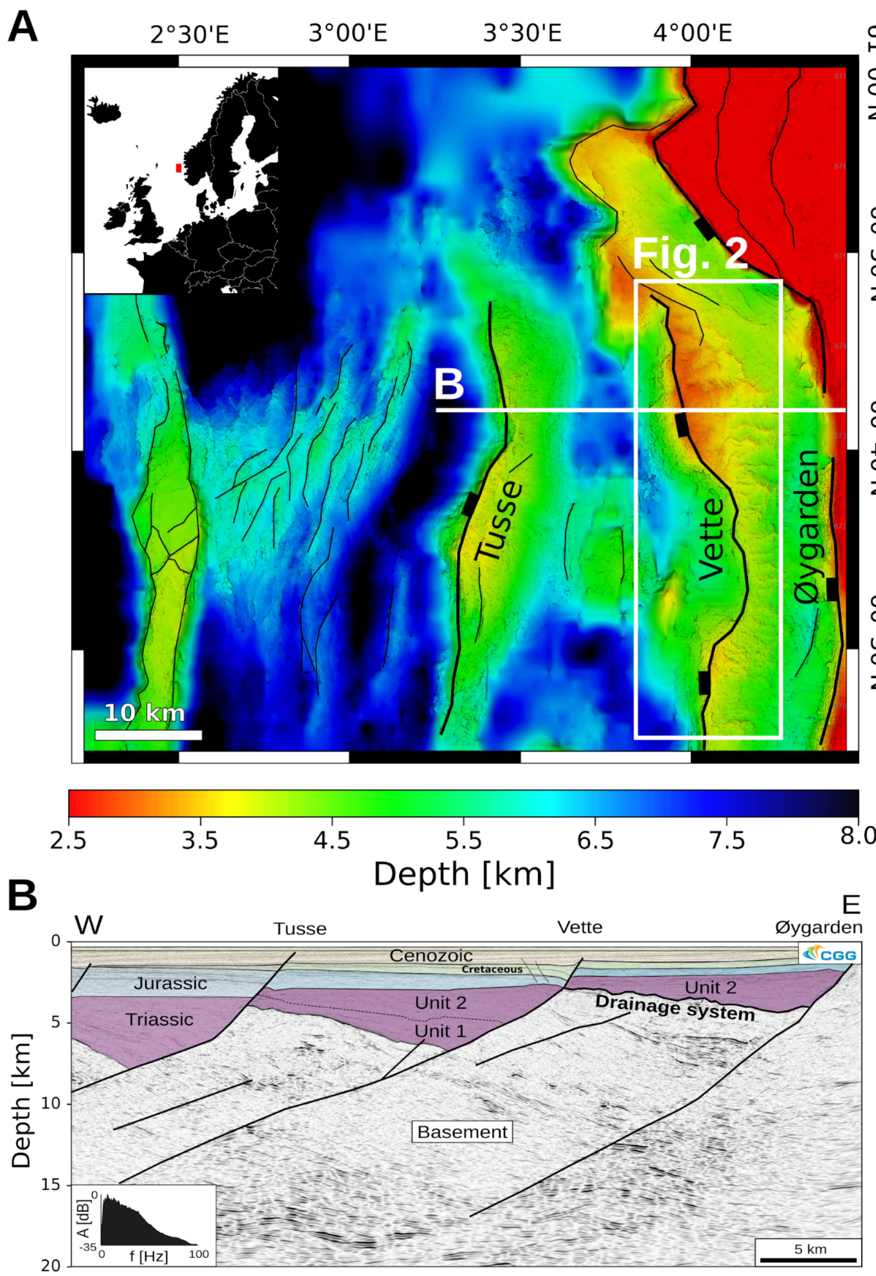

Figure 1. A Basement surface showing rift-related normal faults and drainage system in the northern North Sea. B Seismic section showing the drainage systems situated on top of the basement. Permian-Triassic strata overlying the surface consists of two wedge-shaped units Seismic data courtesy of CGG.

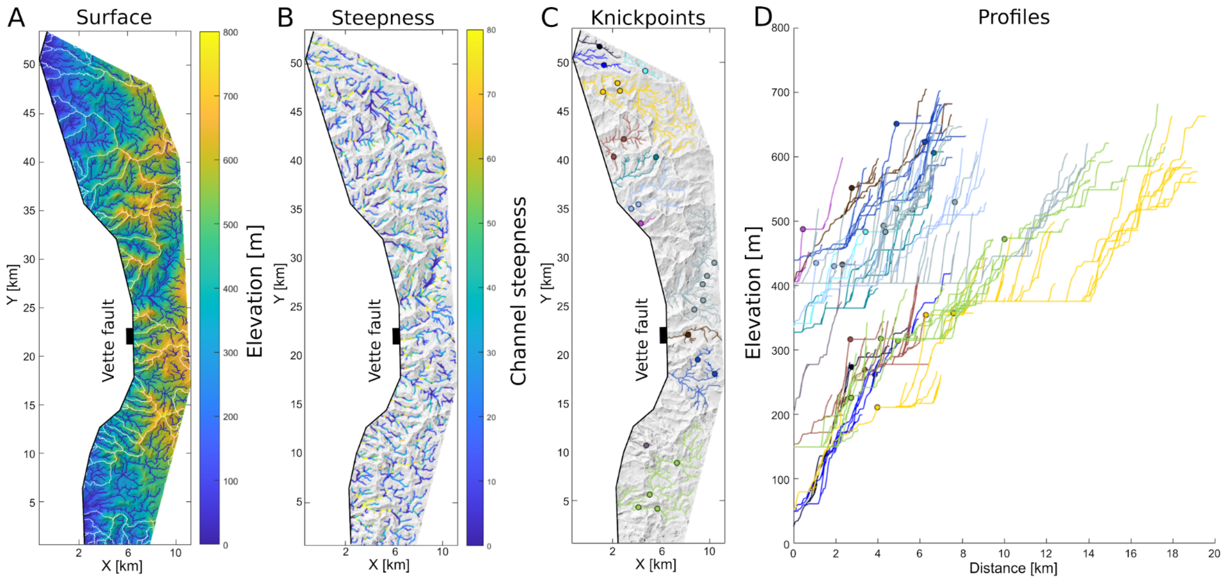

Figure 2. A Restored basement surface with stream network and drainage divides. B Normalized channel steepness index of stream network. C Knickpoints extracted from stream network.

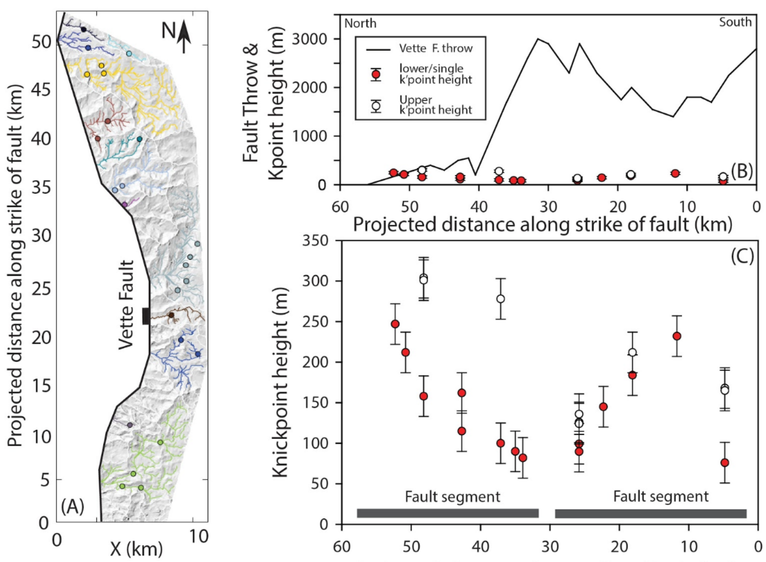

Figure 3: A Knickpoints extracted from stream network. B. Knickpoint height and fault throw along strike (same scale). C Knickpoint height with error bar. Note the two populations of knickpoints (upper-white and lower-red).

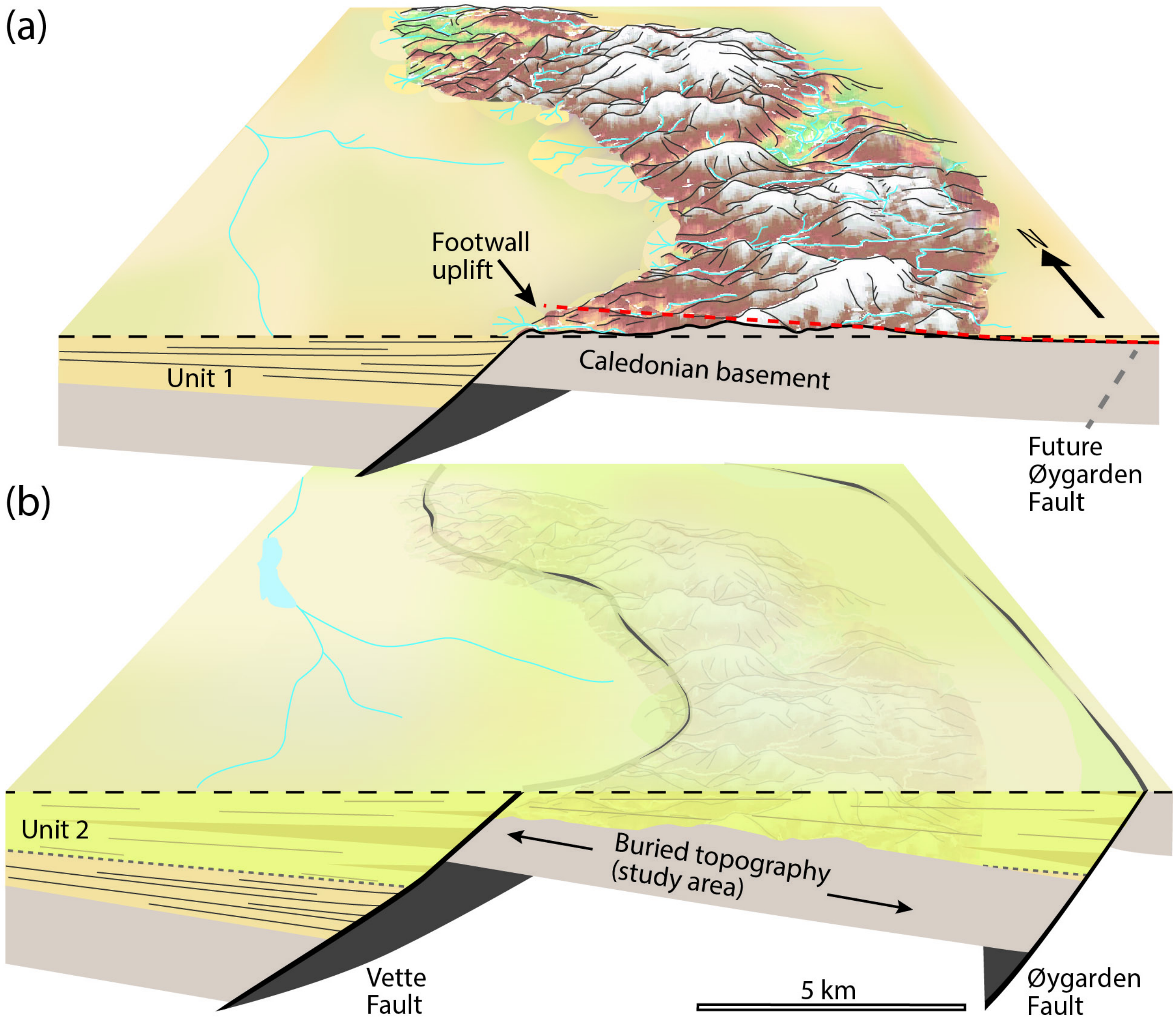

Figure 4: 3D diagram illustrating landscape evolution at the onset of rifting. A Landscape development at the onset of rifting in the northern North Sea, when the young Vette Fault initiated and Permian-Triassic strata (Unit 1) were being deposited in its immediate hanging wall. Knickpoints creation when segments of the Vette Fault were displacing paleo-streams and rivers as they grew, interacted and built footwall relief. B Subsequent subsidence and rapid burial underneath Permian-Triassic strata (Unit 2) leading to landscape preservation.