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New insights into the late Mesozoic-Cenozoic tectono-stratigraphic evolution of the northern Lofoten-Vesterålen margin, offshore Norway

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ABSTRACT

2D multi-channel seismic profiles and a 3D seismic survey were utilised together with potential field and available well data to study the late Mesozoic-Cenozoic tectono-stratigraphic evolution of the northern Lofoten-Vesterålen margin, offshore northern Norway. The analysis resulted in an updated structural and stratigraphic framework, together with new and better refined structural elements. Distinct along-margin basin segmentation is evident and is imposed by NW-SE trending curvilinear transfer zones informally named as the Jennegga transfer zone, Vesterålen transfer zone system, and Andøya transfer zone. These divide the study area into three main margin segments, namely the northern Lofoten, Vesterålen, and Andøya segments. Five main rift phases of varying intensity have been recognised and refined, and they are evidenced by eight mapped fault families: pre-Jurassic, Late Jurassic-earliest Cretaceous, Aptian-Albian, Albian-Cenomanian, three individual fault families within Late Cretaceous, and Paleocene. In addition, compressional deformation features are observed and related to volcanic build-up and doming of Cenozoic successions. Large parts of the study area are dominated by a prominent low-angle detachment fault complex informally named North Utrøst Ridge Fault Complex, and the study of the fault complex with the 3D seismic survey has brought forward new details into the composite Late Cretaceous-Paleocene rifting. A major component of the latter is low-angle detachment faulting that is also observed on the conjugate NE Greenland margin. This is a key evidence of conjugate, more ductile, mode of deformation at intermediate-to-deep crustal levels that consisted of lower- and upper-plate configurations and reflects a multiphase tectonic evolution. The study shows that the northern Lofoten-Vesterålen margin represents an essential area to study the tectono-stratigraphic evolution of the NE Atlantic margins.

1. Introduction

The northern Lofoten-Vesterålen margin is located at ~69°N off mainland Norway and is part of the ~400-km-long composite Lofoten-Vesterålen continental margin (LVM) (Fig. 1). The LVM is separated to the south and north, respectively, from the wide Vøring volcanic passive margin by the Bivrost Lineament and from the SW Barents Sea sheared margin by the Senja Fracture Zone (e.g. Blystad et al., 1995; Faleide et al., 2008). The LVM represents the link between the mid-Norwegian, SW Barents and conjugate NE Greenland margins, and is a key area to study the rift-basin architecture and the tectono-stratigraphic evolution of the NE Atlantic margins (Fig. 1) (e.g. Tsikalas et al., 2012; Faleide et al., 2015; Gernigon et al., 2020). The LVM is characterized by a narrow shelf and steep slope, with an elevated rifted complex of margin-parallel basement ridges and shallow Mesozoic sedimentary basins (e.g. Tsikalas et al., 2001; Bergh et al., 2007; Tasrianto and Escalona, 2015). Furthermore, the LVM physiography, crustal structure, and sedimentary infill and distribution distinctly contrast with the adjacent margins, making the LVM a separate and one of the least understood tectono-stratigraphic provinces within the Norwegian Continental Shelf (e.g. Eldholm et al., 2002; Tsikalas et al., 2005a; Breivik et al., 2020). An updated review of the southern Lofoten margin has been conducted recently by Tsikalas et al. (2019). Here, we continue northwards with the study of the northern Lofoten-Vesterålen margin

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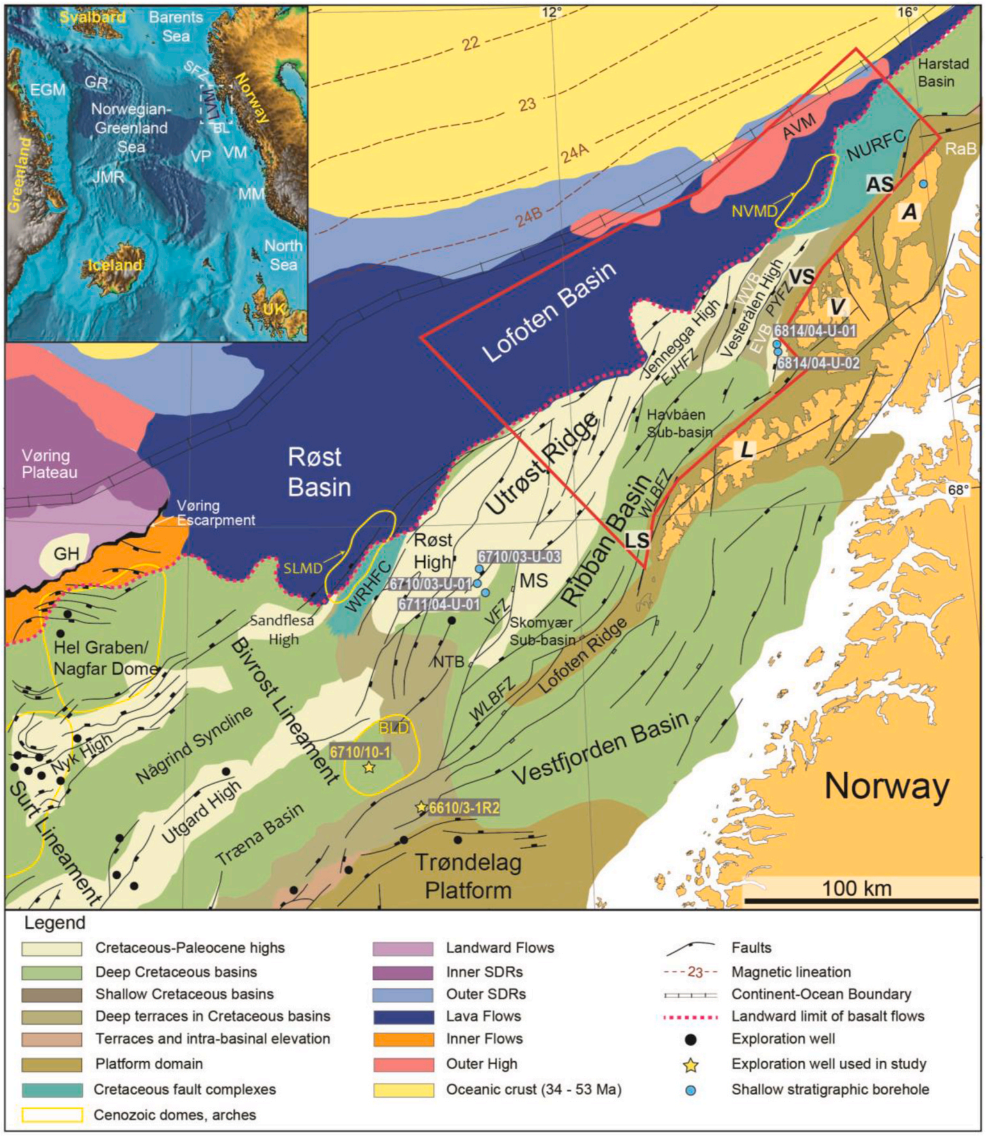

Fig. 1. Refined structural map on the Lofoten-Vesterålen and adjacent margins (modified from Abdelmalak et al., 2017). Inset: Norwegian continental margin formed in response to Cenozoic opening of the Norwegian-Greenland Sea as expressed in bathymetry/topography from the 1 × 1' elevation grid Jakobsson et al. (2000). The study area is defined by the red polygon. Utilised wells/shallow stratigraphic boreholes are indicated in map. A: Andøya island; AS: Andøya segment; AVM: Andøya Volcanic Mound; BL: Bivrost Lineament; BLD: Bivrost Lineament Dome; EGM: East Greenland margin; EJHFZ: East Jennegga High Fault Zone; EVB: East Vesterålen Basin; GH: Grimm High; GR: Greenland Ridge; JMR: Jan Mayen Ridge; L: Lofoten islands; LS: northern Lofoten segment; LVM: Lofoten-Vesterålen margin; MM: Møre margin; MS: Marmæle Spur; NTB: North Træna Basin; NURFC: North Utrøst Ridge Fault Complex; NVMD: northern Vesterålen margin Dome; PYFZ: Pyramiden Fault Zone; RaB: Ramså Basin; SDR: seaward-dipping reflections; SFZ: Senja Fracture Zone; SLMD: southern Lofoten margin Dome; TR: Træna Basin; V: Vesterålen islands; VFZ: Vesterdjupet Fault Zone; VM: Vøring margin; VP: Vøring Plateau; VS: Vesterålen segment; WLBFZ: West Lofoten Border Fault Zone; WRHFC: West Røst High Fault Complex; WVB: West Vesterålen Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

where, prior to the current study, only vintage 2D seismic reflection profiles have been available (e.g. Løseth and Tveten, 1996; Tsikalas et al., 2001; Færseth, 2012, 2020). The area has never been opened for petroleum exploration (NPD, 2010, 2020a), and thus no conventional exploration wells were ever drilled there.

In this study, reprocessed vintage 2D multi-channel seismic (MCS) reflection profiles, and the most recently acquired 2D MCS dataset and a 3D seismic survey that are for the first time available to academia, are utilised together with well (exploration and shallow stratigraphic boreholes) and potential field (gravity and magnetic) data. The late Mesozoic-Cenozoic tectono-stratigraphic evolution of the northern Lofoten-Vesterålen margin is now studied in the context of the LVM and its immediate transition towards the southern Lofoten margin. Through seismic and structural interpretations, the study objectives are to: refine the rift phases affecting the study area, map along-margin tectono-stratigraphic changes, decipher the role of transfer zones in the margin evolution, investigate possible structural inheritance, and view the study area in a conjugate setting for margin evolution considerations.

2. Data and methods

The utilised seismic data comprise ~25,000 km of 2D MCS profiles, including both vintage (1986–1998) profiles and the most recently acquired (2007–2008) profiles, together with a 3D survey (2009) of ~1258 km^2 (Fig. 2; Table 1). Line-spacing of the various 2D surveys ranges in average ~2–6 km. The most dense line coverage is found offshore Andøya in the north and the sparsest towards the southernmost outer part of the study area in the Lofoten Basin (Fig. 2). The most recently acquired 2D MCS dataset and the 3D survey are for the first time available to academia. The seismic resolution quality in the study area is, in general, moderate to good (Table 1), except below the lava flows to the west that represent an acoustic barrier and the imaging below this level is thus relatively poor. The recording time of the various surveys (2D and 3D) ranges between 6 and 8 s twt (two-way travel-time), but it was possible to map with confidence the deepest reflections just down to ~3–4 s twt in the 2D surveys, and down to ~4 s twt in the 3D survey. In addition, the signal-to-noise ratio is decreasing towards the north of the study area, possibly because of shallow water depths that increase the presence of seismic artefacts, including sea-bottom multiples which can be seen on most of the 2D MCS and the 3D dataset, especially in the vintage LO-surveys (Table 1). The relatively best seismic resolution (in average very good) is found south of the study area within the south Lofoten margin segment (Tsikalas et al., 2019).

Five offshore shallow stratigraphic boreholes and an outcrop onshore

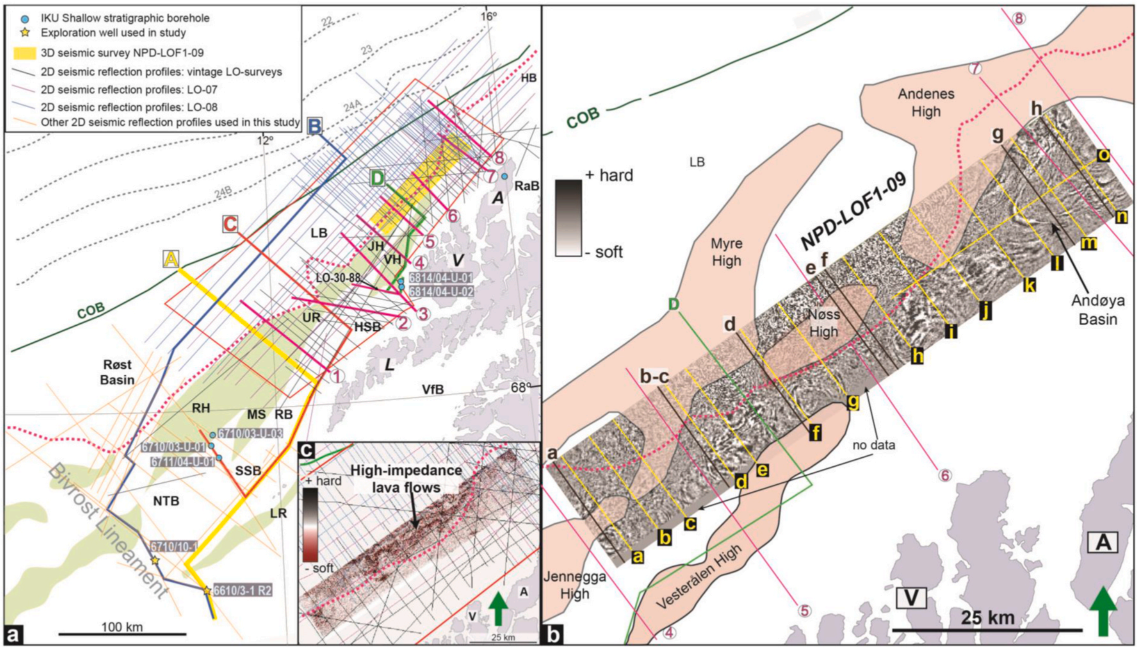

Fig. 2. Seismic reflection coverage and location of utilised wells, overlain on main new/refined structural elements. **(a)** Study area and south part of the LVM. Location of regional seismic cross-section (A-D; Fig. 6) and relevant interpreted seismic sections (1–8; Fig. 11) are indicated. Location of seismic profile LO-30-88 used in Fig. 14 is also indicated in map. **(b)** Zoom-in of the study area within the 3D survey (NPD-LOF-1-09; time-slice 4180 ms) with location of interpreted seismic examples of Fig. 12 (a-h; brown lines) and of Fig. 13 (a-o; yellow lines). Note the curved and elongated reflection belt reflecting the seismic expression of the Andøya Basin on the northern part of the 3D survey, and areal extent of new/refined basement highs defined in this study. **(c)** Zoom-in of the 3D survey (NPD-LOF-1-09; time-slice 1012 ms) showing seismic expression and distribution of high-impedance lava flows and lava boundary. COB: continent-ocean boundary; HB: Harstad Basin; HSB: Havbåen Sub-Basin; JH: Jennegga High; LB: Lofoten Basin; LR: Lofoten Ridge; RB: Ribban Basin; RH: Røst High; SSB: Skomvær Sub-basin; UR: Utrøst Ridge; VfB: Vestfjorden Basin. Other abbreviations in Fig. 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Seismic reflection surveys utilised in this study; twt, two-way traveltime.

Survey	Type	Year	Company/ authority	Recording time (twt, s)	Resolution quality
LO-86[a]	2D	1986	NPD	7	Moderate
LO-87[a]	2D	1987	NPD	7	Moderate
LO-88[a]	2D	1988	NPD	6	Moderate
LO-89[a]	2D	1989	NPD	8	Moderate
LO-07[a]	2D	2007	NPD	9	Moderate
LO-08[a]	2D	2008	NPD	8	Poor
NPD-LOF-1-09[a]	3D	2009	NPD	8	Moderate
TB-87	2D	1987	NPD	7	Good (reprocessed)
LIVB89	2D	1989	NPD	8	Very good (reprocessed)
AMR-N6T	2D	1992	TGS	8	Very good
N6-92R00	2D	1994	TGS	7	Good
GMNR-94	2D	1994	Geco	14	Good
UH-94R00	2D	1994	TGS	7	Good
AMR_TBN96	2D	1996	TGS	8	Very good (reprocessed)
AMR_RHW96	2D	1996	TGS	8	Very good (reprocessed)
RHW96	2D	1996	Geoteam Exploration	8	Very good (reprocessed)
RHS98	2D	1998	Geoteam Exploration	8	Very good (reprocessed)

[a] Seismic survey within the focus study area.

Andøya have been utilised in the study for well-to-seismic ties and regional considerations (Fig. 2) (Dalland, 1981; Hansen et al., 1992, 2012; Smelror et al., 2001). In addition, two exploration wells (6610/3-1R2 and 6710/10-1; Figs. 2 and 3) located in the southernmost part of the LVM were included in order to obtain reliable stratigraphic control and to tie that into the study area. The absence of widely distributed wells within the study area leads to limitations in stratigraphic and sedimentological constraints. Despite this, the available wells have been used to define the best possible well-to-seismic ties and correlation, although the confidence of age constraints is naturally somewhat reduced, especially towards the north and the outer part of the study area. The available well-tops are provided in true vertical depth sub-sea (TVDSS; meters) by the Norwegian Petroleum Directorate (NPD, 2020b).

The main focus of the study is on the Cretaceous-Cenozoic evolution and development of the northern Lofoten-Vesterålen margin. The work included focussed seismic and structural interpretation in order to get a better understanding of the basin architecture and evolution. In this context, thirteen (fourteen including the sea-bottom) main horizons were mapped (Fig. 3). Subsequently, time-structure maps and time-thickness maps were generated in order to provide the lateral and vertical configurations of the sedimentary successions, and to better visualize the tectono-stratigraphic evolution. Gravity and magnetic data (Fig. 4) were utilised to support the interpretation of structural trends and lateral distribution of sediments, and to constrain the interpolation of defined faults where seismic coverage is sparse.

3. Geological setting

The narrow shelf of the LVM comprises several NE-trending shelf-parallel and deeply eroded Precambrian crystalline basement rocks that are often exposed on the seabed and on the Lofoten-Vesterålen archipelago (e.g. Blystad et al., 1995; Løseth and Tveten, 1996). In this context, the study area encompasses several main structural elements, including the composite Utrøst Ridge (composed of the Røst and Jennegga highs), the composite Ribban Basin (composed of the Skomvær and Havbåen sub-basins), the southern part of the Harstad Basin, and the

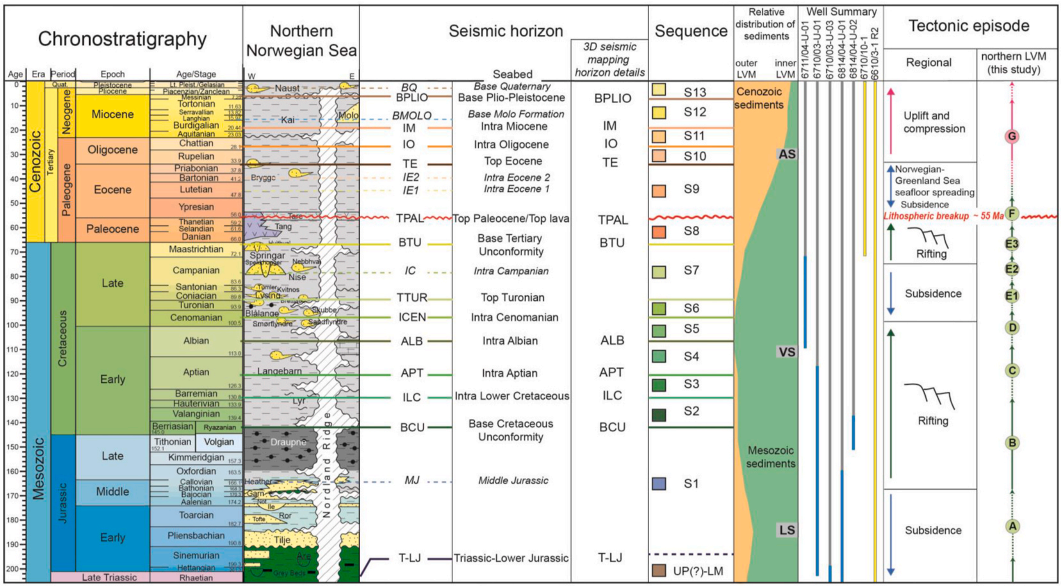

Fig. 3. Seismic stratigraphic framework for the northern Lofoten-Vesterålen margin. Thirteen (fourteen including the seabed) interpreted main horizons bound thirteen seismic sequences. Secondary horizons are marked with dashed lines (see Table 2). Areal extent of Mesozoic sedimentary sequences decreases towards the northern part of study area. Both exploration and IKU shallow boreholes are indicated in yellow and blue, respectively. AS: Andøya segment; LS: Lofoten segment; VS: Vesterålen segment. Chronostratigraphic and lithostratigraphic charts of the Northern Norwegian Sea modified from Norlex (2012). Regional tectonic episodes based on Tsikalas et al. (2012). Local tectonic events (letters A to G) in the northern Lofoten-Vesterålen margin refer to fault family/phase in Table 3. UP(?)-LM: Upper Paleozoic(?)-Lower Mesozoic. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

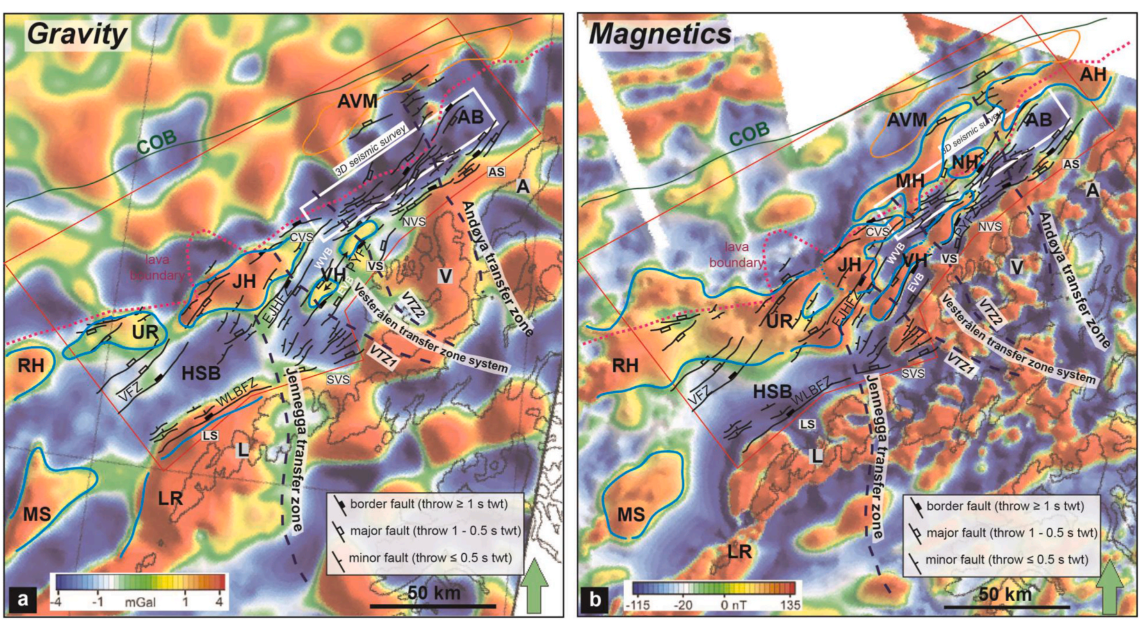

Fig. 4. Potential field anomaly data. **(a)** 50 km high-pass filtered gravity anomaly. **(b)** 50 km high-pass filtered magnetic anomaly. Red polygon indicates study area. Interpreted faults, and new and refined structural elements of this study are indicated. New/better refined structural highs on Base Cretaceous Unconformity (BCU) level are indicated with blue outline. Note how major faults in black lines coincide at the edges of strong positive anomalies. White polygon indicates the NPD-LOF1-09 3D seismic survey. The proposed transfer zones are also indicated in dashed lines: Jennegga transfer zone, Vesterålen transfer zone system, and Andøya transfer zone; separating, respectively, three rifted segments: northern Lofoten, Vesterålen, and Andøya margin segments. AB: Andøya Basin; AH: Andenes High; CVS: Central Vesterålen margin sub-segment; MH: Myre High; NH: Nøss High; NVS: North Vesterålen margin sub-segment; SVS: South Vesterålen margin sub-segment; VTZ1/VTZ2: Vesterålen transfer zone system (southern and northern lineaments, respectively). Other abbreviations in Figs. 1 and 2. Gravity and magnetic data courtesy of TGS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

easternmost part of the Lofoten Basin (Figs. 1 and 5). In addition, gravity and magnetic maps correlate with main structural elements (Berndt, 2002; Olesen et al., 2002, 2007, 2010), showing them as elongated anomalies with similar NE-SW trends (Fig. 4). Moreover, the widest portion of LVM (~150 km in south Lofoten margin) is positioned just north of the Bivrost Lineament and close to the Vøring margin, while the LVM narrows towards the north (~35 km offshore Andøya) when approaching the Senja Fracture Zone in the vicinity of the SW Barents Sea (Fig. 1) (e.g. Tsikalas et al., 2001, 2019; Tasrianto and Escalona, 2015).

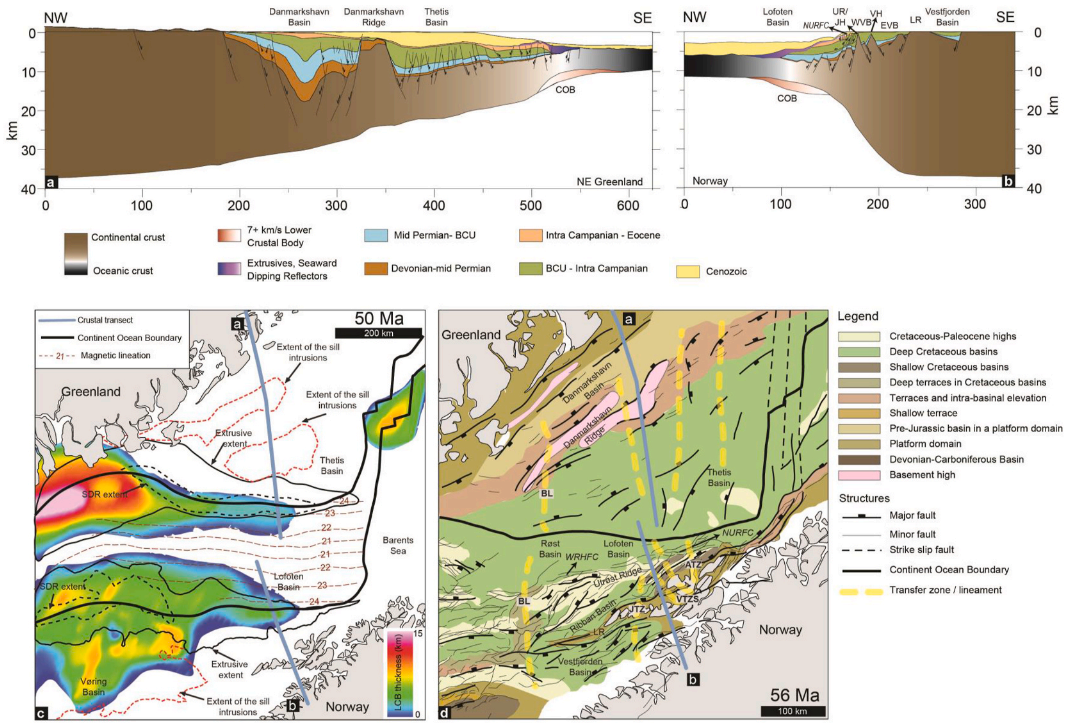

Fig. 5. (a–b) Updated conjugate crustal transect across the NE Greenland and northern Lofoten-Vesterålen margins illustrating the pre- and post-breakup crustal architecture. Inset map **(c)**: regional conjugate crustal structure with 7+ km/s high-velocity Lower Crustal Body (LCB) thickness map for the NE Atlantic conjugate margins restored to Chron C21 (~50 Ma) (modified from Abdelmalak et al., 2017). Inset map **(d)**: regional structure map of the conjugate setting restored prior to breakup (~56 Ma). The map illustrates a better refinement of structural elements and proposed transfer zones. ATZ: Andøya Transfer Zone; JTZ: Jennegga Transfer Zone; VTZS: Vesterålen Transfer Zone System. Other abbreviations in Figs. 1 and 2.

A distinct along-margin crustal differentiation is evident at a conjugate margin setting (e.g. Planke et al., 1991; Faleide et al., 2008, 2015; Abdelmalak et al., 2017). In particular, the narrow LVM is conjugate to a wide Northeast Greenland margin, while a wide and much more extended Vøring margin is conjugate to a narrow part of the Northeast Greenland margin (Fig. 5) (e.g. Eldholm et al., 2002; Tsikalas et al., 2012; Gernigon et al., 2020; Schiffer et al., 2020). Furthermore, the great abundance of sill intrusions, and larger thicknesses and distribution of the high-velocity lower-crustal body (LCB) on the Vøring margin contrast to that along the LVM (Fig. 5) (e.g. Berndt et al., 2001; Mjelde et al., 2003; Tsikalas et al., 2005a, 2012; Breivik et al., 2009, 2017; Abdelmalak et al., 2016, 2017). Moreover, the thick continental crust on the Vesterålen margin is associated with moderate pre-breakup extension, and it exhibits maximum crustal thickness in the order of ~35–36 km towards mainland Norway, while it thins beneath the continental slope reaching ~10–14 km (Fig. 5b–c) (Mjelde et al., 1993, 2003; Faleide et al., 2008, 2015; Breivik et al., 2017, 2020). The region occupied by the continent-ocean transition/boundary (COT/COB) along the LVM becomes narrower northwards, decreasing from 110 to 160 km off Lofoten to 80–90 km off Vesterålen where it corresponds to a narrow margin characterised by a steep continental slope (Figs. 1 and 5) (Tsikalas et al., 2012). On the contrary, the conjugate East Greenland margin exhibits a more extensive and thicker magmatic underplating/LCB region beneath a wider COT associated with a more extended crust (Fig. 5a–c) (e.g. Voss and Jokat, 2007). Furthermore, the Bivrost Lineament along the southern part of the LVM (Fig. 1) has been interpreted as a low-relief Late Jurassic-Early Cretaceous accommodation zone that was reactivated during Late Cretaceous-Paleocene (Tsikalas et al., 2019). The Bivrost Lineament acted as a structural corridor and was responsible for the segmentation and lateral offset between sub-basins and structural highs in its vicinity (e.g. Olesen et al., 2002; Tsikalas et al., 2005a, 2005b, 2019; Wilhelmsen-Rolstad, 2016; Kalač, 2017). In addition, it represented a rift propagation barrier towards the north and a possible tectono-magmatic crustal boundary controlling the change in style and volume of breakup extrusives along the LVM (e.g. Eldholm and Grue, 1994; Berndt et al., 2001; Tsikalas et al., 2008).

The conjugate margins off mid-Norway and East Greenland (Fig. 5) are underlain by Caledonian basement (e.g. Hansen et al., 1992; Bergh et al., 2007; Rotevatn et al., 2018), and the LVM, as part of the NE Atlantic margins, evolved through variously resolvable, post-Caledonian rifting episodes mainly during Mesozoic and early Cenozoic (e.g. Doré et al., 1999; Roberts et al., 1999; Faleide et al., 2008). Several suggestions for the evolution of the rifting events that took place on LVM have been proposed, including a time-progressive evolution (Bergh et al., 2007; Eig and Bergh, 2011; Hansen et al., 2012), and transtension or oblique-normal faulting causing the dominating fault trends and multi-phase rifting (Wilson et al., 2006; Henstra et al., 2015, 2017, 2019). Continental breakup and formation of the Norwegian-Greenland Sea followed rifting and initiation of seafloor spreading at the Paleocene-Eocene transition (~55 Ma) and was accompanied by igneous activity (e.g. Eldholm and Coffin, 2000; Skogseid et al., 2000; Eldholm et al., 2002; Mosar et al., 2002a; Tsikalas et al., 2002, 2012; Barnett-Moore et al., 2018). Observations on rift geometries in the conjugate margins led to the proposal of a rifting model with an upper- and lower-plate margin configuration, and which involves subsequent magmatic overprinting (e.g. Mosar et al., 2002a; Voss and Jokat, 2009). Following breakup and seafloor spreading, further widening and deepening led to increased accommodation, which allowed for sediment deposition and subsequent subsidence, and passive margin evolution (Figs. 1 and 5) (Faleide et al., 2008).

4. Tectono-stratigraphic evolution: new insights

The emphasis of the study on the late Mesozoic and Cenozoic evolution is because the pre-Cretaceous strata along the underexplored northern Lofoten-Vesterålen margin segment appear to be thin and not

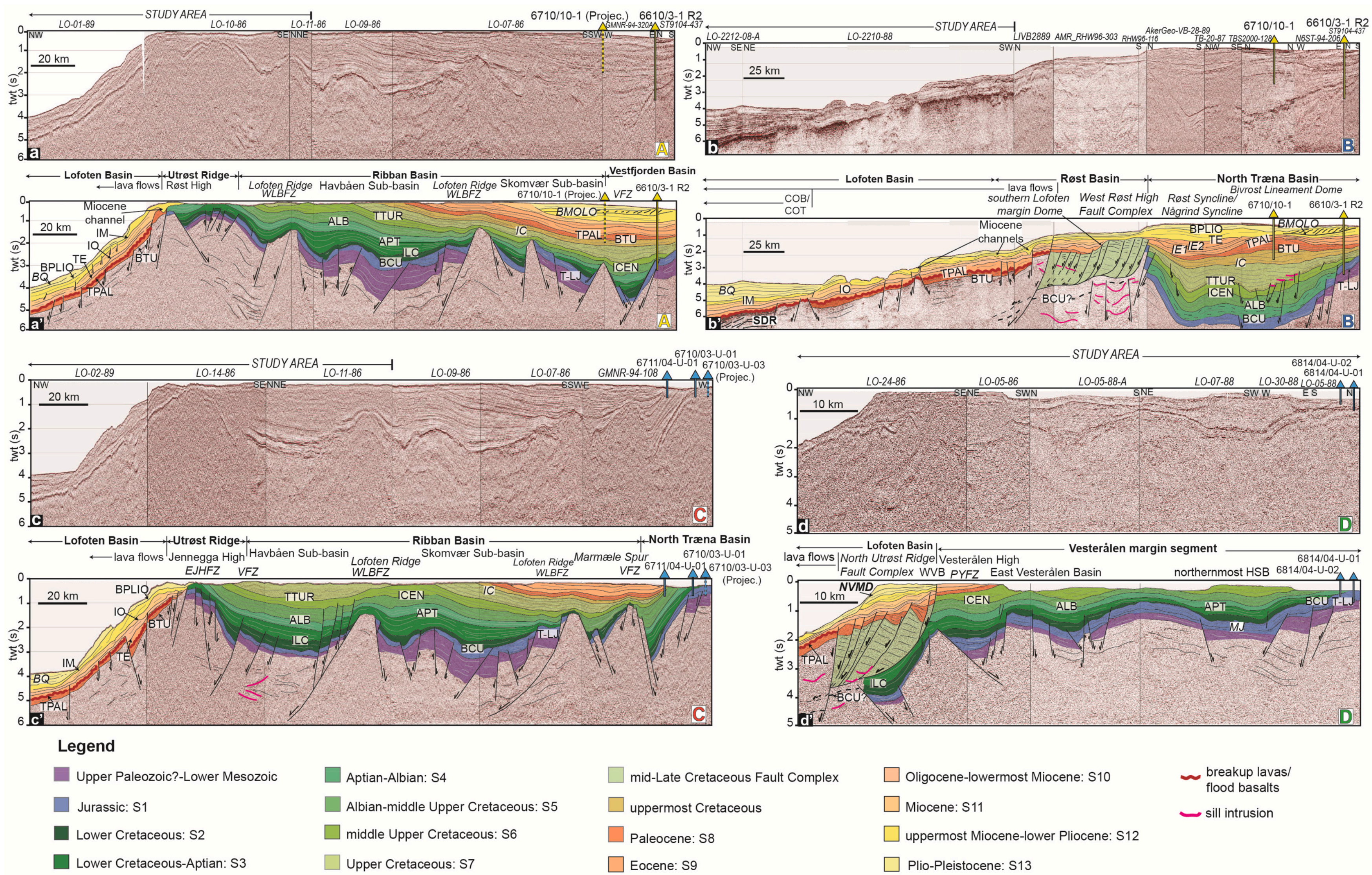

Fig. 6. Composite seismic reflection profile and line drawing interpretations illustrating the well-to-seismic ties to exploration wells 6610/3-1 R2 and 6710/10-1 (profiles A and B), and to shallow stratigraphic boreholes 67710/03-U-03, 6710/03-U-01 and 6711/04-U-01 (profile C) and boreholes 6814/04-U-01 and 6814/04-U-02 (profile D), with correlations within the study area. Colour-rasters indicate interpreted seismic sequences (Fig. 3). Profile locations in Fig. 2a. COB/COT: continent-ocean boundary/transition; NVMD: northern Vesterålen margin Dome. Seismic horizons abbreviations as in Fig. 3 and Table 2. Other abbreviations in Figs. 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Summary of mapped seismic horizons. Main horizons within the focus study area are marked in bold letters. Horizon abbreviations are also indicated in Fig. 3. LVM: Lofoten-Vesterålen margin.

Seismic horizon	Abbr.	Character/Properties	Well tie
Base Plio-Pleistocene	**BPLIO**	Semi-continuous with high amplitude in south Lofoten segment; truncated towards Quaternary seismic units (BQ: base Quaternary). Unconformity character due to younger strata downlap and onlap on it	6610/3-1 R2 6710/10-1
Intra Miocene	**IM**	Semi-continuous to continuous, with medium-to-high amplitude. Locally angular unconformity character due to younger strata downlap on it	6610/3-1 R2 6710/10-1
Intra Oligocene	**IO**	Discontinuous (mainly in inner-to-outer margin transition), medium amplitude. Toplap character onto younger reflectors often observed near the inner-to-outer margin transition	Not drilled in study area
Top Eocene	**TE**	Discontinuous, medium-to-high amplitude intensity character. Onlapping/downlaping (unconformity) character of younger reflections onto TE is observed	6610/3-1 R2 6710/10-1
Intra Eocene 1, Intra Eocene 2	*IE1, IE2*	Semi-continuous, medium amplitude, confined within Skomvær Sub-basin, and within seismic sequence S9	6610/3-1 R2 6710/10-1
Top Paleocene	**TPAL**	Chaotic and semi-continuous to continuous with high amplitude; correlates with top of breakup lavas through the entire outer part of LVM. In the inner-to-outer margin transition and near fault complexes and structural highs, younger and older strata downlap and toplap (unconformity), respectively, on it	6610/3-1 R2 6710/10-1
Base Tertiary Unconformity	**BTU**	Semi-continuous, with low-to-medium amplitude. BTU has often been assisted by the observed downlaping/onlapping reflections (unconformity) onto it in the southern part of LVM, and near or on top of fault complexes	6610/3-1 R2 6710/10-1
Intra Campanian	*IC*	Continuous high amplitude reflector, confined to the Skomvær Sub-basin and North Træna Basin	6711/04-U-01 6610/3-1 R2
Top Turonian	**TTUR**	Semi-continuous with low to medium amplitude strength, confined to the southern LVM. Onlap character onto older horizons in North Træna Basin, where it is also down-faulted and cross-cut by sill intrusions	6711/04-U-01 6610/3-1 R2
Intra Cenomanian	**ICEN**	Semi-continuous with low to medium amplitude strength, confined mainly to southern LVM. Near Marmæle Spur, the horizon drapes above it and younger reflections/sequences appear to onlap/pinch-out onto it (unconformity)	6610/3-1 R2 6711/04-U-01
Intra Albian	**ALB**	Semi-continuous mainly in southern LVM, with medium amplitude strength. It has discontinuous character especially in the northern portions of the study area and near fault complexes	6711/04-U-01
Intra Aptian	**APT**	Semi-continuous mainly in southern LVM, with medium amplitude strength. Mapping of the horizon becomes restricted to west and farther north by the Utrøst Ridge and nearby fault complexes	6710/03-U-01
Intra Lower Cretaceous	**ILC**	Semi-continuous with varying amplitude. Onlaps within the study area against BCU and onto elevated structural elements (e.g. Marmæle Spur, Lofoten Ridge) in southern LVM	Not drilled
Base Cretaceous Unconformity	**BCU**	Regional erosional unconformity with semi-continuous character and varying middle-to-high amplitude intensity; younger reflections onlapping onto it near basin flanks	6710/03-U-03 6814/04-U-01 6610/3-1 R2
Middle Jurassic	*MJ*	Semi-continuous and low amplitude, confined to southern LVM and few parts within the central part of the study area	6710/03-U-03 6814/04-U-01
Top Basement/Triassic-Lower Jurassic	**TB/T-LJ**	Semi-continuous to continuous with varying amplitude and frequency; generally overlying more chaotic or transparent reflectivity. Weaker amplitude character progressively increases towards the northwestern part of LVM	6710/03-U-03 6814/04-U-01 6610/3-1 R2

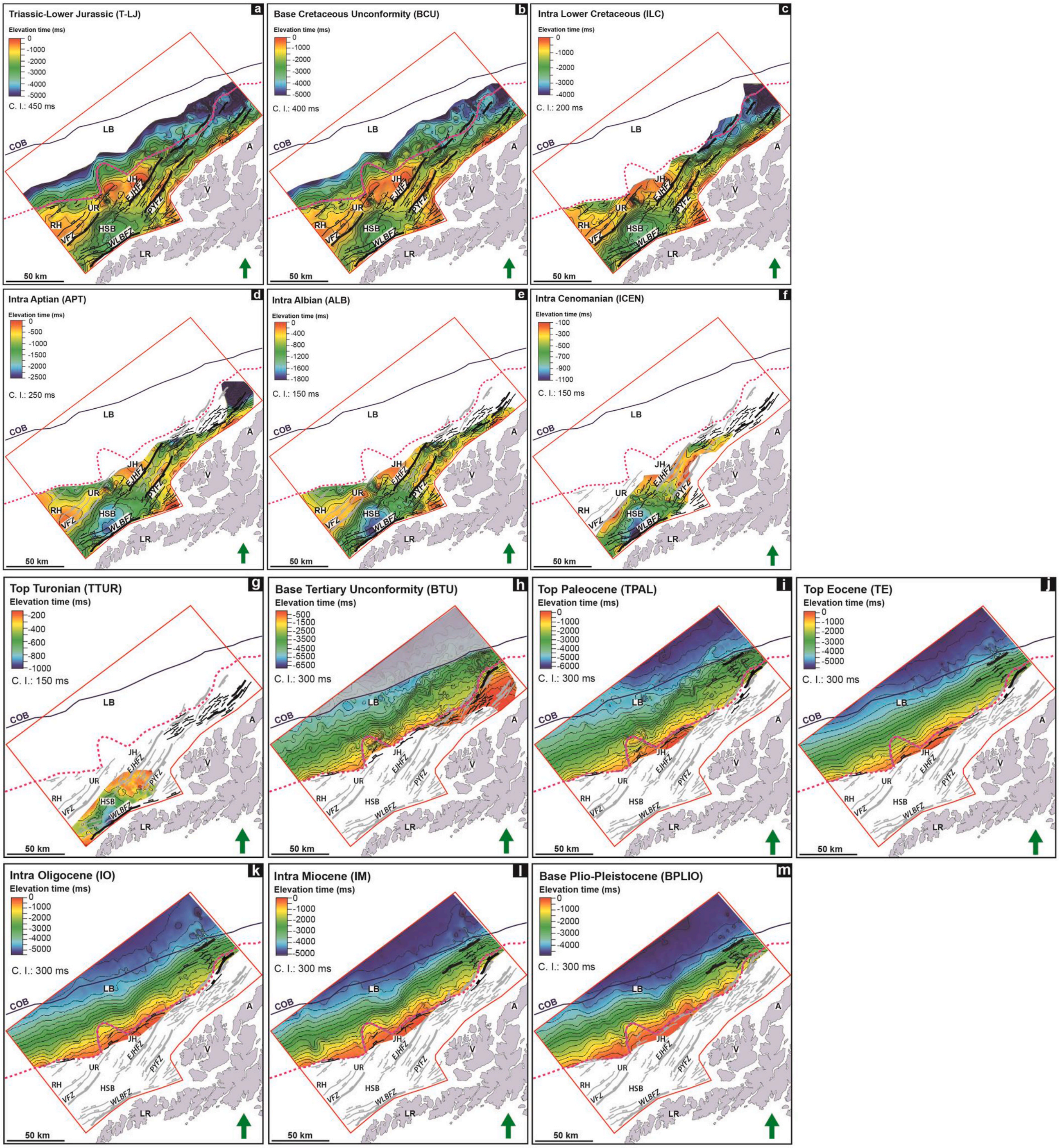

Fig. 7. Time-structure maps **(a–m)** of the main interpreted horizons (Fig. 3). Contour interval (C.I.) for each map is indicated under colour-scale legend. All faults are displayed in black (active) or grey (inactive) and are draped above the surface. Elevated structural highs can be correlated to major basement involved faults and are indicated in thicker black lines. Abbreviations in Figs. 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

properly resolved below a thick Cretaceous succession or below the breakup lavas to the west that hamper seismic resolution (Figs. 1–3 and 6). Mapping of the Base Cretaceous Unconformity (BCU) provided the outline of the prominent Late Jurassic-earliest Cretaceous structural elements in the study area (e.g., Zastrozhnov et al., 2020; Gernigon et al., 2021). Three distinct main horizons representing the Lower Cretaceous basin infill were traced, namely Intra Lower Cretaceous (ILC), Intra Aptian (APT), and Intra Albian (ALB) horizons, together with two main horizons representing the Upper Cretaceous sequences, namely Intra Cenomanian (ICEN) and Top Turonian (TTUR) horizons. Mapping of pre-Cretaceous horizons was also carried out, providing additional information on events prior to Cretaceous times; however, with somewhat reduced resolution. Furthermore, six main Cenozoic horizons were mapped in order to decipher the Cenozoic

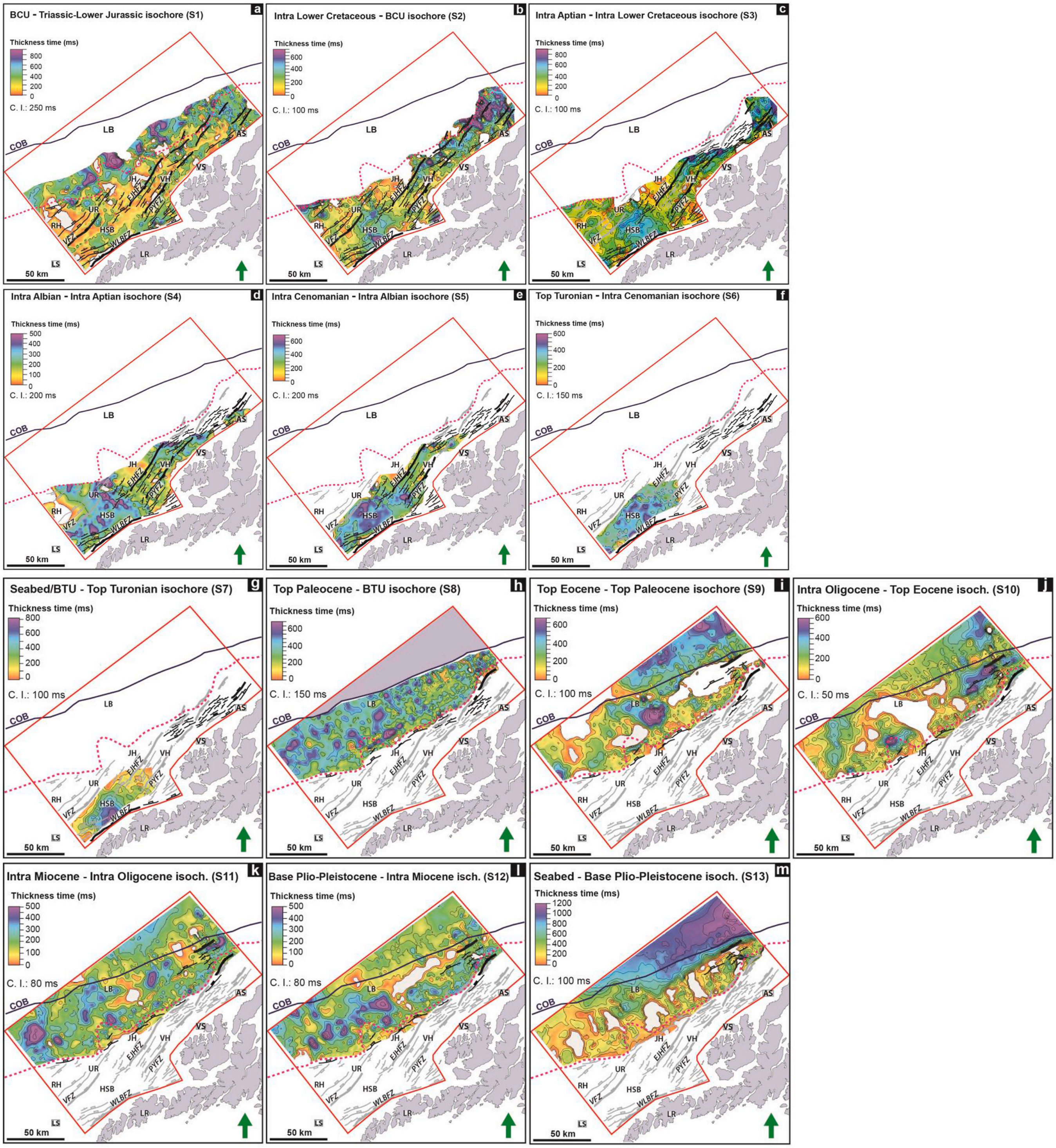

Fig. 8. Time-thickness maps **(a–m)** of interpreted seismic sequences S1–S13. Contour interval (C.I.) for each map is indicated under colour-scale legend. All faults are displayed in black (active) or grey (inactive) and are draped above the surface. Elevated structural highs can be correlated to major basement involved faults and are indicated in thicker black lines. Abbreviations in Figs. 1 and 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tectono-stratigraphic evolution of the study area (Fig. 3; Table 2). We utilise selected seismic sections to illustrate detailed structural and stratigraphic observations, in combination with time-structure and time-thickness maps that provide a better understanding of the lateral and vertical configuration of the sedimentary successions and visualize the tectono-stratigraphic evolution (Figs. 7 and 8). By integrating seismic and potential field data several new and better refined structural elements have been mapped within the study area and are described below prior to the refined late Mesozoic-Cenozoic successions.

4.1. New and refined structural elements

4.1.1. Jennegga High

The Jennegga High is a basement high that is part of the composite

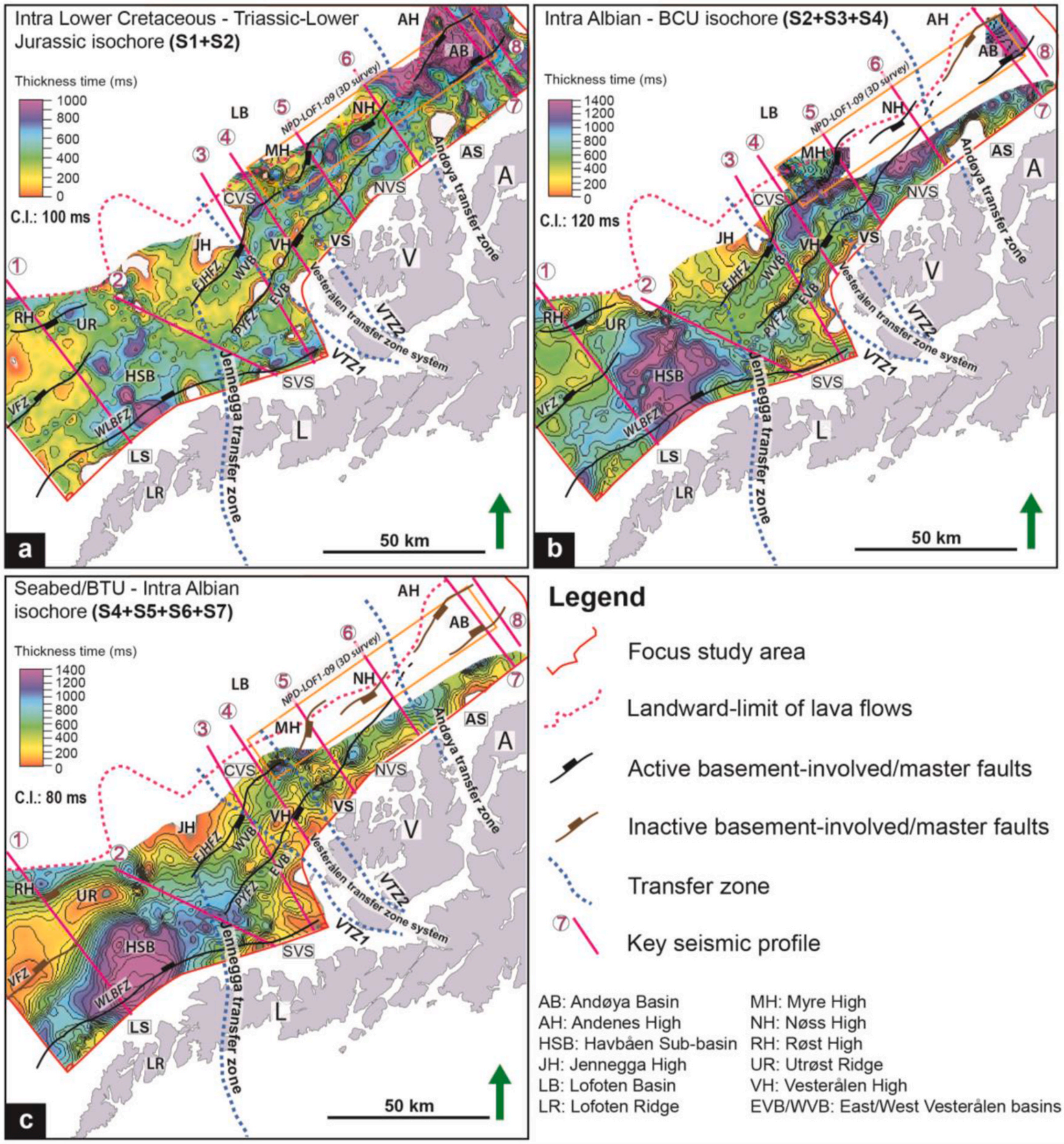

Fig. 9. Composite time-thickness maps of interpreted seismic sequences with proposed transfer zones. The orange rectangle indicates the NPD-LOF1-09 3D seismic survey. Active major faults are displayed in black, while inactive in brown. All faults are draped above the surface. **(a)** S1–S2 sequences (T-LJ to ILC); contour interval (C.I.) 100 ms. **(b)** S2–S4 sequences (BCU to ALB); contour interval (C.I.) 120 ms. **(c)** S4–S7 sequences (ALB to BTU); contour interval (C.I.) 80 ms. Abbreviations in Figs. 1, 2 and 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Utrøst Ridge. It is located in the northeast part of the Utrøst Ridge near the landward breakup lava boundary and shelf edge (Fig. 1). It was first described by Blystad et al. (1995) as an elevated structural high during Early Cretaceous revealed by onlapping of Lower Cretaceous sediments on its flanks (Fig. 6). The Jennegga High remained an elevated structural element also during the latest Cretaceous-earliest Cenozoic tectonic activity preceding and accompanying the opening of the Norwegian-Greenland Sea. Several studies have highlighted the role of the Jennegga High and its nearby vicinity on various proposed margin segmentation models for the LVM (e.g. Tsikalas et al., 2001; Hansen et al., 2012). In this study, the Jennegga High is further refined in its areal extent towards the north where it exhibits abrupt elevation changes of the BCU (Figs. 1 and 7b), and it appears to coincide with a strong positive anomaly in both gravity and magnetic data (Fig. 4). The eastern flank of the high is bounded by a curvilinear fault zone, here informally named the East Jennegga High Fault Zone that acts as a NNE-SSW trending and E-dipping border fault zone along the central part of the study area (Fig. 7b). Towards the transition between the south and central parts of the study area, the Jennegga High is observed to be gradually buried in depth and a low-angle detachment fault complex (cf. North Utrøst Ridge Fault Complex, NURFC, described below) appears to develop in the west (Fig. 6d). This area may, thus, represent a distinct structural shift in basin architecture.

4.1.2. *Myre High*

The informally named Myre High is a new identified structural element in this study, located just north of the Utrøst Ridge/Jennegga High (Fig. 4b). Mapping of the BCU in the central part of the study area indicated the Myre High as a buried, but still distinct structural element with a fault plane bordering its eastern flank where Jurassic and Lower Cretaceous strata are onlapping towards west (Fig. 7b). In addition, the magnetic anomaly map exhibits a strong positive anomaly north of the

Jennegga High (Fig. 4b). The geometry and areal distribution of the Myre High on the magnetic anomaly map may be interpreted to be the northward continuation of the Utrøst Ridge. However, seismic interpretation suggests that the Myre High is an individual structural element that is distinctly separated from the Jennegga High (Fig. 9).

4.1.3. *Vesterålen High*

The informally named Vesterålen High is a refined structural element that was indicated in earlier studies (e.g. Løseth and Tveten, 1996; Tsikalas et al., 2001; Færseth, 2012, 2020), and is now interpreted as a prominent basement-cored fault-block rotated up to ~15° to the west and extending ~70 km along the central part of the study area just offshore the Vesterålen islands (Fig. 1). It is bounded on the eastern flank by a basement-involved, NNE-trending and E-dipping listric fault zone termed by Hansen et al. (2012) as the Pyramiden Fault Zone (Figs. 4 and 6d). On seismic profiles, the Vesterålen High is clearly observed as a pyramid-shaped, and intra-basin elevated horst, where Jurassic and Cretaceous seismic units onlap both its eastern and western flanks (Fig. 6d). In this study, the Vesterålen High is better defined in its areal extent towards the north of the margin (Fig. 1), and it appears to coincide with a strong positive and elongated anomaly in both gravity and magnetic data (Fig. 4).

4.1.4. *East and West Vesterålen basins*

The informally named East and West Vesterålen basins are two new identified basins (Fig. 1). The small and relatively shallow (<2.5 s twt burial depth) basins define two narrow and elongated depocenters located to the east and west of the Vesterålen High, respectively, and they represent the northern continuation of the Havbåen Sub-basin (Figs. 1 and 6d). Both basins exhibit wedge-shaped strata with the thickest parts located in the central part of the basins and with gradual thinning towards the crests of the Vesterålen High (Fig. 7d–f). The East and West Vesterålen basins coincide with strong negative anomalies in both gravity and magnetic data (Fig. 4).

4.1.5. *North Utrøst Ridge fault complex (NURFC)*

Prominent and intense faulting is observed along the northern part of the LVM (Fig. 1). There, we define a new structural element that is informally named in this study, as the North Utrøst Ridge Fault Complex (NURFC). The existence of intensive faulting was earlier indicated in this area (Blystad et al., 1995; Tsikalas et al., 2001; Hansen et al., 2012). However, in this study the NPD-LOF1-09 3D seismic survey is used to properly study the fault complex. Therefore, the NURFC is now better defined on the basis of detailed seismic interpretation. Note that on both the gravity and magnetic data the NURFC coincides with strong negative anomalies (Fig. 4) and this is in accordance with the large thickness of sediments in the hanging-wall growth sequences within the fault complex and the equivalent deep burial of basement. The NURFC is mainly characterized by NE-SW trending and W-dipping faults that extend for ~32 km along partly the central and the entire northern parts of the study area (Fig. 1). In the easternmost part of the fault complex, the faults display low-angle detachment character, and gradually propagate towards west, where they are detached to a common single or to very few fault planes that mostly run sub-parallel to the underlying BCU and the shale-dominated lowermost Cretaceous sequences (Fig. 6d). The detachment plane(s) act, in addition, as pathway for fault propagation at depth.

4.1.6. *Nøss High*

The informally named Nøss High is a new identified basement high, located NE of the Myre High (Fig. 4b). The Nøss High is evident on the BCU time-structure map (Fig. 7b) as a deeply buried but still prominent horst beneath the NURFC. The gravity map does not show presence of any strong positive anomaly due to the thick sedimentary cover in the area, while the magnetic map correlates the Nøss High with a strong positive anomaly (Fig. 4). The eastern flank of the Nøss High is bordered by a NNE-SSW trending and E-dipping basement-involved fault (Fig. 4b).

4.1.7. *Andenes High*

The informally named Andenes High is a new identified basement high, located in the northern part of the study area close to the landward breakup lava boundary (Fig. 4b). Similarly, as the Nøss High, the Andenes High is also evident on the BCU time-structure map (Fig. 7b) as a buried but still prominent horst beneath the NURFC. Due to the extensive and thick sedimentary cover in this area, the Andenes High does not have any particular expression on the gravity data but is correlated with a strong positive anomaly on the magnetic map (Fig. 4). Towards the west onto the outer margin, the Andenes High is locally but intensively intruded by magmatic sills, and there it develops a separate and distinct volcanic complex termed here the Andøya Volcanic Mound (Fig. 8i-m). The latter is, in addition, the structural element located in closest proximity to the continent-ocean boundary/transition (COB/COT; Fig. 1).

4.1.8. *Andøya Basin*

The informally named Andøya Basin is a new identified depocenter located in the northern part of the study area (Fig. 7b). It is evident in the vintage 2D and the 3D seismic datasets (Fig. 2), as well as in both gravity and magnetic anomaly maps that indicate an area of strong negative anomalies (Fig. 4). The Andøya Basin is a narrow basin between the Andenes High and elevated basement on the Andøya island, and may represent the southernmost part of the Harstad Basin (Fig. 1). It appears that locally high subsidence rates may have taken place and may be responsible for the deep and narrow character of the evolved depocenter.

4.2. *Refined upper Mesozoic-Cenozoic successions and experienced rift phases*

4.2.1. *Pre-cretaceous succession and seismic sequence S1 (uppermost triassic-jurassic)*

The Triassic-Lower Jurassic (T-LJ) horizon (Fig. 3; Table 2) is a semi-regional erosional surface often found above deeper patchy reflections that are believed to represent Upper Paleozoic?-lower Mesozoic? sequences (Figs. 6 and 7a). Seismic sequence S1 is bounded between the T-LJ horizon and BCU, and an even distribution of sediments is generally observed for the sequence within the study area (Fig. 8a). The Middle Jurassic (MJ) horizon, or Callovian Unconformity (Hansen et al., 2012), roughly divides the sequence S1 into a lower and an upper stratigraphic unit (Fig. 3; Table 2), but the current seismic resolution only allows to properly map separately these units within a limited area in the North Træna Basin and off the Vesterålen Island (Fig. 6c–d). Locally, a syn-rift character in the northern part of the Havbåen Sub-basin is evident where wedge-shaped internal geometries can be locally observed in rotated fault-blocks (Figs. 6d and 8a). In this context, regionally ascribed pre-Middle/Late Jurassic rifting episodes (e.g. Doré et al., 1999; Brekke, 2000; Brekke et al., 2001; Bergh et al., 2007; Faleide et al., 2008, 2015; Hansen et al., 2012) can be assumed to be related to significant thickness accumulations of sequence S1 observed within the Havbåen Sub-basin (~450 ms twt thickness), within the northern part of the study area at the East and West Vesterålen basins (~350 ms twt thickness), and within the Andøya Basin (~600 ms twt thickness). These depocenters appear to be structurally controlled by faults that were active during sequence S1, such as the W-dipping West Lofoten Border Fault Zone bounding to the east the Havbåen Sub-basin, and the E-dipping East Jennegga High and Pyramiden fault zones bounding the flanks of the East and West Vesterålen basins (Figs. 1 and 6a,c-d).

4.2.1.1. Base Cretaceous Unconformity (BCU). BCU is a regional erosional unconformity (Fig. 3; Table 2) and its time-structure map delineates the configuration of the Cretaceous basins in the inner part of the LVM (Fig. 7b). The BCU time-structure map differs only slightly compared to that of the T-LJ horizon (Fig. 7a). In particular, the Utrøst Ridge area appears as a slightly more elevated and more continuous structural element, and the time-depth contours illustrate larger closures at approximately the same areas within deep inner-margin depocenters (e.g. Havbåen Sub-basin at around ~3200 ms twt depth). Furthermore, the Jennegga High is observed as a well-established elevated feature with its shallowest level at ~500 ms twt depth. Similarly, towards the north, the Vesterålen High lies also at very shallow time-structure levels (less than ~500 ms twt depth) (Fig. 7b). On the other hand, towards the northern part of the study area the BCU time-structure map exhibits a very narrow shelf relief with time-depth contours that abruptly drop from ~1000 ms to more than ~3000 ms, and extend gradually towards the outer margin (Fig. 7b).

4.2.2. Seismic sequence S2 (Berriasian-Hauterivian/Barremian) and Late Jurassic-earliest cretaceous rifting

Seismic sequence S2 is bounded between BCU and the Intra Lower Cretaceous (ILC) horizon (Figs. 3 and 8b; Table 2). The ILC horizon is only observed in the deepest part of the Ribban Basin (Figs. 6 and 7c), while its presence on some portions of the northernmost North Træna Basin and off Vesterålen is uncertain (Figs. 1 and 3; Table 2). Late Jurassic-earliest Cretaceous rifting is evident in the study area through thickness variations of sequence S2 that are often observed with a progressive thinning of sedimentary accumulations towards the crest of rotated fault-blocks where they pinch out. As a result, sequence S2 exhibits wedge-shaped geometries, e.g. in the south of the study area on the Røst High (Fig. 6a) and in the Havbåen Sub-basin (Fig. 6c). A similar character for the equivalent age seismic sequence (as sequence S2) has been reported south of the study area in the Någrind Syncline (Figs. 1 and 6b), where a local Neocomian rift phase is believed to be responsible for the basin infill pattern (Zastrozhnov et al., 2018). In the south Lofoten segment, only a minor part of sequence S2 is present within the North Træna Basin (Fig. 6c), but the sequence becomes thicker towards north-northwest within the study area. On the southern part of the study area, the Havbåen Sub-basin is a well delimited depocenter (~400 ms twt thickness), and the West Lofoten Border Fault Zone is an active structural element that controls sedimentation in the sub-basin. In a similar way, the East Jennegga High Fault Zone appears to guide the sediment distribution and deposition within the West Vesterålen Basin (~500 ms twt thickness). Major thinning and eventual absence of sequence S2 is, however, observed towards the Jennegga High. Farther north, the Andøya Basin is developed where sequence S2 locally reaches a maximum thickness of ~700 ms twt.

4.2.3. Seismic sequence S3 (Hauterivian/Barremian-Aptian)

Seismic sequence S3 is bounded at its top by the Intra Aptian (APT) horizon (Figs. 3 and 7d; Table 2). Stratigraphic correlations for this seismic sequence are limited, however available core information suggests that it may contain sedimentary rocks from the upper part of the Lyr Formation in the southern Lofoten margin (well 6610/3-1 R2; Fig. 3). By Early-to-mid Cretaceous times, the Havbåen Sub-basin (~600 ms twt thickness) represents a better delimited depocenter for seismic sequence S3 compared to sequence S2 due to the greater tectonic activity evidenced at the West Lofoten Border Fault Zone and the more structurally developed Utrøst Ridge (Fig. 6a,c-d and 8c). Similarly, as for sequence S1, lateral thickness variations are also evident in sequence S3 across rotated fault-blocks in the Skomvær and Havbåen sub-basins. The East and West Vesterålen basins were still active but they now represent only minor depocenters for sequence S3 (~400 ms twt thickness). Furthermore, within the western parts of the Utrøst Ridge/Jennegga High area thinning and erosion of sequence S3 is observed. In the central part of the study area, the sedimentation/deposition of sequence S3 appears overall to be larger (>700 ms twt thickness) compared to that in the southern parts of the study area. Nevertheless, in the northern part the intense faulting within the NURFC obscures the detailed mapping and definition of sequence S3 as the sequence obtains there a more reduced areal extent.

4.2.4. Seismic sequence S4 (Aptian-Albian) and Early Cretaceous rifting

Seismic sequence S4 is bounded at its top by the Intra Albian (ALB) horizon (Fig. 3; Table 2). The sequence exhibits a general shallowing-upwards character within the basin configuration towards mid-Cretaceous times (Fig. 8d). In general, there is a rather constant thickness of sequence S4 within the Havbåen Sub-basin and to the east the sequence subcrops close to the seafloor (Fig. 6c). Thickness variations within sequence S4 are largely absent (Fig. 6c–d) and, hence, it can be assumed that the sequence was deposited in a period of tectonic stability (e.g. NPD, 2010) and represents an effective post-rift subsidence infilling of the earlier rift topography as most of the faults terminate below or within the sequence (Fig. 6a). However, a local Early Cretaceous rifting pulse may have also taken place during sequence S4 as there are dragged-up and possible wedge-shaped geometries in the Skomvær Sub-basin (Fig. 6a). Similarly, there is evidence for intense deformation associated with faulting on the eastern parts of the NURFC and within the same structural element towards the northern parts of the study area (Fig. 8d). Accumulations of sequence S4 at this part of the margin appear to be less thick (~450 ms twt thickness), but with increased areal extent and uniformity compared to the lowermost Cretaceous sequence (S3, Fig. 8c). The East and West Vesterålen basins are interpreted as minor depocenters containing thinner accumulations of sequence S4 (~250 ms twt thickness).

4.2.5. Seismic sequence S5 (Albian-Cenomanian) and mid-cretaceous rifting

Seismic sequence S5 is bounded at its top by the Intra Cenomanian (ICEN) horizon (Figs. 3 and 7f; Table 2). The time-thickness map of the sequence illustrates a well-established Utrøst Ridge on the entire LVM (Fig. 8e). The overall depositional character reveals that sequence S5 is limited within the Havbåen Sub-basin (>600 ms twt thickness), and partly within the East and West Vesterålen basins (<400 ms twt thickness) (Fig. 8e). A mid-Cretaceous rift pulse is interpreted on the south LVM area and, in particular, on the eastern part of the Marmæle Spur, where sequence S5 exhibits strong sub-parallel internal reflections with sag geometry associated to faulting on the Vesterdjupet Fault Zone (Figs. 1 and 6c) (e.g. Henstra et al., 2015, 2017; Tsikalas et al., 2019). In addition, the larger thickness of sequence S5 in comparison to sequence S4 (Aptian-Albian) in the Havbåen Sub-basin indicates a local increase in the fault activity on the West Lofoten Border Fault Zone (Fig. 8e). Farther north, the limited areal coverage of sequence S5 indicates higher uplift/erosion rates and a more intense deformation associated to the NURFC. However, it is not possible to confidently correlate sequence S5 along-strike in this fault complex.

4.2.6. Seismic sequence S6 (Cenomanian-Turonian)

Seismic sequence S6 is bounded at its top by the Top Turonian (TTUR) horizon (Figs. 3 and 7g; Table 2). During Late Cretaceous, an intense uplift/erosion is observed in the study area and the currently observed sequence S6 is restricted on the mapped major depocenter within the Havbåen Sub-basin (~600 ms twt thickness; Fig. 8f). In the Røst/Någrind Syncline and in the Marmæle Spur area (Fig. 1), the base of seismic sequence S6 (ICEN horizon) is characterized by a sag geometry, and there sequence S6 reaches its thickest successions (~2 s twt) (Fig. 6b–c). Due to lack of affected sedimentary successions, the E-dipping faults on the studied portion of the LVM (i.e. East Jennegga High and Pyramiden fault zones) are interpreted to be inactive during this time period. Only the W-dipping faults associated with the West Lofoten Border Fault Zone on the Lofoten margin segment are interpreted to be active, together with the faults related to the development of the NURFC farther north. Sediments of sequence S6 may be present within the NURFC, in particular on the northern parts, but it is not possible to confidently differentiate them.

4.2.7. Seismic sequence S7 (turonian to topmost cretaceous) and Late Cretaceous rifting

Seismic sequence S7 is bounded on the top by the Intra Campanian (IC) horizon in the southern Lofoten margin (Figs. 3 and 6b; Table 2), whereas in the northern parts of the margin the sequence subcrops close to the seafloor. The time-thickness map of seismic sequence S7 represents the sedimentary successions that were deposited during late Turonian to topmost Cretaceous, and the sequence is the oldest Upper Cretaceous seismic sequence that was able to be mapped in the study area (Fig. 8g). In the Skomvær Sub-basin and the North Træna Basin, sequence S7 is bounded at its top by the Intra Campanian (IC) horizon, whereas in the northern parts of the margin the sequence subcrops close to seafloor (Figs. 3 and 6a-b; Table 2). The internal configuration of sequence S7 is similar to that of sequence S6 with semi-continuous and medium-to-high amplitude reflections that stratify the sequence. Nonetheless, sequence S7 becomes chaotic and transparent in the study area (Fig. 6c). The Havbåen Sub-basin area (~700 ms twt thickness) represents a more restricted depocenter for sequence S7 in comparison to sequence S6 (Cenomanian-Turonian). Similarly, as for sequence S6, there may be additional depocenters for sequence S7 within the northern parts of the NURFC, however, these cannot be properly correlated/mapped. These latter observations are related to the intense Late Cretaceous fault development and related structures towards the northern part of the study area.

4.2.7.1. Base Tertiary Unconformity (BTU). BTU is a regional erosional unconformity (Figs. 3 and 7h; Table 2) and constitutes the base for the interpreted Cenozoic horizons/sequences within the study area both for the inner and outer parts of the margin. In general, all the Cenozoic time-structure maps are spatially restricted to the Lofoten Basin at the outer part of the LVM and west of the roughly NE-SW oriented landward boundary of the lava flows. All Cenozoic time-structure maps show a distinct deepening towards the northwest corner of the study area (Fig. 7h-m). In this context, the BTU time-structure map exhibits a gradual elevation in the southern part of the study area, reaching a maximum elevation of ~500 ms twt, while the deepest area has been interpreted at more than ~6500 ms in the northwest corner of the study area (Fig. 7h). Towards the northern LVM, the faults located in the transition between the inner to outer margin parts appear to be active during the Paleocene, in particular those within or near the NURFC (Fig. 6d).

4.2.8. Seismic sequence S8 (paleocene) and paleocene rifting

Seismic sequence S8 is bounded at its top by the Top Paleocene (TPAL) horizon (Figs. 3 and 7i; Table 2), and its time-thickness map represents the sedimentary successions that were deposited during the Paleocene, and near the time of continental breakup (Fig. 8h) (e.g. Eldholm et al., 2002). In the south Lofoten margin, sequence S8 exhibits its thickest accumulations within the Bivrost Lineament Dome located in the North Træna Basin (Figs. 1 and 6b) (Tsikalas et al., 2019). Several Paleocene active faults are located just east of the lava boundary along the western part of the margin and mainly along the westernmost flank of the NURFC area. Moreover, a general widespread depositional trend of, more or less, thick sedimentary units is observed within the Lofoten Basin on the outer part of the margin. Maximum time-thickness values for sequence S8 are ~600–700 ms, while thinnest values are ~100–200 ms. More continuous and brighter amplitude reflections are also occasionally observed below the lava flows (top lavas level is considered time equivalent to the TPAL horizon), indicating a likely local preservation of sedimentary successions below them (Fig. 6a–b).

4.2.9. Seismic sequence S9 (Eocene)

Seismic sequence S9 is bounded at its top by the Top Eocene (TE) horizon (Figs. 3 and 7j; Table 2). In addition, the Intra Eocene 1 (IE1) and Intra Eocene 2 (IE2) horizons are interpreted to be contained within sequence S9 in the southern Lofoten margin (Figs. 3 and 6b; Table 2). During Eocene, two well-defined and thick depocenters of sequence S9 developed in the Lofoten Basin (Fig. 8i). One of these corresponds to the thickest accumulations of sequence S9 and is located in the central part of the Lofoten Basin within the study area. There, sequence S9 is observed as a concentric accumulation of sediments and reaches a maximum time-thickness of ~600 ms. This depocenter may have been sourced from the Jennegga High area, or even farther east from the mainland with sediment transportation across the shelf and into the final burial/sink location. At the same depocenter, several reflections often toplap the upper boundary of sequence S9, especially near the NURFC fault complex within the inner-to-outer margin transition (Fig. 6b, d). The second mapped depocenter (~700 ms twt thickness) is observed in the northwestern part of the Lofoten Basin, and it exhibits a wide area for sediment accumulation. Both depocenters are partially bounded by areas of thin or absent deposits for sequence S9, which appear to coincide with the region of volcanic build-up at the Andøya Volcanic Mound (Fig. 8i).

4.2.10. Seismic sequence S10 (oligocene-lowermost miocene)

Seismic sequence S10 is bounded at its top by the Intra Oligocene (IO) horizon (Figs. 3 and 7k; Table 2) and its time-thickness map represents the sedimentary units deposited during Oligocene within the Lofoten Basin (Fig. 8j). The internal configuration of the sequence is, in general, chaotic and transparent with some minor wavy reflections that are visible towards the inner-to-outer margin transition where the sequence pinches out (Fig. 6b). In addition, close to the NURFC the seismic reflection character of sequence S10 gradually shifts from onlapping near the base of the sequence to top-lapping towards the top of it (Fig. 6d). The topographic relief above previously thin or sediment-starved portions of the Eocene seismic sequence S9 (Fig. 8i) is now filled by sequence S10 (~500–600 ms twt thickness). Nevertheless, a large area of non-deposition is observed in the central part of the outer margin near the central part of the study area (Fig. 8j). This region corresponds to one of the thick depocenters of the earlier sequence S9 that was filled during Eocene (Fig. 8i). Moreover, the offshore region adjacent to Vesterålen islands appears to be a fairway for sediment transport towards the outer margin. This is evident by the presence of a distinct canyon illustrated by the V-shaped contour lines in the continental slope of the Vesterålen margin segment at ~3200 ms twt depth (Fig. 7k).

4.2.11. Seismic sequence S11 (miocene)

Seismic sequence S11 is bounded at its top by the Intra Miocene (IM) horizon (Figs. 3 and 7l; Table 2), and its time-thickness map represents the tectono-stratigraphic interval within late Oligocene to early Miocene (Fig. 8k). In general, the sequence exhibits a semi-widespread deposition trend with depocenters reaching a maximum time-thickness of ~400–500 ms. These depocenters are distributed across the entire studied portion of the Lofoten Basin. A similar seismic character as for sequences S9 and S10 is also observed for sequence S11. This includes the transparency in internal reflection geometries and the onlapping/top-lapping character for the base/top reflections, respectively (Fig. 6b). Seismic sequence S11 is also truncated towards the east onto the Utrøst Ridge where is overlies both Eocene and Oligocene strata (Fig. 6a; Miocene canyon/channel), and onto the NURFC (Fig. 6d).

4.2.12. Seismic sequence S12 (uppermost miocene-lower pliocene)

Seismic sequence S12 is bounded at its top by the Base Plio-Pleistocene (BPLIO) horizon (Figs. 3 and 7m; Table 2), but the sequence often subcrops at the seafloor in the outer part of the margin (Fig. 6c). The sequence displays variable thickness with the thickest successions (~500 ms twt thickness) observed in the North Træna Basin where internal geometries of gentle and westward prograding clinoforms are observed (Figs. 6b and 8l). This internal configuration

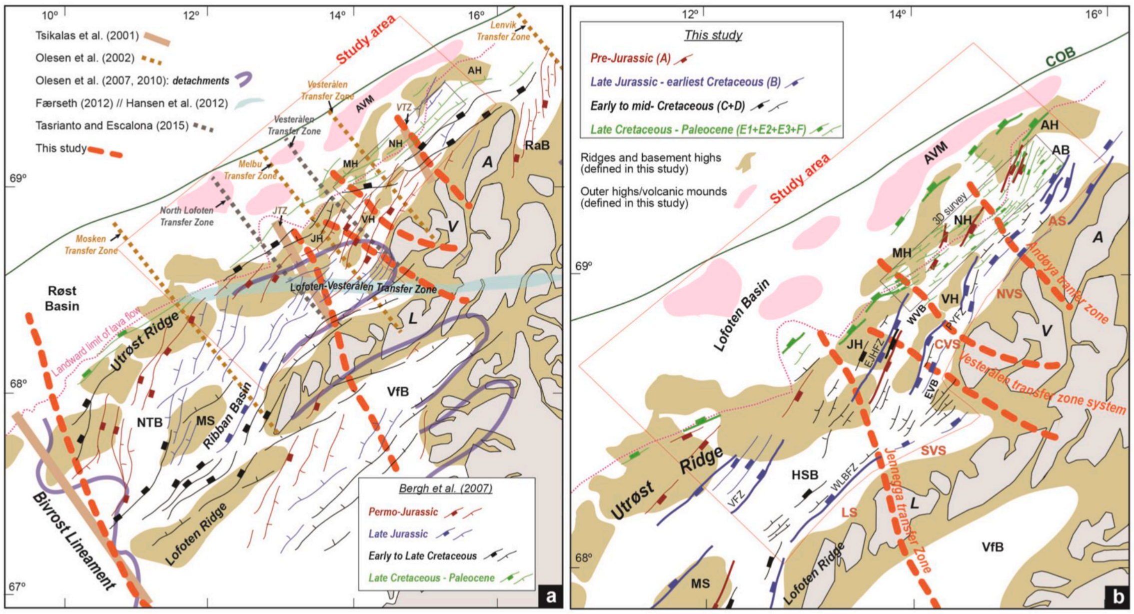

Fig. 10. Margin segmentation and basin evolution model for the LVM. **(a)** Different basin segmentation models based on relevant previous work in the margin. **(b)** Proposed segmentation and basin evolution model for the studied LVM part based on seismic and structural interpretations in this study. Note the relationship of faulting evolution and the identified new and better refined structural elements (see Table 3). The location of the different structural lineaments defined on previous studies is somewhat biased by the available datasets, whereas this study utilises greater more extensive datasets (cf. Figs. 2 and 4; see discussion in the text). JTZ: Jennegga Transfer Zone; VTZ: Vesterålen Transfer Zone. Other abbreviations in Figs. 1, 2 and 4.

corresponds to the Late Miocene-Early Pliocene Molo Formation (BMOLO; Fig. 6b) (Eidvin et al., 2007, 2014; Ottesen et al., 2012; Tsikalas et al., 2019). The northern parts of the Lofoten Basin show a more semi-widespread character for sequence S12 (Fig. 8l; ~200–300 ms twt thickness), and there a narrow and elongated area of thin deposits or non-deposition is observed and it coincides with the region where the Andøya Volcanic Mound is located (Fig. 8l).

4.2.13. *Seismic sequence S13 (Plio-Pleistocene)*

Seismic sequence S13 is composed of glacio-marine sedimentary successions of the Naust Formation in the southern Lofoten margin (wells 6710/10-1 and 6610/3-1 R2; Fig. 3). In the upper part of the sequence a distinct seismic contrast is often observed, and this has been interpreted as the Base Quaternary (BQ) horizon (Fig. 6c; Table 2). In the south of the study area, sequence S13 often lies at the top of the main Cretaceous deposits within the North Træna Basin and the Skomvær Sub-basin (Fig. 6a). On the other hand, this sequence was only mapped within the Lofoten Basin in the outer part of the margin (Fig. 6d). Major erosion is observed on the continental slope across the LVM (e.g. Ottesen et al., 2012), and it is characterized by very thin to absent sedimentary units of sequence S13 (Fig. 8m). The area of major deposition (>1000 ms twt thickness) is located on the northwest corner of the study area and west of the continent-ocean boundary/transition (COB/COT) region.

5. Discussion

The conducted structural interpretations and constructed composite time-thickness maps of interpreted seismic sequences, together with the available gravity and magnetic data, are all used to study the basin architecture and, within this context, to refine earlier proposed and to identify new possible transfer zones. Furthermore, key seismic profiles and geometric correlations with the recently identified West Røst High Fault Complex (WRHFC; Figs. 1 and 6b) and its vicinity in the south Lofoten margin (Tsikalas et al., 2019) are used to identify the main fault families in the study area and to relate them to distinct rift phases within the NURFC and its vicinity. The observations are supported by lateral thickness variations and wedge-shaped character across faults and the fault character, with main emphasis placed on the Late Cretaceous rift phases. The study area is further reviewed in a conjugate margin setting for its Late Cretaceous-Cenozoic evolution.

5.1. *Basin architecture and margin segmentation*

Tectonic boundaries, such as transfer zones, are often observed to correlate with structural lineaments and/or shifts in potential field anomalies along the Norwegian Sea margin (e.g. Jan Mayen and Surt lineaments: Doré et al., 1997; Fichler et al., 1999; Faleide et al., 2008; Mjelde et al., 2009; Bivrost Lineament: Olesen et al., 2002, 2007; Tsikalas et al., 2019). In this context, transfer zones that represent structural lineaments (*sensu* Rosendahl et al., 1986) are defined within the study area to coincide with shifts in gravity and magnetic anomalies (Fig. 4). In the section below we initially discuss and account previously published information on basin architecture and margin segmentation for the LVM. The refined tectono-stratigraphic evolution of the late Mesozoic-Cenozoic sequences and experienced rift phases, together with the new and refined structural elements are utilised to discuss the insights of this study on the basin architecture and the role of transfer zones in along-margin segmentation processes.

5.1.1. *Margin segmentation models*

The present-day basin architecture of the LVM displays a strong geometrical relationship between a set of graben or half-graben basins and elevated structural elements, typical of rift basins. A change in along-margin structural style, fault dip and polarity, depth-to-Moho, and sediment distribution occurs between the islands of Lofoten, Vesterålen, and Andøya (e.g. Løseth and Tveten, 1996; Olesen et al., 2002, 2007). Consequently, three tectonic models that account for the margin evolution have been proposed and the models mainly focus on the lateral along-margin segmentation (Fig. 10a):

- Tsikalas et al. (2001) divided the LVM into three different rifted segments (Lofoten, Vesterålen, and Andøya) defined by border fault geometry and polarity changes across NW-SE trending transfer zones (Fig. 10a). The defined transfer zones were the Bivrost Lineament,

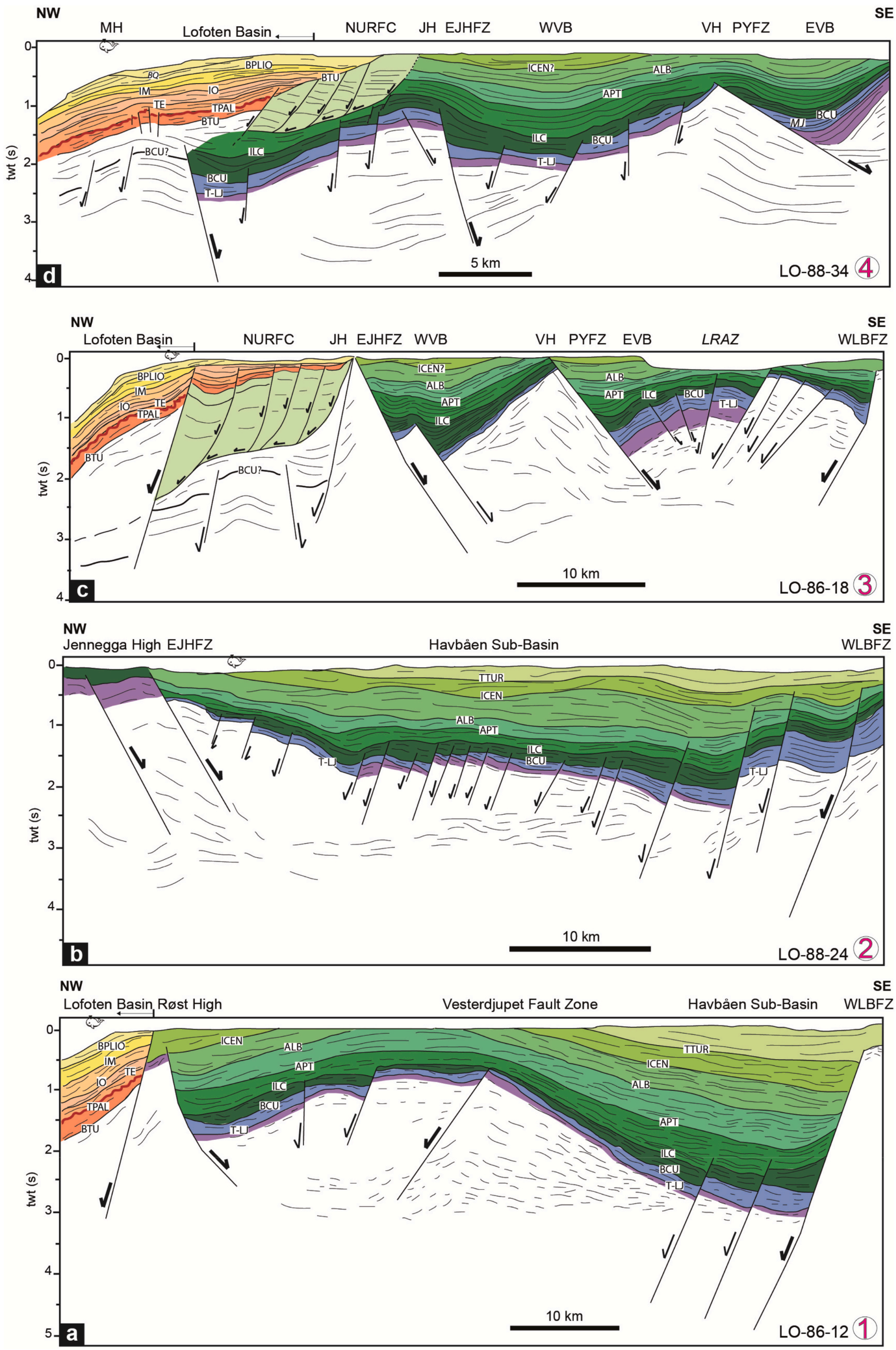

Fig. 11. Line-drawing interpretations (profile locations in Figs. 2a and 9) of relevant seismic profiles depicting basin architecture with main structural elements for the northern Lofoten margin segment (**a-b**: profiles 1 and 2), South Vesterålen margin sub-segment (**c**: profile 3), Central and North Vesterålen margin sub-segments (**d-f**: profiles 4–6), and Andøya margin segment (**g-h**: profiles 7–8). Abbreviations and raster-colour legend in Figs. 1, 4 and 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

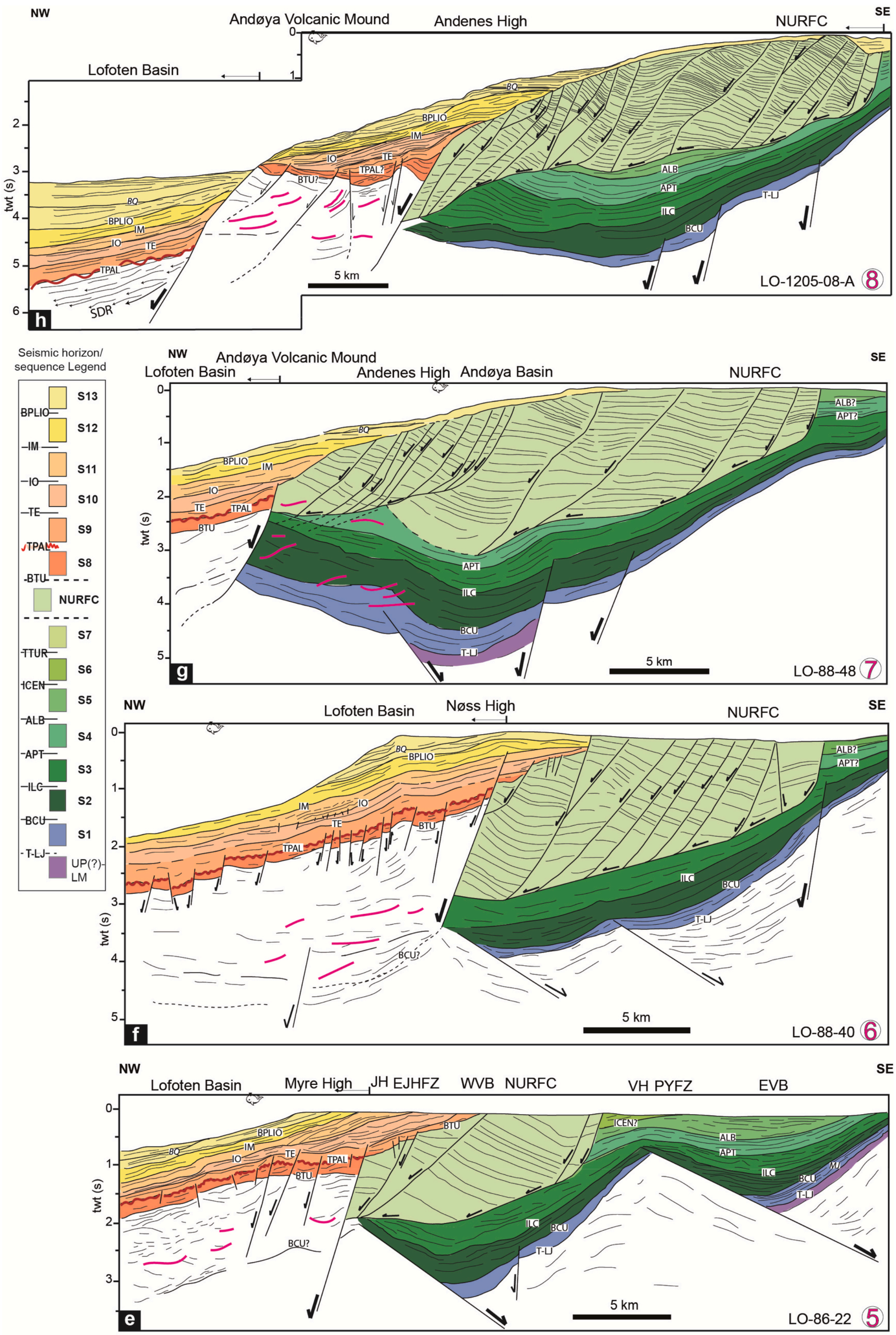

Fig. 11. (*continued*).

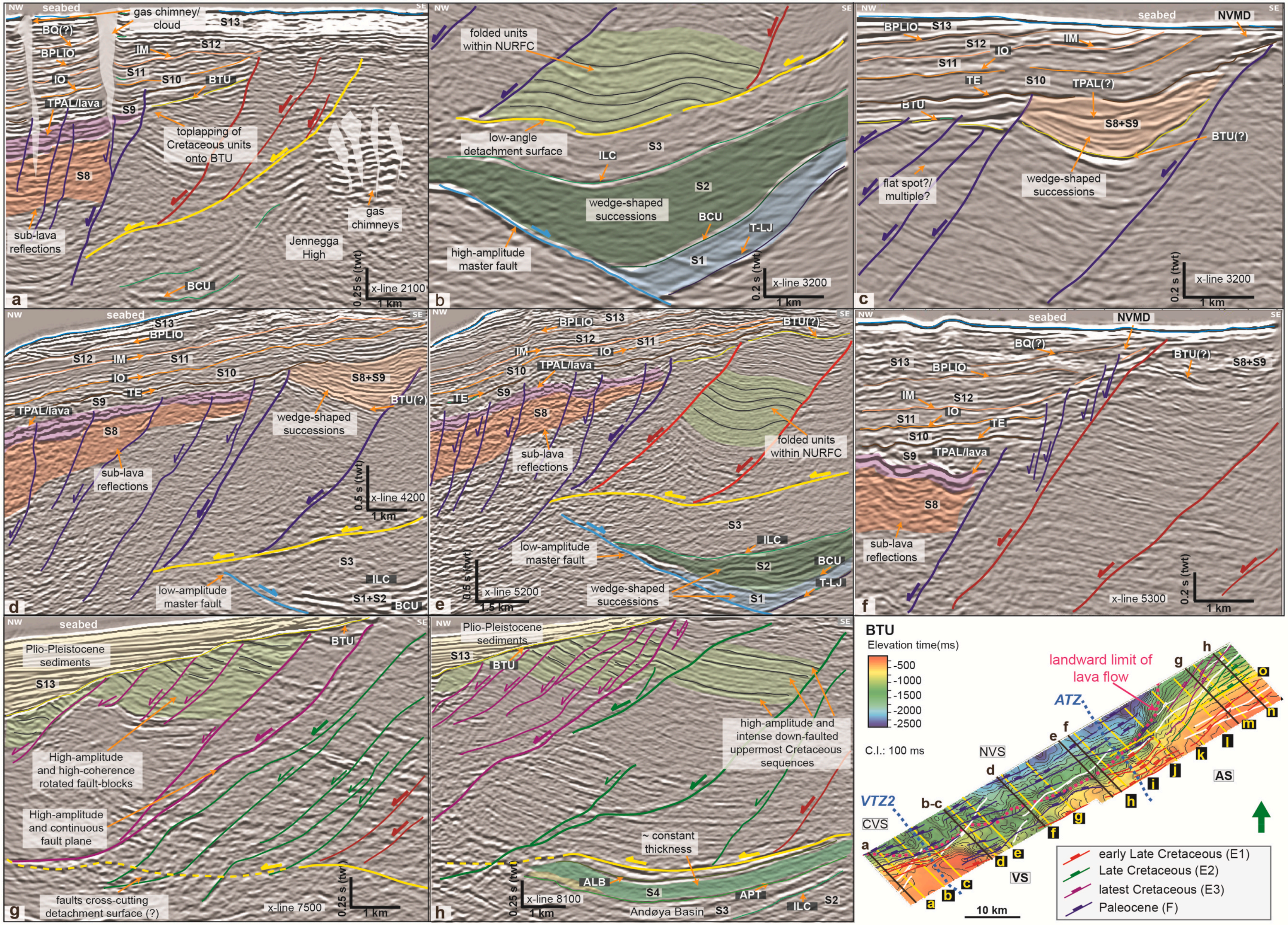

Fig. 12. Seismic examples and interpretations from the NPD-LOF1-09 3D seismic survey within the North Utrøst Ridge Fault Complex (NURFC) and surrounding areas. Location of seismic examples in the panels are indicated in inset map **(a–h)**, together with interpreted profiles in Fig. 13(a–o). Pre-Jurassic/Late Jurassic-earliest Cretaceous master faults are indicated in light-blue lines, while the detachment surface in yellow lines; colour legend for Late Cretaceous and Paleocene fault families in inset map. Inset: Base Tertiary Unconformity (BTU) time-structure map interpretation on the 3D survey with distribution and activity of different fault families. White lines are inactive master faults by Late Cretaceous-Paleocene times; contour interval (C.I.) 100 ms. ATZ: Andøya Transfer Zone; VTZ2: Vesterålen transfer zone 2 (northern lineament). Other abbreviations in Figs. 3, 4 and 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

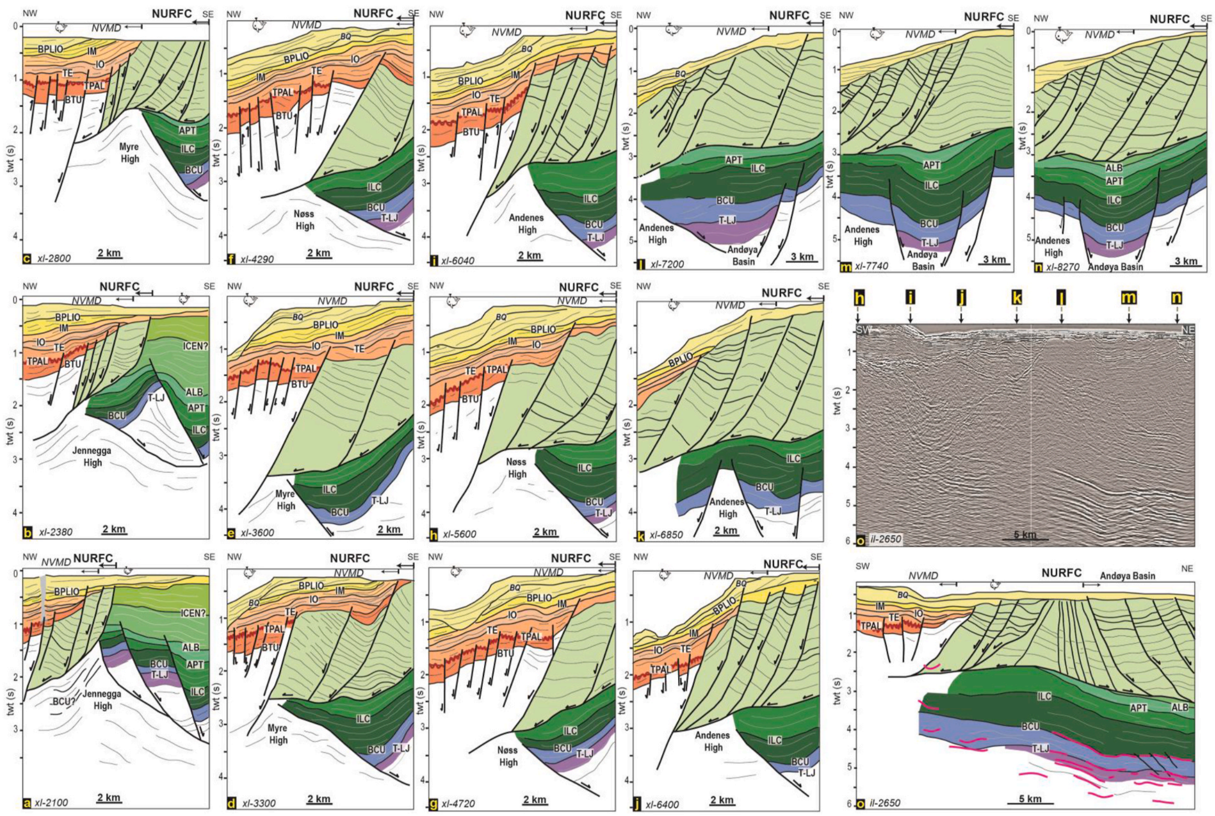

Fig. 13. **(a–o)** Line-drawing interpretations of seismic profiles from the 3D seismic survey (NPD-LOF1-09) illustrating the main structural elements and basin architecture. Note that (o) includes both the seismic example and the line-drawing interpretation. Abbreviations as in Fig. 6. Profile locations in Figs. 2b and 12 (Inset map).

separating the southernmost part of the Lofoten margin from the northernmost part of the Vøring margin, the Jennegga transfer zone, separating the Lofoten and Vesterålen margin segments, and the Vesterålen transfer zone, separating the Vesterålen and Andøya margin segments.

- Bergh et al. (2007) proposed a multi-phase fault initiation with progressive clockwise shear rotation of the stress field from E-W to NNW-SSE that started in the Permo-Jurassic and finalized at Mesozoic-Paleogene times. The proposed lateral segmentation of the margin took place based on the timing of fault initiation, and their corresponding distribution (Fig. 10a). Hence, fault populations are genetically related to distinct rift episodes.
- Færseth (2012) suggested two rift segments within the LVM bounded by an E-W trending accommodation zone just between the Lofoten and Vesterålen segments (Fig. 10a). The change in dip direction of the Jurassic faults across this zone took place without any evidence of strike-slip motion.

Several other studies have proposed different styles of margin segmentation following some of the principles of the three main tectonic models described above, however all these studies were constrained and/or biased by the available datasets (Fig. 10a). Hansen et al. (2012) related the change in dominant fault polarity and basin architecture across a broad E-W trending zone, similar to that of Færseth (2012), but with dextral offsetting of the Lofoten and Vesterålen islands denoted as soft-linked transfer zones (e.g. Eig and Bergh, 2011), and coupled with NE-SW hard-linked transfer zones (e.g. Tsikalas et al., 2001). Tasrianto and Escalona (2015) supported the model of Tsikalas et al. (2001) and separated the LVM into three time-transgressive segments: Southern Lofoten, Northern Lofoten and Vesterålen-Andøya (Fig. 10a).

In this study, our interpretation supports the margin segmentation models of Tsikalas et al. (2001) and Tasrianto and Escalona (2015), together with re-activation and generation of new fault families (Fig. 10b). We utilise more extensive datasets than previous studies (Figs. 2 and 4) and bring further new insights for the tectono-stratigraphic evolution of the study area (Fig. 10b). The change in structural styles (Fig. 7), and distribution of seismic sequences in space and time with respect to the mapped faulting activity/rift phases (Fig. 8), indicate an evolutionary model with three structural lineaments, namely (from south to north) the Jennegga transfer zone, the Vesterålen transfer zone system, and the Andøya transfer zone (Fig. 10b). These proposed lineaments broadly separate the study area into three major and distinct segments: the northern Lofoten, the Vesterålen, and the Andøya margin segments (Figs. 1 and 4). In this context, the mapped rift phases in combination with the NW-SE to NNW-SSE trending and curved transfer zones are viewed in terms of their apparent control on sedimentary infill, fault polarity, and basin geometry (Fig. 10b).

5.1.2. Northern Lofoten margin segment

The major depocenter, the Havbåen Sub-basin, is bounded to the east by the west-dipping West Lofoten Border Fault Zone (WLBFZ) which can be traced for up to ~50 km along the Lofoten Ridge (Figs. 1 and 7b). In this sub-basin, syn-sedimentary faulting is observed on the relatively thin (~500 ms twt) pre-Cretaceous and the thick (>2 s twt) Lower Cretaceous strata as dragged-up geometries near the WLBFZ parts with the largest fault-throws (~1.5 s twt) (Fig. 11a). Farther to the north of the Lofoten margin segment, uplift and erosion rates become more prominent and this is expressed in the gradual thickness reduction of both pre-Cretaceous and Lower Cretaceous sedimentary successions, in particular, as they reach the East Jennegga High Fault Zone to the west of the Havbåen Sub-basin (Fig. 11b). In addition, as the individual faults of the WLBFZ start to display smaller throws towards north (<0.8 s twt) the syn-rift character of the strata is similarly reduced (Fig. 11b).

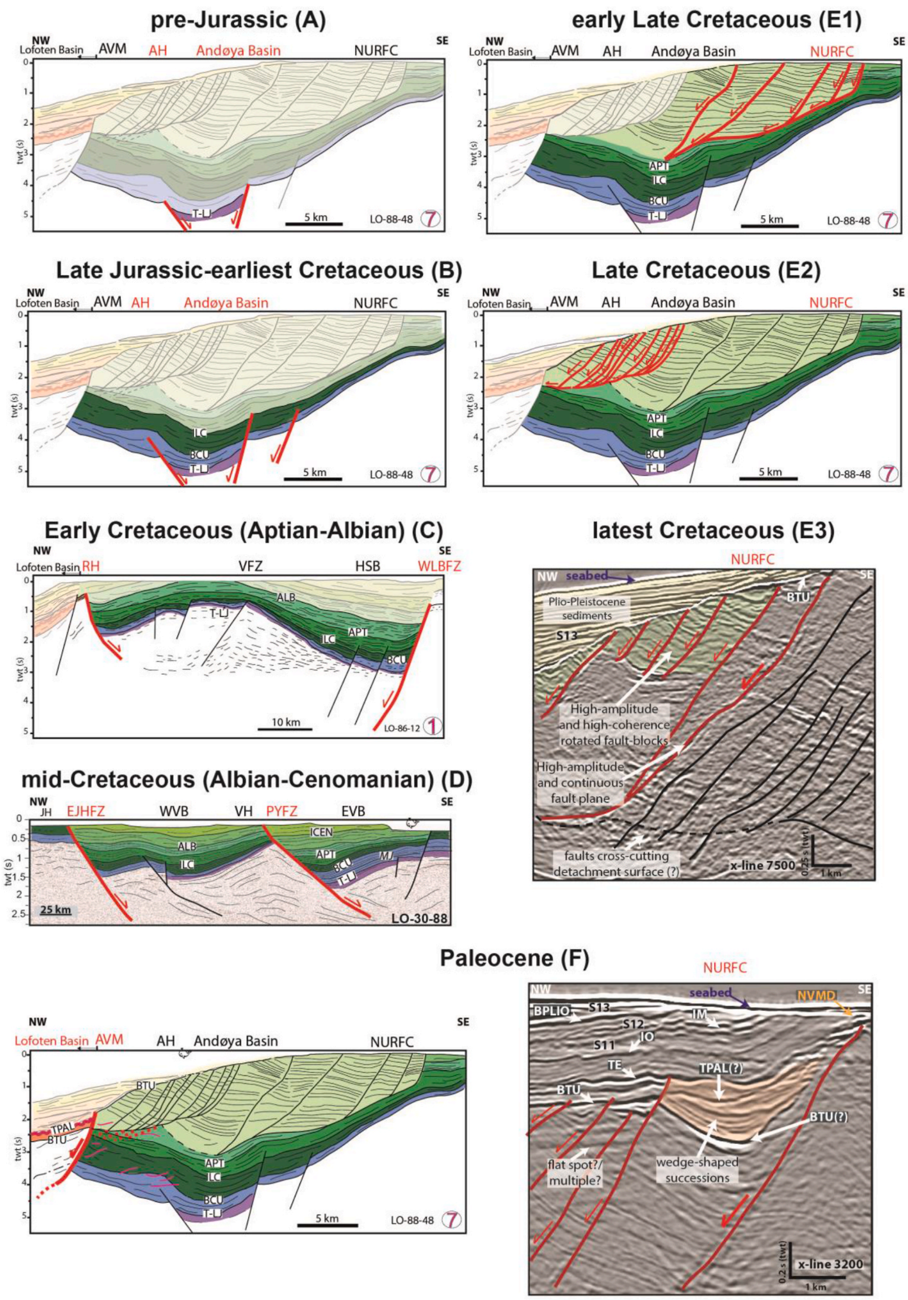

Fig. 14. Time schematic evolution of identified fault families within and in the vicinity of the North Utrøst Ridge Fault Complex (NURFC). Main fault activity is highlighted in red colour, while stratigraphic evolution becomes visible at the progressively younger time stages. Location of line-drawing interpretation (seismic profile LO-30-88) used in fault family D is in Fig. 2a. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.1.3. *Jennegga transfer zone*

The Jennegga transfer zone has been delineated using the gravity map (Fig. 4a) and seismic interpretation (Fig. 9). The transfer zone has been previously interpreted as a structural lineament between the Jennegga High and the Lofoten Ridge (Fig. 1), and was proposed to have had an important role in crustal differentiation and rift segmentation (Tsikalas et al., 2001; Olesen et al., 2002). The interpretation here favours the roughly NW-SE orientation for the transfer zone, which apparently can also be extended through the Lofoten Ridge to central parts of the Vestfjorden Basin and expressed through a gravity low signature signal (Fig. 4a). In this study, the Jennegga transfer zone defines the transition between the northern Lofoten and the southern part of the Vesterålen margin segments, and is evident on 2D seismic profiles as an elevated near-flat relief at the northern part of the Havbåen Sub-basin, where the E-dipping border faults north of this lineament appear to onset (Fig. 11b–c). In addition, faulting related to the NURFC appears to onset farther north of this lineament (Fig. 11c). Similarly, the composite time-thickness maps of interpreted seismic sequences (Fig. 9) suggest that the Jennegga transfer zone exerted structural and depositional control in the south onto the Havbåen Sub-basin within Late Jurassic to early Cenozoic (Fig. 7a–g and 8a-g).

5.1.4. *Vesterålen transfer zone system*

The Vesterålen transfer zone system is defined by two distinct lineaments, VTZ1 and VTZ2 (Figs. 4 and 9), that appear to conform into a single accommodation area. The Vesterålen margin segment is, therefore, subdivided into three sub-segments: South, Central, and North (Figs. 4 and 9). The two NW-SE trending curvilinear structural lineaments are interpreted to extend to the east in the region of the Vesterålen islands, and towards the west where they separate the Myre High from the Jennegga High and extend few kilometres into the outer margin (Fig. 4). The VTZ1 lineament in the south that defines the transition

Table 3
Summary of structural evolution for the study area. BTU: Base Tertiary Unconformity; LVM: Lofoten-Vesterålen margin; NURFC: North Utrøst Ridge Fault Complex.

Time	Fault phase	Affected structural element/feature	Characteristics
pre-Jurassic	A	Vesterålen High, Myre High (?), Nøss High (?), Andøya Basin	Units related to syn-sedimentary faulting preserved in hanging-walls located to east side of elevated basement fault-blocks
Late Jurassic-earliest Cretaceous	B	Utrøst Ridge, Havbåen Sub-basin	Most important tectonic event for the LVM structuration, such as main depocenters and ridges/highs
Early Cretaceous (Aptian-Albian)	C	West Lofoten Border Fault Zone	Moderate-to-weak dragged-up sequences S3 to S5, in particular, on the northern Lofoten margin segment
Mid-Cretaceous (Albian-Cenomanian)	D	Pyramiden Fault Zone, East Jennegga High Fault Zone	Fault re-activation in Vesterålen margin segment together with northwards-oriented burial of ridges/highs
early Late Cretaceous	E1	NURFC	Initial rift phase with wider (in extent) fault-blocks in the east; décollement/detachment surface is developed at slightly deeper levels
Late Cretaceous	E2	NURFC	Rift phase with more intense faulting, narrower in extent fault-blocks; westward migration of rift activity; décollement/detachment surface is developed at shallower levels
latest Cretaceous-Paleocene	E3	NURFC	Local rift phase giving rise to distinctive and narrow in extent fault-blocks located on the uppermost parts of the fault complex; minimal offset of BTU is observed on top of these structures
Paleocene	F	NURFC; breakup lavas	Steep faults located towards west in the outer margin offsetting considerably the BTU; cross-cut the earlier developed Late Cretaceous low-angle décollement/detachment surface(s); associated with sediment wedges on top of the NURFC; landward limit of breakup lava boundary
post-Paleocene	G	Andøya Volcanic Mound; northern Vesterålen margin Dome	Doming and erosion associated to volcanic build-ups in the outer LVM; NW-oriented subsidence trend in the Lofoten Basin

between the South and Central Vesterålen margin sub-segments exhibits a minimal sinistral offset on the southern part of the Vesterålen High (Fig. 9). Moreover, the VTZ1 structural lineament is defined as an intra-basin low-relief accommodation zone (*sensu* Rosendahl et al., 1986, Fig. 11c). On the contrary, the VTZ2 lineament in the northern part separates the Central from the North Vesterålen margin sub-segments and is revealed as gradual northwards diminishment of both fault-throw intensities and basement topography (Fig. 11d–e). In addition, the VTZ2 structural lineament delimits the northern termination of the Utrøst Ridge/Jennegga High, and correlates with the area on the northern part of the Vesterålen High where a dextral offset of this high takes place, together with a gravity low signature signal (Figs. 4b and 9). Similarly, the transfer zone system appears to be related with sedimentary pathways feeding the East and West Vesterålen basins through relay-ramps or incipient transfer faults (Fig. 9) (*sensu* Gawthorpe and Hurst, 1993; Gabrielsen et al., 1995).

5.1.5. *Vesterålen margin segment*

In the South Vesterålen sub-segment, the basin architecture and the rift geometry have undergone a shift in structural style near the Jennegga High. This area is characterized by the partial overlapping of the different set of faults and fault-blocks within the southern (VTZ1) lineament of the Vesterålen transfer zone system, and the northern termination of both the WLBFZ and the Havbåen Sub-basin (Figs. 9 and 11c) (e.g. Færseth, 2012, 2020). Once the WLBFZ dies out in a northward direction the displacement and deformation towards the northern part of the South and within the Central Vesterålen sub-segments are taken up by the major NNE-SSW striking and E-dipping faults of the East Jennegga High and Pyramiden fault zones (Figs. 9 and 11d-f). Both these fault zones can be traced along-strike for more than ~60 km and ~80 km, respectively (Figs. 4 and 9). In the same area and within the thin (~600 ms twt thickness) Jurassic sequence S1, the Middle Jurassic (MJ) horizon (Fig. 3; Table 2) appears to be dragged-up, thus supporting the locally syn-rift character of these strata (Fig. 11d–e). In addition, towards the Central and near the North Vesterålen sub-segments, and near the northern (VTZ2) lineament of the Vesterålen transfer zone system, syn-sedimentary faulting is present on both the East and West Vesterålen basins. This is evidenced locally by low-amplitude reflections below the Triassic-Lower Jurassic (T-LJ) horizon (Table 2) and by sediment-wedges of thick (~1.3 s twt) Lower Cretaceous (S2 and S3) strata (Fig. 8a–d and 11d-e). Furthermore, the Lower Cretaceous sequences are observed to blanket the basement-imposed rift topography by the Myre and Nøss highs along the entire area, and no major accumulations (<500 ms twt in thickness) of Upper Cretaceous sequences are preserved in this part of the study area (Fig. 11d–f). Therefore, all the above observations indicate evidence of local pre-Jurassic rift structures that were re-activated during Middle-Late Jurassic (e.g. Løseth and Tveten, 1996) and escalated further during earliest Cretaceous with development of more evolved faults.

Farther north, the fault-throws on both the East Jennegga High and Pyramiden fault zones is substantially reduced from ~1.5 s twt to less than ~0.5 s twt (Fig. 11f). To the west, the NURFC rests on top of a rather buried Jennegga High on the South Vesterålen sub-segment (Fig. 11d), and extends in a north-eastward manner as the basement is further buried following the same trend. In addition, several faults with small vertical offsets (~200 ms twt) cross-cut the Jurassic strata and the lower part of sequence S2 at the BCU level. However, towards the north of the North Vesterålen margin sub-segment these faults disappear. Only the Jurassic (S1) and the lowermost Cretaceous (S2 and S3) sequences appear to be present under the NURFC, whereas the upper Lower Cretaceous (S4 and S5) sequences (and likewise the APT, ALB, and ICEN horizons) are abruptly truncated by the prominent fault complex (Figs. 6d and 11f). There is evidence of syn-sedimentary faulting towards the upper part of the NURFC, and some of the westernmost fault-planes are onlapped by Cenozoic sequences (S8 and S9) (Figs. 6d and 11d-f). These sequences exhibit thicker accumulations within the

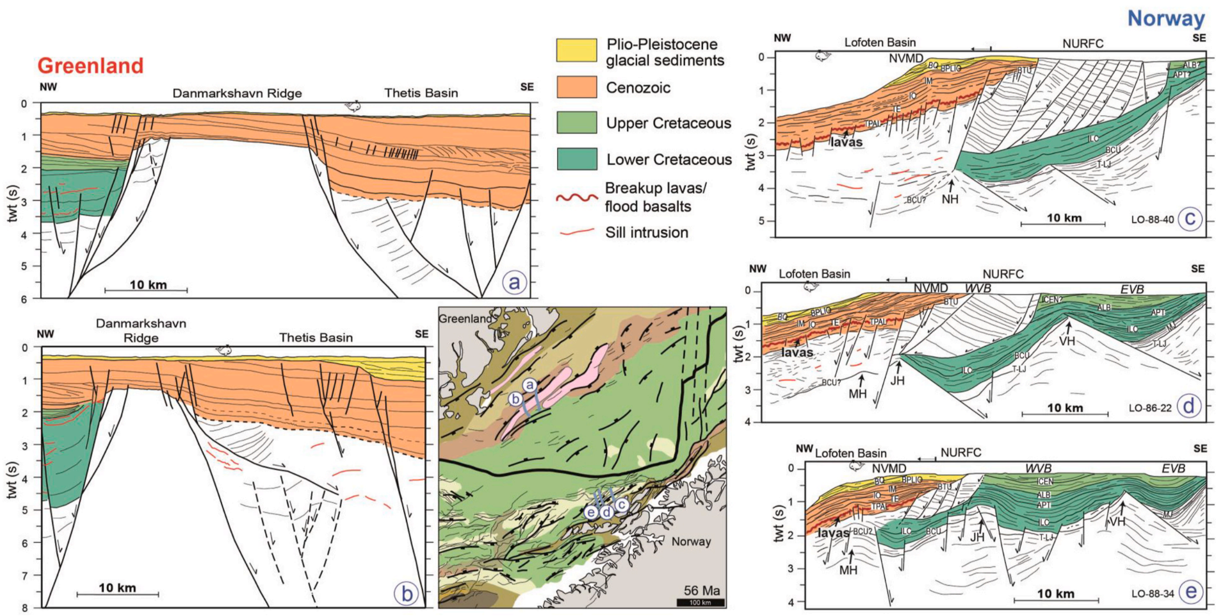

Fig. 15. Interpreted seismic profiles illustrating Late Cretaceous low-angle detachment fault systems from the conjugate NE Greenland (**a-b**; Tsikalas et al., 2005b) and northern Lofoten-Vesterålen (**c-e**; this study) margins. Profile locations in inset-map that illustrates the plate reconstruction prior to breakup (~56 Ma). Abbreviations in Figs. 1 and 2.

Vesterålen margin segment (~2 s twt thickness) compared to the south, as the outer part is widened in a north-easterly direction (Fig. 8h-m).

5.1.6. *Andøya transfer zone*

The Andøya transfer zone is an inferred accommodation zone defined in this study to separate the North Vesterålen sub-segment from the Andøya margin segment. There are several aspects that point out to the existence of a transfer zone at this location. The first aspect is that the E-dipping faults of the East Jennegga High and Pyramiden fault zones on the Vesterålen segment appear to gradually die-out towards the northern parts of the study area (Figs. 7b and 9). Although no obvious/definite (high- or low-relief) accommodation zone is observed, the presence, although minimal, of basement-involved W-dipping faults suggests that a shift in structural style occurs between the area offshore the Andøya island and the northern parts of the Vesterålen margin segment. In addition, the magnetic anomaly map displays a significant shift just north of the Nøss High that separates this high from the Andenes High (Fig. 4b).

5.1.7. *Andøya margin segment*

The Andøya margin segment comprises an area with substantially increased structural complexity, and the margin is dominated by the prominent Cretaceous NURFC fault complex (Fig. 11f–h). Intense NURFC faulting is clearly present to the northernmost part of the study area, almost until the southernmost part of the Harstad Basin (Figs. 1 and 4). Thus, this part of the LVM has shifted to dominant NE-striking and W-dipping faults linked to the development of the NURFC, together with few deep-rooted faults (Fig. 11g–h). For most part of this margin segment, the Lower Cretaceous succession was deposited on top of the Jurassic one that is resting unconformably on Precambrian basement, such as in the onshore Ramsså Basin located on the inner part of the Andøya island (Fig. 1) (Johansen et al., 2020). Nonetheless, as there is a north-westward increase in accommodation space underneath the NURFC on the Andøya margin segment, pre-Jurassic strata may have been preserved there, in particular within the Andøya Basin (Fig. 11g). In addition, the Jurassic (S1) and the Lower Cretaceous (S2–S4) seismic sequences increase in thickness within the Andøya Basin and towards the fault plane in the eastern flank of the Andenes High. Furthermore, the previously truncated APT and ALB horizons can now be interpreted below the fault complex (Fig. 11g–h). Therefore, within the Andøya margin segment there is evidence for Late Jurassic-Early Cretaceous extension with a shift in basin architecture.

On the Andøya margin segment, basement-related seismic reflections are observed at deeper levels (>3 s twt) (e.g. Tsikalas et al., 2001) than equivalent (basement-related) reflections on the central part of the Vesterålen margin segment (Fig. 11f–g). In addition, basement-related faults are not linked to NURFC in the Andøya margin segment. However, farther west and between the Andenes High and the Andøya Volcanic Mound the faults seem to be linked to deeper crustal levels, and as in the Vesterålen margin segment, they are interpreted to deform Paleogene strata (Fig. 11g–h). Paleogene-related extension in the outer part of the margin is related to a prominent W-dipping fault-plane (~2.5 s twt) in the western flank of the Andøya Volcanic Mound (Fig. 11h). This fault separates the thick (~2 s twt) Cenozoic seismic sequences at the Lofoten Basin from the faulted Mesozoic terrain of the inner part of the Andøya margin segment. Furthermore, the lava flows are confined by this fault and they can neither flow/reach farther to the east on the continental slope nor on top of the NURFC (Figs. 4 and 11g-h). On the other hand, the continent-ocean boundary/transition (COB/COT) region is defined by the presence of seaward dipping reflectors (SDR) as in the southernmost LVM (Fig. 6b) (e.g. Sellevoll and Mokhtari, 1988; Skogseid et al., 2000; Berndt et al., 2001; Tsikalas et al., 2001, 2012) and can be also observed in the northernmost part of the Andøya margin segment and in the western vicinity of the prominent fault described above that bounds the western flank of the Andøya Volcanic Mound (Fig. 11h).

5.2. *North Utrøst Ridge fault complex and vicinity: tectono-stratigraphic evolution*

The 3D seismic survey (NPD-LOF1-09) is used to further study and to characterize in a better and more detailed manner the Late Cretaceous-Cenozoic deformation related to the development of the NURFC (Fig. 2b). The 3D seismic survey displays moderate to good seismic resolution (except below the lava flows; Fig. 2c), and has provided novel details for the understanding of the structurally complex area. In this way, seismic interpretation suggests that the Upper Cretaceous

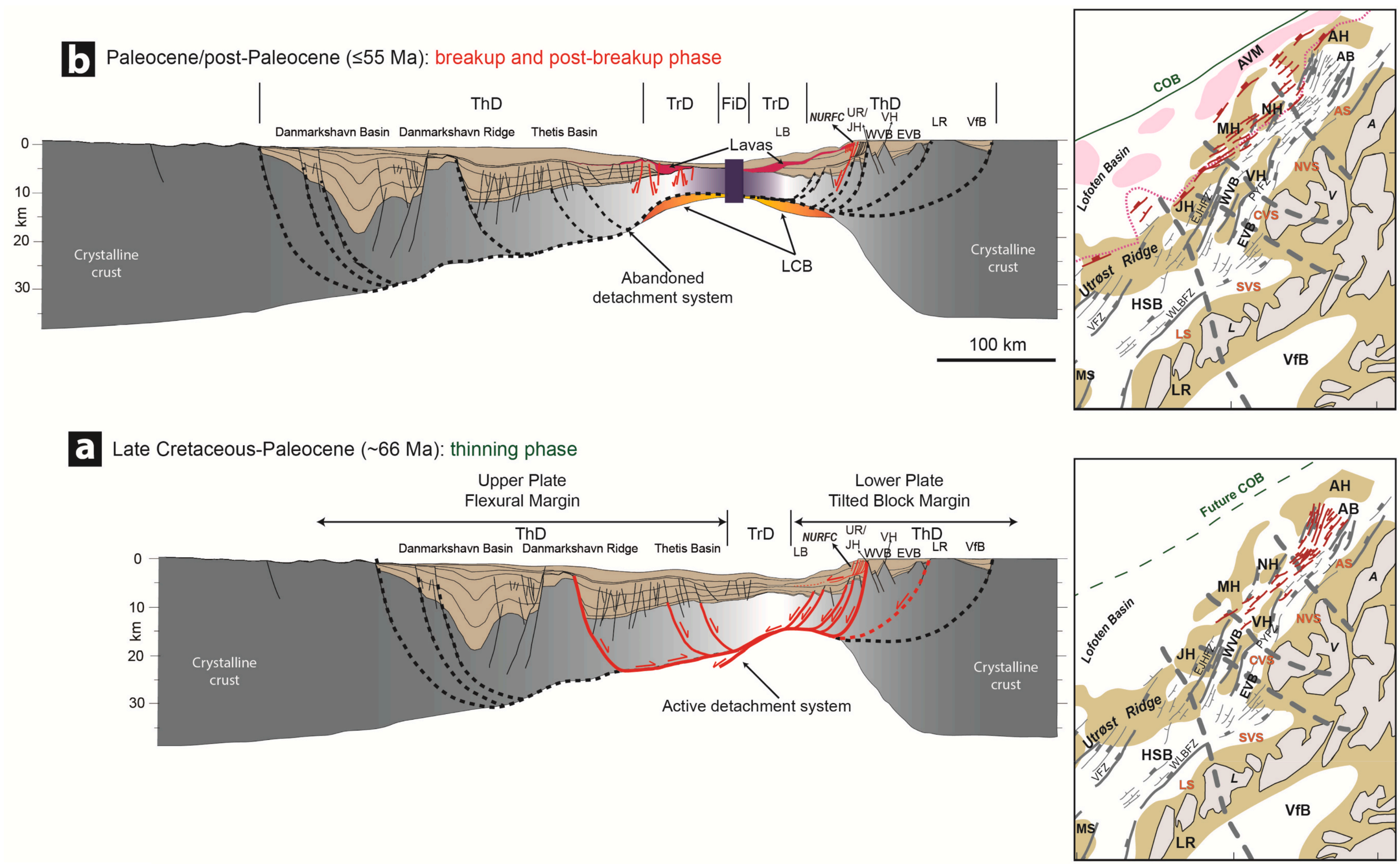

Fig. 16. Conceptual tectonic model illustrating the multiphase evolution of the NE Greenland-northern Lofoten-Vesterålen conjugate margins. **(a)** Late Cretaceous-Paleocene thinning phase showing a lower and upper plate rift geometry triggering a detachment system that developed through the ductile lower crust and lithospheric mantle. Possibly, depth-dependent stretching is the main mechanism responsible for crustal thinning in the area (i.e. ThD and part of the TrD following the concepts of Blaich et al., 2011 for the South Atlantic margins). Relevant map-view panel for this evolution phase/stage of the study area is also indicated (simplified from Fig. 10b). **(b)** Paleocene/post-Paleocene breakup and post-breakup phase accompanied by intense volcanic activity (i.e. FiD), breakup-related lava, and abandonment of the detachment system. The detachment system was possibly interrupted by the emplacement of oceanic crust into the margin that subsequently resulted in an increase of crustal densities leading to post-breakup subsidence of the area by volcanic loading (e.g. Blaich et al., 2011). A lower-crustal body (LCB), typical for magma-rich margins, is placed underneath the crust and it is contemporaneous with the latter described events. Relevant map-view panel for this evolution phase/stage of the study area is also indicated (simplified from Fig. 10b). FiD: fully igneous crust; ThD: thinned crystalline crust domain; TrD: transitional domain. Other abbreviations and annotations in Figs. 1, 2, 4 and 10.

sequences progressively become more dominant in thickness and occupy the largest part within the NURFC towards the northeastern corner of the LVM on the North Vesterålen sub-segment and the Andøya margin segment (Figs. 12 and 13l-n). In addition, the wedge-shaped geometries on the lower and upper parts of the NURFC are evidence of syn-sedimentary faulting (Fig. 12a–c,e and 13a-i), yet the more listric geometries at depth may indicate large-scale tectonism and displacement, associated with long-lasting faulting activity (e.g. Lister et al., 1991; Blaich et al., 2011).

5.2.1. Rift events and fault families

Figs. 10b and 14 together with Table 3 present the tectono-stratigraphic evolution summary of the studied portion of the LVM. Several fault families are recognised indicative of the associated distinct rift activity/phases. Pre-Jurassic tectonism (fault family A) and associated strata are preserved in few places including the area beneath the NURFC, the East and West Vesterålen basins (Fig. 13a–i), and probably the Andøya Basin (Fig. 13l-o). The boundaries of all these syn-rift successions are east-dipping faults bordering the eastern flank of diverse basement highs (Fig. 14). The prominent Late Jurassic-earliest Cretaceous rifting event (fault family B) is reflected in the considerable thickening of the lowermost Cretaceous seismic sequence S2 (Fig. 13a–k). Furthermore, along the transition between the North Vesterålen sub-segment and the Andøya margin segment (i.e. Andøya transfer zone) the Lower Cretaceous successions appear below a "negative flower structure" within the NURFC. This is composed of faults with a SW-dipping orientation that gradually change into a more NE-dipping trend (Fig. 13o).

In the southern part of the 3D seismic survey, the Jennegga High is still bounded by east-dipping faults but it now appears to plunge at deeper depths below a set of individual fault-blocks that are tilted to the west and detach to a single décollement plane underneath the NURFC (Figs. 4 and 13a-b). As deformation continues towards north, the Myre High becomes an elevated and more prominent high (Fig. 13b–e). The Myre High, in turn, is also buried at deeper depths towards the north, and the deformation is taken up by an E-dipping fault bordering the eastern flank of the Nøss High (Figs. 4 and 13f-j). Seismic and structural interpretations clearly exhibit that the E-dipping faults in the studied area of the LVM have been initiated prior to Jurassic and continued to be active until at least earliest Cretaceous. This observation contrasts the suggested Late Jurassic initiation for E-dipping faults along the LVM by Bergh et al. (2007). Based on the rather constant thickness of sequences S3 and S4 towards the northern margin segments, a period from active syn-sedimentary faulting to local tectonic quiescence is interpreted for both the North Vesterålen margin sub-segment and the Andøya margin segment during Early Cretaceous (Fig. 6a,c, 12h and 13). However, an Aptian-Albian distinct rift pulse (fault family C; Figs. 10b and 14 and Table 3) is evidenced in the southernmost part of the northern Lofoten margin segment as moderate-to-weak dragged-up sequences (S3–S5) that are controlled by the West Lofoten Border Fault Zone in the Havbåen Sub-basin (Fig. 11a). Moreover, fault re-activation is also interpreted to take place during Early to mid-Cretaceous times (Albian-Cenomanian; fault family D) on the southernmost part of the Vesterålen High along the South and Central Vesterålen sub-segments (Figs. 10b and 14; Table 3), and within the area where the Jennegga High becomes a buried structural element (Fig. 13a–b).

The subsequent extensional events are evidenced in the study area as rifting pulses of varying time spans and fault-throw intensities that resulted in further structuration within the NURFC. The maximum vertical offset of faults in the central parts of the NURFC is ~1 s twt (Fig. 13a–h) with a small increment towards north (Fig. 13i-n). In addition, faults located towards the west of the NURFC seem to become steeper, as some appear to reactivate pre-existing structures or to generate several detachment surfaces (Fig. 11g). Moreover, the NURFC formation and main tectonic activity is ascribed to a composite Late Cretaceous (possibly initiated at Campanian/Maastrichtian based on regional considerations) to Paleocene rifting that is evidenced on the LVM and adjacent margins (e.g. northern Vøring Basin/margin: Blystad et al., 1995; Ren et al., 2003; Zastrozhnov et al., 2018, 2020; southern LVM: Tsikalas et al., 2019; northern LVM: Hansen et al., 2012; Meza-Cala, 2020; and western Barents Sea: Blaich et al., 2017; Tsikalas et al., 2021). An early Late Cretaceous pulse (fault family E1) is interpreted to first develop towards the easternmost part of the NURFC, and then an additional tectonic pulse takes place as deformation gradually shifts towards the western part of the fault complex during Late Cretaceous (fault family E2; Figs. 10b and 14 and Table 3). Following this event, distinct fault-block rotation is observed towards the top of the NURFC and farther north on the Andøya margin segment, hence, a latest Cretaceous pulse (fault family E3) is evidenced by the steeper rotated uppermost Cretaceous reflections (Figs. 12h and 13d,f). The Base Tertiary Unconformity (BTU) horizon is interpreted as an erosional surface on the upper part of the fault complex (Fig. 12c–h), which indicates that the NURFC could have been more pronounced, affecting an initially thicker package of sedimentary units. The final stage of the NURFC structural evolution is recorded during Paleocene (fault family F), and is characterized by successions with wedge-shaped geometries on top of the fault complex and by steeper faults in comparison to the latest Cretaceous faults (Figs. 10b and 11-13; Table 3). Locally, the Paleocene faults represent re-activation of earlier Late Jurassic-earliest Cretaceous and Cretaceous faults as in the south Lofoten margin (e.g. Tsikalas et al., 2019), but in various places initiation of several new faults are evident (Fig. 12a–d). The new faults with Paleocene affinity down-fault the BTU horizon, mainly to the west of the NURFC, and locally cross-cut the low-angle detachment surface and the Lower Cretaceous units (Figs. 6, 11h, 12e-h and 13b-f). Farther west, the Paleocene faults impede the eastward up-dip flow of lavas on top of the NURFC, and demonstrate that the fault complex was an elevated feature prior to continental breakup and the extrusion of the lava flows (Figs. 12 and 13a-j). Therefore, these faults possibly acted as tectono-magmatic barriers for lava flows towards the east of the LVM, and separated the continental domain from the later evolved oceanic domain in the north-westernmost part of the study area (Fig. 11h).

5.2.2. Post-paleocene evolution

Following continental breakup at the Paleocene-Eocene transition, the post-Paleocene evolution of the LVM is that of a continental passive margin (e.g. Eldholm et al., 2002). The Cenozoic units rest on top of the NURFC, and are observed to be gradually eroded. In particular, the Paleocene sequence S8 is extensively eroded towards the northern parts of the study area (Fig. 8h) in close proximity to the NURFC on the Andøya margin segment, where only thin glacial-related Plio-Pleistocene strata are present (Fig. 13). In addition, mapping of Cenozoic units has revealed dome-like features at the transition between the inner and outer parts of the LVM. The presence, dimensions, shape and evolution of these features may be related to the emplacement of volcanic bodies in the outer margin and other processes discussed below, and the dome-like features are visualized in both seismic profiles and time-thickness maps of sequences S9 to S13 (Fig. 8i-m and 11g-h). The most prominent identified volcanic structure, the Andøya Volcanic Mound (AVM), is a NE-SW oriented and elongated structure located in the northwestern part of the Vesterålen and Andøya segments (Fig. 1).

The Eocene (S9) and Oligocene-lowermost Miocene (S10) seismic sequences encompass the most prominent volcanic build-up structures in the study area, and this is depicted by the wide extent of the AVM (Fig. 8i–j). Additionally, towards the west of the NURFC and in the area between the inner to outer margin transition, a prominent dome-like feature is observed within the Cenozoic sequences as these appear to drag near the fault complex (Figs. 6d and 13a-h). The dome is informally named in this study as the northern Vesterålen margin Dome (NVMD) and its development seems to be closely linked to the evolution of the NURFC (Fig. 1). However, due to reduced seismic resolution and lack of absolute confident ties the exact rate of deformation and the precise extent of the dome are difficult to be resolved in order to account for the detailed evolution of the dome. Nonetheless, in the southern part of the 3D seismic survey compressional deformation is evident as Paleocene/post-Paleocene sequences (e.g. S8–S10) gradually onlap the upper part of the NURFC (i.e. the BTU horizon) just beneath the NVMD (Fig. 13a–f). Farther north where the NVMD appears to be inflated and the NURFC is more elevated and closer to the seafloor, the S8–S10 sequences become thin or absent (Fig. 13g–k,o). In the same area, tilting of the remaining S11–S13 Cenozoic sequences is increased, and this suggests progressive northwards migration of both the faulting intensity and the influence of the NVMD until Miocene (Fig. 8k-l and 13k-n). Based on regional considerations and geometric similarities with structures in areas farther south (south Lofoten margin, Vøring margin) a multi-phase growth evolution can be suggested for both the AVM and the associated NVMD as there is evidence of distinct episodes of vertical movements and inflation initiated since the latest Cretaceous-Paleocene in the proximity of the NURFC, followed by post-Paleocene to mid/late Miocene doming (e.g. Vågnes et al., 1998; Lundin and Doré, 2002; Tsikalas et al., 2005b, 2012, 2019; Doré et al., 2008). Moreover, in the south Lofoten margin it was postulated that the Bivrost Lineament in the proximity of dome-like structures (i.e. Bivrost Lineament Dome and southern Lofoten margin Dome) (Fig. 1) has acted as a structural pathway for the transfer of imposed deformation along the evolving passive margin (Tsikalas et al., 2019). In a similar way, it can be suggested that the Jennegga, Vesterålen, and Andøya transfer zones can also act as “structural corridors” and pathways to transfer any exerted regional deformation during Cenozoic within the study area. These transfer zones are furthermore located at the proximity of the rift-shear interaction between the dominantly rifted mid-Norwegian margin and the dominantly sheared western Barents Sea margin (e.g. Faleide et al., 2008; Tsikalas et al., 2012). Finally, the post-Miocene to Present tectonic evolution of the LVM culminates with north-westward deepening of the Lofoten Basin (i.e. S13; Fig. 8m), uplift and post-Miocene erosion of nearly 2 km of rock successions off northern Vesterålen, and Plio-Pleistocene glaciations and related gravity mass-waste processes on the entire LVM continental slope (Fig. 8m) (Hendriks and Andriessen, 2002; Hendriks, 2003; Rise et al., 2013; Faleide et al., 2015; Breivik et al., 2020).

5.3. Late Cretaceous-Cenozoic conjugate basin evolution

Late Cretaceous-Paleocene rifting with prominent low-angle detachment faults is observed both at the Vesterålen margin and the NE Greenland conjugate margin counterpart, in addition to showing an apparent seaward propagation of fault activity (Figs. 5 and 15). However, some differences exist between the NURFC and similar structures observed on the conjugate NE Greenland margin. In general, evident NE-oriented fault propagation is observed at NURFC towards the inner part of the Vesterålen margin with further enhancement in lateral extent as it reaches the northern LVM (Fig. 15c–e). This process may have been facilitated due to the progressively deeper burial with the same NE-trend of the northern part of Utrøst Ridge/Jennegga High within a narrowing margin, and thus, supporting the role of elevated basement highs acting as obstacles for the intense NURFC faulting (Fig. 15d). On the contrary, low-angle detachment faults on the conjugate NE Greenland margin appear to be confined only to the east of the prominent Danmarkshavn Ridge, which may have acted as a barrier for Late Cretaceous fault propagation into the inner parts of the conjugate margin (Fig. 15a–b). Furthermore, the individual fault-blocks within the NURFC are observed to be less wide and thick compared to those massive and larger in dimension blocks found at the conjugate NE Greenland margin; the latter also displays less seismic internal reflectivity and layering (Fig. 15). Locally, Late Cretaceous low-angle detachment faults beneath the NURFC appear with a greater ductile behaviour and with lower-angle than those few seen on the conjugate side (Fig. 13).

The Cenozoic sedimentary cover appears different on the conjugate margin parts (Fig. 15). Late Cretaceous rifting was followed by smaller-scale, but distinct rifting during Paleocene, with reactivation of earlier faults and locally initiation of new faults (Fig. 14). Paleocene uplift is indicated by early Cenozoic truncation of Cretaceous successions (Figs. 12 and 13), as the NURFC has an elevated and dome-shaped character, and both the COB/COT, that represent the final breakup location, and the landward breakup lava boundary lie very close to the western side of this fault complex (Fig. 5). At the NE Greenland margin, however, the Late Cretaceous low-angle detachment faults are located at some distance away from the landward lava boundary (Figs. 5 and 15). In addition, the Late Cretaceous fault-blocks on the NE Greenland margin are overlain by very thick successions of Cenozoic sequences, with a wedge-shaped Plio-Pleistocene sequence above (Fig. 15a–b). The general northward decrease of the Cenozoic sequence, including the glacial sediments, in the immediate vicinity of the NURFC and conjugate side implies an increasing northward uplift and erosion along both margins, with the greatest erosion of Cenozoic sequences observed within the Vesterålen margin segment (Figs. 13 and 15).

Late Cretaceous-Paleocene rifting at the outer LVM, including a separate Paleocene rift phase recognised in this study and earlier work, preceded continental breakup at the Paleocene-Eocene transition (Fig. 5) (e.g. Tsikalas et al., 2005a, 2005b, 2019; Abdelmalak et al., 2017; Breivik et al., 2017). Consequently, a Late Cretaceous-Paleocene rift zone of ~300 km width was estimated to be present between the Lofoten-Vesterålen and NE Greenland conjugate margins (Fig. 5c–d) (e.g. Skogseid, 1994; Tsikalas et al., 2012; Abdelmalak et al., 2017). Within this rift zone, prominent low-angle detachment fault complexes are evident, locally concentrated along the outer Vøring margin (e.g. Gjallar Ridge; Gernigon et al., 2003), along the outer south Lofoten margin (WRHFC; Fig. 1; Tsikalas et al., 2019), and along the northern part of the LVM documented in this study by the prominent NURFC fault complex (Fig. 15). These fault complexes are evidence for a more ductile mode of deformation towards breakup (e.g. Pedersen and Skogseid, 1989; Skogseid et al., 1992, 2000; Keen and Boutilier, 2000) on both conjugate margins.

The conjugate crustal transect (Fig. 5a–b) and the reconstructed maps of the conjugate setting (Fig. 5c–d) illustrate, respectively, the revised and updated basin architecture, and the oblique axis of breakup. The presence of listric faults and the configuration of a conjugate detachment system can control the resulting asymmetric rift geometry observed in the study area in great similarity with other rifted margins (e.g. Mosar et al., 2002a; Blaich et al., 2011; Huismans and Beaumont, 2011), and support a tectonic model leading to the obliquity in the breakup axis location along the LVM-NE Greenland conjugate margins (Fig. 5c–d and 15). The Late Cretaceous-Paleocene extension direction in the study area is dominantly NE-SW oriented faults as evidenced by the map-view orientation of fault families E1, E2 and F, and it is oblique compared to the pre-Jurassic and Late Jurassic-Early Cretaceous extensional trends that display a more NNE-SSW orientation (Figs. 7, 8 and 12 inset). Subsequently, the breakup axis, in general, follows the trend of the Late Cretaceous-Paleocene structures, and the divergence direction is perpendicular to the first magnetic anomaly 24B (e.g. Eldholm et al., 2002; Mosar et al., 2002b).

Due to the presence of prominent Late Cretaceous-Paleocene low-angle detachment structures on both the Lofoten-Vesterålen and NE Greenland conjugate margins we propose a tectonic multiphase evolution model for lithospheric extension (Fig. 16). A primary first stage (Fig. 16a) is interpreted to be related to a thinning phase during Late Cretaceous-Paleocene that is characterized by detachment faulting and possibly depth-depending stretching as proposed for the NE Atlantic margins (e.g. Kusznir et al., 2005; Tsikalas et al., 2008) and similar rifted margins worldwide (e.g. Blaich et al., 2011). A second stage related to breakup is then followed, together with an increase in magmatic activity and abandonment of the detachment system (Fig. 16b) (e.g. Blaich et al., 2011). In detail, the resulting rift geometry for the asymmetric conjugate margins is controlled by listric faults and the configuration of the detachment system through an upper- and lower-plate configuration when restored prior to breakup (Fig. 16a) (e.g. Mosar et al., 2002a; Nonn et al., 2017; Péron-Pinvidic et al., 2017). Similarly, the obliquity in the breakup axis location together with the morphology of the basins and structural highs, and the location of possible structural lineaments and transfer zones across the margin can be explained by this model.

6. Conclusions

Integrating seismic and potential field data and analyses, and available well information, an updated structural and stratigraphic framework is established for the northern Lofoten-Vesterålen margin, together with new and better refined structural elements. The latter include the (formally and informally named) Jennegga, Myre, Vesterålen, Nøss and Andenes highs; the East and West Vesterålen basins, and the Andøya Basin; and the prominent North Utrøst Ridge Fault Complex (NURFC). We utilise more extensive datasets than previous studies and account for earlier proposed tectonic evolution models, and we bring forward new insights for the tectono-stratigraphic evolution of the study area. The study area has been divided into three main margin segments (from south to north), i.e. the northern Lofoten, Vesterålen, and Andøya segments, separated by NW-SE trending curvilinear lineaments informally named as the Jennegga transfer zone, Vesterålen transfer zone system, and Andøya transfer zone. The criteria for segmentation relay on the observed changes of basin architectural elements, such as shift in fault dip-polarity, diminishing fault-throw intensity, and down-thrown burial of ridges and basement highs. The defined transfer zones constitute structural pathways for the distribution of sediments and deformation initiated prior to Jurassic and lasting until early Cenozoic times.

Five main rift phases of varying intensity and lateral extent have been recognised and refined in the study area, and are evidenced by eight fault families. The pre-Jurassic rifting is clear in few parts of the central and northern portions of the Vesterålen segment, particularly in the vicinity of the Vesterålen High. Late Jurassic-earliest Cretaceous rifting controlled the initial structuring of the main structural elements. Evidence for an Aptian-Albian rift phase exists as dragged-up reflections at the West Lofoten Border Fault Zone within the Havbåen Sub-basin. Mid- Cretaceous rifting (Albian-Cenomanian) was responsible for the initiation of faulting at the NURFC in the southern part of the Vesterålen segment, while extension there continued during the composite Late Cretaceous rifting with a westward propagation of three distinct rift phases and corresponding fault families. Paleocene rifting generated new faults and reactivated several Late Jurassic-earliest Cretaceous and Cretaceous faults, prior to continental breakup and seafloor spreading initiation at the Paleocene-Eocene transition. The post-Paleocene evolution is that of a continental passive margin, and specifically for the northern Lofoten-Vesterålen margin intense uplift and erosion phases took place together with related gravity mass-waste processes.

Cenozoic compressional deformation is evident at a prominent volcanic structure named the Andøya Volcanic Mound and a dome-like feature (named northern Vesterålen margin dome) in the west of the NURFC where Cenozoic successions are truncated and curved-up towards the fault complex. Furthermore, due to the presence of prominent Late Cretaceous-Paleocene low-angle detachment structures on both the Lofoten-Vesterålen and NE Greenland conjugate margins we propose a tectonic multiphase evolution model for lithospheric extension. The model consists of a Late Cretaceous-Paleocene thinning phase that shows lower- and upper-plate rift geometries, possibly triggering a detachment system that developed through the lower crust with a more ductile behaviour towards breakup. The current study demonstrates that the northern Lofoten-Vesterålen margin represents a key area to study the Late Mesozoic-Cenozoic rift-basin architecture and the tectono-stratigraphic evolution of the NE Atlantic margins.

Authors' contribution statement

J.C.M.-C., F.T. and J.I.F designed and directed the research. J.C.M.-C. interpreted the seismic and potential field data. J.C.M.-C., F.T., J.I.F., and M.M.A. analysed the results and contributed to interpretation. J.C M.-C. prepared the figures and wrote the manuscript text. M.M.A. contributed on selected figures. All authors reviewed to the writing of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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