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- Updated crustal model of the rift and rifted margin evolution

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Crustal and basin evolution of the southwestern Barents Sea: From Caledonian orogeny to continental breakup

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Abstract A new generation of aeromagnetic data documents the post-Caledonide rift evolution of the southwestern Barents Sea (SWBS) from the Norwegian mainland up to the continent-ocean transition. We propose a geological and tectonic scenario of the SWBS in which the Caledonian nappes and thrust sheets, well-constrained onshore, swing from a NE-SW trend onshore Norway to NW-SE/NNW-SSE across the SWBS platform area. On the Finnmark and Bjarmeland platforms, the dominant inherited magnetic basement pattern may also reflect the regional and post-Caledonian development of the late Paleozoic basins. Farther west, the pre-breakup rift system is characterized by the Loppa and Stappen Highs, which are interpreted as a series of rigid continental blocks (ribbons) poorly thinned as compared to the adjacent grabens and sag basins. As part of the complex western rift system, the Bjørnøya Basin is interpreted as a propagating system of highly thinned crust, which aborted in late Mesozoic time. This thick Cretaceous sag basin is underlain by a deep-seated high-density body, interpreted as exhumed high-grade metamorphic lower crust. The abortion of this propagating basin coincides with a migration and complete reorganization of the crustal extension toward a second necking zone defined at the level of the western volcanic sheared margin and proto-breakup axis. The abortion of the Bjørnøya Basin may be partly explained by its trend oblique to the regional, inherited, structural grain, revealed by the new aeromagnetic compilation, and by the onset of further weakening later sustained by the onset of magmatism to the west.

1. Introduction

How a mountain range will evolve in a rifted continental domain leading ultimately to a nascent ocean is a fundamental geodynamic aspect in the Earth sciences. The southwestern Barents Sea (SWBS), situated at the junction of the North Atlantic and Arctic provinces, represents a pertinent study area to investigate such fundamental tectonic processes (Figure 1). When correlated with potential field and seismic data, onshore-offshore correlation is a valuable approach to study and better understand the origin and nature of the crustal units influenced by the Caledonian orogen, its post-orogenic rift development, and its evolution during subsequent lithospheric thinning leading to breakup. The tectonic influence of Caledonian and older Precambrian, inherited basement structures on sedimentary basin development and the structural configuration of the rift and margin development in the Barents Sea have long been recognized [*Harland and Gayer*, 1972; *Gabrielsen*, 1984; *Doré*, 1991; *Fichler et al.*, 1997; *Braathen et al.*, 1999; *Ritzmann and Faleide*, 2007; *Barrère et al.*, 2009; *Tsikalas et al.*, 2012]. The SWBS has been affected by major tectonic episodes including the collision of Baltica and Laurentia in mid-Paleozoic time followed by Mesozoic rifting events and Cenozoic breakup [*Gabrielsen et al.*, 1990; *Faleide et al.*, 2008; *Gee et al.*, 2008; *Smelror et al.*, 2009]. Thanks to extensive petroleum exploration, and recent petroleum discoveries (e.g., Skrugard, Havis, Norvag, and Wisting), the outlines and structures of the main Mesozoic grabens, intervening highs, and associated platforms in the SWBS (Figure 1) are also relatively well constrained by seismic data and borehole calibrations [*Gabrielsen et al.*, 1990; *Smelror et al.*, 2009; *Henriksen et al.*, 2011, including references herein]. However, the outline and deep architecture of the late Paleozoic basins and their relationship to the Scandinavian Caledonides and younger Mesozoic basins (Figure 1) still remain unclear in most of the SWBS. One issue is the sparse distribution of long-offset, refraction seismic profiles to image the deepest settings of the SWBS [*Breivik et al.*, 1995; *Ritzmann and Faleide*, 2007]. Over the last 30 years, the structural grain of the basement in the SWBS has been also a matter of debate and two main tectonic models have been proposed. In an early stage of exploration of the Barents Sea, it was suggested that the Scandinavian Caledonides extend northwestward to link up with the Innutian fold belt (northern Greenland) through the Caledonides of Svalbard [*Ziegler*, 1988]. Subsequent

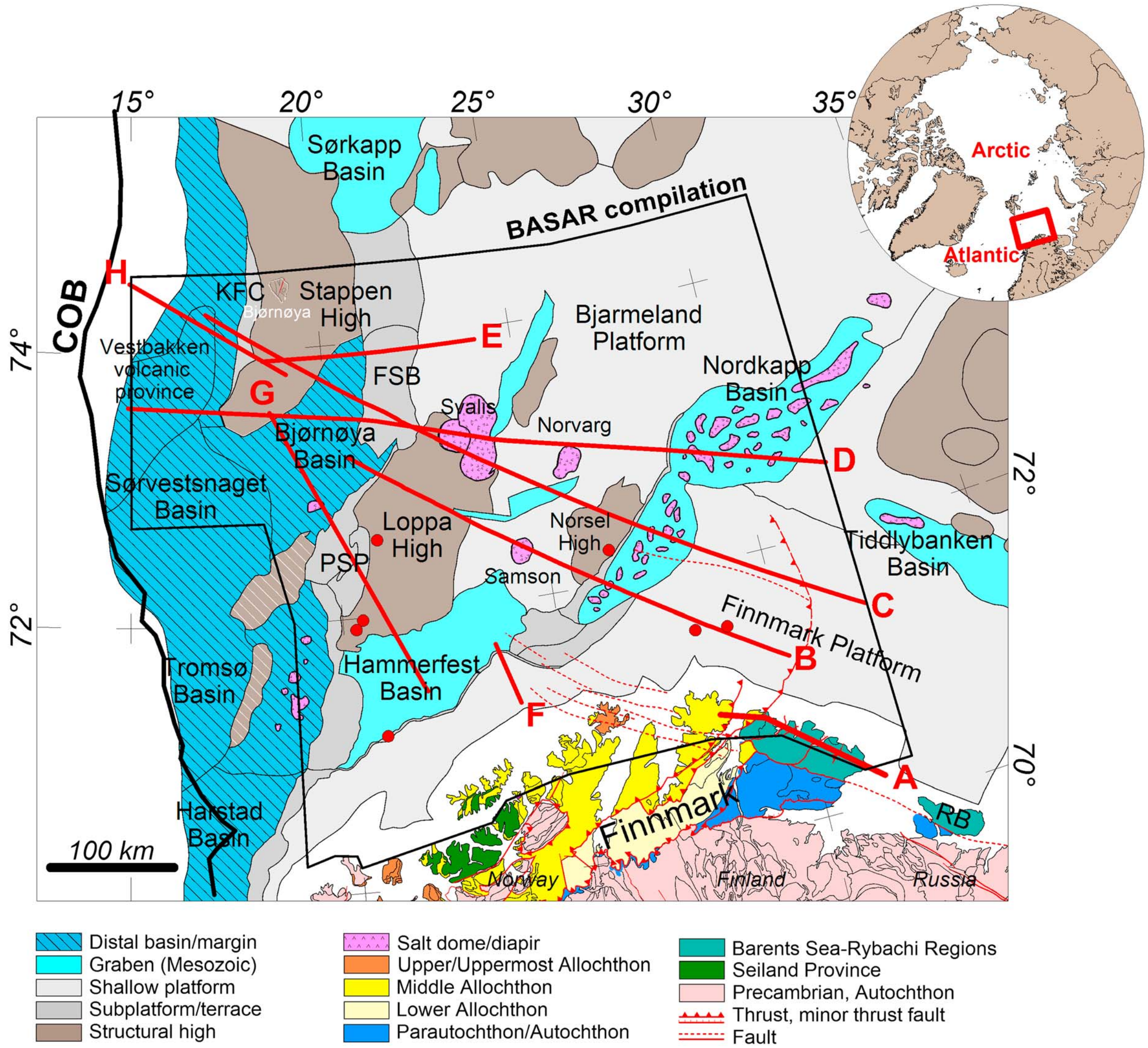

Figure 1. Structural framework of the southwestern Barents Sea (SWBS), Norwegian Arctic region (modified after the offshore NPD geological maps of *Gabrielsen et al.* [1990]). The structural and geological boundaries have been modified after existing onshore [*Siedlecka and Roberts*, 1996; *Sigmond*, 2002] and offshore [*Gabrielsen et al.*, 1990] geological maps. Tectonostratigraphical subdivisions of the Scandinavian Caledonides after *Roberts and Gee* [1985]. The map shows the outline of the Barents Sea Aeromagnetic compilation. The red lines A to F represent the location of the sections shown in Figures 7 and 9–11. The red circles represent the boreholes that penetrate basement rocks. COB: approximate limit of the continental-ocean boundary. KFC: Knølegga Fault Complex; PSP: Polhem Subplatform; FSB: Fingerdjupet Sub-basin; RB: Rybachi Peninsula.

interpretations, however, have favored a model where the general structural grain and the Baltica-Laurentia suture of the Scandinavian Caledonides extend in a northeasterly direction across the central Barents Sea [*Doré*, 1991; *Harland*, 1997; *Gudlaugsson et al.*, 1998; *Breivik et al.*, 2005; *Gee et al.*, 2008]. Some authors have also suggested that the subsequent late Paleozoic basins (Late Devonian-Carboniferous, undifferentiated) developed along a trend almost subparallel to the present-day Mesozoic graben system and may extend over most of the SWBS following a dominant NE-SW to NNE-SSW regional trend associated with the inferred and inherited structural grain [*Dengo and Røssland*, 1992; *Gudlaugsson et al.*, 1998; *Breivik et al.*, 2005; *Ritzmann and Faleide*, 2007]. However, the influence of these inherited basement structures on the subsequent development of the platform grabens and the distal margin complex remains poorly understood and requires better documentation. Previous contributions on the basis of modeling [*Dunbar and Sawyer*, 1988; *van Wijk*, 2005; *Autin et al.*, 2013] or field observations [*Morley*, 1999; *Holdsworth et al.*, 1997; *Roberts and Lippard*, 2005; *Bergh et al.*, 2007] show that inherited tectonic fabrics can influence both rift and margin deformation and evolution. The influence of inherited tectonic fabrics during the actual transition from rift to breakup in terms of crustal deformation and basin development is questionable in the SWBS. A good understanding of both basin and basement history and architecture is therefore a prerequisite for understanding the complex relationships between inherited structures and subsequent rifted margin and sedimentary basin development.

In an endeavor to solve some of the previous issues, in 2006 we initiated a remapping and regional interpretation project of the whole SWBS, including a complete high-resolution aeromagnetic coverage of the SWBS shelf and near-onshore areas. The resulting data set improved the data quality immeasurably and has been used in a profound reassessment of the tectonic setting of the SWBS. In the light of the new aeromagnetic data in combination with gravity and seismic, the main aim of this paper is to discuss and develop further the various aspects and problems related to the prolongation of the Caledonian basement beneath the sedimentary basins and the post-Caledonian rift evolution of the SWBS. We propose and discuss an updated regional tectonic model and specific crustal and continental rifted margin issues related to the question of inheritance and the evolution of the SWBS from the end of the Caledonian orogeny to the final breakup.

2. The Southwestern Barents Sea: Geodynamic and Geological Background

The geology of the Barents Sea area can be explained by a complex combination of large-scale tectonic processes and varying climatic and depositional conditions [*Gabrielsen et al*., 1990; *Worsley et al*., 2008; *Smelror et al*., 2009; *Henriksen et al*., 2011]. The main tectonic phases in the geological framework of the SWBS are, successively, the Timanian, Caledonian, and Uralian orogenies; the proto-Atlantic rifting episodes in the west; and the subsequent breakup and opening of the northern North Atlantic along the western margin of the shelf [*Doré*, 1991; *Tsikalas et al*., 2012].

The tectonic and basement history of the Barents Sea is quite complex and locally still debatable, but the main outline is relatively well established up to the Paleoproterozoic (Karelian) orogeny, setting the stable Russian-European platform adjacent to the Archaean Fennoscandian Shield [*Gee et al*., 2006]. The Timanian orogen developed as a fold-and-thrust belt along the northeastern passive margin of Baltica and the southeastern Barents Sea during Vendian (Ediacarian) time [*Roberts and Olovyanishnikov*, 2004]. The Caledonian orogeny culminated approximately 400 Ma and resulted in consolidation of the Laurentian and Baltic plates into the Laurasian continent and closure of the Iapetus Ocean [*Roberts*, 2003; *Gee et al*., 2006, 2008; *Gasser*, 2014]. The Caledonides in Scandinavia extend for a distance of nearly 2000 km from SW Norway to the far north, involving a large part of Sweden, and are now widely exposed in the country of Finnmark. Many years of extensive fieldwork and bedrock mapping have yielded a remarkably well constrained and comprehensive overview of the geology, sedimentology, structures, and petrophysical properties of the onshore formations [*Sigmond et al*., 1984; *Gayer et al*., 1987; *Olesen et al*., 1990; *Karpuz et al*., 1993; *Siedlecka and Roberts*, 1996; *Roberts and Siedlecka*, 2012; *Rice*, 2014] (Figure 1). As well as a variety of nappes and thrust sheets overlying the Fennoscandian Shield, major tectonostratigraphic domains corresponding to the Lower, Middle, Upper, and Uppermost Allochthons of *Roberts and Gee* [1985] have been identified (Figure 1).

Following the orogeny, the Devonian to early Carboniferous times were characterized by exhumation and extensive erosion of the hinterlands. Regional extension dominated the SWBS area during the late Paleozoic. On seismic data, rift structures are locally recognized below the extensive, upper Carboniferous to Lower Permian, carbonate platform deposits which cover larger parts of the Barents Shelf [*Gudlaugsson et al*., 1998; *Larssen et al*., 2005]. In late Carboniferous time, thick successions of evaporites deposited in the different graben systems formed on the southwestern parts of the shelf (i.e., Tromsø Basin, Bjørnøya Basin, Nordkapp Basin, Tiddlybanken Basin; Figure 1). A major Early Triassic rift episode has also been reported in the SWBS and is also recognized in many parts of the Arctic and across the North Atlantic region [*Tsikalas et al*., 2012]. The Lower to Middle Triassic succession in the SWBS composes transgressive-regressive cycles of marine, deltaic, and continental clastics and a number of discrete minor tectonic events have been recognized [*Glørstad-Clark et al*., 2010]. Middle-Late Triassic times were generally characterized by postrift thermal subsidence in the North Atlantic and Arctic basins. At this time, a significant change in the paleogeography of the Barents Shelf area occurred with the initiation of a progressive uplift of the northern, eastern, and southern Barents Sea regions [*Worsley et al*., 2008; *Smelror et al*., 2009].

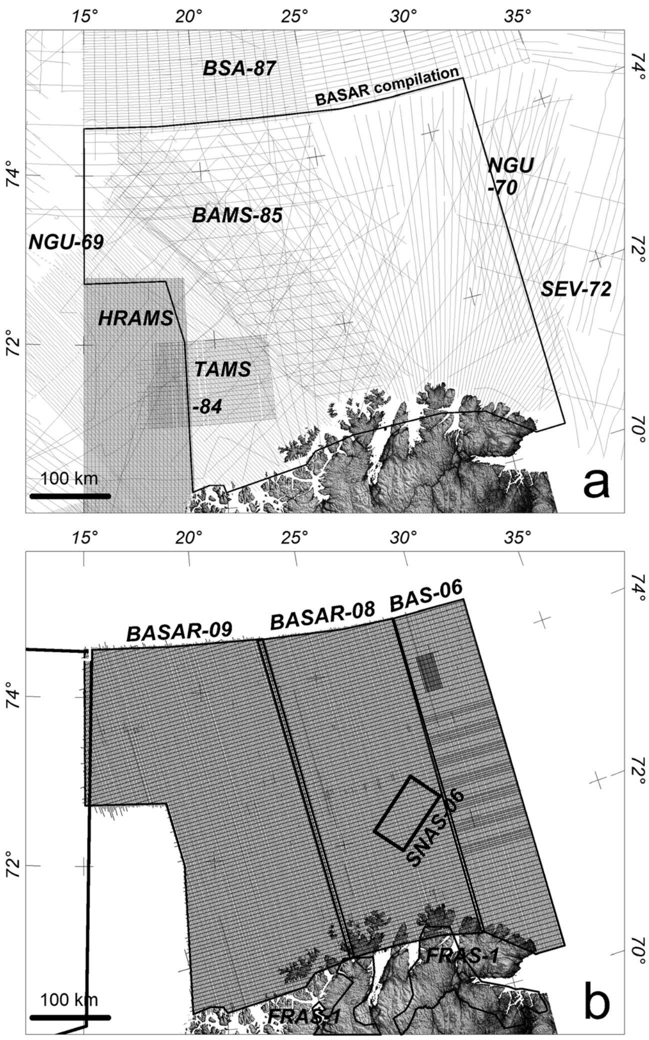

Figure 2. (a) Vintage magnetic profiles of the southwestern Barents Sea. The old data set dates mostly from the 1970–1980s and was relatively sparse and of poor quality compared to the modern acquisition. Until now, the High Resolution Aeromagnetic Survey (HRAMS) survey acquired between the Troms Basin and the Bjørnøya Basin is the only high-resolution and modern acquisition in that area. (b) Outline and configuration of the new aeromagnetic profiles acquired during the BASAR obtained by NGU between 2006 and 2009 and the onshore FRAS-1 experiments. BASAR represents more than 174,000 km of new aeromagnetic offshore profiles, with an average line/tie-line configuration of 2 × 5 km, a configuration that is necessary for a detailed and proper leveling and processing of the data. The FRAS-1 survey (east and west parts shown on the map) has a much higher resolution with a line/tie-line configuration of 0.2 × 2 km not showed on the map for reasons of clarity.

To the west of the Hammerfest Basin, a latest Permian to Early Triassic rifting event is inferred to have occurred and may have continued until Middle Triassic time [*Smelror et al.*, 2009]. During that period, salt diapiric movements are interpreted to have begun and continued into Late Triassic time in the Nordkapp Basin [*Nilsen et al.*, 1995]. Renewed tectonic activity was apparent toward the end of Late Triassic time in both the North Atlantic and the Arctic regions, continuing into earliest Jurassic time.

In the SWBS, the northern progradation of the Middle Jurassic to Early Cretaceous Atlantic rifting affected in particular the western margin of the Barents Sea Shelf and triggered the development of a marine connection across the shelf [*Brekke et al.*, 2001; *Faleide et al.*, 2006; *Tsikalas et al.*, 2012]. During the Early Cretaceous, the northern Barents Sea area was subsequently uplifted and large amounts of sediment were abraded from the uplifted continental areas in the northeast into deeply subsiding basins in the west [*Worsley et al.*, 2008; *Smelror et al.*, 2009]. Along the SWBS, successive rifting episodes during the Cretaceous led to rapid subsidence and development of major deep basins such as the Harstad, Tromsø, Bjørnøya, and Sørvestsnaget Basins (Figure 1). The Late Cretaceous to Paleocene period between Norway and Greenland was progressively taken up by strike-slip movements and deformation leading to the formation of pull-apart basins in the westernmost parts of the Barents Sea [*Faleide et al.*, 1996]. The Paleocene-Eocene transition marks the continental breakup of the North Atlantic margin and opening of the Norwegian-Greenland Sea at around 55–54 Ma. Since Oligocene time, separation of the Barents Sea Shelf and Greenland/North America has continued, leading to the opening of the Fram Strait and establishing a North Atlantic-Arctic marine connection in the Miocene [*Faleide et al.*, 1996].

3. New High-Resolution Aeromagnetic Surveys in the Southwestern Barents Sea and Finnmark Areas

Potential field methods (gravity and magnetics) are commonly used on a regional scale for the delineation of regional structures (basins, basement highs, regional fault structures) in either the early and/or advanced

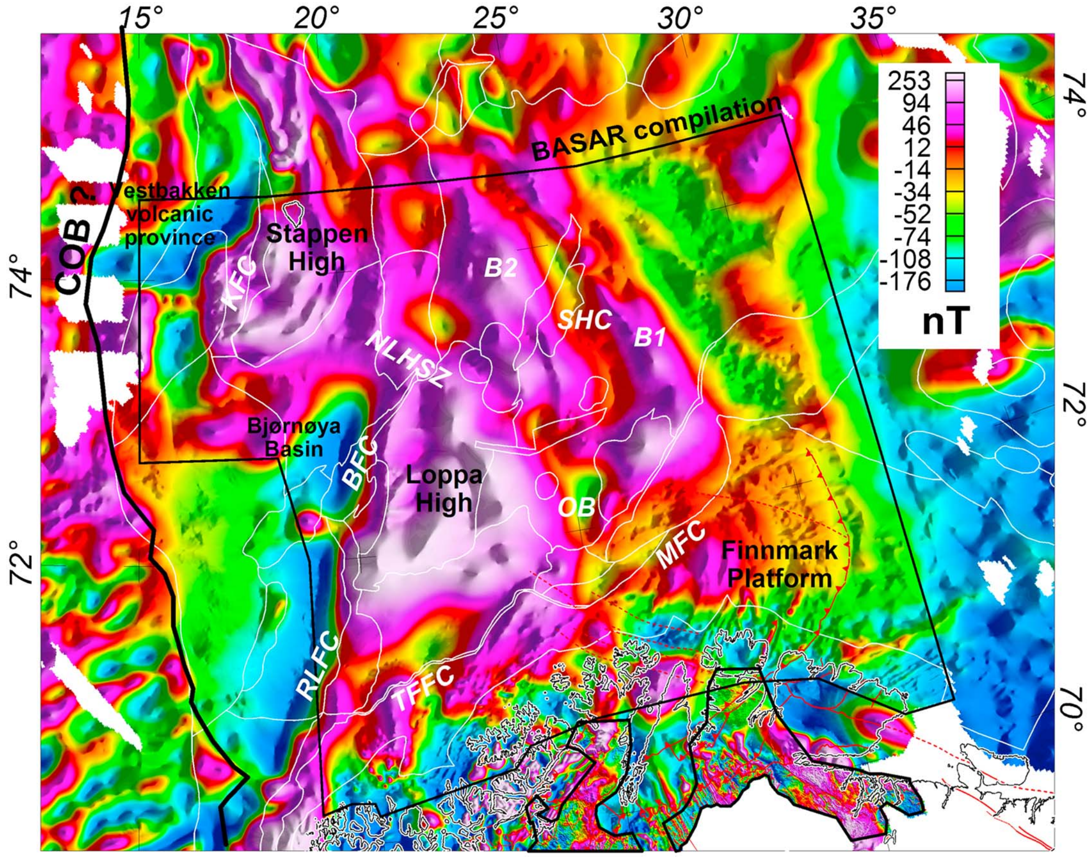

Figure 3. New magnetic total field anomaly map of the southwestern Barents Sea after processing, International Geomagnetic Reference Field (IGRF) correction, and merging with the preexisting data set. The grid cell size of the map displayed is 500 m × 500 m. BFC: Bjørnøyrenna Fault Complex; OB: Ottar Basin (south); RLFC: Ringvassøy-Loppa Fault Complex; SHC: deep late Paleozoic Scott Hansen Complex (informal); MFC: Måsøy Fault Complex; NLHSZ: North Loppa High shear zone (informal name); TFFC: Troms-Finnmark Fault Complex. B1 and B2 represent the main NNW-SSE positive magnetic anomalies observed in the Bjarmeland Platform area.

stages of sedimentary basin investigation [*Hinze et al.*, 2013]. In frontier areas where seismic data are sparse or nonexistent, aeromagnetic acquisition is the most efficient and economical way to assess or refine the structural setting. Aeromagnetic data in particular have been applied in investigating the basement and deeper structures of the SWBS [*Åm*, 1975; *Skilbrei*, 1995] and have recently been used to model the 3-D crustal architecture of the Barents Sea Shelf [*Barrère et al.*, 2009; *Marello et al.*, 2013]. However, because of diurnal artefacts, navigation errors and poor resolution of the vintage magnetic data (Figure 2a), acquired in the 1970s and 1980s, the preexisting magnetic data set of the SWBS [*Olesen et al.*, 2010; *Gaina et al.*, 2011] was of relatively low quality and not entirely reliable for accurate qualitative and quantitative interpretation at the basin scale. Consequently, a systematic remapping of the entire SWBS with state-of-the-art, high-resolution aeromagnetic data was required in order to update and replace the vintage magnetic field data set (Figure 2b). Acquired during the summers of 2006, 2008, and 2009, respectively, the new Barents Sea Aeromagnetic Survey 2006 (BAS-06), Southern Nordkapp Aeromagnetic Survey 2006 (SNAS-06), and Barents Sea Aeromagnetic Remapping 2008 (BASAR-08) and 2009 (BASAR-09) surveys, compiled and presented in this paper, cover most of the SWBS, extending from the coastline of Troms and Finnmark, northern Norway, up to the Bjarmeland Platform at around 74°30′N (Figures 1 and 2). The final BASAR compilation extends from about the Tromsø Basin in the west to the border of the former disputed area between Norway and Russia to the east close to 32°W (Figure 2). The new aeromagnetic offshore surveys were carried out in a line/tie-line configuration with profile spacings of 2/6 km (for BAS-06), 2/5 km (for BASAR-08 and BASAR-09), and 500 m/1000 m (for SNAS-06) (Figure 2b). During the acquisition, the sensor altitude was located around 230 m above sea level. For onshore-offshore comparison, we also included and interpreted in our study the recent FRAS-12 (Finnmark Region Airborne Survey) acquired during 2011 and 2012 in northern Norway (Figure 2b). Compared to the offshore

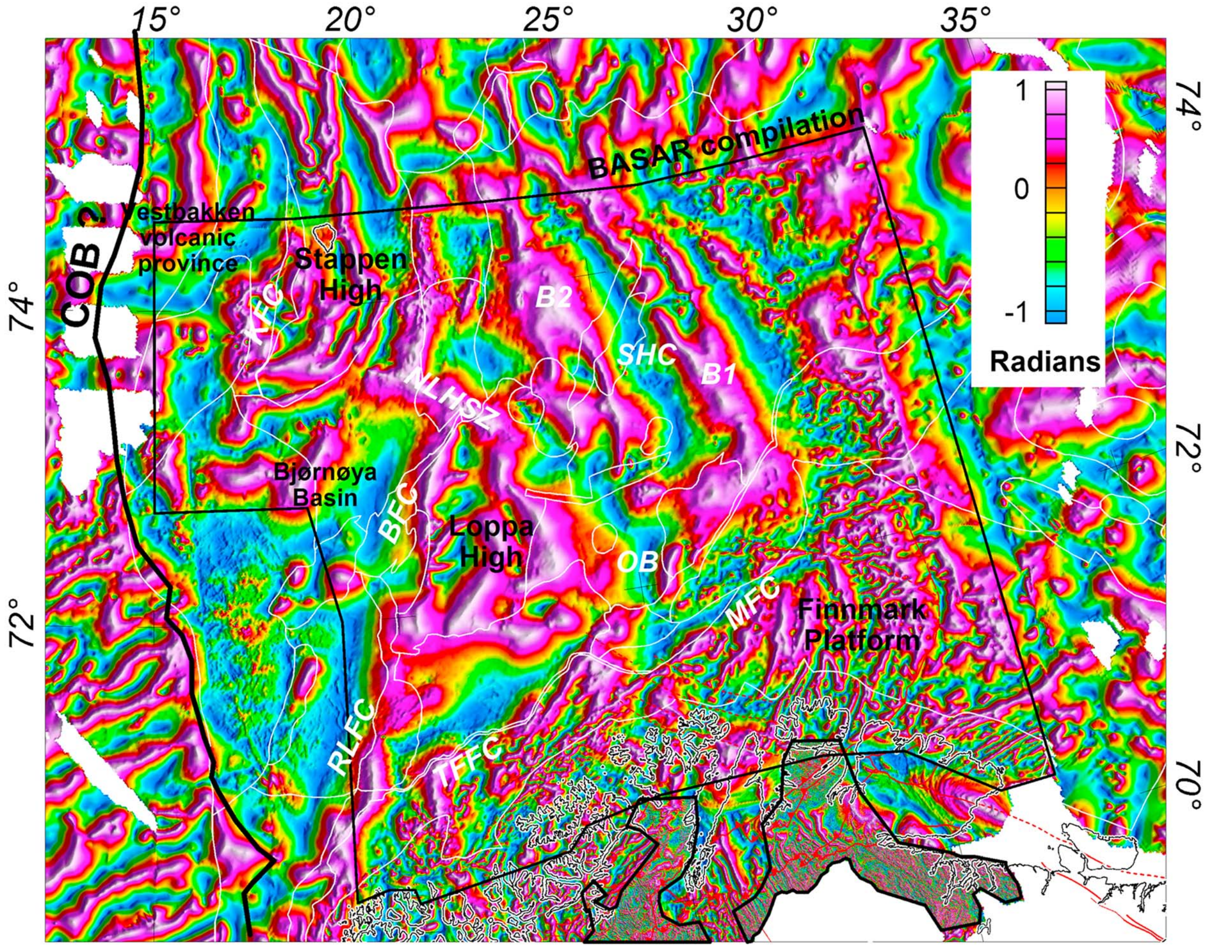

Figure 4. Tilt-derivative filter of the magnetic total field. The filter enhances the subtle magnetic anomalies and maximizes the geometrical contrasts of the internal basin structures. Note the prominent NNW-SSE anomalies that characterize the central Barents Sea and the Bjarmeland Platform. Abbreviations as in Figure 3.

acquisition, the onshore surveys have a much higher resolution with a line/tie-line configuration of 200 × 2000 m and a nominal drape flying altitude of 60 m.

The relatively high number of tie-lines accounts for the large diurnal variations as they occur in such high-latitude areas and were therefore required to ensure proper processing and leveling of the data. Several external, time-varying, field factors usually influence and cause errors during aeromagnetic acquisition. These include altitude variations, magnetic effects of seawater swells, and diurnal variations of the magnetic field (e.g., solar winds), factors which usually explain the errors at crossover points between lines and tie-lines. The most complex and significant problem is probably the diurnal variation of the Earth's magnetic field influenced by solar winds, which is particularly important in such northern latitudes. Even though all the BASAR surveys were carried out during a cycle of low solar activity, diurnal variations in the magnetic field still remained and caused tie-line and regular survey lines to have different readings at intersections. These effects are usually visually distracting, particularly on image-enhanced displays, and would produce artefacts during interpolation and consequently erroneous interpretation if not suitably corrected. The raw data have been processed using both statistical and microleveling methods (using the Oasis Montaj software) including an in-house median filter technique [*Mauring and Kihle*, 2006]. We processed ~174,000 km of new magnetic data in the Barents Shelf, covering a total area of ~216,500 km^2. The onshore FRAS-1 survey was similarly processed by NOVATEM airborne geophysics on behalf of the Geological Survey of Norway (NGU). The onshore magnetic data are composed of 141,400 km of new magnetic profiles, covering a large part of the Finnmark region, and are included in the final grid compilation (Figure 3). A comparison of the vintage magnetic grid with the new one

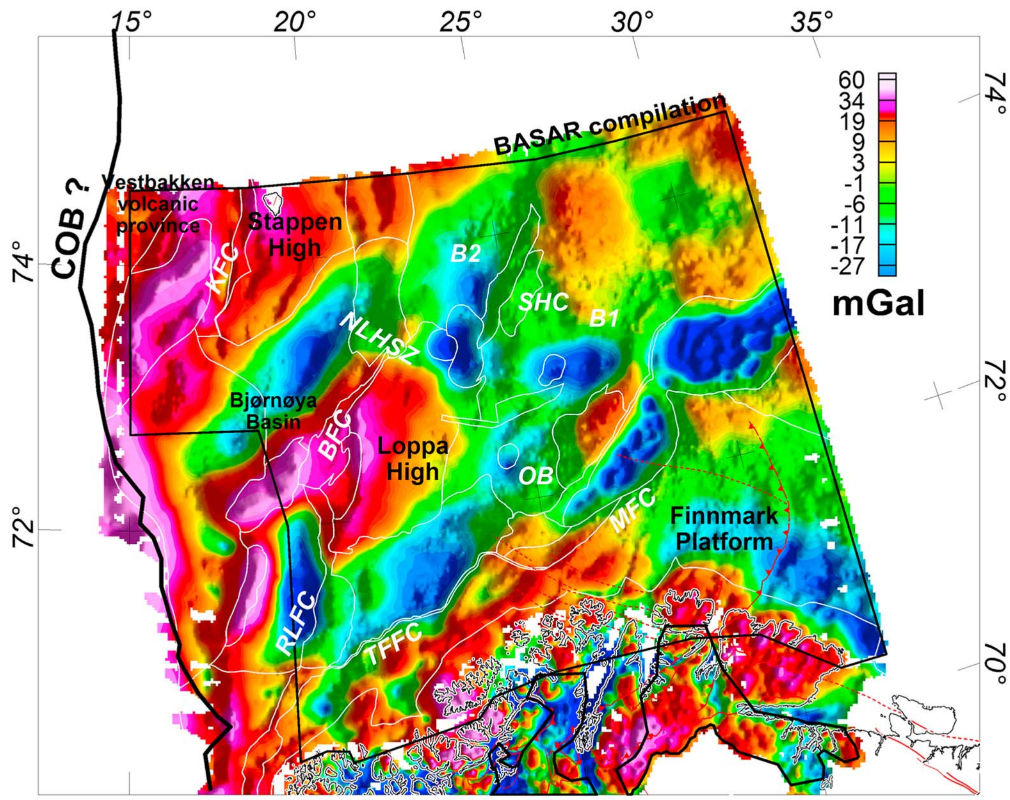

Figure 5. Ship track free-air gravity compilation (2 × 2 km) of the southwestern Barents Sea [after *Olesen et al*., 2010]. Abbreviations as in Figure 3.

shows a major improvement in resolution and a significant change in the visible magnetic anomalies and trends, both onshore and offshore. Significant amplitude discrepancies have been observed, reaching locally up to 70 nT in differences in many parts of the SWBS.

A number of filtering and image enhancements have been subsequently calculated from the magnetic total field to enhance specific magnetic trends and anomalies. Filtering and derivative calculations, especially the normalized tilt-derivative filtering [*Miller and Singh*, 1994] (Figure 4), helped to define different basement domains, subvertical geological boundaries, and faults, together with the gravity map (Figure 5).

4. Interpretation and Geological Implications of the New Aeromagnetic Compilation

4.1. Onshore-Offshore Relationships

For a better link with the geology and tectonic features of northern Norway, the new BASAR surveys were designed to overlap the coastal parts of the Norwegian mainland (Figures 1 and 2). Later, combined with the new FRAS survey, the final compilation allowed us to establish a reliable onshore-offshore correlation and geological interpretation of the magnetic anomalies (Figure 6).

In the Barents Sea Region (Figure 6), about 9 km of Neoproterozoic, deep-to-shallow marine sedimentary rocks was deformed and metamorphosed under lower greenschist facies conditions during the Caledonian orogeny [*Roberts*, 1985; *Rice and Frank*, 2003; *Rice*, 2014]. The southern limit of the Barents Sea Region is delineated by the regional NW-SE trending Trollfjorden-Komagelva Fault Zone, a major Precambrian fault zone that was reactivated during the Timanian and Caledonian orogenies and episodically during late Paleozoic and Mesozoic times (Figure 6). It is well documented onshore [*Siedlecka and Siedlecki*, 1967; *Roberts*, 1972; *Rice et al*., 1989; *Karpuz et al*., 1993; *Roberts and Lippard*, 2005; *Herrevold et al*., 2009] and locally offshore [*Gabrielsen*, 1984; *Roberts et al*., 2011]. Previous authors have proposed a possible extension of this regional fault zone toward the adjacent Hammerfest Basin (Figures 1 and 6), notably to explain the transfer system observed between the Troms-Finnmark Fault Complex and the Måsøy Fault Complex (Figure 6) [*Gabrielsen*, 1984; *Berglund et al*., 1986; *Gabrielsen and Færseth*, 1989].

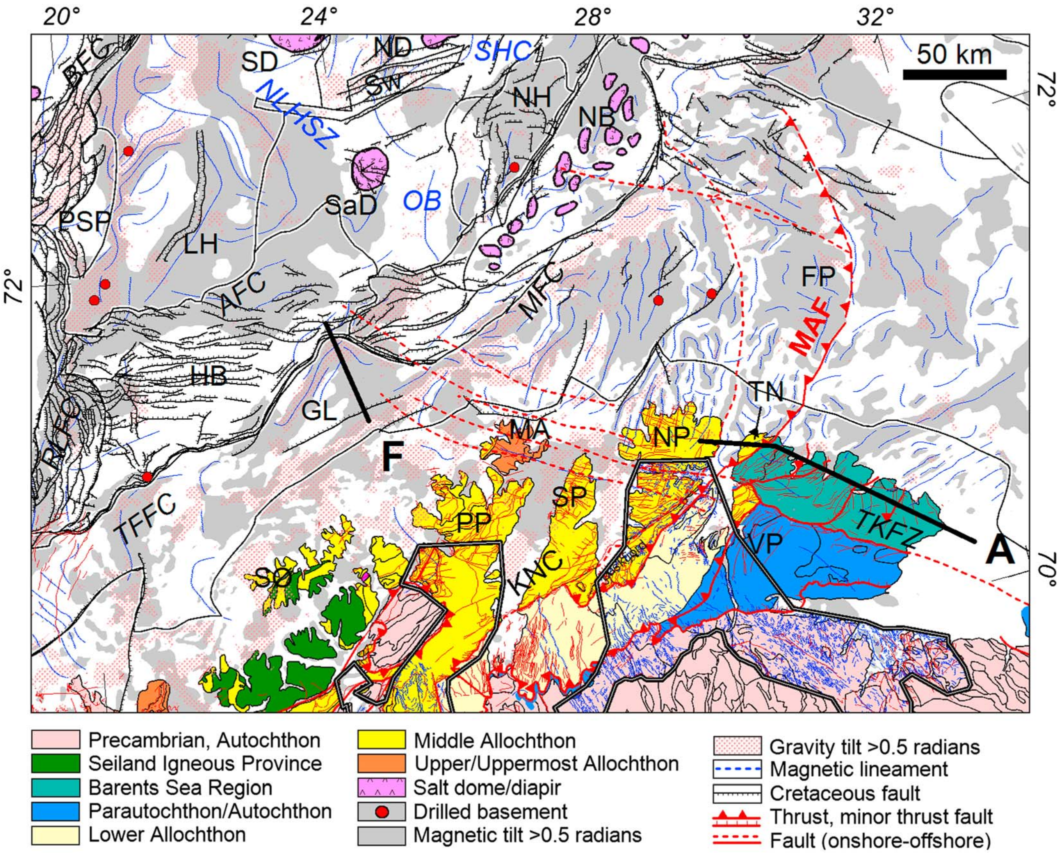

Figure 6. Interpretation of the onshore-offshore structures between the Varanger Peninsula and the surrounding offshore areas on the Finnmark Platform and SWBS. Abbreviations: BFC: Bjørnøyrenna Fault Complex; BP: Bjarmeland Platform; FP: Finnmark Platform; GL: Gjesvær Low; HB: Hammerfest Basin; KNC: Kalak Nappe Complex; LH: Loppa High; MA: Magerøya; MAF: Middle Allochthon front; MFC: Måsøy Fault Complex; NB: Nordkapp Basin; ND: Norvarg Dome; NLHSZ: North Loppa High shear zone (informal); NH: Norsel High; NP: Nordkinn Peninsula; OB: Ottar Basin (south); PP: Porsanger Peninsula; PSP: Polhem Subplatform; RLFC: Ringvassøy-Loppa Fault Complex; SaD: Samson Dome; SD: Svalis Dome; SHC: Paleozoic Scott Hansen Complex (informal); SP: Sværholt Peninsula; Sw: Swaen Graben; SØ: Sørøya; TFFC: Troms-Finnmark Fault Complex; TKFZ: Trollfjorden-Komagelva Fault Zone; TN: Tanahorn Nappe; VP: Varanger Peninsula. The red circles represent the boreholes that penetrate basement rocks. The structural and geological boundaries have been modified after existing onshore [*Siedlecka and Roberts*, 1996; *Sigmond*, 2002] and offshore [*Gabrielsen et al.*, 1990] geological maps. Tectonostratigraphical subdivisions of the Scandinavian Caledonides after *Roberts and Gee* [1985]. A and F represent the sections displayed on Figures 7 and 9.

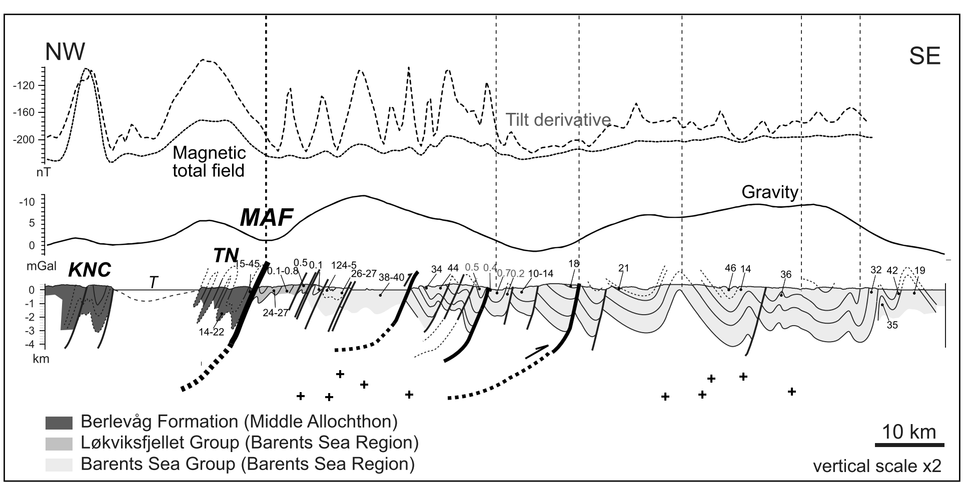

Figure 7. Geological cross section across the Kalak Nappe Complex and the Barents Sea Region of the Varanger Peninsula. A good correlation between the onshore Caledonian thrust-and-fold-belt and the prominent NE-SW magnetic trends is observed (cf. Figure 6). Numbers indicate the susceptibility measurements (×1000 SI) recorded along the geological section. KNC: Kalak Nappe Complex; MAF: Middle Allochthon front; T: Tanafjorden (fjord); TN: Tanahorn Nappe. Location in Figures 1 and 6, line A.

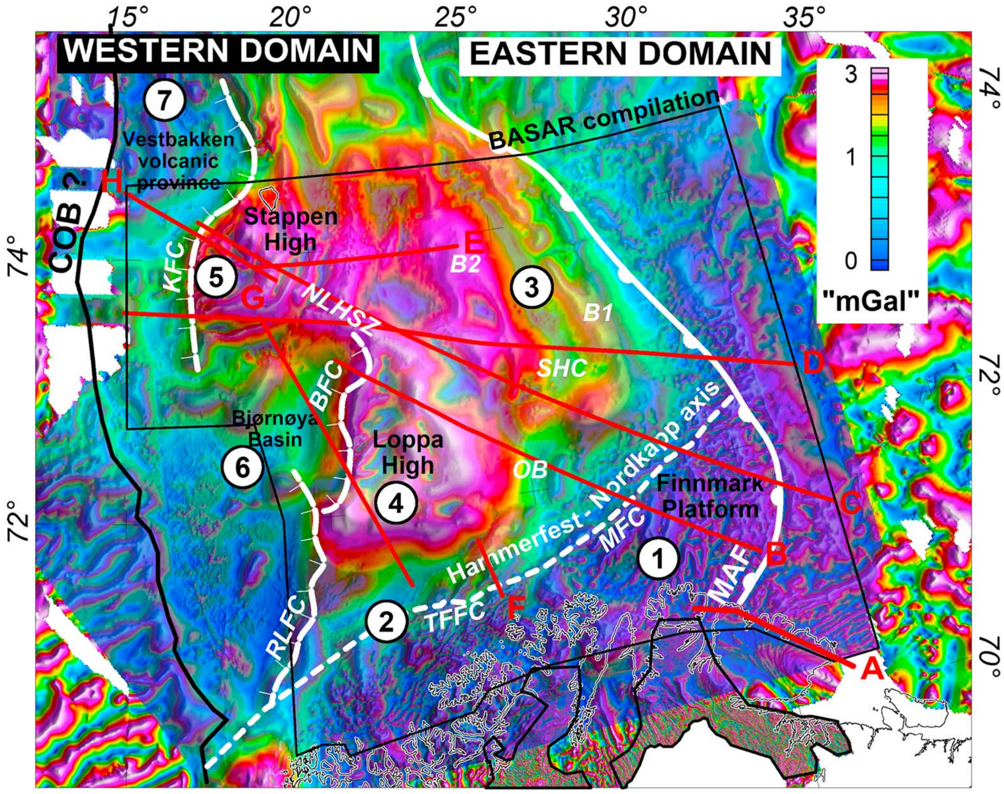

Figure 8. Combined picture of the magnetic TDR together with the pseudogravity signal of the new magnetic total field. The pseudogravity filtering of the magnetic field was used to "simulate" a gravity anomaly that would be observed if density contrasts were proportional to magnetization contrasts and under the assumption that the basement is magnetized uniformly by induction [*Baranov*, 1957]. This picture illustrates well the main crustal domains identified in the southwestern Barents Sea and further discussed in the text. One can recognize (1) the Finnmark Platform, in dominant blue/purple colors, where the original Caledonian structural grain is best preserved as indicated by the tilt-magnetic pattern. Both late Paleozoic and Mesozoic extensions appear to have been more seriously active NW of a major structural trend defined by (2) the Hammerfest-Nordkapp axis which is a major crustal hinge zone between the stable domain and the northern and western domains affected by both late Paleozoic and Mesozoic extensions. North of the Hammefest-Nordkapp axis, (3) late Paleozoic reactivation of the Caledonian nappe is proposed in the Ottar Basin and in the Scott Hansen Complex (SHC), where deep late Paleozoic basins are expected along the NNW-SSE trends. In this western domain, the Loppa and Stappen Highs (4 and 5) represent rigid continental block as ribbons, interpreted to be part of a massive crustal and possibly autochthonous Precambrian crustal substratum (underlined by the dominant red pseudogravity colors) that is expected to occur beneath the Caledonian nappes. Around and inside the massive substratum, the blue pseudogravity colors highlight the necking zones of relatively highly extended basins, observed at the level of the Bjørnøya Basin (6) and west of the Stappen High (7). The pseudogravity was computed using a density contrast of 1.5 g cm^{-3} and a magnetization of 3 A/m and assumes a Poisson relationship between gravity and the magnetic total field [*Blakely*, 1995]. Abbreviations as in Figure 3.

Caledonian folding and minor thrusting along a broadly NE-SW structural trend have affected the Neoproterozoic sedimentary successions of the Barents Sea Region [*Roberts*, 1972; *Rice et al.*, 1989] (Figure 6). In addition, rocks in the extreme northeast of Varanger Peninsula were earlier deformed during the Timanian orogeny and show a general NW-SE to NNW-SSE structural grain, as on the nearby Rybachi Peninsula of NW Russia [*Roberts*, 1995]. In northwestern Varanger Peninsula, the Tanahorn Nappe [*Siedlecka and Roberts*, 1992] forms part of the Middle Allochthon but has disputed affinity, correlating with either the Kalak or the Laksefjord Nappe Complex (Figure 6). Rocks of the Kalak Nappe Complex (Middle Allochthon) occur extensively on the nearby Nordkinn Peninsula and father southwest. Their mylonitic thrust base represents a major tectonic and boundary in the Caledonides of Finnmark [*Gayer et al.*, 1987; *Siedlecka and Roberts*, 1996].

In general, several structural elements of the Varanger and Nordkinn peninsulas show a good correlation with the new and dominant, NE-SW to NNE-SSW, Caledonian and magnetic trends revealed by the recent surveys (Figures 3, 4, and 6). In the Barents Sea Region, we can locally see the prolongation and magnetic influence of the NW-SE to NNW-SSE anomalies trends observed in the Fennoscandian Shield (Archaean to Paleoproterozoic Autochthon; Figures 1, 3, and 6). Local N-S Caledonian faults are also observed farther south and correlate with the new magnetic features. In the Middle Allochthon and in the Lower Allochthon of the Barents Sea Region

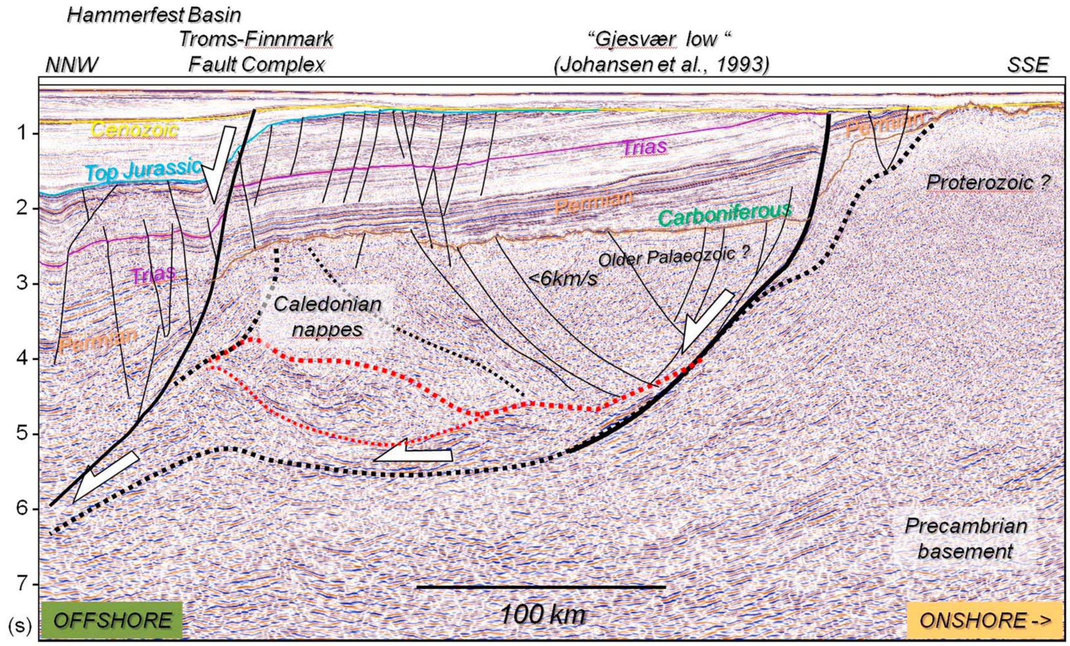

Figure 9. Seismic line across the edge of the Hammerfest-Nordkapp axis (see Figures 6 and 10). Here we can recognize evidence of several cases of major reactivation of Caledonian structures. The main detachment was already active during the late Paleozoic and reactivated later during Mesozoic time. Locally, the low-angle reactivation is bending to a higher angle at the margin of the Hammerfest and Nordkapp Basins, which represent graben features already developed in late Paleozoic time.

(Figure 6), the observed magnetization of the contrasting Caledonian nappes derives mostly from deformed, Neoproterozoic, cross-bedded sandstones with foresets containing dark-grey to black, heavy-mineral layers up to 2.5 cm thick and composed mainly of high magnetic minerals such as magnetite, hematite, and ilmenite [*Olesen et al*., 1990]. There are also abundant metadolerite dykes of probable Ediacaran age [*Rice et al*., 2004], now aligned parallel to the dominant trend of the Caledonian folds and reverse faults, and which are likely to contribute locally to the higher magnetic response observed in the Finnmark Platform (Figures 4 and 6). Compared to previous magnetic studies [*Åm*, 1975; *Karpuz et al*., 1993], the magnetic expression associated with the Trollfjord-Komagelva Fault Zone and subparallel faults is now particularly well resolved on the Finnmark Platform, and the northern part of the FRAS-1 data (Figures 3, 4, and 6) clearly highlights the importance of the NW-SE lineations interpreted as reactivated faults and/or dykes (no age dating available) emplaced along the regional trend of this major fault zone (Figures 4 and 6). In the proximal offshore domain, the noticeable main magnetic signature is associated mainly with the Caledonian structures observed onshore (Figures 4, 6, and 7). For example, the N°25 to N°45 trends observed in the southwestern part of the survey area northward to the Nordkapp Basin coincide with Caledonian fault-propagation folds and thrusts that gradually steepen to near vertical toward the southeast (Figure 7). East of the Tanahorn Nappe, the magnetic trends vary mainly from N°45 close to the Tanahorn basal thrust (Figures 6 and 7) to N°70–N°80 farther to the east in the direction of the former disputed sea area between Norway and Russia. Offshore from Vardø, the NW-SE Timanian structures are almost completely overprinted by the Caledonian but are clear to see on bathymetric data [*Roberts et al*., 2011]. The well-established onshore-offshore relationships also show that the Caledonian grain linked with the magnetics remains relatively well preserved and does not show any strong evidence of later, major crustal deformation. A large part of the Finnmark Platform has remained relatively stable since the end of the Caledonian orogeny, i.e., since Early to Middle Devonian time, and just shows minor reactivation of the basement trends.

Farther westward, it appears not only that the low magnetic Kalak Nappe Complex increasingly blurs the signal of the underlying Precambrian basement [*Åm*, 1975; *Olesen et al*., 1990, *Brönner et al*., 2010] but also that the mapped contacts and faults are less well expressed in the magnetic data. An exception is provided by the highly magnetic, ultramafic, and mafic complexes of the Seiland Igneous Province in western Finnmark, in the highest thrust sheet of the Kalak Nappe Complex (Figure 1). On Magerøya and on the Porsanger and Sværholt Peninsulas (Figure 6), the magnetic anomalies have rather small amplitudes but a comparison with onshore geology still reveals a

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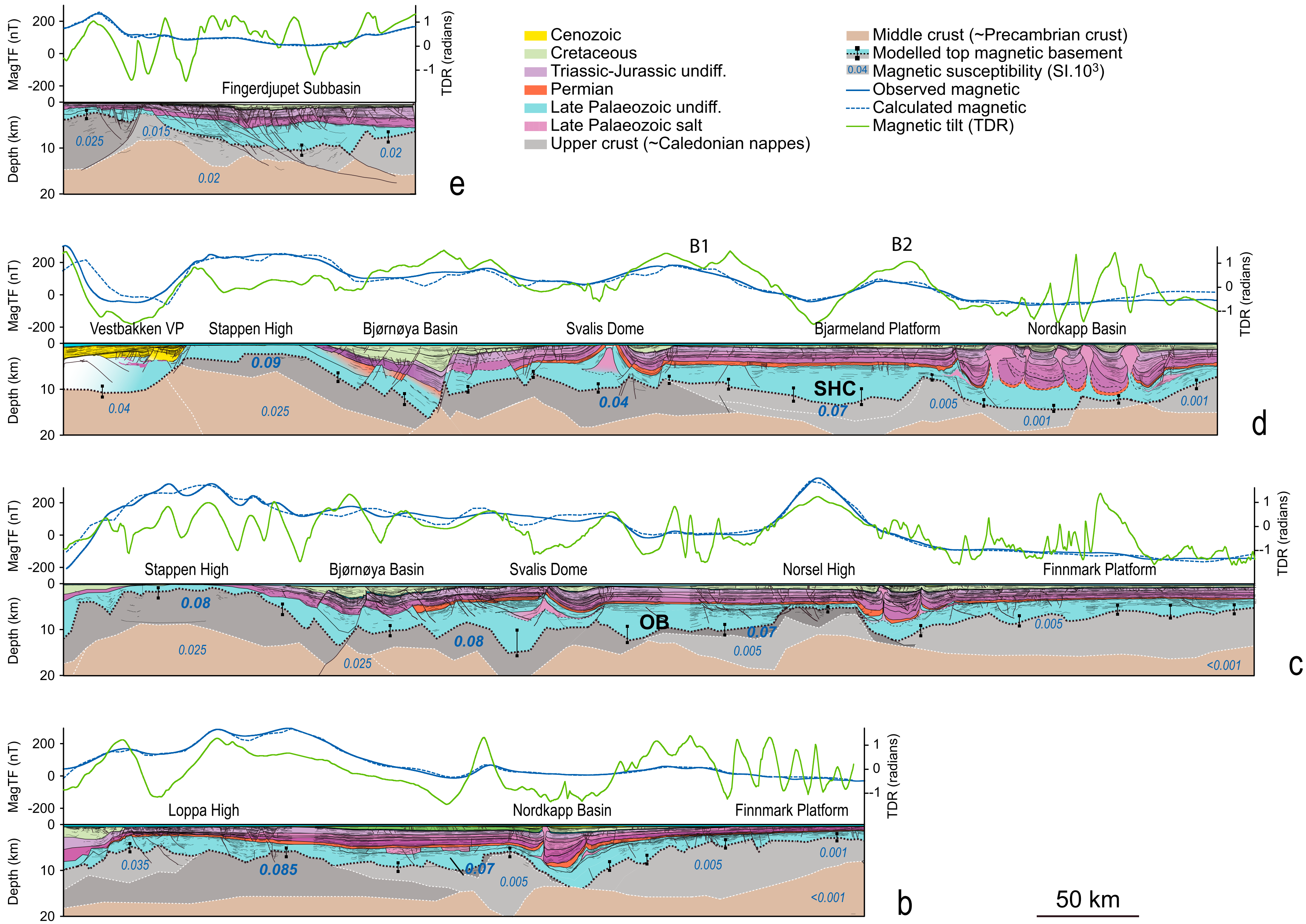

Figure 10. (a) Regional crustal cross sections of the southwestern Barents Sea (Lines B, C, D, E on Figures 1 and 8). The black dashed lines and vertical error bars in Figure 10a indicate the depth estimation (and its uncertainties) to top (magnetic) basement obtained by potential field modeling. The white dashed lines indicate the limit of magnetic blocks defined in the magnetic modeling. The magnetic anomalies mostly reflect the deep (pre-Permian) basement highs (B1 and B2 also in Figure 4) and lows that are thought to occur beneath the thick Mesozoic platforms and grabens. OB and SHC indicate the locations of the deep Paleozoic N-S Ottar Basin and the adjacent NNW-SSE Scott Hansen Complex, respectively, which are expected to occur beneath the Mesozoic sediments. The top magnetic basement has been estimated using the classic forward modeling approach of *Talwani and Heirtzler* [1964]. Indicated values indicate the rock susceptibilities modeling (in SI units) extrapolated from the onshore measurements and subsequently adjusted to obtain the best fit between the observed and calculated magnetic field.

correlation of contacts and faults with the magnetic signature. The dominant NW-SE trend subparallel to the Trollfjorden-Komagelva Fault Zone is gradually fading out to the northwest and a NNE-SSW magnetic trend parallel to the Hammerfest-Nordkapp axis gradually becomes dominant.

4.2. Late Paleozoic Reactivation of the Epicontinental Grabens on the SWBS

The Neoarchaean to Paleoproterozoic crystalline basement beneath the Finnmark Platform and its cover of latest Mesoproterozoic to Neoproterozoic metasedimentary rocks usually show a progressive deepening toward the Nordkapp Basin and the Bjarmeland Platform (Figure 1). This mostly explains the decrease in high frequency of the magnetic field anomalies, which appear to be smoother to the north where the basement is deeper (Figures 3). The transition between the northern magnetic domain (lower frequencies) and the Finnmark Platform (higher frequencies) coincides with the Hammerfest-Nordkapp axis that defines a clear geophysical and crustal boundary in the SWBS. An exception, however, is the Nordkapp Basin where the high frequencies observed (Figure 4) mostly reflect shallow, salt diapir-related features [*Gernigon et al*., 2011]. Combined with the magnetic tilt derivative, the pseudogravity filtering [*Baranov*, 1957] delineates and highlights better the main magnetic and crustal domains of the SWBS and illustrates the main differences on both sides of the Hammerfest-Nordkapp axis (Figure 8). The Hammerfest-Nordkapp axis represents a narrow (100–200 km wide) crustal hinge zone that delimits in space and time the Finnmark Platform from the northern areas affected by significant crustal stretching and graben formation (e.g., Figure 6). Along this hinge zone, reactivated old detachment surfaces (interpreted as old Caledonian thrusts) have been detected and locally cut at a higher angle to form farther north the major graben border fault complexes (e.g., Troms-Finnmark, Måsøy, and Thor Iversen Fault Complexes; Figures 6, 8, and 9). Low-angle detachment surfaces observed south of the graben border fault complexes show evidence of both Paleozoic and Mesozoic reactivation, particularly well expressed at the level of the Gjesvær Low, southeast of the Hammerfest Basin (Figure 9) [e.g., *Johansen et al*., 1994; *Gudlaugsson et al*., 1998]. These detachment surfaces have been interpreted as old thrust faults, reactivated later during late Paleozoic extension. West and north of the Hammerfest-Nordkapp axis, preexisting late Paleozoic basins have been further reactivated and affected by subsequent Mesozoic extension and salt tectonics [*Jensen and Sørensen*, 1992; *Gabrielsen et al*., 1990; *Nilsen et al*., 1995].

In the Bjarmeland Platform (Figure 1), older Paleozoic basins and half-grabens related to phases of crustal extension have also been suggested for Middle-Late Devonian, Carboniferous, and Permian times [*Dengo and Røssland*, 1992; *Bugge et al*., 1995; *Breivik et al*., 1995; *Gudlaugsson et al*., 1998]. However, except for the presence of the salt pillows and a few well calibrations [*Larssen et al*., 2005], poor seismic resolution usually makes the determination of Paleozoic sediment thicknesses and structures of these deeply buried basins very uncertain in most of the SWBS. Only a few wells have penetrated the Early to Middle Paleozoic and/or older crystalline basement in the SWBS [*Bugge et al*., 1995; *Larssen et al*., 2005; *Slagstad et al*., 2008] (Figures 1 and 6, red circles). The presence of deeply buried salt pillows (e.g., Samson and Norvarg domes in Figure 1) suggests, however, that poorly mobilized mid-Carboniferous to Early Permian, stratified salt deposits exist and are still preserved underneath the main platform areas of the SWBS. Compared to the Nordkapp and the Bjørnøya Basins, a large part of the Bjarmeland Platform and its deep salt structures was hardly, if at all, affected by significant (crustal scale) Mesozoic extension and halokinesis [*Nilsen et al*., 1995; *Gernigon et al*., 2011]. Our potential field modeling suggests that thick Paleozoic basins are expected to lie beneath the Permian succession on the southern Bjarmeland Platform (Figure 10). Thick and deep, late Paleozoic basins are also expected in the "Ottar Basin," defined between the Norsel and the Loppa Highs [e.g., *Breivik et al*., 1995]. On the northern Bjarmeland Platform, the new aeromagnetic surveys clearly highlight prominent NNW-SSE to NW-SE trending magnetic anomalies (Figure 4). Correlated with seismic, the main magnetic features do not correspond to any particular Mesozoic structures within the Bjarmeland Platform, which remains a relatively uniform platform above the top Permian marker (see Figure 10). The magnetic properties from published well-core measurements in the Barents Sea area [*Lauritsen et al*., 2007] also confirm that the Mesozoic sedimentary rocks in the SWBS have low magnetic susceptibilities. Such low susceptibilities (<0.001 SI) cannot explain the important amplitudes observed. Due to the strong magnetization required to produce the observed magnetic signal and because of the lack of observed intrusions and/or volcanic material in the Mesozoic section, we proposed that the magnetic pattern in the Bjarmeland Platform reflects deeper basement bodies with high susceptibility and/or remanent magnetization [*Gernigon and Brönner*, 2012]. The forward modeling carried out across the NNW-SSE trending anomalies observed on the Bjarmeland Platform

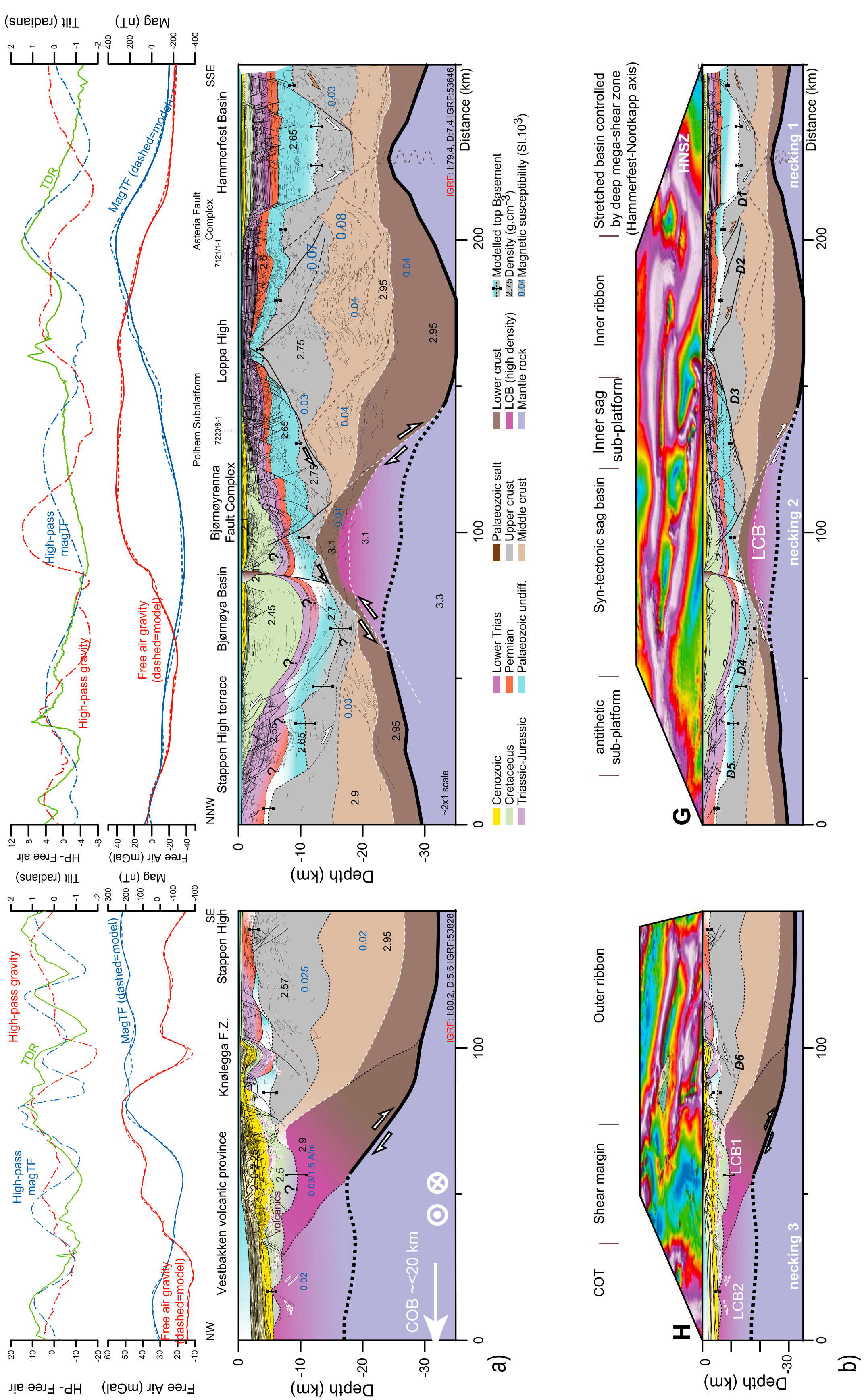

Figure 11. (a) Crustal section across the western rifted complex and margin derived from long-offset seismic observation and potential field modeling (see location and correlation with Figures 1 and 8). (b) Similar section at 1:1 scale with the outline of the main structural features discussed in the text. In this western domain, we propose a model of crustal boudinage where both the Stappen and the Loppa Highs represent massive and rigid continental ribbons, separated by thin to very thin crust and basins (one propagating observed at the level of the Bjørnøya Basin and another necking zone associated with the Late Cretaceous–Paleocene shear margin development west of the Stappen High). LCB: high-density lower crustal body. D1 to D5 refer to the main detachment faults discussed in the text.

and surroundings suggests a significant thickness (up to 5 km) of late Paleozoic sediments and the underlying, folded, but nonmagnetic, (meta)sedimentary successions (Figure 10). The sedimentary/metasedimentary depocenter underneath the Permian, suggested by the modeling, fits with the location of the dominant, NNW-SSE, low magnetic, elongated anomalies highlighted by the tilt-derivative filtering of the total magnetic field (Figures 4 and 10). For example, anomalies B1 and B2 (Figures 4 and 10) are further interpreted and modeled as two Paleozoic basement highs separated by a basement low modeled in the vicinity of the Norvarg Dome, a large late Paleozoic salt pillow slightly mobilized during Mesozoic and Cenozoic times [e.g., *Gabrielsen et al*., 1990] (Figure 1). The low magnetic anomaly signatures observed on the Bjarmeland Platform represent for us the signature of a deep Paleozoic basement (horst and graben) system, which has been informally named the Scott Hansen Complex [*Gernigon and Brönner*, 2012]. As part of this complex, the B1 anomaly (interpreted as a basement high) extends to the south and correlates with the Norsel High magnetic signature, which also correlates with a prominent basement high, flanked by deep NNW-SSE striking basins with low magnetic signatures (Figure 10). The Norsel High (Figures 1 and 6) has been tested by the well 7226/11-1 and bottoms in a metamorphic basement (gneiss and schist) directly overlain by Bashkirian carbonates at around 5 km depth [*Slagstad et al*., 2008]. This depth almost fits the magnetic top basement estimation derived from our section modeling located close behind the well (Figure 10).

Southwest of the Scott Hansen Complex, a low magnetic signature also correlates with the (southern) Ottar Basin, which has earlier been considered to be a major Paleozoic rift basin following a NE-SW orientation [*Breivik et al*., 1995]. Our potential field modeling also agrees with the presence of a deeper magnetic basement here, which may also witness the presence of a late Paleozoic basin (Figure 10). Our study suggests, however, that the main structural trends of the Ottar Basin should be predominantly N-S to NNE-SSW in the light of the new aeromagnetic results (Figure 4). The magnetic pattern suggests that the southern Ottar Basin and the NNW-SSE Scott Hansen Complex, as defined and revised in the present study, are two separate structural provinces and do not necessarily represent a unique and uniform, NE-SW oriented, Paleozoic system. However, we consider that they could have had a relatively similar history. At a regional scale, the depocenters of the Norvarg and Samson Domes both coincide with the low magnetic, tilt-derivative anomalies and the outlines of the proposed late Paleozoic basins (Figure 4). The transition between the southern Ottar Basin and the NNW-SSE trending Scott Hansen Complex is interpreted as a late Paleozoic transfer zone that matches with the outline of the narrow Swaen Graben defined at the Mesozoic level (Figures 1 and 6) [*Gabrielsen et al*., 1990]. The Swaen Graben is associated with deeper Paleozoic and basement structures, highlighted by the new surveys, and reactivation of the deep structure may have controlled the present-day geometry of the overlying Mesozoic graben. The deep, NNW-SSE trending basement highs (anomalies B1 and B2) and adjacent basins identified from the magnetic data do not have any clear gravity signature (Figure 5), which confirms the low-grade mobilization status and high degree of compaction of the deeper sedimentary succession expected beneath the Permian sediments ($>$5 km depth). It is likely that the low-density contrast with the surrounding basement makes these basins almost invisible on gravity data due to the lack of contrast between the deeply buried metasedimentary rocks and original crystalline basement. The incompressible salt layers, locally witnessed by the salt pillows, could also have extended over the original NNW-SSE graben and these may also have contributed with their low-density properties, simply blurring the gravity signature of the deeper Paleozoic and basement structures. Assuming close relationships between the low tilt-derivative anomalies and the locations of the deep basins, we also expect to find thick late Paleozoic basins near to the Svalis Dome and in the deep parts of the Fingerdjupet Sub-basin (Figures 10b and 10c). This last basin could have been controlled by a major NE dipping detachment that has been observed locally on seismic [e.g., *Gudlaugsson et al*., 1998]. Our top basement estimation proposes a maximum top basement at 10 km, shallowing to less than 5 km at the level of the Stappen High (Figure 10d).

5. The Western Rifted Complex and Margin

The western rifted complex is characterized by a complex system of basins and basement highs illustrated by the transect shown in Figure 11. This western rifted complex illustrates the ultimate stage of stretching and thinning of the Precambrian and Caledonian continental crust until it reached the stage of continental breakup in early Tertiary time [*Faleide et al*., 2008]. Combined with seismic modeling, the new magnetic data set and the gravity outline the main crustal architecture of the western rifted complex and margin.

5.1. Main Crustal Elements

5.1.1. Hammerfest Basin

The Hammerfest Basin (Figures 1, 6, and 11) is a relatively shallow Mesozoic basin, 50–75 km wide, and located between the Finnmark Platform and the Loppa High [*Berglund et al*., 1986]. The basin is separated from the Finnmark Platform to the SSE by the Troms-Finnmark Fault Complex and from the Loppa High to the north by the Asterias Fault Complex (Figures 6 and 11). The basin developed at the edge of the regional Hammerfest-Nordkapp axis where the origin of the Hammerfest Basin can be traced back to the stage of inferred, post-Caledonian, orogenic collapse (e.g., Figures 8 and 9). This graben-type feature has been affected by extension in the Carboniferous [*Berglund et al*., 1986] and also from Triassic to Early Jurassic time [*Gabrielsen et al*., 1990]. The basin was a distinct depocenter already in Early Triassic time *Smelror et al*. [2009] and the main stretching episode is clearly documented to have been initiated in the Middle Jurassic and continued during a period of major tectonic subsidence in Early Cretaceous time. The structure of the basin is mostly dominated by extension and shows a clear graben (stretching type) feature. Strike-slip deformation was also suggested to have occurred in Late Jurassic–Early Cretaceous [*Gabrielsen and Færseth*, 1989]. The Hammerfest Basin includes both deep-seated, high-angle faults along the basin margin (Figure 9) and shallower normal faults that detached in the Permian-Carboniferous strata as earlier suggested by *Gabrielsen and Færseth* [1989] (Figure 11). The prolongation of the Trollfjord-Komagelva fault trend, now well constrained by the new magnetic data set (Figures 4 and 6), could explain the subdivision of the Hammerfest Basin [*Roberts and Lippard*, 2005]. The Hammerfest Basin has a clear magnetic low signature and the top crystalline (magnetic) basement has been estimated at a maximum depth of 9–10 km, also supporting the presence of deep Paleozoic sediments between the reactivated Caledonian basement and the Mesozoic formations (Figure 11).

5.1.2. Loppa High

Farther north, the Loppa High is one of the main structural and basement highs of the SWBS (Figures 1, 10, and 11). Deep-seated block faulting coincides with the Loppa High's diamond-shaped magnetic outline, which also fits with a clear gravity signature (Figures 5 and 11). Bordering the Loppa High to the west, the Bjørnøyrenna and Ringvassøy-Loppa Fault Complexes [*Gabrielsen et al*., 1990] are well characterized by positive N-S magnetic anomalies on the tilt-derivative filtered grid (Figures 3 and 4). Some of these faults detached near the base Permian, possibly above thin salt layers that are identified on the southern flank of the Loppa High (Figure 11).

The seismic profile crossing the western boundary of the Loppa High shows clear evidence of syntectonic sedimentation in response to down-to-the-west normal downfaulting toward the Bjørnøya Basin (Figures 10 and 11). The faulting occurred mostly in the Mesozoic (Jurassic-Cretaceous), although earlier movements are also documented from the Permian to the Early Triassic. An angular unconformity at the crest of the Loppa High was partly caused by footwall uplift and erosion in response to tectonic "unroofing" during the Carboniferous rifting phase [*Gudlaugsson et al*., 1998]. Flank uplift could have initiated earlier in Late Devonian time during the inferred post-orogenic collapse [*Barrère et al*., 2009].

The Loppa High has been affected by several phases of uplift/subsidence and subsequent tilting and erosion. Recent reassessment of the upper Paleozoic stratigraphy [*Larssen et al*., 2005] interprets this structure as a mid-Carboniferous rift (topography) filled and draped successively by upper Paleozoic siliciclastic deposits, evaporates, and carbonates. The relatively thick Upper Permian successions observed west of the High were likely sourced from the paleo-Loppa High and potentially also from the paleo-Stappen High or NE Greenland Platform which were closely related before the rifting and thinning of the Bjørnøya Basin.

Our interpretation of sections G and H (Figures 1 and 11) suggests the presence of synrift and pre-Permian wedges on the footwall of the main Loppa High that could represent Carboniferous and/or older, late Paleozoic, undifferentiated sedimentary rocks. On the eastern flank of the Loppa High, faulting and block tilting on the section are documented from the Late Permian to the Early Triassic, and gradual onlaps of the Early and Middle Triassic sequences are observed before an unclear phase of rapid subsidence documented in the Late Triassic [*Larssen et al*., 2005; *Glørstad-Clark et al*., 2010]. Early-Middle Triassic fault activity also coincides with a phase of minor uplift, associated with footwall uplift accommodated by the Bjørnøyrenna and Ringvassøy-Loppa Fault Complexes. Between the Polhem Subplatform and Loppa High, we have observed a major seismic contrast between the continuous reflections of the sedimentary layers of the Polhem Subplatform and the irregular, low-reflective, seismic facies interpreted as crystalline basement (Figure 11). This contrast can be followed obliquely underneath the Polhem Subplatform toward the bottom of the Bjørnøya Basin and explains the magnetic slope which is also observed at the same level (Figures 3 and 11). A major crustal detachment is proposed at that level (Figure 11, D3) The shallow faults observed on the Polhem Subplatform were formed during Triassic, Jurassic, and Cretaceous time, leading to the formation of numerous faulted blocks and traps such as the Havis and Skrugard prospects.

5.1.3. Bjørnøya Basin

The Bjørnøya Basin is a large (100–150 km wide) and deep sag basin (depth up to 10 km) limited to the west by the Bjørnøyrenna Fault Complex and to the north by the shallower Fingerdjupet Sub-basin (Figure 1). On the new magnetic compilation, the outline of the Bjørnøya Basin coincides with a V-shaped, low magnetic anomaly lying between the two prominent high magnetic domains defined by the Stappen and Loppa Highs and fitting more or less with the outline of the main Cretaceous depocenter (Figures 3, 4, and 11).

One of the difficulties encountered in the present study was the poor seismic imaging of the deeper parts of the Bjørnøya Basin. Local chaotic facies, salt, and mostly multiples did not allow us to properly constrain the geometry of the basin, neither the nature nor the ages of the deeper horizons, and which are thus still speculative in our interpretation. Before the Middle Triassic, the basin was closely associated with the paleo-Stappen High and paleo-Loppa High to the west. It may also contain a thick Late Permian or older late Paleozoic sedimentary successions [*Barrère et al.*, 2009; *Gabrielsen et al.*, 1990; *Gudlaugsson et al.*, 1998] and possibly much older (nonmagnetic) sedimentary/metasedimentary rocks as suggested by the estimated deep top basement (Figure 11). Tentatively, we propose an estimation of the regional base Cretaceous unconformity along the transect in Figure 11. Despite large uncertainties due to the lack of calibration from wells, the deepest Cretaceous horizon that we could detect and map (at up to 9–10 km, in depth) confirms that the rate of sedimentation during the Cretaceous period was significant. The Late Jurassic–Middle Cretaceous period possibly marks a “sag” phase of the Bjørnøya Basin. Even if minor faulting has affected the basin (mostly on the flanks), the tectonic processes leading to such a deep Cretaceous basin are relatively unclear and could have been driven by a tectonic downflexure of the entire system. The thick Cretaceous successions found in the Bjørnøya Basin are thinning slightly toward the northern part of the Stappen High and the Fingerdjupet Sub-basin and eventually disappeared due to erosion resulting from a significant Tertiary uplift. Compressional features have also been detected by seismics at the edge of the Stappen High. They represent reactivation and inversion of deeper, southeast dipping, low-angle, Cretaceous faults relatively similar to related processes described by *Gabrielsen et al.* [1997] from the eastern side of the Bjørnøya Basin. This phase of compression (Cretaceous-Tertiary) on the eastern flank of the Stappen High has probably been underestimated in previous studies. Accordingly, the Bjørnøya Basin, to some extent, also represented a poorly developed piggyback basin in its latest stage of evolution.

5.1.4. Stappen High and the Western Shear Margin

Northwest of the Bjørnøya Basin, the Stappen High is a pronounced structural high that is also a major crustal element of the western rift complex (Figures 8 and 11). The Stappen High is limited to the west by the Knølegga Fault Complex and to the east by the Sørkapp Basin (Figure 1).

At the level of the Stappen High, a major detachment dipping to the northwest has been observed along the northern flank of the Stappen High, most likely controlling the deep part of the Fingerdjupet Subplatform (Figure 10e) and possibly the southern Sørkapp Basin. It contrasts significantly with the opposite, SW to W dipping, detachment/fault complex that controls the Bjørnøya Basin (Figures 10b, 10c, and 11). It seems that between the Stappen High and the Loppa High, a complex accommodation or relay zone developed between the major detachments. This accommodation zone fits with the termination of the Bjørnøya Basin toward the north and its complex transition with the Fingerdjupet Sub-basin. This transition/accommodation zone is also characterized by a prominent, NW-SE elongated, magnetic anomaly defined as the North Loppa High shear zone in this study (Figures 4 and 8).

One of the interesting aspects of the Stappen High is that this massive block crops out at the level of Bjørnøya Island (Figure 1). There, its metamorphic basement is exposed and has been considered to have a potential Laurentian affinity [*Smith*, 2000]. Although the island is situated on top of the Stappen High, its basement is noticeably low magnetic and thus cannot contribute to the regional high magnetic anomaly which is very similar to the Loppa High. The origin of the high magnetic basement of the Stappen High therefore remains enigmatic. However, the basement and the late Paleozoic to Triassic strata exposed on Bjørnøya [*Braathen et al.*, 1999; *Mørk et al.*, 1990; *Worsley et al.*, 2001] provide direct geological and subsidence information for the Stappen High. Like the Loppa High, the Stappen High experienced a complex but poorly understood tectonic history consisting of phases of faulting, tilting, uplift, and subsidence that resulted in several condensed sequences of Paleozoic and

Triassic sedimentary rocks [*Worsley et al*., 2001]. Southeast of the Stappen High, rifting is thought to have commenced in the late Paleozoic. Carboniferous and Permian fault movements also occurred on Bjørnøya [*Gudlaugsson et al*., 1998; *Braathen et al*., 1999]. During the Early Cretaceous, the Stappen High developed into a shallow marine environment and could have emerged in Valanginian-Barremian time [*Smelror et al*., 2009]. This event initiated the period of major subsidence and the extreme deepening of the Bjørnøya Basin and Sørvestnaget Basin during most of the Cretaceous [*Smelror et al*., 2009; *Worsley et al*., 2001; *Blaich et al*., 2012].

West of the Stappen High, the Late Cretaceous to Paleocene rift phase recorded between Norway and Greenland was progressively dominated by strike-slip movements and deformation within the De Geer Zone leading to the formation of pull-apart basins between the Stappen High and the northeast Greenland margin [*Faleide et al*., 1996; *Tsikalas et al*., 2012]. On the new magnetic map, the basins located west of the Stappen High mostly show a low magnetic signature. The continental strike-slip system was active from the Paleocene to the Eocene. The development of a sheared margin located south and west of the Stappen High is locally associated with a phase of magmatism (e.g., the Vestbakken volcanic province) [*Faleide et al*., 1996]. Due to the volcanism (Figure 11), and also the lack of high-quality magnetic data west of the BASAR survey (Figures 2 and 3) , the nature of the continent-ocean transition and the age of the breakup are still not so well constrained but could have initiated progressively from late Eocene to earliest Oligocene [*Faleide et al*., 1996, 2008].

5.2. Crustal Configuration of the Western Rifted Complex and Margin: Deep Insights

The western rifted complex coincides with prominent positive regions on the gravity and magnetic signal including the features of the Loppa and Stappen Highs (Figures 3 and 5). These anomalies have been interpreted as thick crustal units when combined and modeled together with seismic. The Loppa and Stappen Highs together seem to represent a thick continental domain expected in the western part of the SWBS and highlighted by the pseudogravity map (Figure 8).

Located at the edge of the Hammerfest-Nordkapp axis, the Hammerfest Basin is characterized by a first but moderate necking of the crust at the edge of the Fennoscandian Shield (Figure 11b). Our top basement estimation suggests that the pre-Permian sediments and/or metasedimentary rocks are maximum 5 km thick and confirms the presence of a deeper and older late Paleozoic graben that originally formed along this weakness zone and before the onset of Mesozoic extension.

To the west, the Loppa High represents a thick basement unit. Detachments and/or shear zones (D1, D2, and D3) have been seismically identified on both sides of this basement culmination (Figure 11a). The detachment D1 coincides with the highest magnetic zone observed south of the Loppa High. To explain such a high magnetic signature (Figure 11), we have considered a high susceptibility contrast between D2 and D1 (0.07 and 0.08 SI compared to 0.002–0.003 SI commonly expected as an average for Caledonian nappes. D1 seems to be cut at a higher angle by a steeper and deeper basement fault at the edge of the Hammerfest Basin as observed on the conjugate flank (Figure 9). D2 is delimited to the west by a shallow terrace observed between the Loppa High and the Asterias Fault Complex and shows evidence of reactivation and local inversion. A small Paleozoic graben is expected between D2 and D1 and its outline can be identified and extrapolated on the tilt derivative (Figure 4). The crustal detachment D1 and the Asterias Fault Complex can eventually be associated with a "pop-up" and force-folded structure that is observed adjacent to well 7121/1-1 (Figure 11a). We interpret these features as local transpressional structures that reactivated preexisting, south dipping, Caledonian detachments originally stacked (backthrusted?) on top of the paleo-Loppa High, possibly acting since Caledonian time as a preexisting, Precambrian, autochthonous block.

With a top magnetic basement relatively well constrained on top of the Loppa High, the result of our modeling also shows that the crust at that level is poorly thinned with a crystalline crust reaching from 25 to 35 km in thickness. The maximum crustal thickness of the Loppa High is observed at the level the upper crustal breakaway defined by the major D3 detachment at the eastern edge of the Polhem Subplatform. The top basement reaches 9–11 km in depth underneath the Polhem Subplatform and is expected to attain a maximum depth of 15 km in the central part of the Bjørnøya Basin, assuming that the deeper sediments have been poorly compacted (salt layers are to be expected). West of the Loppa High, D3 defines a supradetachment that controlled the development of the Polhem Platform since late Paleozoic. D3 has been observed on seismic up to 15 km in depth and coincides with a major density contact and contrast between the crystalline crust (2750 kg/m^3) and the deep, preserved, Paleozoic basin lying beneath the Permian (2650 kg/m^3). Here the magnetic signal almost mimics the detachment surface geometry (Figure 11). In the southeastern terrace, the

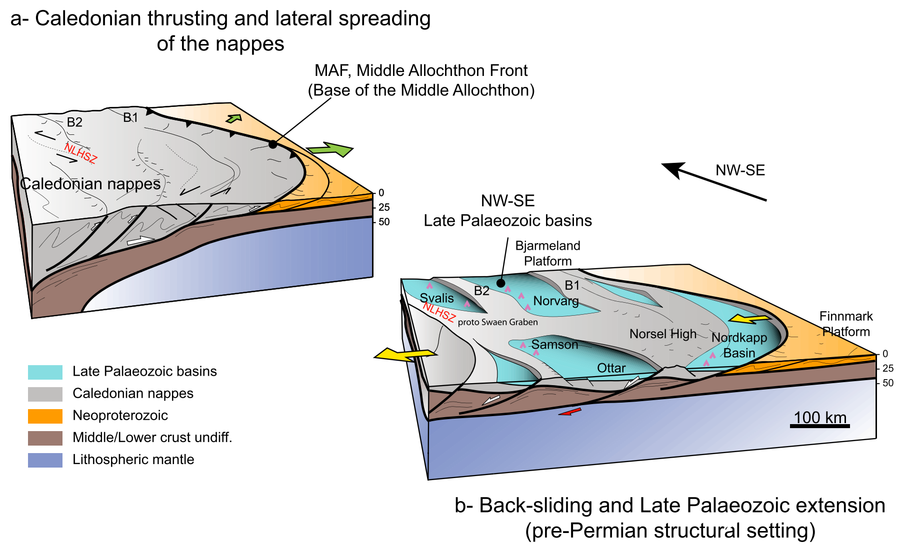

Figure 12. Cartoon illustrating the deep structural evolution of the Bjarmeland Platform. We propose that the original Caledonian grain may have controlled the regional pre-Permian extensional system (Late Devonian–Carboniferous) by reactivation of a Caledonian thrust that collapsed or simply reactivated in the Bjarmeland Platform. The reactivation and backsliding of the main thrusts probably led to the formation of Late Devonian–Carboniferous grabens along the dominant NW-SE to NNW-SSE inherited Caledonian structural grain. NLHSZ: North Loppa High shear zone.

shape of the Tilt derivative filter (TDR) filter fits well with the modeled top basement geometry. The low NE-SW TDR anomalies coincide with the southwestern end of a narrow NE-SW elongated Paleozoic graben (sub-Permian) situated east of the main basement high which itself represents the top of the hanging wall controlled by D3. In its shallow part, D3 separates the sedimentary reflectors of the Polhem Subplatform from irregular and poorly reflective crustal facies in the crystalline basement. At 12 km depth, D3 crosscuts the basement rocks of the Polhem Subplatform, separating two crustal blocks at depth. The detachment dip changes from an angle of 30° to 10° at depth, suggesting a ramp-and-flat geometry. The total apparent throw along this supradetachment D3 is therefore estimated to between 15 and 20 km. Even though more structural investigation is required, we tentatively propose that the steeper Bjørnøyrenna Fault Complex, mostly defined at Mesozoic level, could be the result of flexural rotation/rolling-hinge processes [*Axen and Bartley*, 1997] associated with the uplift of the Loppa High, possibly controlled by active slip motion along D3. The supradetachment D3 could therefore represent a primary breakaway from the Bjørnøyrenna Fault Complex, and this mechanism may help to explain both the progressive westward migration of the Mesozoic faulting that cuts the preexisting basin at higher angles and the episodic flank uplift of the Loppa High.

The Polhem Subplatform, which represents a transitional structural element between the Loppa High and the Bjørnøya Basin, shows a progressive thinning of the continental crust. The uplift of the Moho defines a more pronounced necking zone in our model (Figure 11b, necking 2). Underneath the Bjørnøya Basin, pre-Cretaceous structures and the nature of the crust still remain relatively unclear from seismics due to greater depths and poor imaging, and probably also due to the presence of Paleozoic salt. The quality of the data and the depth of such a block do not allow us to constrain accurately their geometry, but the modeling suggests that the crust underneath the sag is highly thinned. We also expect highly rotated and faulted Paleozoic to Mesozoic structures in the deeper part of the Bjørnøya Basin. A layered seismic pattern is observed beneath the interpreted near-base Cretaceous unconformity that already reaches depths greater than 10–15 km in the central part of the sag. In the shallower part of the Bjørnøya Basin, sediments and metasedimentary rocks (density < 2700 kg/m^3) are suggested to occur beneath the thick Cretaceous succession. Based on the depth of the pre-Cretaceous sediments ($>$10 km), they are most likely affected by low-grade, possibly greenschist facies metamorphism.

In our final model, the Moho was modeled at relatively shallow (20–25 km) depth below the deeper part of the Bjørnøya Basin where the remaining continental crust is extremely thin (maximum thinning is 6–7 km). To explain the gravity signal, a relatively dense lower crust similar to the seismic layered lower crust required underneath the Loppa High is also modeled underneath the Polhem Subplatform and the Bjørnøya Basin

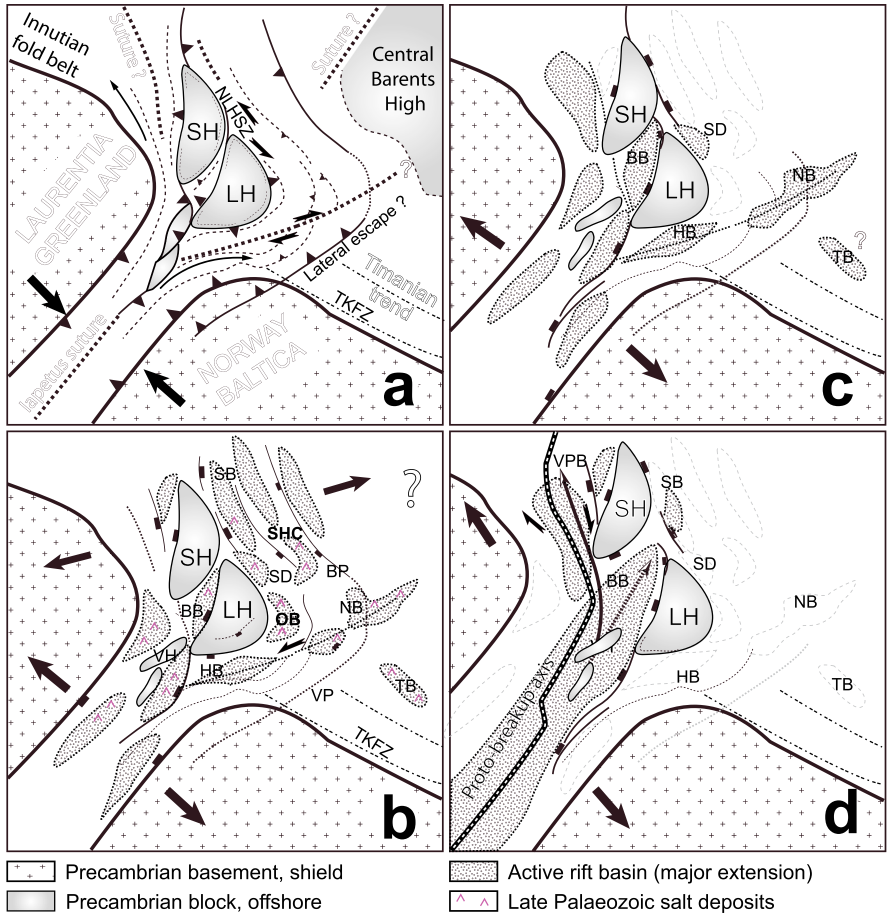

Figure 13. Conceptual sketches of the geodynamic evolution of the southwestern Barents Sea [modified after *Gernigon and Brönner*, 2012]. (a) Lateral escape of the Caledonides between Laurentia and Baltica in Devonian time; (b) reactivation of the main inherited features and shear zones and late Paleozoic graben development during the latest Devonian-Carboniferous; (c) early to middle Mesozoic rifting episodes leading to main stage of graben formation and salt tectonics; and (d) late Mesozoic increase of crustal thinning in the westernmost part of the Barents Sea and westward migration of the deformation leading to a sheared margin and final breakup between Laurentia and Baltica in early Cenozoic time. Abbreviations: BB: Bjørnøya Basin; BP: Bjarmeland Platform; HB: Hammerfest Basin; LH: Loppa High; NB: Nordkapp Basin; NLHSZ: North Loppa High shear zone (informal); OB: Ottar Basin (south); SB: Sørkapp Basin; SD: Svalis Dome; SH: Stappen High; SHB: Paleozoic Scott Hansen Complex (informal); VH: Vestlemøy High; TB: Tiddlybanken Basin; TKFZ: Trollfjorden-Komagelva Fault Zone VP: Varanger Peninsula; VVP: Vestbakken volcanic province.

(Figure 11). Such a lower crustal body (LCB) underneath the sag basin is modeled with a high density (3100 kg/m^3) and a susceptibility of 0.01 SI. The interpretation of this LCB is unclear but since high volcanic activity is mostly observed in the Vestbakken volcanic province farther west, we disregard a significant magmatic underplating interpretation and rather favor a preexisting high-grade/mafic lower crust. Possible serpentinization of the uppermost mantle associated with the drastic thinning of the basin is also possible depending on how much preexisting lower crust can really be interpreted. Like most similar continental LCB observed in the North Atlantic realm, it indeed remains difficult to evaluate and decipher the relative contribution of each crustal entity (i.e., preexisting lower crust, serpentinized mantle, or massive underplating) due to the almost identical geophysical properties [e.g., *Gernigon et al.*, 2004].

To the northwest, at the level of the Stappen High, a maximum thickness of the crystalline basement of 30 km is thinning to less than 25–20 km toward the Bjørnøya Basin. On its southeastern flank, the Stappen High borders a transitional basement terrace with a top basement located at a depth of 11–12 km. The Moho is deepening toward the NNW and is close to 27–30 km in the northern part of the Stappen High. Both Mesozoic and Paleozoic sediments are expected to occur at the edge of the Stappen High, but clear structures and boundaries have been difficult to resolve properly on seismics. Considering a conjugate system, the southeastern flank of the Stappen High could be relatively similar to the Polhem Subplatform and may also contain Permian to Jurassic formations and possibly older late Paleozoic strata. A similar petroleum system could also be expected. At the eastern edge of the Stappen Terrace, both modeling and a gravity change suggest the existence of a contact, possibly a southeast dipping border fault or detachment (Figure 11, D4), modestly indicated by seismics. This contact fits with the eastern edge of a prominent NE-SW trending, tilt-derivative magnetic anomaly, which can also be correlated with a gravity change. Farther west, a major basement shift is also observed and shows a clear magnetic contact. It is interpreted as a major crustal fault (Figure 11, D5) with a top basement on the hanging wall located at a depth of 5–7 km.

West of the Stappen High, a second level of necking is expected at the level of the Vestbakken volcanic province, to the west of the Knølegga Fault Zone (Figures 1 and 11, section H). The presence of thick Mesozoic or Paleozoic sediments in the Vestbakken volcanic province is questionable due to the lack of seismic imaging beneath the volcanics observed in this area. Our modeling rather suggests that some sedimentary rocks could be expected underneath the sill complex with a top basement not deeper than 10 km where high-density ($>$2900 kg m^{-3}) and high magnetic material (0.02–0.03 SI) is required to explain the gravity and magnetic signatures. Farther west and close to the first evidence of oceanic magnetic chrons, we propose that exhumed lower crust and/or some kind of intruded mantle may be present west of the Knølegga Fault Zone.

6. Discussion: An Updated Tectonic Model of the Southwestern Barents Sea From the Caledonian Orogeny to Ultimate Breakup

6.1. Arc-Shaped Prolongation of the Caledonian Nappes Underneath the Southwestern Barents Sea: Results and Implication of the New Data Set

The new aeromagnetic compilation shows a number of new features that document the structural style and the crustal evolution of the SWBS from the time of the Caledonian orogeny to the breakup. The new magnetic data set from the Barents Sea Region (Figures 6) shows that the folded rocks and minor thrust sheets, located east of the Tanahorn Nappe, extend northeastward into the inner Finnmark Platform. However, the structures of the Middle Allochthon (Tanahorn and Kalak Nappes) extend to the north-northeast offshore and then swing into a NNW-SSE trend toward the Nordkapp Basin and the Bjarmeland Platform. In the Bjarmeland Platform, the NNW-SSE magnetic trends of the Scott Hansen Complex (e.g., B1 and B2 in Figures 3 and 4) are interpreted as prominent (crystalline) basement features involving Caledonian thrust sheets composed of the preexisting Neoproterozoic formations (and possibly older crystalline basement units). We thus propose a tectonic scenario in which the magnetic pattern highlights arc-shaped Caledonian nappes that swing anticlockwise from a NE-SW orientation close to the Varanger Peninsula to NNW-SSE/NW-SE across the Nordkapp Basin and the Bjarmeland Platform (Figures 8 and 12a). This pattern could be part of a larger system involving several nappes and thrust sheets, suggesting the preexistence of salients and recesses along the Baltoscandian margin of the Fennoscandian Shield [*Gernigon and Brönner*, 2012]. The arc-shaped regional configuration, highlighted by the new magnetic data (Figures 3, 4, and 8), reflects the trend of the Caledonian nappes but also matches relatively well with the main, post-orogenic, highland provinces proposed for the Late Devonian paleogeography (Frasnian) [*Smelror et al.*, 2009; *Henriksen et al.*, 2011]. A nappe flow process [*Merle*, 1998] could also have involved lateral crustal shearing which in our model could explain the proto–Hammerfest-Nordkapp axis in terms of a major, intraplate, strike-slip deformation belt developing along the western margin of the Baltic Shield (Figures 12 and 13a). The new, high-resolution, aeromagnetic surveys do not favor the existence of prominent NE-SW Caledonian structural trends as proposed in previous papers [*Doré*, 1991; *Ritzmann and Faleide*, 2007; *Gee et al.*, 2008]. Moreover, the inferred presence of a possible and unique suture in the SWBS [*Breivik et al.*, 2002; *Gee et al.*, 2008; *Lorenz et al.*, 2013] does not appear to be in any way conspicuous on the new data set and its location still remains unclear and still questionable in this particular part of the Barents Sea (Figure 13a).

6.2. Post-orogenic Extension, Inheritance, and Proposed Late Paleozoic Rift Architecture

Several investigations, including the present study, have recognized that the SWBS basement structures are undeniably inherited from the Caledonian orogen [e.g., *Gabrielsen et al.*, 1990; *Gudlaugsson et al.*, 1998; *Ritzmann et al.*, 2007]. The stratigraphic studies of *Bugge et al.* [1995] and *Larssen et al.* [2005] in the SWBS show that sedimentary successions of Carboniferous and possibly Late Devonian age were deposited directly on top of the magnetic basement comprising the Caledonian thrust sheets. Late Paleozoic extension is most likely required to explain the accumulation and preservation of the observed and/or expected, thick Carboniferous salt deposits at the level of deep late Paleozoic basins (Figures 1 and 10). The architecture of the Caledonian thrust belt is inferred to have been reactivated in an extensional phase during Devonian?-Carboniferous time at the level of the Ottar Basin and Scott Hansen Complex. Such a hypothesis could explain both the link with the onshore fold-and-thrust belt and the presence of the Carboniferous basins and salt layers reported offshore (Figures 1 and 10). Assuming late Paleozoic extension and thrust reactivation, *Gernigon and Brönner* [2012] already suggested that this configuration could approximate to the outline of the northern Scandinavian Caledonides crystalline basement as it was at around Middle-Late Devonian time. The original Caledonian structural grain may have controlled the regional, pre-Permian, extensional regime (Late Devonian?–Carboniferous) by brittle reactivation (and/or collapse?) of the Caledonian thrust system which is expected to underlie the Mesozoic basins and correlate with the regional magnetic pattern (Figures 12 and 13). The southern Ottar Basin and the Scott Hansen Complex beneath the Bjarmeland Platform could represent deep, late Paleozoic basins, accommodating thick Carboniferous salt deposits, later reactivated as diapirs or still preserved as stratified units.

Whether this inferred older, post-orogenic, extensional offshore event (Devonian?–early Carboniferous) included an episode of possible ductile backsliding and/or simply a brittle reactivation of the preexisting thrusts remains unclear. Post-orogenic collapse and associated Early to Late Devonian basins are indeed well known in western and central Norway and in the Fjord Region of east Greenland [*Braathen et al*., 2002; *Fossen*, 2010]. However, with the exception of the Lofoten-Rombak Region [*Rykkelid and Andresen*, 1994], structural evidence for extensional collapse and reactivation is sparse in the northern Troms and Finnmark Regions [*Fossen*, 2011; *Steltenpohl et al*., 2011] and brittle thrusting is known to have continued into Early-Middle Devonian time [*Roberts and Sundvoll*, 1990]. Isotopic ages from ultrahigh-pressure metamorphic Caledonian assemblages in NE Greenland [*Gilotti et al*., 2004] have also revealed that the Caledonian collision was possibly still continuing in that region during Devonian–lowermost Carboniferous times, whereas an extensional deformation regime had most likely taken over in the rest of the Caledonian orogenic belt [*Fossen*, 2010; *Steltenpohl et al*., 2011].

In this regional context, the timing of the early post-orogenic phase of extension of the SWBS remains partly unconstrained and could have started indiscriminately in Late Devonian–early Carboniferous times in the SWBS. However, regional phases of Carboniferous extension have been reported, including the reactivation of old Caledonian thrusts in the SWBS and Svalbard regions [*Gabrielsen et al*., 1990; *Gudlaugsson et al*., 1998; *Braathen et al*., 1999; *Worsley et al*., 2001; *Larssen et al*., 2005].

The new magnetic surveys suggest that in terms of crustal deformation, the main regional basement structures developed along prominent NNW-SSE basement trends. Most of the main late Paleozoic basin development and rifting seems to have occurred along and northwest of the Hammerfest-Nordkapp axis which is interpreted in this paper as an old and major, Caledonian, dextral shear zone that developed at the edge of the Fennoscandian Shield (Figures 8 and 13a). This Hammerfest-Nordkapp axis also reflects a major, present-day crustal configuration with a Moho depth shallowing from 40 km under the Finnmark Platform to 30 km beneath the Nordkapp Basin [e.g., *Clark et al*., 2013].

6.3. Onset of Continental Thinning and Continental Breakup: Ribbon-Style and Inherited Structures

The variety of rift orientations in the southwestern Barents Sea partly challenged in that study assumes the presence of a mechanical anisotropy inherited from the ancient Caledonian and even older accreted terranes. Such an anisotropy and upper crustal compositional layering have most likely controlled the crustal deformation since the post-orogenic “collapse” (or brittle reactivation) and up to the breakup stage.

At crustal scale, the Stappen and Loppa Highs most likely represent very old basement terranes that amalgamated and were closely connected by the end of the Caledonian orogeny [e.g., *Brönner et al*., 2009; *Barrère et al*., 2009; *Marello et al*., 2013]. Onshore-offshore investigations and the regional magnetic signature suggest that the Loppa High basement may partly represent the northern prolongation of the highly magnetic, old Precambrian terranes possibly linked with the (1.8–1.7 Ga) Transscandinavian Igneous Belt observed onshore [*Barrère et al*., 2009; *Olesen et al*., 2010]. Consequently, the Loppa High could have been part of the outermost Baltoscandian margin of Baltica before the closure of the Iapetus Ocean and the onset of the Caledonian orogeny (Figure 13a). An alternative but related interpretation is that part of the Loppa High may represent the root zone of the allochthonous and mafic Seiland Igneous Province (Figure 1).

The magnetic signature of the Stappen High appears similar to that of the Loppa High, but its basement origin prior to the Caledonian orogeny could be different. Some authors have assumed that Bjørnøya and the whole of the Stappen High were part of Laurentia before the closure of the Iapetus Ocean [*Smith*, 2000]. In that case, any Caledonian, strike-slip, orogen-parallel displacements and possible suture(s) must have been located outboard of the combined Bjørnøya-Greenland craton, and the main suture should be expected to be located underneath the Bjørnøya Basin, possibly at the level of the high-density lower crust (LCB) that has been interpreted and modeled in the present study (a high-density migmatite/peridotite/eclogite melange?; Figure 11). The presence of a suture west of the Loppa High is most likely and could have been an effective upper mantle weakness zone, facilitating the localization of deformation and explaining the drastic Mesozoic stretching (Figure 13c), thinning, and necking (Figure 13d) of the Bjørnøya Basin in the prolongation of the Lofoten, Harstad, and Troms Basins. Farther north, the inferred suture could crosscut the entire Bjørnøya Basin and the Fingerdjupet Basin *Ritzmann and Faleide* [2007] or may simply bifurcate southwest of the Stappen High and control the late shear margin system leading to breakup between the SWBS and NE Greenland (Figure 13d). Alternatively, we may have several sutures or significant Caledonian deep shear zones as suggested in Figure 13a.

In terms of crustal deformation, the Loppa and Stappen Highs, in their latest stage of the rift evolution, may be interpreted as a series of old rigid continental blocks (or continental ribbons after *Lister et al*. [1986]) of poorly thinned crust compared to the adjacent young Hammerfest and Bjørnøya Basins and the basins of the Vestbakken volcanic province (Figure 11b). Such ribbons represent relatively preserved (poorly affected by thinning) continental blocks, bounded by opposed and shallow, fault, and/or detachment zones, associated with crustal necking zones (Figure 11b). We propose that both the Loppa and the Stappen Highs earlier represented rigid continental (Precambrian) blocks, behaving as buffers during the Caledonian orogeny and subsequent late Paleozoic-Mesozoic rifting episodes (Figure 13). After the Caledonian orogeny, we believe that the rigid blocks were reactivated and probably acted as continental ribbons and locking zones during the subsequent late Paleozoic and Mesozoic rift history and consequently influenced the development and sedimentation patterns in both the late Paleozoic and late Mesozoic basins (Figure 13). Analogue models [*Sun et al*., 2009] show that when stretched, preexisting rigid blocks can behave as a platform and its weak extension can cause its neighboring areas to be thinned rapidly, leading to the formation of lateral deep sag basins. Such blocks can eventually rotate which may explain both the transtensional and the transpressional features which we have observed along the edges of the Loppa High.

Compared to the platformal basins that developed east of the Loppa High, the crust observed between the ribbons of the western rift system is much thinner and shows a maximum apparent crustal beta factor of more than 2.5–3 at the level of the necking zones. The Bjørnøya Basin, in particular, acted as a flexural sag basin during Late Jurassic to Early (Middle?) Cretaceous times that coincided with a period of extreme thinning of the continental crust (Figures 11 and 13). As in the Hammerfest Basin, the stretching and thinning systems that developed in the Bjørnøya Basin most likely focused on the preexisting late Paleozoic basins, originally expected west of the Loppa High. The presence of a deep supradetachment D3, observed underneath the Polhem Platform and already controlling the deep late Paleozoic basin, is also in agreement with such a long-lived history of this proto-sag basin. Such extreme thinning may also explain the crustal necking at depth, characterized by an upwelling lower crust/mantle (Figure 11). The relationship between the crustal detachments and the necking of the crust/lithosphere seems relatively similar to many other observations and models, suggesting that both upper crustal detachment and deep mantle shears play an important role in the thinning process, leading eventually to the exhumation of the preexisting lower crust and/or serpentinized mantle before breakup [*Brun and Beslier*, 1996; *Reston*, 2007; *Manatschal*, 2004; *Lavier and Manatschal*, 2006; *Van Avendonk et al*., 2009; *Sibuet and Tucholke*, 2012]. The large rate of crustal thinning underneath the Bjørnøya Basin was probably important enough to support the presence of an exhumed lower (continental) crustal lens beneath the sag, as indicated by possible analogues in the Alps and Pyrenees [*Mohn et al*., 2011; *Jammes et al*., 2010]. However, we cannot determine if the thinning system observed at the level of the Bjørnøya Basin ultimately reached the stage of exhumation/denudation. We cannot verify whether the Loppa High crustal detachment has affected the upper mantle or if it has simply soled out in a ductile middle/lower continental crust as suggested by the cold lithospheric rift model of *Weinberg et al*. [2007]. In the former case, low brittle deformation of the mantle associated with rapid sedimentation and filling of the Bjørnøya Basin would not necessarily have promoted and facilitated active serpentinization. Wide-angle refraction studies along a similar ribbon-sag system have been carried out in the Orphan Basin [*Chian et al*., 2001] and showed that failed sags showing a significant thickness of sediments do not necessarily lead to clear pervasive serpentinization even though a drastic thinning of the crust is observed.

Even if hyperextended, the Bjørnøya Basin did not succeed in disrupting the entire lithosphere and the rifted system "aborted" around Middle Cretaceous time. At that time, all deformation focused south and west of the Stappen High where a third active necking zone (Figure 11b, necking zone 3) developed along the shear margin and finally reached the breakup stage in early Cenozoic time.

North of the Bjørnøya Basin along the northern flank of the Stappen High, the seismic interpretation suggests a major detachment dipping toward the northwest, most likely controlling the deep basin underneath the Fingerdjupet Sub-basin (Figure 10). This contrasts significantly with the opposite, SW to W dipping, detachment fault complex that is considered to have controlled the Bjørnøya Basin, and it seems that a complex accommodation zone developed between the Stappen High and the Loppa High (informally interpreted and named as the North Loppa High shear zone). This accommodation zone is highlighted by a NNW-SSE magnetic trend (Figures 3, 4, and 8) and most likely had a significant influence on the tectonic development and abortion of the Bjørnøya Basin. South of the North Loppa High shear zone, a drastic thinning of the crust led to formation of the tectonic sag and thick Cretaceous depocenter. North of the shear zone, no sag has been detected; the Cretaceous sedimentation was reduced but Late Jurassic–Early Cretaceous faulting created minor horst and graben features in the Fingerdjupet Sub-basin. This structural style may witness a reduced thinning activity from the Bjørnøya Basin to Fingerdjupet Sub-basin, rather indicating a transition from extreme thinning to a moderate stretching type of deformation [e.g., *Lavier and Manatschal*, 2006]. As outlined in the cartoons of Figure 13, the decrease of thinning and the late abortion of this propagating (aulacogen-type) sag basin may be partly explained by its trend oblique to the inherited, regional, structural grain revealed by the new aeromagnetic compilation. In the SWBS situation, the regional NW-SE late Mesozoic extension was locally oblique to the previous Caledonian and late Paleozoic NW-SE to NNW-SSE inherited structures (Figures 13a and 13b). It could have been difficult for the extension to further stretch and thin the crust and upper mantle that had already inherited oblique deformation fabrics [*Tommasi and Vauchez*, 2001]. This may explain why some deep late Paleozoic basins did not reactivate significantly during subsequent Mesozoic rifting episodes (Figures 13c and 13d).

The final abortion of the Bjørnøya Basin coincides with a migration and complete reorganization of the crustal extension toward the western volcanic sheared margin and proto-breakup axis (Figure 13d). Due to the lack of calibration and poor seismic west of the Stappen High, the timing of the rift migration is still unclear, but it may coincide with the end of faulting activity in the Fingerdjupet Sub-basin at around early Middle Cretaceous time. However, rifting could have occurred earlier west of the Stappen High if we consider that, after a certain critical thinning factor along a first necking zone, a complete shift and relocalization of the deformation toward a second necking zone could have become difficult to achieve [*Yamasaki and Gernigon*, 2010]. Ultimately, the main thinning of the lithosphere and the stability of the intra-ribbons basin may have been controlled and/or favored by shearing and a resultant heating process [*Brune et al.*, 2012; *Minakov et al.*, 2013], triggered by the strike-slip motion between the SWBS and Greenland. In addition, the compositions and shapes of weakness zones in the uppermost mantle (old suture?), whether or not influenced by magmatism (underplating), may also have favored the localization of the deformation required to initiate the breakup [*Autin et al.*, 2013; *Yamasaki and Gernigon*, 2010].

6.4. Global Implications for the Mode of Rifting and Extension

In general, analogue and numerical models dealing with rifted margins and extension often reflect a simplification of the reality and assume, on purpose, an almost homogeneous and uniform setting for the initial lithosphere [e.g., *Brun and Beslier*, 1996; *Lavier and Manatschal*, 2006]. Such models already show the complexity of the crustal styles produced by the extension of an oversimplified initial lithospheric configuration. In such a context, our study tends to show that inheritance can also favor stress concentration and shear localization and is manifested at all scales in the continental lithosphere. The presence of crustal and mantle weakness zones such as basal thrust detachments and interplate sutures has a significant influence on subsequent basin and crustal development. The long-term architecture of inheritance discussed in this paper could explain the complexity of the continental deformation zone also highlighted by the potential field data. Old structures from long-lived zones of weakness tend to accommodate successive components of crustal strain often in preference of new zones of displacement until breakup time. This impact seems to be particularly important if the inherited fabrics represent initial and major inherited crustal deformation zones (suture, mega shear zone). The crustal and structural style described in this paper suggests that inherited fabrics and blocks most likely initiate and influence the onset of thinning and the "ribbon style of deformation" of the extended continental. Earlier introduced by *Lister et al*. [1986], similar intriguing structures have been recognized in different rifted margin settings (Newfoundland [*Chian et al*., 2001], offshore Brazil [*Zalán et al*., 2011], South China Sea [*Sun et al*., 2009; *Franke et al*., 2013], Rockall-Faroes margins, [*Funck et al*., 2008]). This led to further speculations about how similar inheritance histories and mechanisms could have eventually controlled their development.

7. Conclusions

1. We have summarized the tectonic and regional implications of a modern generation of aeromagnetic data that cover almost the entire SWBS with reliable, high-resolution, and high-quality data. We have also illustrated and documented the importance and influence of inherited terranes and structures in subsequent rift and continental margin development.
2. Onshore-offshore correlation has been carried out to link offshore magnetic anomalies and lineations with adjacent geological features documented onshore by detailed mapping in northern Norway.
3. Different levels of the Caledonian allochthons can be linked to a pattern of NE-SW trending anomalies. They were identified as the magnetic expression of a northeastward propagation of the thrust sheets into the SWBS.
4. The diverse nappes and thrust sheets and their associated magnetic anomalies swing anticlockwise from the initial NE-SW trend in the southern part of the Finnmark Platform to NNW-SSE striking across the Nordkapp Basin and into the Bjarmeland Platform.
5. Compared to previous interpretations and models, the structural trends that are clearly detectable from the aeromagnetic compilation in this part of the Barents Sea differ from the NE-SW or NNE-SSW configuration of basement highs and sub-basins previously proposed for the late Paleozoic rift system. The new upper crustal model, developed as a consequence of the new high-quality magnetic data, raises new and interesting questions regarding the offshore extent of the Caledonides, the basement geometry, and the early development of the late Paleozoic basins in the SWBS (e.g., Ottar Basin, Scott Hansen Complex, and Bjørnøya Basin).
6. The crustal architecture and younger tectonic evolution of the western rift complex leading to continental breakup in early Cenozoic time are described in the last part of this contribution. We propose a model of crustal "boudinage" involving rigid blocks such as the Loppa and Stappen Highs, which are interpreted as a series of thick and poorly thinned, continental crustal ribbons as compared to the adjacent sedimentary basins and shear margin. As part of this extensive complex system, the Bjørnøya Basin is interpreted as an extremely thinned and propagating system that aborted in late Mesozoic time. This thick Cretaceous sag basin is characterized by a deep-seated, high-density body (LCB) rather interpreted as an exhumed part of the preexisting metamorphic lower crust.
7. The abortion of this propagating basin may be partly explained by its trend oblique to the regional, inherited, structural grain, and/or the presence of an underlying thick and rheologically strong substratum is expected to be present in the region of the Loppa and Stappen Highs. The rift abortion also coincided with a rift migration and a complete reorganization of the crustal extension toward the western volcanic sheared margin and proto-breakup axis possibly located along a preexisting Caledonian suture.
8. In terms of further understanding of rifted margin formations, our study shows that the role played by inherited structures and their local reactivation has an impact on continental reactivation, and rift deformation should consequently not be underestimated.

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