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Late Palaeozoic architecture and evolution of the western Barents Sea: Insights from a new generation of aeromagnetic data

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REPORT

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Title:

Late Palaeozoic architecture and evolution of the western Barents Sea: Insights from a new generation of aeromagnetic data

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Summary:

A new generation of modern aeromagnetic surveys highlight the Caledonian basement and pre-Permian basin architecture of the southwestern Barents Sea. This configuration involved several Caledonian thrust sheets that collapsed and controlled the post-Caledonian rift development of the southwestern Barents Sea during Late Palaeozoic time. Contrary to previous geological models, we consider that the sub-Permian basins and underlying basement grain have a dominantly NNW-SSE orientation in most of the platform area. Moreover, we do not see magnetic evidence that could support a major NE-SW or NNE-SSW regional axis that has commonly been proposed for the Late Palaeozoic rift system and inherited Caledonian structural grain in the Barents Sea.

Keywords: Geofysikk	Berggrunnsgeologi	Magnetometri
Kontinentalsokkel		
		Fagrapport

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1 . INTRODUCTION

The southwestern Barents Sea (SBS) was affected by major tectonic events including the collision of Baltica and Laurentia in the Mid Palaeozoic time and later influenced by rifting and breakup events (Faleide *et al.* 2008, Gee *et al.* 2008, Smelror *et al.* 2009). Thanks to extensive petroleum exploration, the main outlines and structure of the Mesozoic grabens, intervening highs and associated platforms in the SBS (Fig. 1) are relatively well constrained by seismic and borehole calibrations (Gabrielsen *et al.* 1990; Smelror et al., 2009; Henrikssen et al., 2011). However, the regional architecture of the deep basement structures and its link with the Caledonian nappes, well described from onshore Norway, still remains uncertain due to the lack of long-offset refraction data and the poor quality of seismic reflection data beneath the Permian formations (Barrère *et al.* 2009). Over the last 30 years, the structural grain of the basement in the SBS has been 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 Norwegian Caledonides extend northwestward to link up with the Innutian fold belt (northern Greenland) through the Caledonides of Svalbard (Ziegler 1988).

Subsequent interpretations, however, have favoured a model where the general structure and Baltica-Laurentia suture of the Norwegian Caledonides extend in a northeasterly direction across the Central Barents Sea (Doré 1991, Gudlaugsson *et al.* 1998, Breivik *et al.* 2005, Gee *et al.* 2008). Some authors have also suggested that the deep Late Palaeozoic basins are almost sub-parallel to the Mesozoic graben system and may extend over most of the SBS following a dominant NE-SW to NNE-SSW regional strike trend associated with the inferred, inherited structural grain (Dengo and Røssland 1992, Gudlaugsson *et al.* 1998, Ritzmann and Faleide 2007, Faleide *et al.* 2008). In the light of new aeromagnetic data combined with gravity and seismics, we discuss and challenge several of the previous interpretations and propose a new simplified and coherent regional model for the basement and pre-Permian basin development of the SBS.

2 . NEW HIGH-RESOLUTION AEROMAGNETIC SURVEY IN THE SOUTH-WESTERN BARENTS SEA

The delineation of gravity and magnetic anomalies should normally be the first method to be applied in the evaluation of new basin or region. In frontier areas where seismic data are sparse or non-existent, aeromagnetic acquisition remains the easiest way to assess or refine the structural setting. Aeromagnetic data are particularly adapted to investigate the basement and deep structure of the SBS (Skilbrei 1995, Barrére *et al.* 2009, Marello *et al.* 2010, Olesen *et al.* 2010). However, because of artefacts, navigation errors and poor resolution of

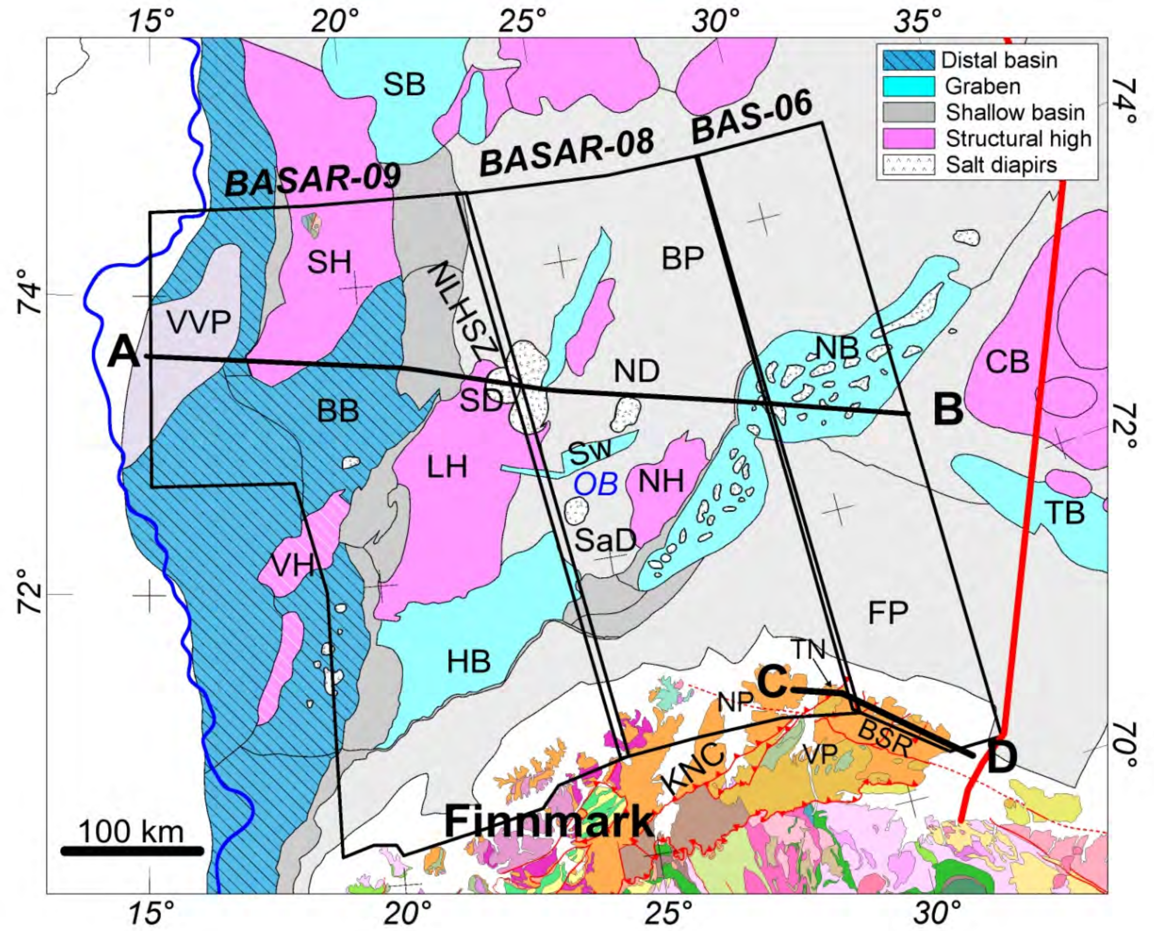

Figure 1 Structural framework of the southwestern Barents Sea (modified after pre-existing onshore (Sigmond 2002) and offshore (Gabrielsen et al. 1990) geological maps, and the outlines of the new high-resolution aeromagnetic surveys acquired by NGU between 2006 and 2009. A-B: WNW-ESE profile shown in Fig. 5. C-D, NW-SE profile shown in Fig. 4. Abbreviations: BB: Bjørnøya Basin; BP: Bjarmeland Platform; BSR: Barents Sea Region; CB: Central Barents High; HB: Hammerfest Basin; KNC: Kalak Nappe Complex; LH: Loppa High; NB: Nordkapp Basin; ND: Norvarg Dome; NLHSZ: North Loppa High Shear Zone; NP: Nordkinn Peninsula; OB: Ottar Basin; SB: Sørkapp Basin; SaD: Samson Dome; SD: Svalis Dome; SH: Stappen High; Sw: Swaen Graben; TN: Tanahorn Nappe; VH: Vestlemøy High; TB: Tiddlybanken Basin; VP: Varanger Peninsula; VVP: Vestbakken volcanic province.

the pre-existing magnetic data, acquired in the 1970s and 1980s, the Geological Survey of Norway (NGU) decided to remap the entire SBS with state-of-the-art, high resolution aeromagnetic data in order to update and improve the magnetic field dataset. Acquired during the summers of 2006, 2008 and 2009, the new BAS-06, BASAR-08 and BASAR-09 surveys cover most of the SBS, extending from the Varanger Peninsula up to the

Bjarmeland Platform at around 74°30' North (Figs. 1,2) . The new aeromagnetic surveys were carried out in a line/tie-line configuration with a profile distance of 2/6 km and 2/5 km. We processed and interpreted a total area of c. 216,500 km2 including 165,400 km of new magnetic profiles. The raw data have been processed using both statistical and micro-levelling methods including a median filter technique (Mauring and Kihle 2006). A number of filtering and image enhancements have been calculated from the total magnetic intensity (TMI) and qualitatively interpreted. Filtering and derivative calculations, especially the normalised tilt-derivative (TDR) filtering (Miller and Singh 1994), helped to define thesub-vertical edges of intra-basement blocks, the edges of supra-basement disturbances and/or faults. This technique highlights sub-domain structures and boundaries, such that the magnetic lineations of the SBS could be displayed more prominently.

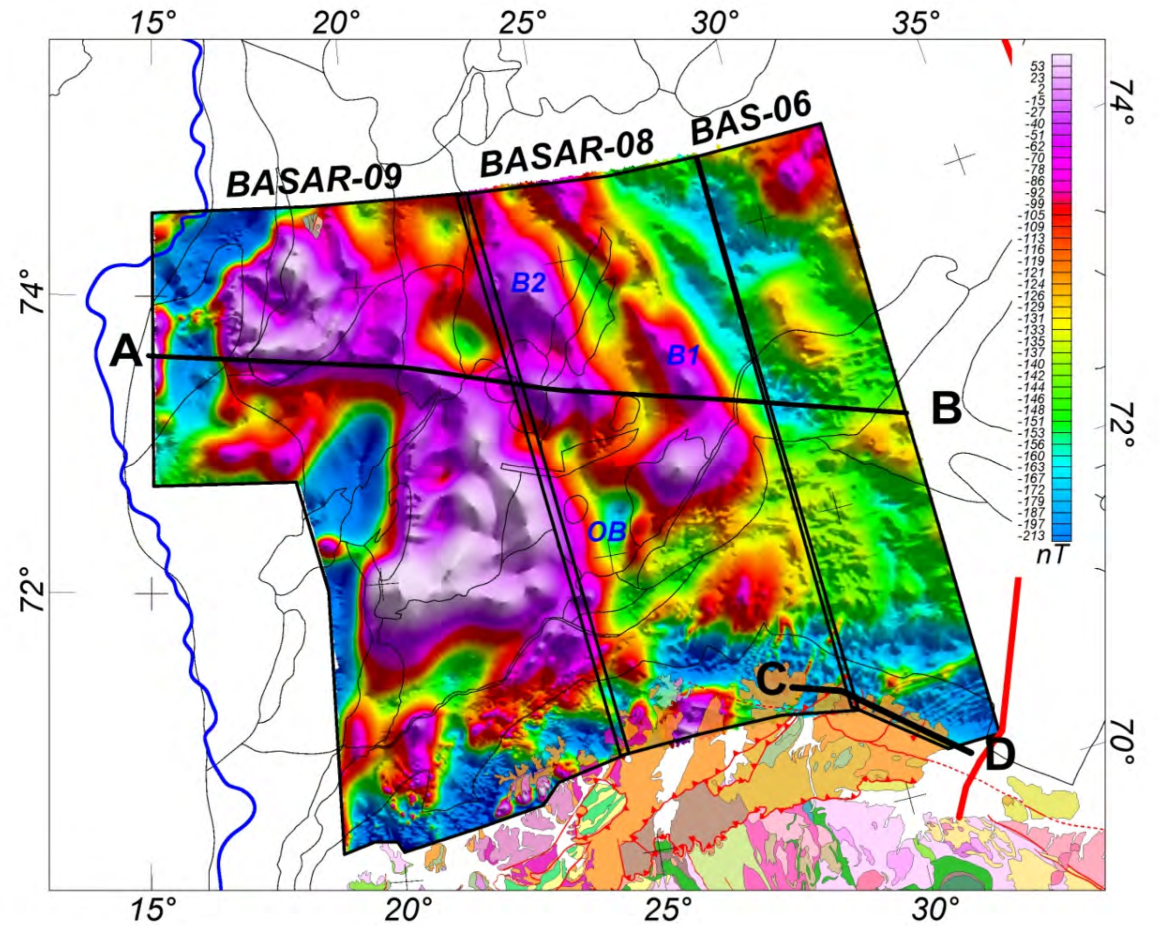

Figure 2 New magnetic total field anomaly map of the southwestern Barents Sea.

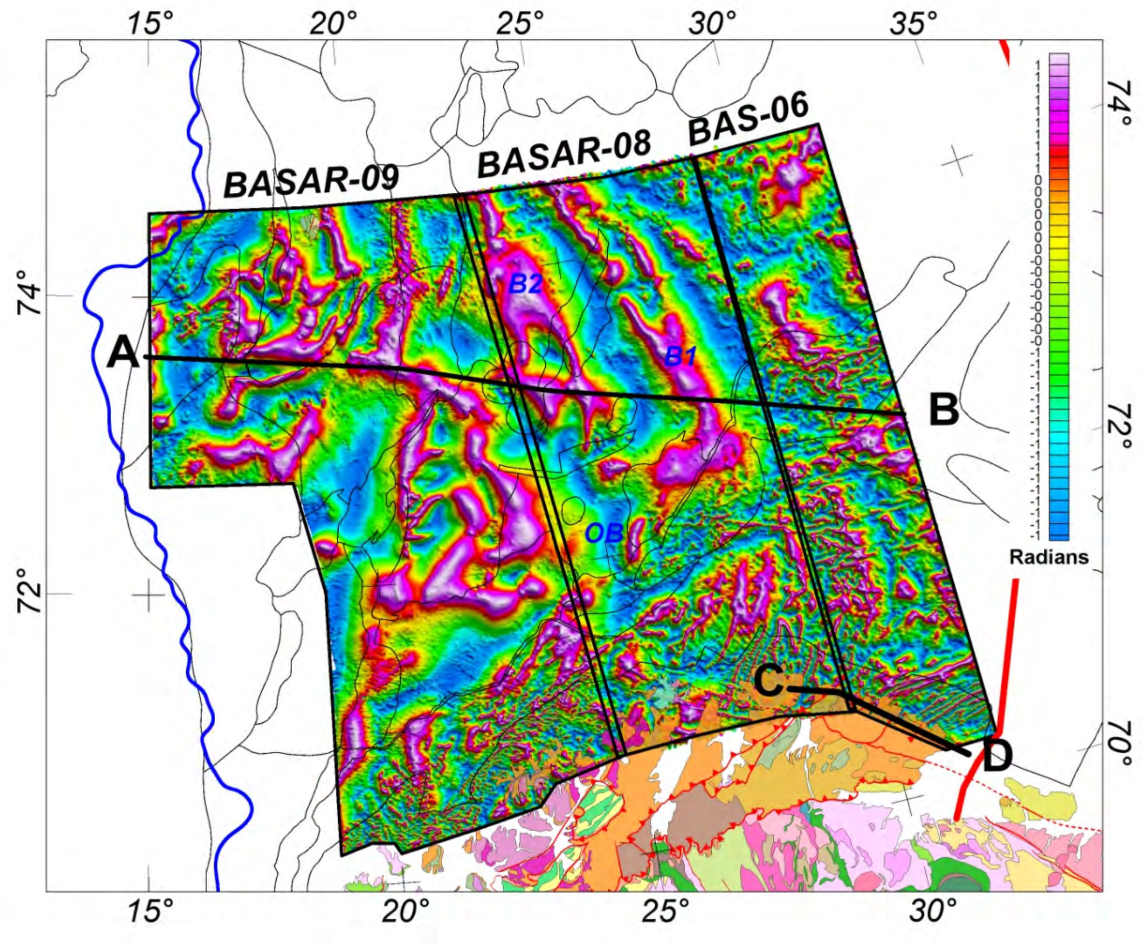

Figure 3 Tilt-derivative filter (TDR) of the magnetic total field. The TDR enhances the subtle magnetic anomalies and maximizes the geometrical contrasts of the internal basin structures. Note the prominent NNW-SSE anomalies that characterise the central Barents Sea and the Bjarmeland Platform.

3 . INTERPRETATION

3.1 Onshore-offshore relationships

The surveys overlap the coastal parts of the Norwegian mainland, thus allowing a good onshore-offshore correlation of the geophysical signal and associated geological structures. Here, thanks to many years of extensive fieldwork and mapping in the Caledonides of Finnmark, the geology, structure and petrophysical properties of the onshore formations are remarkably well constrained (Sigmond et al., 1984, Olesen *et al.* 1990, Karpuz *et al.* 1993, Siedlecka and Roberts 1996) (Figs. 1, 4). The northeastern part of the Varanger Peninsula (Barents Sea Region, BSR, Fig. 1) is underlain by about 9 km of Neoproterozoic, deep- to shallow-marine sedimentary rocks, a succession that was deformed and metamorphosed under lower greenschist-facies conditions during an early phase of the Caledonian orogeny (Roberts 1985, Rice and Frank 2003). Eastern areas also carry evidence of pre-Caledonian, Timanian (Ediacaran) deformation (Roberts 1995, Herrevold *et al.* 2009). Caledonian folding and minor thrusting decrease in intensity from NW to SE across the peninsula (Fig. 4) (Roberts 1972, Karpuz *et al.* 1993), and much of the BSR succession forms part of the Lower Allochthon of Caledonide tectonostratigraphy. In northwestern Varanger Peninsula, this allochthon is overlain by the Tanahorn Nappe (Siedlecka and Roberts 1992), comprising slightly higher-grade rocks of the Middle Allochthon (Kalak Nappe Complex, KNC). Rocks of the KNC occur extensively on nearby Nordkinn Peninsula (Fig. 4) and their mylonitic thrust base represents a major tectonic boundary in the Caledonides of Finnmark (Gayer *et al.* 1987, Siedlecka & Roberts 1996).

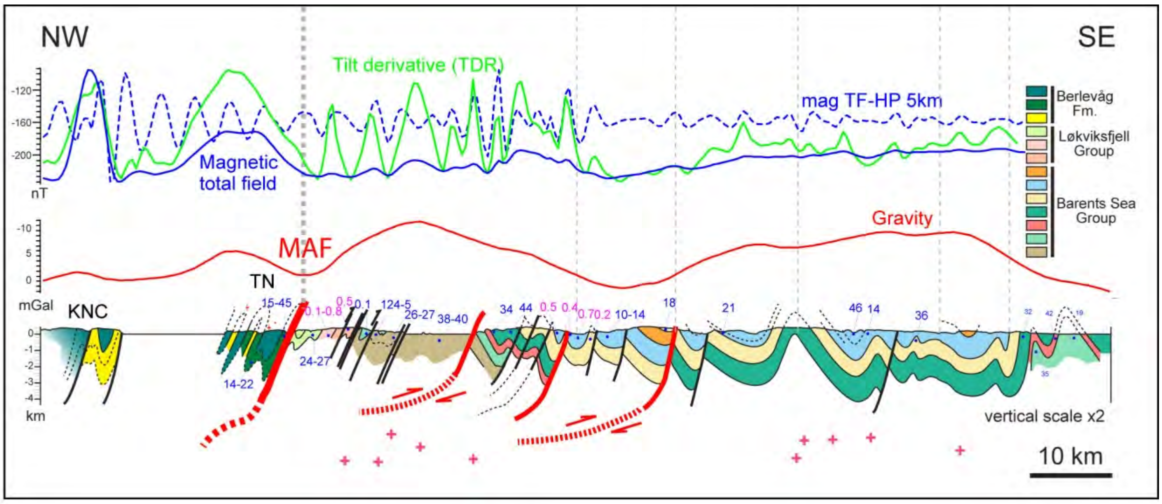

Figure 4 Geological cross-section across the Barents Sea Region of Varanger Peninsula. A good correlation between the onshore Caledonian thrust-and fold belt and the prominent NE-SW magnetic trends (cf. Fig. 3). Numbers indicate the susceptibility measurements (x 1000 SI) recorded along the geological section. KNC: Kalak Nappe Complex; MAF: Middle Allochthon front; TN: Tanahorn Nappe. Location on Figure 1, line C-D.

All the structural elements observed and mapped onshore on the Varanger and Nordkinn peninsulas show a good correlation with the new magnetic trends revealed by the new surveys (Fig. 3). The NNE-SSW to NE-SW trends observed in the southwestern part of the survey area and up to the Nordkapp Basin coincide with fault-propagation folds and thrusts that gradually steepen to near vertical towards the vertical toward the southeast. East of the Tanahorn Nappe, the magnetic trends vary mainly from N°45 close to the Tanahorn basalt thrust (Fig. 2, 3) to N°70-N°80 farther to the east. The magnetisation observed derived from deformed cross-bedded sandstones with foresets composed almost exclusively of high-magnetic minerals (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 to the higher magnetic response.

4.1 Offshore prolongation of the Caledonian nappes

The Finnmark Platform marks the progressive deepening of the crystalline basement and overlying Proterozoic metasedimentary rock succession towards the Nordkapp Basin and the Bjarmeland Platform to the north (Fig. 1). In the northern areas, the structural configuration of the SBS basins is largely the result of Mesozoic rifting events and associated salt tectonics. Stratigraphy and structures located above the regional Top Permian marker in the SBS are relatively well imaged on seismics and locally calibrated by wells. Older Palaeozoic basin and half-graben related to phases of crustal extension have also been suggested for the Mid-Late Devonian, Carboniferous and Permian times (Bugge et al., 1995; Gudlaugsson *et al.* 1998). However, the deep Late Palaeozoic basinal system is still poorly constrained and only a few wells have penetrated the Palaeozoic and/or crystalline basement in the SBS (Bugge *et al.* 1995, Larssen *et al.* 2005, Slagstad *et al.* 2008). The presence of deeply buried salt pillows (e.g. Samson and Norvarg domes) suggests, however, that poorly mobilised Mid-Carboniferous to Early Permian stratified salt deposits extend underneath the main platform areas of the SBS, which were hardly, if at all affected by the Mesozoic extension (Fig. 1). Since Early Triassic time, these salt deposits have undergone several phases of remobilisation leading to diapir development, but only within the confines of the main Mesozoic grabens (Nilsen *et al.* 1995, Gernigon *et al.* 2010).

North of the Finnmark Platform, thick and deep Late Palaeozoic basins such as the Ottar Basin between the Norsel and the Loppa highs (Fig. 1) have earlier been ereported (Breivik *et al.* 1998, 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 makes the determination of Palaeozoic sediment thicknesses and structures of these deeply buried `grabens´ very uncertain in most of the SBS.

On the Bjarmeland Platform, the new aeromagnetic surveys clearly highlight prominent NNW-SSE to NW-SE, magnetic trends (Figs. 2, 3). Correlated with seismics, these features (B1, B2; Fig. 5) do not coincide with any particular Mesozoic structures within the Bjarmeland Platform, which is a relatively uniform platform above the Top Permian marker (see the seismic example in Figure 5). The magnetic properties from published well core measurements in the Barents Sea area (Lauritsen *et al.* 2007) show that the Mesozoic sedimentary rocks in the SBS have low susceptibilities. Due to the strong magnetisation required to produce the observed magnetic signal and because of the lack of intrusions in the Mesozoic section, it is reasonable to propose that this magnetic pattern in the Bjarmeland

Platform mostly and simply reflect the presence of deeper basement bodies with higher susceptibility and/or remanence values. This hypothesis has also been tested and confirmed using gravity and magnetic modelling along specific 2D seismic sections and validated in 3D (Brönner et al., unpublished work). The forward modelling was performed to test the origin of the magnetic sources, associated with the NW-SE trends observed on the Bjarmeland Platform. The methods used to calculate the gravity and magnetic model response are based on the methods of Talwani (Talwani and Heirtzler 1964, Talwani 1973, Won and Bevis 1987). The result suggests a significant thickness for the pre-Permian basins and the possibly folded but non-magnetic (meta)sedimentary successions that are present underneath the Bjarmeland Platform (Fig. 5b). We suggest that the sediment depocentres underneath the Permian fit with the dominant NNW-SSE magnetic trends revealed by the tilt derivative filtering (TDR) beneath the Bjarmeland Platform (Figs. 3, 5). B1 and B2 are interpreted and modelled as two Palaeozoic basement highs separated by basin lows, which also show the same prominent NNW-SSE trend. The tilt derivative (TDR) filter (Miller and Singh 1994) usually highlights the edge of major basement block and crustal units. The coherent picture of a prominent magnetic anomaly at the Norsel High (Fig. 1, 6) and the NNW-SSE trending tail- like, B1 structure support this assumption since this prominent basement high, tested by well 7226/11-1 at around 5 km depth, is flanked by deep NNW-SSE-striking basins with low-magnetic signatures. A similar low-magnetic signature is observed at the level of the Ottar Basin to the west, which has been considered to be of Palaeozoic age (Breivik *et al.* 1995). Our study suggests, however, that the main structural trend of the Ottar Basin is predominantly N-S to NNW-SSE and not NE-SW as previously suggested. The locations of the Norvarg and Samson domes also coincide with the outline of the Late Palaeozoic basins, fitting with the low TDR anomalies (Fig. 6). The transition between the Ottar Basin and its expected prolongation towards NNW (between B1 and B2) is interpreted as a complex Late Palaeozoic transfer zone which matches with the outline of the Swaen Graben defined at the Mesozoic level between the Norvarg and Samson domes (Fig. 1) (Gabrielsen *et al.* 1990). This narrow graben is associated with the deep and Palaeozoic structures, highlighted by the new surveys. The deep, NNW-SSE-trending basement highs (B1, B2) and basins indentified on the magnetic data are not obvious from gravity alone (Fichler *et al.* 1997, Olesen *et al.* 2010), which confirms the low-grade mobilisation status and high degree of compaction of the deeper sedimentary succession. The low density contrast with the surrounding basement makes them almost invisible from gravity data. The incompressible salt layers, partly witnessed by the salt pillows, could also have extended over the original NNW-SSE graben and this may also have contributed to blurring the gravity signature of the deeper Palaeozoic structures.

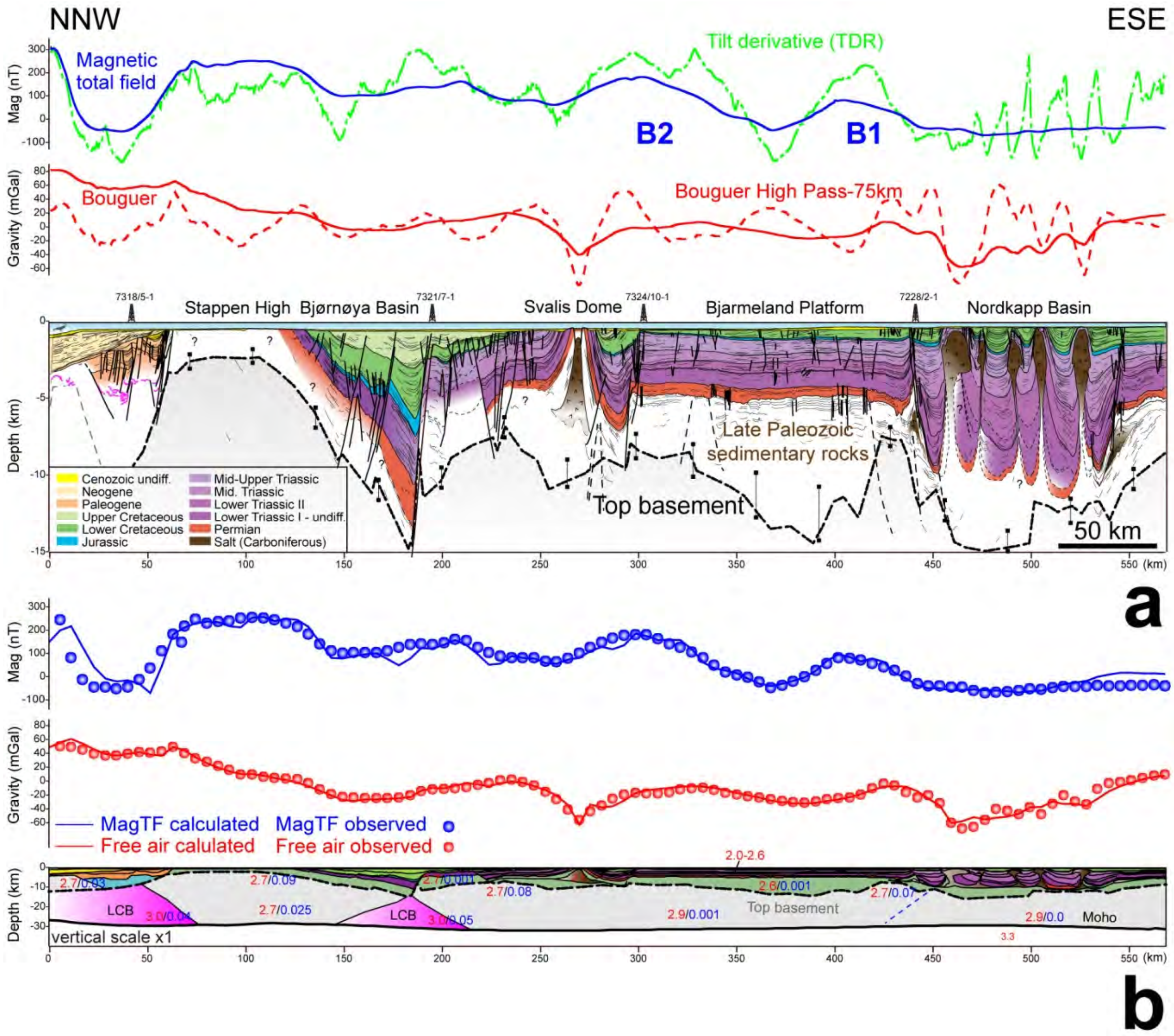

Figure 5: a) Regional ESE-WNW cross-section of the southwestern Barents Sea (line A-B in figure 1 and 3) and b) potential field modelling carried out along the transect. The black dashed line and vertical error bars in (a) indicate the depth estimation (and its uncertainties) to crystalline basement obtained by potential field modelling. The magnetic anomalies mostly reflect the deep (pre-Permian) basement highs (B1, B2) and lows that are thought to occur beneath the thick Mesozoic platforms and grabens.

4 . DISCUSSION

5.1 Lateral escape of the Caledonian nappes

The high-resolution magnetic pattern correlates perfectly with the thrust belt structures observed onshore and their prolongation offshore (Figs. 4, 6). In the Barents Sea Region, the thrust sheets of the Lower Allochthon, located east of the Tanahorn Nappe, extend northeastwards into the inner Finnmark Platform (Fig. 6). However, the structures of the Tanahorn and Kalak nappes extend to the north-northeast offshore but then swing into a NNW-SSE trend close to the Nordkapp Basin and on the Bjarmeland Platform. In the Nordkapp Basin itself, shallow and densely distributed salt diapirs hinder a correct interpretation of the deeper magnetic signal (Gernigon *et al.* 2010).

Compared with previous interpretations, the NNW-SSE magnetic trends are interpreted as prominent basement (crystalline) features involving Caledonian thrust sheets. The trends in this part of the SBS do not fit with the NE-SW or NNE-SSW basement highs and sub-basin configuration previously proposed for the Late Palaeozoic rift system (Dengo and Røssland 1992, Breivik *et al.* 1995, Gudlaugsson *et al.* 1998, Faleide *et al.* 2008).

In terms of deeper Caledonian structures, the new aeromagnetic surveys do not particularly highlight any prominent NE-SW Caledonian structural trends as proposed in previous papers (Doré 1991, Ritzmann and Faleide 2007, Gee *et al.* 2008). Moreover, the presence of a possible suture in the SBS (Breivik *et al.* 2002, Cocks and Torsvik 2005) does not appear to be supported by the new dataset.

Based on our present-day geological onshore-offshore knowledge and in order to explain the magnetic trend geometries observed at present, we propose a tectonic scenario in which the magnetic pattern highlights an arc-shaped Caledonian nappes that swung anticlockwise from a NE-SW orientation close to the Varanger Peninsula to NW-SE across the Nordkapp Basin and the Bjarmeland Platform during the terminal stages of the Caledonian orogeny (Figs. 3, 6). The arc-shaped geometry, highlighted by the new magnetic compilation east of the Loppa High (Fig. 3), is relatively similar in terms of shape, size and proportion to several salients that are typically involved in fold-and thrust belts, along many foreland margins of orogens worldwide (Macedo and Marshak 1999). This pattern could be part of a larger system involving several nappes and thrust sheets fitting a mechanism of flowing and spreading (Merle 1998) (Figs. 6, 7). The arc-shaped structure supported by the new magnetic data also fits relatively well with the main erosion and highlands province proposed in the Late Devonian (Frasnian) palaeographic maps of Smelror *et al.* (2010) and Henriksen *et al.* (2011). The arc-shaped outline of the eroded highland province matches with our magnetic observations, highlighting the proposed architecture of a Caledonian thrust belt that is inferred to have collapsed during Devonian time.

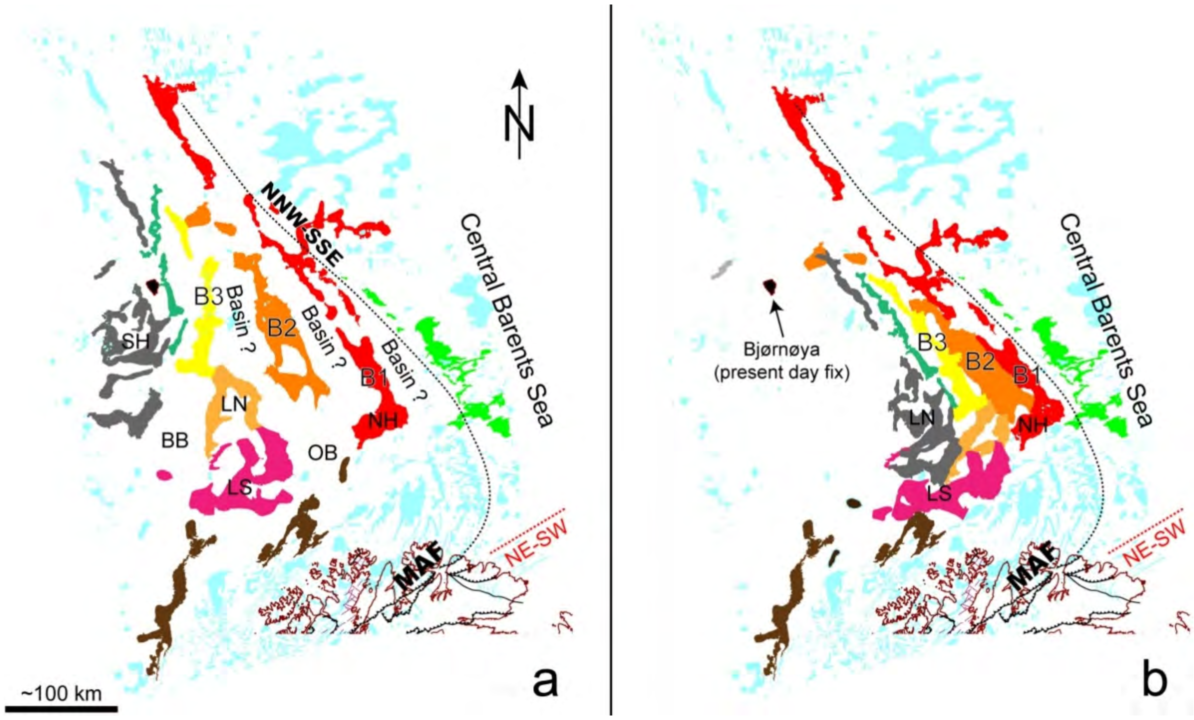

Figure 6: a) Main highs observed from the tilt derivative at the present day in the southwestern Barents Sea. b) Tentative of restoration of napes in arc-shaped Caledonian thrust belt before back-sliding and Late Palaeozoic basin formation. BB: Bjørnøya Basin; B1, B2, B3: prominent NNW-SSE magnetic anomalies interpreted as basement highs underneath the Bjarmeland Platform; LN: Loppa High north; LS: Loppa High south; MAF: Middle Allochthons front; NH: Norsel High; OB: Late Palaeozoic Ottar Basin; SH: Stappen High.

6.1 Post-orogenic back sliding of the nappes and Late Palaeozoic extension

The post-Caledonian phases of extension during Late Palaeozoic and Mesozoic time cannot be underestimated in this scenario because the extensional defomation subsequently affected the basement. This can be shown locally by seismics but also by the edges of several magnetic anomalies. Assuming roughly the retro deformation of the main Palaeozoic basins as expected, the edges of the TDR positive anomalies are clearly fitting well together on both sides of the TDR lows (Fig. 6). We propose that the original Caledonian structural grain may have controlled the regional, pre-Permian, extensional regime (Late Devonian-Carboniferous) by a reactivation of the Caledonian thrust system that collapsed in the vicinity of the high magnetic Loppa High and Central Barent Sea High provinces (Fig. 6).

The Loppa High appears to be a thick, old and rigid (Precambrian?) block which possibly controlled the geometry of the Caledonian nappes behaving as a local indentor during the orogeny and subsequently as a continental ribbon during the Late Palaeozoic and Mesozoic crustal stretching and thinning events (Figs. 7a, 7b). The locations of the main thrusts and shear zones could also explain the formation and location of the major transfer zones when later Mesozoic rifts developed perpendicularly over pre-existing basement discontinuities (Fig. 7c). This could also explain the segmentation of the Nordkapp Basin where each segment seems to be controlled in depth by the inherited N-S to NNW-SSE trends (Fig. 3).

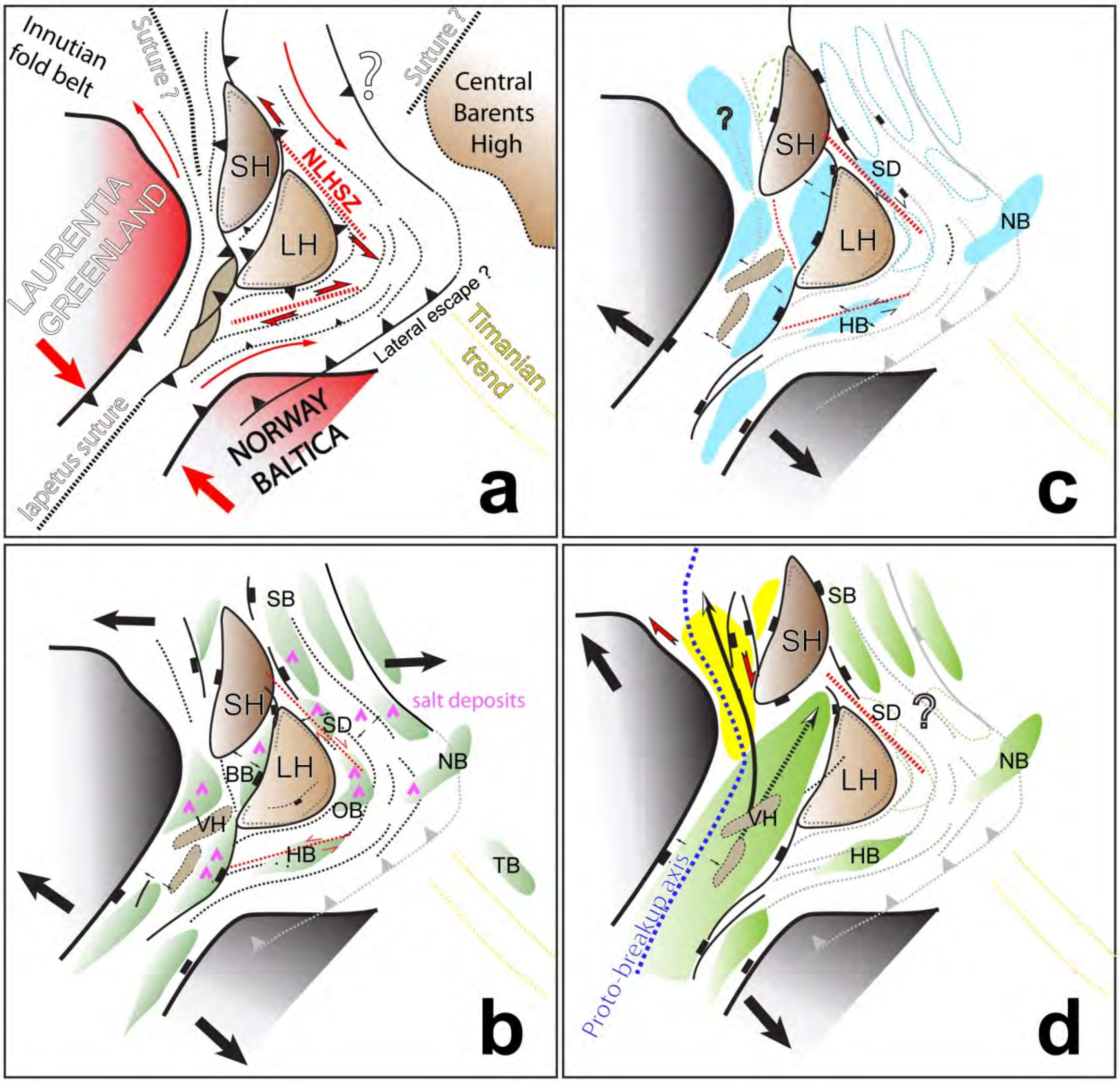

Figure 7: Conceptual models of the geodynamic evolution of the southwestern Barents Sea. a) lateral escape and initiation of the post-orogenic collapse of the Caledonides between Laurentia and Baltica in Late Devonian time; b) reactivation of the main inherited features and shear zones and Late Palaeozoic graben development during the Late Devonian-Carboniferous; c) Early to Mid Mesozoic rifting episodes leading to main stage of graben formation and salt tectonics, d) Late Mesozoic increase of crustal thinning in the westernmost part of the Barents Sea and westward migration of the deformation leading to the final breakup between Laurentia and Baltica in Early Cainozoic time. Abbreviations as in Figure 1.

5 . CONCLUSIONS

In this report we summarise the results and the tectonic implications of a new generation of aeromagnetic surveys which cover and refine almost the entire SBS with new, reliable, high-resolution, high-quality aeromagnetic data. Onshore-offshore correlation has been used to link observed geological features with magnetic lineaments and follow their offshore extensions.

Different levels of the Caledonian allochtons can be linked to a pattern of northeastward-trending anomalies and identified as the magnetic expression of this propagation of the thrust sheets into the SBS. However, the nappes and their 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. This upper crustal model, developed as a consequence of the new magnetic data, challenges pre-existing interpretations and poses new interesting questions regarding the offshore extent of the Caledonides, the basement geometry and the development of the Late Paleozoic basins in the southwestern and central Barents Sea.

6 . ACKNOWLEDGEMENTS

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8 . FIGURE LIST

Figure 1: Structural framework of the southwestern Barents Sea (modified after pre-existing onshore (Sigmond 2002) and offshore (Gabrielsen *et al.* 1990) geological maps, and the outlines of the new high-resolution aeromagnetic surveys acquired by NGU between 2006 and 2009. A-B: WNW-ESE profile shown in Fig. 5. C-D, NW-SE profile shown in Fig. 4. Abbreviations: BB: Bjørnøya Basin; BP: Bjarmeland Platform; BSR: Barents Sea Region; CB: Central Barents High; HB: Hammerfest Basin; KNC: Kalak Nappe Complex; LH: Loppa High; NB: Nordkapp Basin; ND: Norvarg Dome; NLHSZ: North Loppa High Shear Zone; NP: Nordkinn Peninsula; OB: Ottar Basin; SB: Sørkapp Basin; SaD: Samson Dome; SD: Svalis Dome; SH: Stappen High; Sw: Swaen Graben; TN: Tanahorn Nappe; VH: Vestlemøy High; TB: Tiddlybanken Basin; VP: Varanger Peninsula; VVP: Vestbakken volcanic province.

Figure 2: New magnetic total field anomaly map of the southwestern Barents Sea.

Figure 3: Tilt-derivative filter (TDR) of the magnetic total field. The TDR enhances the subtle magnetic anomalies and maximizes the geometrical contrasts of the internal basin structures. Note the prominent NNW-SSE anomalies that characterise the central Barents Sea and the Bjarmeland Platform.

Figure 4: Geological cross-section across the Barents Sea Region of Varanger Peninsula. A good correlation between the onshore Caledonian thrust-and fold belt and the prominent NE-SW magnetic trends (cf. Fig. 3). Numbers indicate the susceptibility measurements (x 1000 SI) recorded along the geological section. KNC: Kalak Nappe Complex; MAF: Middle Allochthon front; TN: Tanahorn Nappe. Location on Figure 1, line C-D.

Figure 5: a) Regional ESE-WNW cross-section of the southwestern Barents Sea (line A-B in figure 1 and 3) and b) potential field modelling carried out along the transect. The black dashed line and vertical error bars in (a) indicate the depth estimation (and its uncertainties) to crystalline basement obtained by potential field modelling. The magnetic anomalies mostly reflect the deep (pre-Permian) basement highs (B1, B2) and lows that are thought to occur beneath the thick Mesozoic platforms and grabens.

Figure 6: a) Main highs observed from the tilt derivative at the present day in the southwestern Barents Sea. b) Tentative of restoration of napes in arc-shaped Caledonian thrust belt before back-sliding and Late Palaeozoic basin formation. BB: Bjørnøya Basin;

B1, B2, B3: prominent NNW-SSE magnetic anomalies interpreted as basement highs underneath the Bjarmeland Platform; LN: Loppa High north; LS: Loppa High south; MAF: Middle Allochthons front; NH: Norsel High; OB: Late Palaeozoic Ottar Basin; SH: Stappen High.

Figure 7: Conceptual models of the geodynamic evolution of the southwestern Barents Sea. a) lateral escape and initiation of the post-orogenic collapse of the Caledonides between Laurentia and Baltica in Late Devonian time; b) reactivation of the main inherited features and shear zones and Late Palaeozoic graben development during the Late Devonian-Carboniferous; c) Early to Mid Mesozoic rifting episodes leading to main stage of graben formation and salt tectonics, d) Late Mesozoic increase of crustal thinning in the westernmost part of the Barents Sea and westward migration of the deformation leading to the final breakup between Laurentia and Baltica in Early Cainozoic time. Abbreviations as in Figure 1.