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Double-folding and thrust-front geometries associated with the Timanian and Caledonian orogenies in the Varanger Peninsula, Finnmark, North Norway

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ABSTRACT: On Varanger Peninsula, the c. NW-SE-trending Trollfjorden-Komagelva Fault Zone separates Neoproterozoic successions that accumulated in a shallow-marine platformal domain to the southwest of the fault from deep-marine basinal to deltaic sediments to the northeast. In Ediacaran time the fault scarp acted as a buttress in a period of basinal inversion during the top-SW, contractional Timanian orogeny. During the subsequent, top-SE to ESE, polyphase Caledonian orogenesis the fault acted as a dextral strike-slip megafracture and lateral ramp. In the northeastern terrane, Timanian and Caledonian fold interference has produced several examples of double-folding and intersecting cleavages. In the southwestern terrane, the Lower Allochthon Gaissa Thrust Belt overlies the Parautochthon, below which a 45 km-long deformation front has been mapped. Tectonic shortening within this frontal zone varies from top-SSE in the west to top-ESE in the east. Imbricate thrust sheets disrupt the succession in the northeastern terrane, below which a floor décollement is speculated to emerge as a frontal fault along a prominent footwall of the precursor fault acted on the seabed in outermost Varangerfjorden. By use of potential field data, the Caledonian structures on Varanger can be followed to the north into the Barents Sea where the nappe pile in the pre-Carboniferous basement reaches a thickness of several kilometres.

Key words: Caledonian, Timanian, Northern Norway, Trollfjorden-Komagelva Fault Zone, double-folding, Barents Sea

1. INTRODUCTION

The Neoproterozoic to Early Ordovician, low-grade, metasedimentary successions on the Varanger and Digermul peninsulas in East Finnmark, North Norway, display structures ascribed to two, major, fold-and-thrust systems, parts of which expose prominent double-folding (Fig. 1) (e.g., Roberts, 1972, 1996; Gayer et al., 1987). Although originally assumed to be associated solely with Caledonian contraction (Roberts, 1972; Teisseyre, 1972), more recent investigations have revealed that the fold complexity arises from deformation in both the Timanian and the Caledonian orogenies (Roberts, 1995; Roberts and Siedlecka, 2002). The 1800 km-long Timan-Varanger Belt of the Timanide Orogen (Olavyanishnikov et al. 2000; Gee et al. 2006; Pease et al. 2016) is situated along the northeastern margin of the Fennoscandian Shield and extends for a further 1000 km into the northern and Polar Urals. The main Timanian orogenic movements involved SW-directed folding and thrusting (Roberts and Olovyanishnikov, 2004; Herrevold et al., 2009) and are dated to Ediacaran time (Gee et al., 2000; Larionov et al. 2004); but in the northern Urals, related metamorphism extended into the earliest Cambrian (Beckholmen and Glodny, 2004). Initially, subduction polarity faced away from the craton but is considered to have reversed in connection with slab break-off during Cryogenian times (Scarrow et al., 2001; Roberts and Siedlecka, 2002).

In the Varanger-Digermulen region, contrarily, the principal tectonic transport direction in this part of the Scandinavian Caledonides was top-SE, later ESE, such that the dominant strike of Caledonian fold axes and associated cleavage and thrusts is approximately NE-SW and, thus, in harmony with the top-SE transport vector. Important exceptions to this do occur, particularly close to the Trollfjorden-Komagelva Fault Zone (TKFZ) (Fig. 1). However, although the Caledonian structural grain predominates in the greater part of the Varanger Peninsula, there is a significant fold system oriented roughly transverse to the Caledonian trend, notably in the northeastern part of the peninsula (Fig.1). Here, there are folds with amplitudes on the scale of tens to hundreds of metres, wavelengths up to several kilometres, and NW-SE to NNW-SSE-striking fold axes with axial planar slaty cleavage, which are considered to be of Timanian origin (Roberts, 1996; Siedlecka and Roberts, 2020).

In the present contribution we expand on the known and previously published structural data and observations on Varanger Peninsula by referring to the detailed field studies of Sygnabere (1997) and Gjelsvik (1998) as well as to more recent field data and structural observations acquired by the first author. These new and hitherto unpublished data, together with a closer assessment of high-resolution multibeam bathymetric data from outer Varangerfjorden originally reported in Roberts et al. (2011), have allowed us to refine the Caledonian structural history of the peninsula whilst concurrently acknowledging the existence of the earlier Timanian structures.

2. DEPOSITIONAL AND TECTONIC FRAMEWORK

The Tonian to Cambrian sedimentary rocks of the Varanger Peninsula were deposited in two quite different basinal regimes, separated by a major precursor fault of the NW-SE-trending Trollfjorden-Komagelva Fault Zone and an affiliated structural high (Siedlecka and Siedlecki, 1967; Johnson et al., 1978; Siedlecka et al., 2004). The northeastern part of the peninsula is generally known as the *Barents Sea Region* (Siedlecka and Siedlecki 1967), but has also been called the North Varanger Region or Terrane by some workers; e.g., Rice (1994, 2014), a term also used intermittently here. To the southwest of the TKFZ lies the *Tanafjorden-Varangerfjorden Region* (Fig. 1). Here we describe briefly the depositional framework of the two regions as a prelude to documenting the new structural observations in a regional tectonic context also involving offshore areas.

2.1. Barents Sea Region

The Barents Sea Region (BSR) hosts two allochthonous sedimentary sequences – the Barents Sea Group and the Løkvikfjellet Group – with a combined thickness of c. 15 km (Siedlecka and Siedlecki, 1967; Siedlecki and Levell, 1978). The Barents Sea Group, of Tonian-Cryogenian age, comprises a 9 km-thick succession of deep-marine submarine-fan turbidites grading up into prodelta, delta-front and shallow-marine deposits. The Løkvikfjellet Group lies with marked angular unconformity upon diverse formations of the Barents Sea Group and consists mostly of shallow-marine siliciclastic sediments with subordinate fluvial incursions. Although a Vendian or even Cambrian age had been suggested earlier (Vidal and Siedlecka, 1983; Rice et al., 2012), a detrital zircon study has now shown that the succession is Cryogenian (Zhang et al., 2015). Forming part of the Caledonian Lower Allochthon, these two groups are characterised by stronger deformation and slightly higher grade (epizone) metamorphism compared with the parautochthonous and autochthonous rocks of the Tanafjorden-Varangerfjorden Region southwest of the fault zone (Bevins et al., 1986; Rice et al., 1989a).

The eastern part of the Barents Sea Region, around and west of Vardø, is characterised by a series of NNW-SSE to NW-SE-trending folds (Roberts, 1972; Gayer et al., 1987; Rice et al.1989b) that in places interfere with ENE-WSW folds (Siedlecka and Roberts, 2020b). As noted earlier, the dominant NNW-SSE to NW-SE folds and associated cleavage in this area are considered to be Timanian structures. The same structural trend has been registered widely on the seabed to the east of Vardø by multibeam bathymetric data (Roberts et al., 2011) and can be followed across outer Varangerfjorden to the Rybachi Peninsula in nearby Russia.

In contrast, the structural grain in the western part of the Barents Sea Region is dominated by a NE-SW trend of the major folds, the thrust beneath the Tanahorn Nappe (Middle Allochthon) and branch lines (e.g., Gayer et al., 1987, Rice et al., 1989b). The Tanahorn thrust can be followed offshore, changing strike gradually, anticlockwise, from NE-SW to NNW-SSE well to the north of Varanger Peninsula (Gernigon et al., 2012, 2014). In the Berlevåg district, a separate thrust sheet (Rákkočearru thrust sheet of the Lower Allochthon; Roberts, 2009) occurs below the Tanahorn Nappe, with another thrust sheet (named Máhkirčearru; Siedlecka and Roberts, 2012) below that to the east (Fig.1 and 2). The area farther to the southeast between Syltefjorden and Vardø/Kiberg constitutes a third thrust sheet, here named Langryggen.

Two distinct phases of Caledonian tectonic transport have been identified in the western area where strain indicators in the fault rocks and folds suggest that the principal top-SE transport was succeeded by ESE-directed thrusting (Johnson et al., 1978; Townsend et al., 1986; Townsend, 1987; Rice and Frank, 2003; Rice, 2014). Folds and associated schistosity or slaty cleavage of the early, ductile, top-SE event have been dated to early Ordovician, late-Finnmarkian time, whereas the more brittle top-ESE movements are considered to relate to Scandian reactivation (Rice and Frank 2003) in Silurian to Early Devonian time.

The central transitional area between these two, eastern and western, domains also displays top-SE and top-ESE tectonic transport indicators, albeit with a more dominant eastsoutheasterly direction as reflected in the NNE-SSW fold axial trend as seen in the Båtsfjord area (Fig. 1). Going from northwest to southeast in the Barents Sea Region, the Caledonian structures thus display contrasting deformation styles. The western segment is characterised by overturned, SE/ESE-vergent, fault-propagation folds with associated low- to moderate-angle thrusts (Roberts1972; Teisseyre, 1972), whereas large fold trains with fairly upright axial planes and, in places, thrust-related duplexes characterise the central and eastern segments, respectively (Fig. 2).

A significant feature in this region is the presence of mafic dykes. Metadolerite dykes of Ediacaran age (Rice et al., 2004) are common in all formations in the Rákkočearru and Máhkirčearru thrust sheets and in places occur as mappable NE-SW-trending swarms (Roberts, 1975; Siedlecka, 1989; Siedlecka and Roberts, 2020b). Conversion of the original dolerites to metadolerites occurred coevally with the principal, Caledonian, ductile top-SE folding in earliest Ordovician time. In the Langryggen thrust sheet, metadolerite dykes appear to be almost absent but their subsurface presence is suspected by the occurrence of several linear, ENE-WSW-trending, positive anomalies on tilt-derivative aeromagnetic maps (Nasuti et al. 2015). Younger, un-metamorphosed dolerite dykes of Late Devonian age occur in a few places in eastern areas, also south of the TKFZ (Guise and Roberts, 2002). Dolerite dykes of Carboniferous (Visean) age representing yet another rifting episode are known from Magerøya (Lippard and Prestvik, 1997, Roberts Robins, 2020) and the Digermulen Peninsula (Rice et al., 2004) and can be followed across Tanafjorden into the subsurface of western Varanger Peninsula by high-resolution aeromagnetic data (Nasuti et al., 2015).

2.2 Tanafjorden-Varangerfjorden Region

This is the part of Varanger Peninsula (TVR, Fig.1) to the southwest of the TKFZ and comprises the Caledonian Parautochthon and subjacent Autochthon, as well as the frontal part of the Gaissa Nappe Complex (also called the Gaissa Thrust Belt), which, in our study area, includes the Skiipagurra fold belt of Rice (2014). The Tonian to Cambrian sedimentary rocks of this region – also here called the 'southern terrane' -- accumulated in a fluvial to shallow-marine, platformal domain that in Cryogenian to Ediacaran time developed into the Gaissa Basin, which then functioned as a foreland basin to the Timanide Orogen (Gorokhov et al., 2001; Zhang et al. 2015). The 4 km-thick succession comprises three groups – Vadsø, Tanafjorden and Vestertana -- with the youngest, Ediacaran to Cambrian, Vestertana Group including two diamictite formations (Smalfjord and Mortensnes formations; Fig.3) which have been suggested to correlate, respectively, with diamictites of the worldwide Marinoan and Gaskiers glaciations (Gorokhov et al. 2001; Halvorsen et al., 2005; Rice et al., 2012) (Fig. 3). Recent geochronological studies and correlations (Kjøll 2019; Kumpulainen et al 2021), however, now suggest that both the Smalfjord and the Mortensnes diamictite formations were deposited during the Marinoan glaciogenic event, also called the Varangerian in northern Norway.

Metamorphic grade in the rocks of this region is generally in anchizone, highest in the Gaissa Thrust Belt where the Caledonian ductile strain was also high, but gradually decreasing eastwards and not exceeding diagenesis grade in the autochthonous Vadsø Group (Bevins et al., 1986; Rice et al., 1989a, 1989b). Several thrust sheets, imbricate zones and duplexes have been named and described from areas farther west in the Gaissa Nappe Complex (Townsend et al., 1986, 1989; Welbon, 1986; Roberts and Rice, 2008; Rice, 2014) but these do not concern us in this contribution.

The area studied by us encompasses several formations in the Tanafjorden and Vestertana groups (Banks et al., 1974; Røe, 2003; Siedlecka and Roberts, 2019; Røe and Roberts, 2019) (Fig.3). The sole thrust to the Gaissa Thrust belt is clearly seen far to the west of the Tana river and then swings northeastwards into the western part of the Tanafjorden-Varangerfjorden Region (Fig. 1) (Herrevold et al. 2009; Rice 2014). A comparable detachment has been inferred towards inner Varangerfjorden (Townsend, 1987; Townsend et al., 1986; Rice 2014), but has proved difficult to trace, partly because of poor exposure, and a blind thrust has been proposed. Although no true discrete thrust-fault has been recorded beyond Mortensnes, a Caledonian deformation front has been mapped and described by Sygnabere (1997) at or close to the base of the Stangnes Formation as far east as the coast just northeast of Vadsø, at Jamteberget (Fig. 4). This feature, which is a sort of 'semi-detachment' beneath the contractional folding in the Parautochthon, was called the *Mortensnes-Jamteberget thrust-and-fold zone* by Sygnabere (1997), here renamed the 'Mortensnes-Jamteberget deformation front' (MJDF; Fig.4). The term deformation front best describes this feature, as noted by Townsend (1987) and Rice (2014), and is recorded as such on several 1:50,000 bedrock map-sheets published by NGU (e.g., Siedlecka and Roberts, 2018).

Although Timanian deformation has had little effect on the rocks southwest of the TKFZ, there are small areas where SW-verging, inferred Timanide, small folds and cleavage are present, particularly in the vicinity of the footwall escarpment to the fault zone (Karpuz et al., 1993; Herrevold et al., 2009). Interfering cleavages of both NW-SE Timanide and NE-SW Caledonide trend are also clearly seen in the intertidal zone at Komagnes (Fig. 1). There are also areas of more complex deformation, possibly due to multiple stages of Caledonian thrusting (e.g., Townsend 1987; Rice 2014). Thus, overall, the Tanafjorden-Varangerfjorden Region has a tectonic style that is quite different from that seen in the successions of the North Varanger Terrane. The Caledonian Gaissa thrust front in the Tanafjorden-Varangerfjorden Region crops out in the far northwest of the terrane (Hanadalen Thrust; Rice 2014), hence not linking directly with the Caledonian frontal systems of the Barents Sea Region, the two regions being separated by the TKFZ that acted as a lateral ramp to the Caledonian thrusting and folding coeval with dextral strike-slip translation. The amount of dextral offset along this major fault zone has been a bone of contention since the early work of Kjøde et al. (1978) and Bylund (1994), with the latest minimum value of 207 km based on the shortening estimates and detailed restoration work of Rice (2014).

The present contribution aims at documenting the interference between these two, disparate, fold populations to demonstrate the contrasting structural styles and shortening in the hangingwall and footwall to the Trollfjorden-Komagelva Fault Zone; and finally, to view these new observations in a regional tectonic context involving also offshore areas in the southern Barents Sea based on potential field data. To this end, we divide the regions into specific areas and provide descriptions of the folds, double-folds, cleavages and associated structures.

3. STRUCTURAL DESCRIPTIONS

Structural geological fieldwork and analysis of the data on which the present work is based have taken place over an extended period, including extensive work under projects at the Geological Survey of Norway and in several master and PhD programmes. Over the last few years, high-quality reflection seismic potential field data have become available, adding to our understanding of the offshore extension of the various structural elements. The significant new data from key areas in the study area are presented below. However, because the Varanger Peninsula has been the subject of detailed structural studies, particularly since the

1970s, we include references to previous field and analytical data where these add to a more comprehensive description of the structures in each of the areas described in the following.

3.1 East-Central North Varanger Terrane: Storflogdalen

Storflogdalen, c. 3 km west of Persfjorden (UTM 7893403-1079942), was selected for a detailed study of the interference between the prominent NNW-SSE and NE-SW-trending fold systems. Storflogdalen offers a continuous, combined, coastal and eroded valley exposure of characteristic structural features of the east-central North Varanger Terrane (Fig. 2). Here, in sandstones and shales of the Kongsfjord and Båtsnæringen formations, meso- and macro-scale, NNW-SSE- and NE-SW-trending, fold families interfere, each with associated axial-surface cleavages (see also Roberts, 1972; Hjellbakk, 1993; Siedlecka and Roberts, 2020a). Also present in places are modest reverse-faults or low-angle thrusts affiliated to both fold systems.

The most prominent structures are trains of NNW-SSE-striking anticlines and synclines with wavelengths and amplitudes of more than 100 metres (Fig. 5). One dominant anticlinal fold occupies the whole of Storflogdalen, whereas many subparallel subordinate folds define minor structures, which either belong to the same fold train or are parasitic folds to the master anticline. In the northern part of Storflogdalen, a few NNE-SSW-trending anticline-syncline pairs with a folding style similar to that of the NNW-SSE folds coexist with the latter. Some of the minor NNW-SSE-striking folds have chevron-type geometries with disrupted fold hinges and show a pronounced NE-dipping fracture cleavage in sandstone beds and slaty cleavage in the fine-grained lithologies. All the folds of this trend are tight to open with upright to steeply ENE-dipping axial surfaces. Thrust planes are rare in the central part of Storflogdalen, but small-scale (decimetre to metre) bedding-parallel shear-zones and reverse faults associated with chevron-type folds are common. Outside the areas with the largest folds, however, there are reverse-faults and small thrusts with dominant, synthetic, top-SW offsets and antithetic top-NE displacements, and in places associated fault-propagation folds with axes striking NNW-SSE. Some structures belonging to this family of folds display configurations where mildly shortened and displaced strata rest directly above folded beds, signifying that bedding-parallel shortening was concentrated at particular stratigraphic levels, promoting the development of localised décollements and fault-propagation folds, duplexes and local back-thrusts, in this case with a dominant WSW-directed tectonic transport.

The fold-and-thrust structures described above locally interfere with an array of NE-SW-striking folds with amplitudes and wavelengths of 10-30 metres and in places down to metre scale, giving the appearance of double folding. These NE-SW-trending folds also have dominantly upright axial surfaces and in places a cuspate geometry in units of thick, competent, sandstone beds within cleaved mudstones. In areas away from the hinge zones of macro-scale NNW-SSE-trending folds, one finds asymmetrical, top-SE, fault-propagation folds with NE-SW-striking fold axes, e.g., at Godkeila in eastern Persfjorden. Also, there are box-folds present in some places that displace vertical quartz-filled fractures belonging to the NE-SW-striking group of folds.

Although this deformation event with NNW-SSE-trending folds has yet to be reliably dated, Taylor and Pickering (1981) obtained a Rb-Sr whole-rock isochron age of 520 ± 47 Ma for the slaty cleavage (Fig.6) in the Kongsfjord Formation just 5 km northwest of Storflogdalen. This is a date that can be construed to relate to either Finnmarkian or Timanian deformation and accordingly must be rejected. Nevertheless, based on the regional structuring in the Barents Sea Region and comparisons with previous studies on Varanger and in nearby Northwest Russia (e.g., Roberts, 1995, 1996; Roberts and Olavyanishnikov, 2004; Herrevold et al., 2009), it is most likely that this family of NNW-SSE-trending folds and related structures developed during the Ediacaran Timanian Orogeny.

3.2. EASTERN NORTH VARANGER TERRANE

Siliciclastic rocks of the Båtsnæringen Formation are exposed on the mainland west of the town of Vardø and along the coast southwest of Kiberg as far as the TKFZ (Fig. 1) (Siedlecka and Roberts, 2020). The Båtsnæringen Formation includes four members; from bottom to top the Næringselva, Seglodden, Godkeila and Hestman members (Fig. 3). The Hestman and Seglodden members consist of massive, red to greenish-grey sandstones that were deposited in braided river channels, whereas the Godkeila and Næringselva members are mainly pelitic, alternating mudstone and thin sandstone units deriving from delta-front environments (Siedlecka and Edwards, 1980). These lithological and mechanical contrasts, together with changing geometries and strain intensity close to the TKFZ are reflected in the large-scale fold pattern in this easternmost area of the Varanger Peninsula.

The northern coastal part of this terrane between Vardø and Syltefjorden is dominated by folds with NNW-SSE to NNE-SSW-trending axes (Roberts, 1972). Inland, towards the south, the axial traces of these large-scale folds show an apparent clockwise drag that is consistent with dextral shear along the Trollfjorden-Komagelva Fault Zone (Fig. 1) (Siedlecki, 1980), which acted as a lateral ramp/accommodation zone during the early-Caledonian, SE-directed thrusting.

The coastal and adjacent inland zone between Komagelva and Vardø reveals a more composite structuring (Fig. 4). An array of folds and associated slaty cleavage with NW-SE to NNW-SSE orientation is ubiquitous and particularly so in the hangingwall of the TKFZ. The axes of open folds with upright to steeply NE-dipping axial planes strike NW-SE closest to the fault zone (see also Herrevold et al., 2009), swinging more to NNW-SSE farther away from the fault. These folds are not arranged in any *en échelon* pattern; nor are they common inside the actual fault zone and, accordingly, they do not fit the configuration that would be expected for fold arrays associated with a right-lateral strike-slip system (as described by Crowell, 1974 and Dooley and Schreurs, 2012). Rather, the NW-SE folds and accompanying cleavage (Fig.6) are also associated with top-SW minor thrusts and reverse-faults (see also Karpuz et al., 1993; Herrevold et al., 2009). Field observations thus indicate that these are the oldest preserved folds in this particular area. The relative age, position and configuration of the NW-SE to NNW-SSE fold family therefore corroborate earlier suggestions that these structures were generated during the Timanian orogenic event, which is characterised by southwest-directed tectonic transport (Roberts, 1995; Roberts and Olavyanishnikov, 2004; Siedlecka et al., 2004; Herrevold et al., 2009).

A younger set of NE-SW to ENE-WSW-trending folds overturned to the SE/SSE have locally generated a dome-and-basin pattern (cf., Ramsay and Huber, 1986) north of the TKFZ where they, in places, interfere with the NW-SE to NNW-SSE folds. The NE-SW folds are open and upright to inclined, with axial planes and associated spaced cleavage dipping to the northwest, and may also be present in the hangingwalls of small, SE-vergent thrusts. This group of folds is clearly younger than the NW-SE to NNW-SSE-oriented folds and in places is associated with larger (frontal?) thrusts belonging to the Caledonian, top-SE/SSE, contractional events (cf., Roberts, 1972). Some of the folds with NE-SW-striking axes occur in the hangingwalls of very persistent reverse-faults or thrusts over large distances. Examples of this are the Slaktefjellet Fault and the Svartnes-Kiberg Fault which are both accompanied by open hangingwall anticlines that can be followed for several kilometres (Fig. 4).

In areas west of the town of Vardø, where there is direct interference between the (Timanian) NNW-SSE and (Caledonian) NE-SW-trending folds, patterns of irregular to symmetrical and elongate, basin-and-dome geometries (classes E and H of Ramsay and Huber, 1987; Gjelsvik, 1998) are developed. Hence, the bedding measurements presented in Fig. 4 have been taken outside the areas of direct fold interference. The western segment of the ENE-WSW-trending *Slaktefjellet fault* (Figs. 7a, b and 8) appears as if it may merge into the TKFZ at its termination although exposure there is non-existent (Siedlecka and Roberts, 2019). Cutting obliquely through the Godkeila and Hestman members of the Båtsnæringen Formation (Gjelsvik 1998), the Slaktefjellet fault includes dissected lenses of these rocks with their longest axes aligned parallel to the fault trace. Deformation along the fault is characterised by mylonite and cataclasite where semi-ductile mylonite and phyllonite are overprinted by thin laminae of cataclasite (Figs. 7c-f). The fault can be traced in Landsat satellite imagery over relatively poorly exposed ground for more than 12 km before it is separated from its almost E-W continuation by a fault jog or splay. After another 10-11 km it suddenly swings into a N-S trend close to the large lake Oksevatnet (Fig. 8) but does not appear to offset any of the boundaries between the several members of the Båtsnæringen Formation.

The *Kiberg duplex* system (7876680-109206; Fig. 9) is associated with a thrust that strikes parallel to the regional trend of the folded beds of the Godkeila and Hestman members (Gjelsvik 1998), albeit with a greater angle of dip. It is most likely the same feature as observed by Reusch (1891) who noted that “around Kiberg . . . . dips in all directions were observed, making it difficult to get an overview of the structural relations” (our translation from Norwegian). The main structures of the duplex system strike NW-SE. The duplex cannot be followed along strike for more than a few hundred metres, suggesting that it is likely to be a fault lens trapped in the core of a thrust zone, incorporating horses with dismembered fold closures, isolated fold limbs, and with parts with intact primary sedimentary (locally onlap) relationships. The roof and floor faults of the duplex are unfortunately not completely exposed.

On closer inspection in the Kiberg area, structures similar to those described above are seen developing along some bedding surfaces before cutting up-section at an obtuse angle. Along strike and where deformation becomes more intense, these structures grade into fully fledged duplexes which include isolated horses with rootless recumbent folds and with axes paralleling the fault branch lines of the duplex. These smaller imbricate thrusts and reverse-faults swing into a more N-S orientation around Kiberg, such that the thrust-and-fold system as a whole has the configuration of sheath folds that are commonly associated with the development of a thrust system (e.g. Alsop and Holdsworth, 2006; Alsop and Carreras, 2007). It is therefore suggested that this family of thrusts is part of the most external, imbricate thrust system of the Caledonides in the Barents Sea Region of Varanger Peninsula, belonging to the Scandian stage of ESE- to E-directed displacement. Earlier, Rice et al. (1989b) had in fact suggested that a major décollement may be present at depth beneath the Barents Sea Region.

In view of the observations presented above, we speculate that the very thrust front may be situated just offshore on the seabed in the outermost part of Varangerfjorden. Support for such an offshore location of the thrust front comes from morphological features in the subcropping bedrock on the seafloor revealed by Simrad multibeam bathymetric data (Roberts et al. 2011). At a distance of c. 7-8 km offshore from Kiberg, two prominent parallel escarpments trend approximately NE-SW and merge northeastwards before curving into a N-S to NNW-SSE orientation east of Vardø (Fig. 8). Accordingly, we consider it quite conceivable that the Caledonide thrust front emerges along or adjacent to one or other of these escarpments.

3.3. Southern and Easternmost Tanafjorden-Varangerfjorden Terrane

Although tectonically less complicated than the Barents Sea Terrane, the Tanafjorden-Varangerfjorden Region is characterised in its northwestern part by the prominent Caledonian folding and thrusting of upper anchizone-grade rocks of the Gaissa Nappe system(Townsend et al., 1986). According to Rice (2014), the easternmost part of the Gaissa Thrust Belt is represented by his Hanadalen Thrust Sheet (Fig. 1), to the southeast of which lies the lower anchizone-grade Parautochthon. It has long been known that open to tight folds and small thrusts could be traced along and to the west of the southern shoreline of Varanger Peninsula in this region (Fig. 4) (Williams, 1979; Chapman et al.1985; Townsend, 1987; Townsend et al. 1986). In fact, it was Reusch (1892) who had first described the intense fold deformation in the Mortensnes area, now a part of what Rice (2014) has called the Skiipagurra Fold Belt.

Recent structural analysis has been focused on tracking this particular deformation zone, and Sygnabere (1997) found that the road locality c. 2 km west of Mortensnes (7841433-102273209) offers a section through what he had mapped out and named the *Mortensnes-Jamteberget thrust-and-fold zone,* now the Mortensnes-Jamteberget deformation front (MJDF) (Figs. 4). This 45 km-long, Caledonian thrust zone, localised towards the base of the Stangnes Formation, marks the base of the Parautochthon, and defines an ESE-vergent duplex including horses with trains of asymmetrically stacked folds, isolated dismembered fold limbs and several small thrusts (Fig. 10), all of which show a general SE to SSE vergence. No roof to the deformation zone has been observed and the overall structure has the character of an imbricate thrust system with blind faults steepening up-section, the fault dips varying between 20 and 70°. Like the duplexes and thrusts in the Barents Sea Region, the faults in the MJDF are characterised by semi-ductile fault rocks that are overprinted by brittle shearing.

Although the main tectonic transport and shortening in the western and central parts of the deformation zone is generally top-SE to SSE, it is also locally south-directed, whilst in the east around Jamteberget small-scale structures show variations from top-SE to top-E. This large swing gives an overall impression of sheath folding, perhaps accompanied by gravity-influenced spreading of the frontal part of the thrust system. Although in general, the oldest stratigraphic unit affected by the fold-and-thrust zone is the Stangnes Formation, the deformation front migrates up-section in the west to affect the Nyborg and Mortensnes formations; and in places in the east, the subjacent Grønneset Formation is also affected, though to a milder extent. However, in these eastern areas the pelitic rocks of the Stangnes Formation are far more strongly involved in the folding and thrusting than the sandstones of the Grønneset Formation, showing that the flats of the master thrusts travelled preferentially through the Stangnes mudstones rather than the subjacent sandstone unit. Whilst the deformation zone does appear to cut into slightly deeper stratigraphic levels to the northeast, the deformation there seems to have been distributed over a larger rock volume, albeit with asymmetrical chevron folds, displaced fold limbs and fewer minor thrust faults. Although the diagenesis-grade Autochthon is very little affected by the Caledonian deformation, rare open folds and minor, top-SSE, reverse faults have been recorded in just a few places.

Back-thrusting, which might have occurred out-of-sequence but still related to the main top-SSE shortening and thrusting event, occurs locally in the east, whereas minor transverse (top-NE) transport is also recorded in small, NW-SE-trending folds in one area close to the TKFZ; but the latter structures are clearly subordinate to those generated by the major, ESE-directed thrusting (Sygnabere 1997).

Although the Tanafjorden-Varangerfjorden Terrane is dominated by Caledonide folds and thrusts with shortening directed between top-S in the southwest and top-ESE in the east, there are small areas directly south of the TKFZ that expose Timanide small folds, slaty cleavage and minor thrusts. One easily accessible area is the intertidal zone in the vicinity of Komagnes in mudstones of the Stáhpogiedde Formation where there are interfering WNW-ESE-striking, NNE-dipping (Timanide) and NE-SW-striking, NW-dipping (Caledonide) cleavages, small folds and reverse faults (Herrevold et al., 2009).

Our field observations confirm the general model for the structural development of the Varanger Peninsula that the rocks of the area have been subjected to tectonic shortening, albeit that the Trollfjorden-Komagelva Fault Zone separates terranes of interfering Timanian top-SW and strong Caledonian top-SE shortening in the Barents Sea Region from an area of almost entirely Caledonian top-SE, relatively mild contraction in the Tanafjorden-Varangerfjorden Terrane to the south. The Caledonian thrust system has a curvilinear, lobate, frontal geometry (Fig. 8). It is therefore likely that this pattern can be traced offshore parallel to the thrust front.

3.4. Geometry of the fold-and-thrust System in the Nordkapp Basin – Finnmark Platform Area

The Caledonian thrust-and-fold system exposed on the Varanger Peninsula is considered to strike northeastward from the North Varanger Terrane into the Barents Sea where it interferes with the Timanide orogenic belt (Gee et al. 2008; Pease 2011; Gernigon et al. 2014, 2018; Aarseth et al. 2017). Utilising potential field data, Gernigon et al. (2018) showed that the thrust-fault of the Tanahorn Nappe of the Middle Allochthon (MAF) coincides with an arcshaped structure that crosses the central segment of the Nordkapp Basin (Fig. 1). This implies that the rocks of the Lower Allochthon, and the concealed or emergent Caledonian front, must be situated to the southeast of this arcuate structure. We have combined reflection seismic and bathymetric data with onshore mapping to constrain these structures. As reported above, a curvilinear structure is identified offshore east of the thrust-fault system. A similar, top-ESE, Caledonian thrust has been suggested to exist beneath the Nordkapp Basin by Koehl et al. (2018, 2019), and termed the Sørøy-Ingøy shear zone. This system appears to include northward extensions of the Slaktefjellet fault and the Kiberg duplex, and consequently we suggest that this submerged structure may represent the real front of the Caledonide thrust system. No reflection seismic data are available between the Barents Sea Region of the Varanger Peninsula and the seismic lines of the BSSE survey that covers the Nordkapp Basin, and we have therefore applied potential field data to support this correlation (Fig. 11a). On approaching the Nordkapp Basin, coverage is offered by the BSSE seismic survey and several sections of this survey, with a depth cut-off at 9 sec twt, image contractional structures in the basement below the Nordkapp Basin and its marginal Finnmark and Bjarmeland platforms. On the regional scale, the top-basement (base Carboniferous?) displays a low-relief horst-and-graben topography. NW-SE- and NE-SW-striking normal fault systems define Carboniferous-Triassic basins filled with evaporite of Pennsylvanian-early Permian age and younger siliciclastics (e.g., Gabrielsen et al. 1990; Gernigon et al. 2018; Koyi et al. 1993; Rojo et al. 2019; Hassaan et al. 2020, 2021b). These include particularly the southwestern and northeastern Nordkapp and Tiddlybanken basins (e.g. Koehl et al. 2018, 2019; Hassaan et al. 2020, 2021a, b) and the Ottar Basin (Breivik et al. 1995) in the study area.

Two, regional, deep reflection seismic lines have been included in the present study (lines BSSE 14RE-1240 and line CFI-4992-0357 (Fig.11). The selected seismic profiles were depth converted based on the constructed velocity model (Petrel v.2021, Schlumberger) that was built with the migration velocities (related to sedimentary strata) provided by TGS. However, within the basement a constant velocity of 6200 m/s has been utilised based on our regional knowledge of the Barents Sea and detailed interpretation of the top basement (at Base Carboniferous level) with high confidence.

The NNE-SSW-oriented line BSSE 14RE-12040 gives one example of the structural configuration in the basement (Fig. 13). Because the thrust front is curved (Figs. 8 and 11), the angle between the line orientation and the assumed local Caledonian tectonic transport direction is smallest in the southwestern part of the line. Several anticlines and synclines with wavelengths in the order of 25-50 km and amplitudes of 10-20 km are separated by thrusts with dip angles of c. 10 to 20° (depth-converted) to the NW-WNW. The frontal thrust fault is situated north of the Haapet Dome in the Bjarmeland Platform and has a parallel, open, anticline-syncline fold pair in its hangingwall (Fig. 13). The correlation of marker reflections on the footwall side is uncertain since the structure is undrilled, but visual correlation may indicate a normal offset indicating back-gliding after contraction. This is common for the Caledonian structures in the area (e.g., Gernigon and Brönner 2012; Gernigon et al. 2014). The area between the Haapet and the Veslekari domes at the northeastern margin of the Nordkapp Basin is dominated by a wide asymmetrical anticline with a wavelength in the order of 75 km and with a sharp syncline near its trailing edge indicating top-N shortening. The anticline is dismembered by subordinate internal faults (Fig. 12b). The trailing-edge syncline is likely a member of a fold train dismembered by a top-N thrust on its southern flank, so that the entire structure defines a fold-and-thrust duplex system. It is noteworthy that the Veslekari Dome is positioned on the top of the duplex, which defines a local basement high, suggesting that the sub-Carboniferous relief influenced both salt deposition and the ensuing diapirism.

The ENE-WSW-striking seismic line CFI-4992-0357 (Fig. 13) is oriented parallel to the regional Caledonian tectonic transport direction, but oblique to the tectonic transport that is expected for the southeastern flank of the offshore thrust lobe as identified in magnetic data (Fig. 11a). Except for some deep parts, line CFI-4992-0357 displays very modest reflectivity between 4000 and 6000 ms as compared with line BSSE 14RE-12040 described above. Even so, the reflectivity is good below 6000 ms. The full structural interpretation was achieved by pursuing the deep structures up-section, as anastomosing bands of positive and negative reflections. The reflective crust can be divided into four levels. From top to bottom, the highly reflective late Palaeozoic to Cenozoic sequence (above 2000 – 3000 ms) is tilted towards the ENE and is generally undeformed, only with minor draping anticlinal-synclinal pairs mainly positioned above deeper normal faults (Fig. 13b). The deformation is focused in the deepest part of the late Palaeozoic sequence, but dies out up-section. The sequence between c. 3000 and 6000 ms is less reflective, but some distinct normal faults are seen. As also seen in line BSSE 14RE-1240 there is a complex system of overturned to open, upright anticline-syncline pairs. For the longer (upper for inclined folds) fold limbs, parasitic folds can be distinguished in places (Fig. 13). The fold trains are separated by a set of west-(northwest?)-dipping thrust planes with a westerly (to northwesterly?) tilt of 10-20^o (depth-converted; Fig. 14).. The sequence below 6000 ms has a higher reflectivity with stacked fold-trains with wavelengths of 34 to 44 km and amplitudes of up to 650 to 1075 ms. The folded sequence seems to be constrained down-section by inclined planes with a west-southwesterly dip component, probably representing basal thrust planes. These basal structures appear to flatten into the top of the reflective lower crust as also seen beneath the Viking Graben basin system (Fossen et al. 2014, Gabrielsen et al. 2015). Generally, the geometry is consistent with a deeply seated, upper lithosphere, top-east, fold-and-thrust system and is in harmony with that reported from line BSSE 14RE-12040.

Although double-folding is observed in the eastern North Varanger Terrane (e.g. Storflogdalen; see above), a similar structural pattern cannot be observed in the reflection seismic nor in the potential field data in the present offshore study area. This is likely due to a lack of resolution and wide spacing in the reflection seismic lines, but may also signify that the Timanian deformation offshore is constrained to the areas farther north in the Barents Sea (e.g. Koehl et al 2022; *in press*) and in the areas closer to the Trollfjorden-Komagelva Fault Zone that likely defined a buttress or a terrane boundary may have focused the strain during the (SW-SSW-vergent) Timanian Orogeny (Herrevold et al. 2009).

4. DISCUSSION

A precursor megafracture to the Trollfjorden-Komagelva Fault Zone most likely existed as a major, deep-seated, tectonic divide and terrane boundary already in Neoarchaean time (Gaál and Gorbatchev, 1987; Roberts et al., 1997; Kostyuchenko et al., 2006), and later, during the Meso- and Neoproterozoic, functioned mainly as an extensional fault between developing platformal and basinal domains (Roberts and Siedlecka, 2002). During the Ediacaran Timanian orogenesis, the fault likely acted as a buttress that, to a large extent, resisted the SW/WSW-directed contraction, thus averting significant folding and thrusting in its footwall (Herrevold et al., 2009). The influence of the Timanian orogenic deformation is therefore largely restricted to the southeastern Barents Sea offshore and the North Varanger Terrane on the Varanger Peninsula, leaving the Tanafjorden-Varangerfjorden Region affected to only a minor degree.Hence, the macro-scale Timanide folds in the northern terrane were prone to become influenced (rotated, refolded and rethrusted) during the later ductile Finnmarkian and more brittle Scandian main stages of the polyphase Caledonian orogeny. This may have involved differential rotation due to contrasting transport velocities with dextral drag along the TKFZ and its inferred offshore prolongation (Åm, 1975; Gabrielsen and Færseth, 1988). A narrow zone of relatively intense Timanian contraction is found in the immediate hangingwall of the TKFZ (Herrevold et al., 2009), supporting the buttressing effect of this major geofracture which was later to become a focus of lateral Caledonian shearing when it acted as a transfer zone above a lateral ramp (Gayer et al., 1987; Rice et al., 1989b; Rice, 2014). The major fold-and-thrust system in the eastern Barents Sea Region is therefore dominated by folds and axial planar cleavage that are in harmony with the regional, top-SW to WSW Timanian shortening (Roberts, 1995, 1996; Roberts and Olavyanishnikov, 2004; Koehl et al. 2022; *in press*), which later became influenced by the two-stage, Caledonian, top-SE/SSE and top-ESE contractional deformation. Timanian structures closest to the buttressing TKFZ became deflected and rotated into parallelism with the fault zone itself. Subordinate NW-SE-striking, outcrop-scale folds, slaty cleavage and small reverse-faults in the southeasternmost corner of the North Varanger Terrane were also almost certainly generated during the Timanian orogenesis (Herrevold 1993; Gjelsvik, 1997; Herrevold et al., 2009).

As noted above, during the early-Caledonian, top-SE/SSE shortening stage the TKFZ acted as a lateral ramp and separated the two terranes, both of which included thrust-sheet systems of contrasting tectonic styles above separate basal detachments (Roberts, 1972; Chapman et al., 1985; Gayer et al., 1987; Rice et al, 1989b; Rice, 2014). This development is likely to have involved two stages of shortening and thrusting where an early stage of fairly ductile top-S/SSE displacement was later overprinted by a more brittle top-SE to ESE transport (Townsend et al., 1986; Sygnabere, 1997). The minimum dextral displacement of c. 207 km along the fault zone (Rice, 2014) occurred principally in early Ordovician time (Rice and Frank, 2004) though with a more brittle, minor Silurian offset, and was terminated by the Late Devonian (Johnson et al., 1978; Guise and Roberts, 2002). A later reactivation of a more extensional nature occurred in Carboniferous time (Gabrielsen and Færseth, 1988), concurrent with mafic dyke emplacement on Magerøya (Lippard and Prestvik, 1997; Nasuti et al., 2015), and a half-graben has been detected by seismic-reflection profiling in the hangingwall of the Trollfjorden-Komagelva Fault Zone in outer Varangerfjorden (Roberts et al., 2011), also inferred to be a part of the same Carboniferous rifting phase.

The basal thrusts beneath the two disparate northern and southern terranes are likely to have travelled at different stratigraphic levels and contrasting depths. In the Tanafjorden-Varangerfjorden Region, the basal detachment is inferred to lie at the base of the easternmost thrust sheet of the Gaissa Thrust Belt; the Hanadalen Thrust Sheet (Rice, 2014). No discrete emergent detachment is known below that level as the Parautochthon is floored by a more gradational deformation front, the Mortensnes-Jamteberget thrust-and-fold zone (Sygnabere, 1997). Thrust-faulting along this deformation front is largely confined to the westernmost Mortensnes area, whereas the main stretch of this frontal zone is characterised by intense, mainly zig-zag type folding with just minor reverse- or thrust-faults. By and large, cumulative Caledonian strain in this southern terrane of Varanger Peninsula was far less than in areas north of the major fault zone. Nevertheless, the MJDF has the total geometry of a major sheath fold with its western and central parts characterised by top-SSE/SE and its eastern part by top-ESE tectonic transport (Sygnabere, 1997).

In the Barents Sea Region, two imbricate thrust sheets, the Rákkočearru and Máhkirčearru, are recorded in the Lower Allochthon in western and central areas beneath which a blind décollement is speculated to continue southeastwards and most likely emerge on the seabed east of Vardø (Fig. 11b). In this regard, the Komagelva-Vardø-Storflogdalen section of this northern terrane – the Langryggen thrust sheet -- is particularly instructive in exposing an array of mesoscopic reverse- and thrust-faults with curved traces and with associated hangingwall folds that can be followed for more than 20 km along strike. In places they define complete duplexes with subhorizontal floor and roof faults. The curved geometry of the structures and the architecture of the system do suggest that this easternmost area lies close to the Caledonian thrust front, which we suggest is situated just offshore. The rocks of this area have been influenced by differential shear accompanied by an element of gravity collapse to produce sheath folding, which in turn resulted in a composite, lobe-shaped, leading edge of the thrust system. This shape, convex facing away from the coastline, is also visible in the bathymetry (Fig. 8). The frontal Caledonian thrust zone can be traced into the Finnmark Platform of the southeastern Barents Sea by use of potential field data. Here, the pre-Carboniferous basement displays top-east or top-southeast(?) folds and thrusts with a style of deformation similar to that seen in the Caledonides onshore in the Barents Sea

Region. In this offshore region the nappe pile reaches a thickness of several kilometres, perhaps indicating that the onshore thrust system is more deeply rooted than hithereto anticipated. It cannot be ruled out that some of the contractional structures identified in seismic sections on the Finnmark Platform may be of Timanian origin, but we think that the Timanian structures are mainly constrained to the areas north and northeast of the Nordkapp Basin and areas where deep relief has supported stress concentration. The present data coverage, however, does not allow for distinguishing between Caledonian and potential Timanian structures.

4. CONCLUSIONS

A forerunner geofracture to the Trollfjorden-Komagelva Fault Zone was established in late Mesoproterozoic to Neoproterozoic time as a major extensional fault defining a threshold that separated a deeper area of basinal deposition to its northeast (Barents Sea Group) from a shallower platformal area to the southwest (Vadsø and Tanafjorden groups). This tectonic high acted as a buttress during top-SW to top-WSW, Timanian, basin inversion and thrusting, and also focusing strain along it. Following the establishment of the Gaissa Basin in the platformal domain, which had its comparatively shallow depocentre farther to the west, Caledonian thrusting was affected by the contrasting thicknesses of the sedimentary successions north and south of the fault zone; and the composite, Caledonian, top-SE to -ESE shortening took place broadly parallel to this megafault, exploiting it as a lateral ramp. The Caledonian structures in the North Varanger Terrane can be followed to the north-northeast into the southeastern Barents Sea, where the nappe pile reaches a thickness of several kilometres.

As a consequence of the shortening and depth-to-basement being different on the opposing sides of the TKFZ, separate floor detachment faults, bulk shortening and frontal thrust systems were established in the two regions. Accordingly, although the rocks to the north of the fault zone experienced thrust directions similar to those to the south, the Barents Sea and Løkvikfjellet groups of the northern terrane had been deposited more than 200 km farther to the northwest, just to the north of where Magerøya is situated today (Roberts and Siedlecka, 2012; Rice, 2014), prior to their dextral displacement along the TKFZ by more than 200 km during the Caledonian orogeny. As a result, the rocks of the Barents Sea Region were displaced farther to the southeast than the rocks in the Tanafjorden-Varangerfjorden Region. The floor detachment fault of the Barents Sea Region is thus speculated to emerge along or adjacent to a prominent, NE-SW-trending, dual escarpment on the seabed a few kilometres offshore from Kiberg.

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Conflict of interest: The authors declare that they have no conflict of interest.

Data availability statement

The seismic data that support the findings of this study are available from NPD and TGS. Restrictions apply to the availability of these data, which were used under licence for this study.

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Figure captions

Figure 1:

Tectonic framework of the Varanger Peninsula showing the Barents Sea Region (BSR = North Varanger Terrane) and Tanafjorden – Varangerfjorden Region (TVR). The terranes are separated by the Trollfjorden-Komagelva Fault Zone (TKFZ). The BSR includes the Tanahorn Nappe (TN) and the Rákkočearru (RTS), Máhkirčearru (MTS) and Langryggen (LTS) thrust sheets. MAF – Middle Allochthon fault, base of the Tanahorn Nappe. The section line A-A' is shown in Figure 2. Inset map: location of the study area (V – Varanger Peninsula) at the transition between the Timanian and the Caledonian structural trends. BS – Barents Sea; NGS – Norwegian-Greenland Sea; NB – Nordkapp Basin; SV – Svalbard; TBP – Timan-Pechora Basin; HT – Hanadalen Thrust; RT – Ruoksadas Thrust. T1, T2, T3 -- see caption to Figure 2. The map is modified from Herrevold et al. (2009).

Figure 2:

Schematic NW-SE cross-section of the Barents Sea Region (North Varanger Terrane) displaying positions of master thrust faults T1 and T2 that penetrate the present-day surface. The inferred location of the frontal thrust T3 is also shown. The northwestern segment is characterised by overturned, SE/ESE-vergent, fault-propagation folds with associated low- to moderate-angle thrusts, whereas large fold trains with fairly upright fold axial planes and, in places, thrust-related duplexes characterise the southeastern segment. These two segments are separated by a transitional central segment with more densely spaced fault-propagation folds and duplexes. Note that the colour code of the top layer (shades of brown) corresponds to that of Fig 1.

Figure 3:

Lithostratigraphic columns for the Barents Sea Region (North Varanger Terrane) and Tanafjorden-Varangerfjorden Region, modified from Herrevold et al. (2009) and Roberts and Siedlecka (2022). The symbols in the footwall and hangingwall fault blocks of the Trollfjorden-Komagelva Fault Zone (TKFZ) indicate late Proterozoic (blue), Timanian (orange) and Caledonian (green) displacements, respectively.

Figure 4:

Major thrusts and folds in central and eastern Varanger Peninsula. **a)** Structures in the easternmost areas are based mainly on the field mapping of Sygnabere (1997) and Gjelsvik (1998), but also partly on earlier 1:50,000 bedrock mapping by Anna Siedlecka. The geographical locations of structural subareas B, G, K, N and S are indicated. (b) Poles to bedding, and fold axes and statistical fold exes (β-axes) for each of the subareas B, G, K, N and S.

Figure 5:

Double-folding with interference between folds with NNW-SSE-trending and NE-SW fold axes in the LTS in Storflogdalen, eastern BSR, Varanger Peninsula. See fig. 4 for location**. a)** Photograph showing an oblique view of the NNW-SSE (Timanian) master fold in Storflogdalen and **b)** a view parallel to the (Caledonian) NE-SW crossfolds. **c-d)** Interpretation of the fold systems in figure a) and b). The steep WNW limb of the master fold seen in all photographs has an elevation of c. 70 metres from the bottom to the top of the exposure. **e)** Stereogram (lower hemisphere) for s_0 (great circles and poles) defining folds of the NNW-SSE system. **f**) Stereogram (lower hemisphere) for s_0 (great circles and poles) defining the folds of the NE-SW fold system. Red dots are fold axes measured in the field; the yellow dot is the calculated π-axis.

Figure 6:

Field photos of a NW-SE-trending fold and associated axial-planar cleavage in eastern coastal areas of the BSR. (a) Penetrative spaced cleavage in the northeastern limb of an anticline at Grunnes, looking northwest. The notebook is lying on a bedding surface. The locality is at grid-reference 36WVD 41870 789625. (b) Hinge zone of an anticlinal fold where the penetrative axial-planar slaty cleavage is oriented at right-angles to the bedding. Notebook for scale lying on a bedding surface. Photo looking north-northwest. Locality on the island Vardøya at grid-reference 36WVD 42805 78100. The many folds and associated cleavage in this eastern part of the LTS are characteristic of Timanian structures with top-SW tectonic transport.

Figure 7:

(a-b) Outcrops along the Slaktefjellet fault. This fault was previously assumed to be a splay from the right-lateral Trollfjorden-Komagelva Fault Zone, but on account of its dip-angle (c. 40^0) and semi-ductile deformation mode, and **(c-e)** multiple stages of mylonitisation and brecciation, it is now considered to be one of several minor imbricate thrust faults in the Lower Allochthon of the Caledonian nappe system.

Figure 8:

The easternmost onshore thrust sheet (LTS) of the eastern Barents Sea Region (North Varanger Terrane) and the local inferred tectonic transport directions (black arrows). Note that bathymetric features to the east of Kiberg and Vadsø parallel the onshore nappe structure, indicating that the thrust front of the Lower Allochthon is situated just to the east-southeast of the Varanger Peninsula.

Figure 9:

The Kiberg duplex system. **(a)** N-S-section through the most completely exposed part of the duplex system at Kiberg. **(b)** Simplified interpretation of the structure. (c) Sketch showing the main elements of the duplex system. **(d)** Stereoplot of fold axial planes and fold axes of the Kiberg duplex.

Figure 10:

The Mortensnes Duplex belongs to the Mortensnes-Jamteberget thrust-and-fold zone. **a)** 2 km west of Mortensnes the Mortensnes-Jamteberget thrust-and-fold zone is seen to involve sandstones and shales of the Nyborg Formation, representing the Caledonian deformation front (MJDF) in the Parautochthon in the Tanafjorden – Varangerfjorden Region (Fig. 4). The section is oriented WNW-ESE. The structures here denote a top-SE tectonic transport. **(b)** An interpretative sketch of the folds and faults visible at this locality.

Figure 11:

Tilt-derivative of the total magnetic field map (Gernigon et al., 2018) overlaid with the structural configuration based on seismic and magnetic data interpretation in the southeastern and southwestern Barents Sea (see Hassaan et al., 2021b for full description), and deep offshore nappe structures (based on the current study). B – Caledonian magnetic anomaly; BP – Bjarmeland Platform; BS – Barents Sea; CBA – Central Barents Arch; CBSM – central Barents Sea magnetic domain; FH – Fedynsky High; FHN – Fedynsky High north; FHS – Fedynsky High south; FP – Finnmark Platform; G – Graben; HD – Haapet Dome; HFB – Hammerfest Basin; HFC – Hoop Fault Complex; LH – Loppa High; MAF – Middle Allochthon Front; MB – Maud Basin; MH – Mercurius High; MIC – Mjølnir Impact Crater; NB – Nordkapp Basin; ND – Norvarg Dome; NH – Norsel High; OB – Ottar Basin; SD – Samson Dome; SG – Swaen GRABEN; SHC – Scott Hansen Complex magnetic low domain; SHD – Signalhorn Dome; Sv – Svalbard; T – Timanian magnetic anomaly; TB – Tiddlybanken Basin; TPB – Timan-Pechora Basin; VD – Veslekari Dome; VP – Varanger Peninsula; TKFZ – Trollfjorden-Komagelva Fault Zone. The positons of seismic lines (Figs. 12 and 13) are marked as blue lines.

Figure 12

Schematic three-dimensional model illustrating basement inheritance, extension of thrust faults, their control on the late Devonian to early Carboniferous basin configuration and subsequent Pennsylvanian-early Permian accumulation of evaporites (modified after Gernigon et al., 2018 and Hassaan et al., 2021b).

Figure 13:

The NNE-SSW-oriented line BSSE 14RE-12040 (see Fig. 11 for location) gives one example of the structural configuration of the basement. Because the thrust front is curved, the angle between the line orientation and the assumed local Caledonian tectonic transport direction is smallest in the southwestern part of the line. Assumed primary late Proterozoic layering in basement (yellowish reflections) define several anticlines and synclines with wavelengths in the order of 25-50 km and amplitudes of 10-20 km are separated by thrusts with dip angles of 10 to 25° to the northwest/west-northwest. The frontal thrust fault is situated north of the Haapet Dome in the Bjarmeland Platform and has a parallel open anticline-syncline fold pair in its hangingwall. The seismic line is depth-converted. Note a vertical exaggeration of 3x.

Figure 14:

The ENE-WSW-striking seismic line 4992-0357 (see Fig. 11 for location) is oriented parallel to the regional Caledonian tectonic transport direction, but oblique to the tectonic transport that is expected for the southeastern flank of the offshore thrust lobe as identified in magnetic data. The fault and fold dimensions and style (defined by yellowish reflections) are similar to those seen in line BSSE 14RE-12040. The seismic line is depth-converted. Note a vertical exaggeration of 3x.

Figure 1

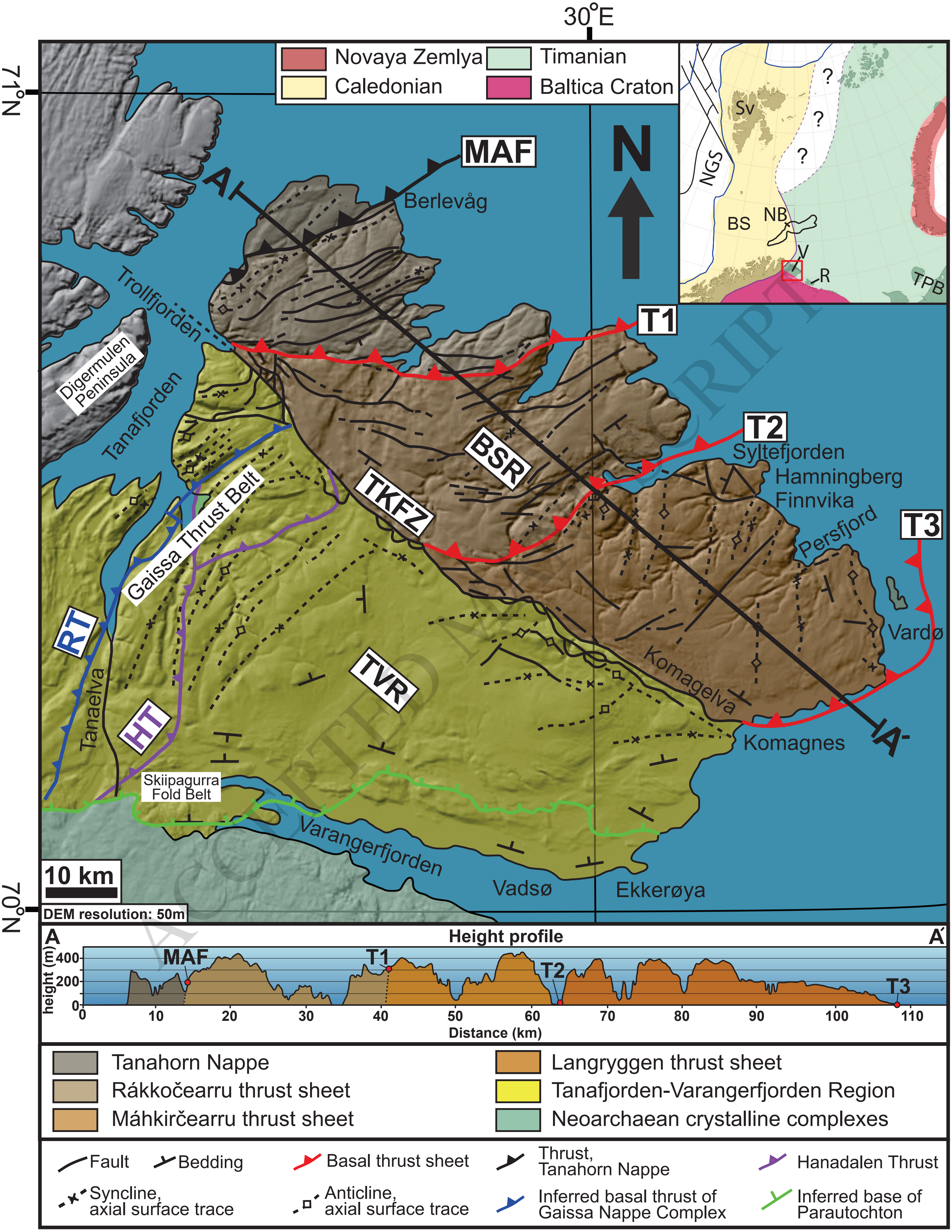
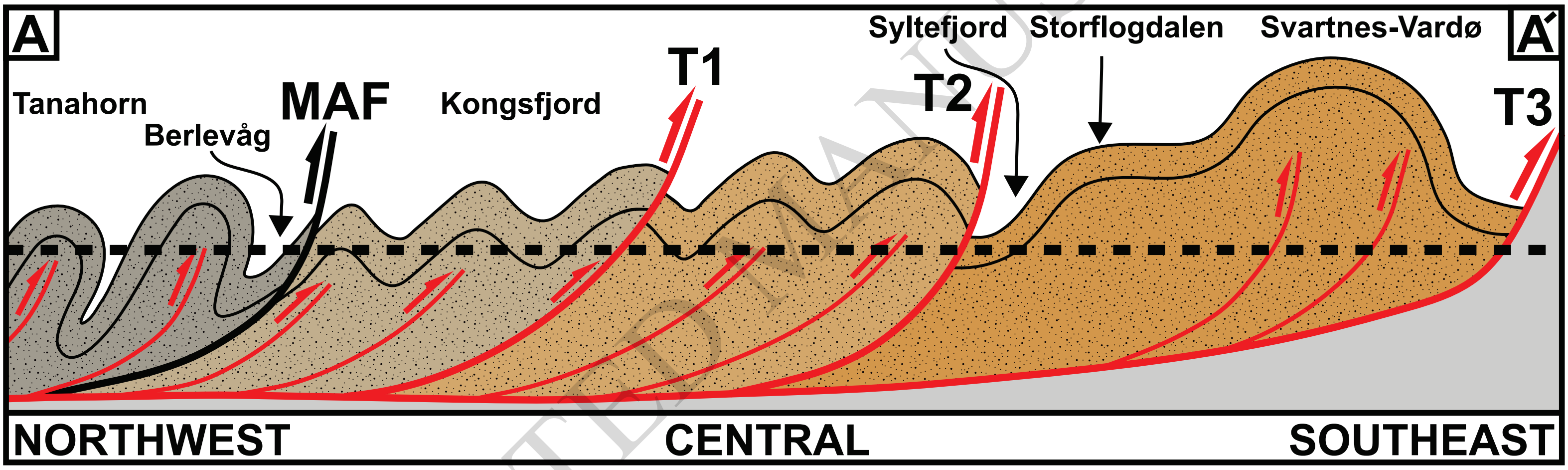

30°E
71°N
70°N
Novaya Zemlya
Timanian
Caledonian
Baltica Craton
Sv
NGS
BS
NB
V
R
TPB
?
N
MAF
A
Berlevåg
Trollfjorden
Digermulen Peninsula
Tanafjorden
T1
T2
T3
BSR
TKFZ
Gaissa Thrust Belt
RT
HT
Tanaelva
TVR
Syltefjorden
Hamningberg
Finnvika
Persfjord
Vardø
Komagelva
Komagnes
A′
Skiipagurra Fold Belt
Varangerfjorden
Vadsø
Ekkerøya
10 km
DEM resolution: 50m
Height profile
A
A´
height (m)
400
200
0
MAF
T1
T2
T3
0
10
20
30
40
50
60
70
80
90
100
110
Distance (km)
Tanahorn Nappe
Rákkočearru thrust sheet
Máhkirčearru thrust sheet
Langryggen thrust sheet
Tanafjorden-Varangerfjorden Region
Neoarchaean crystalline complexes
Fault
Bedding
Basal thrust sheet
Thrust, Tanahorn Nappe
Hanadalen Thrust
Syncline, axial surface trace
Anticline, axial surface trace
Inferred basal thrust of Gaissa Nappe Complex
Inferred base of Parautochton

Figure 2


A
A´
Tanahorn
Berlevåg
MAF
Kongsfjord
T1
Syltefjord
Storflogdalen
Svartnes-Vardø
T2
T3
NORTHWEST
CENTRAL
SOUTHEAST

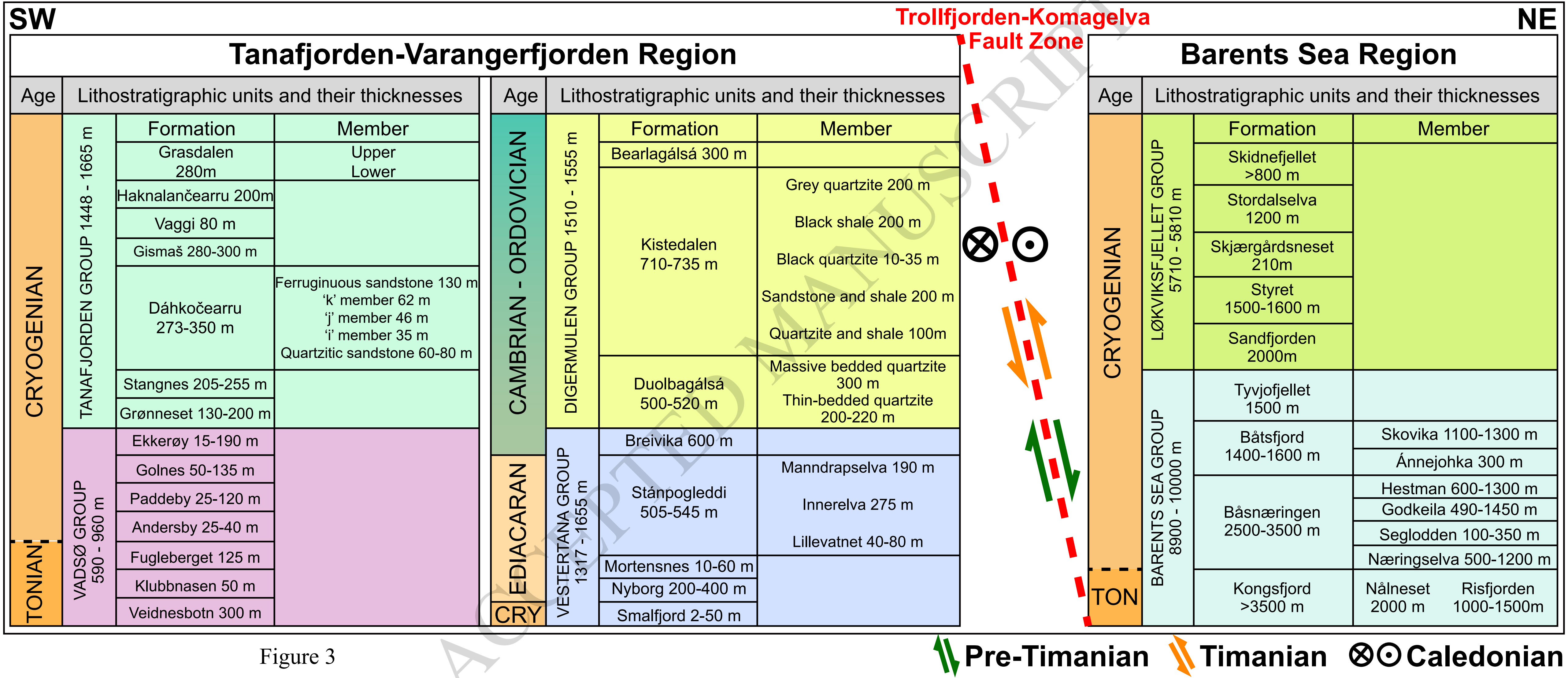

SW
NE
Trollfjorden-Komagelva Fault Zone
Tanafjorden-Varangerfjorden Region
Barents Sea Region
Age
Lithostratigraphic units and their thicknesses
Formation
Member
CRYOGENIAN
TONIAN
TANAFJORDEN GROUP 1448 - 1665 m
Grasdalen 280m
Upper
Lower
Haknalančearru 200m
Vaggi 80 m
Gismaš 280-300 m
Dáhkočearru 273-350 m
Ferruginuous sandstone 130 m
'k' member 62 m
'j' member 46 m
'i' member 35 m
Quartzitic sandstone 60-80 m
Stangnes 205-255 m
Grønneset 130-200 m
VADSØ GROUP 590 - 960 m
Ekkerøy 15-190 m
Golnes 50-135 m
Paddeby 25-120 m
Andersby 25-40 m
Fugleberget 125 m
Klubbnasen 50 m
Veidnesbotn 300 m
Age
Lithostratigraphic units and their thicknesses
CAMBRIAN - ORDOVICIAN
EDIACARAN
CRY
DIGERMULEN GROUP 1510 - 1555 m
Formation
Member
Bearlagálsá 300 m
Kistedalen 710-735 m
Grey quartzite 200 m
Black shale 200 m
Black quartzite 10-35 m
Sandstone and shale 200 m
Quartzite and shale 100m
Duolbagálsá 500-520 m
Massive bedded quartzite 300 m
Thin-bedded quartzite 200-220 m
VESTERTANA GROUP 1317 - 1655 m
Breivika 600 m
Stánpogleddi 505-545 m
Manndrapselva 190 m
Innerelva 275 m
Lillevatnet 40-80 m
Mortensnes 10-60 m
Nyborg 200-400 m
Smalfjord 2-50 m
Age
Lithostratigraphic units and their thicknesses
CRYOGENIAN
TON
LØKVIKSFJELLET GROUP 5710 - 5810 m
Formation
Member
Skidnefjellet >800 m
Stordalselva 1200 m
Skjærgårdsneset 210m
Styret 1500-1600 m
Sandfjorden 2000m
BARENTS SEA GROUP 8900 - 10000 m
Tyvjofjellet 1500 m
Båtsfjord 1400-1600 m
Skovika 1100-1300 m
Ánnejohka 300 m
Båsnæringen 2500-3500 m
Hestman 600-1300 m
Godkeila 490-1450 m
Seglodden 100-350 m
Næringselva 500-1200 m
Kongsfjord >3500 m
Nålneset 2000 m
Risfjorden 1000-1500m
Pre-Timanian
Timanian
⊗⊙ Caledonian

Figure 3

Figure 4

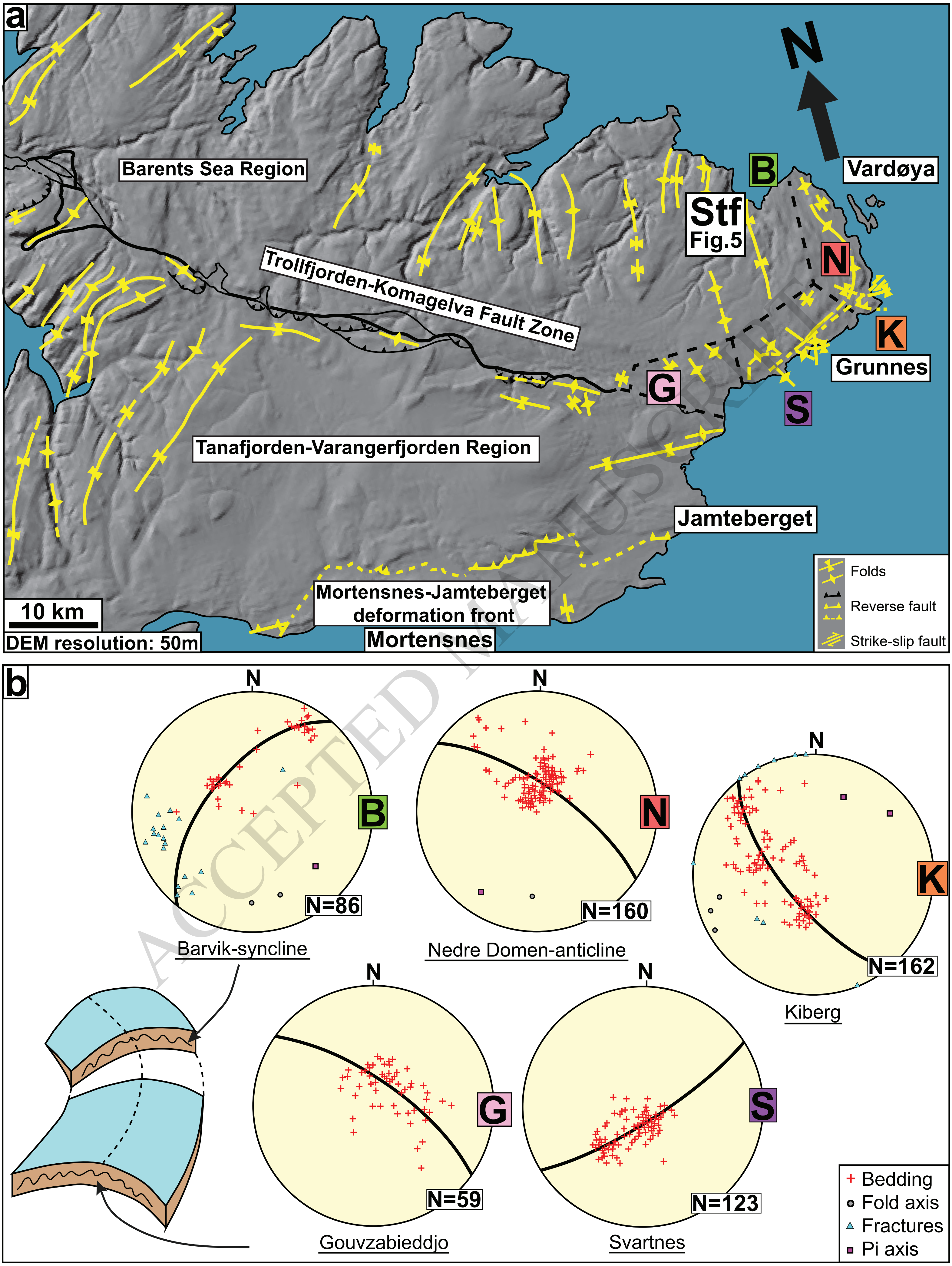

a
N
Barents Sea Region
B
Vardøya
Stf
Fig.5
N
Trollfjorden-Komagelva Fault Zone
K
Grunnes
G
S
Tanafjorden-Varangerfjorden Region
Jamteberget
Mortensnes-Jamteberget
deformation front
Mortensnes
10 km
DEM resolution: 50m
Folds
Reverse fault
Strike-slip fault
b
N
B
N=86
Barvik-syncline
N
N
N=160
Nedre Domen-anticline
N
K
N=162
Kiberg
N
G
N=59
Gouvzabieddjo
N
S
N=123
Svartnes
+ Bedding
○ Fold axis
▲ Fractures
■ Pi axis

Figure 5

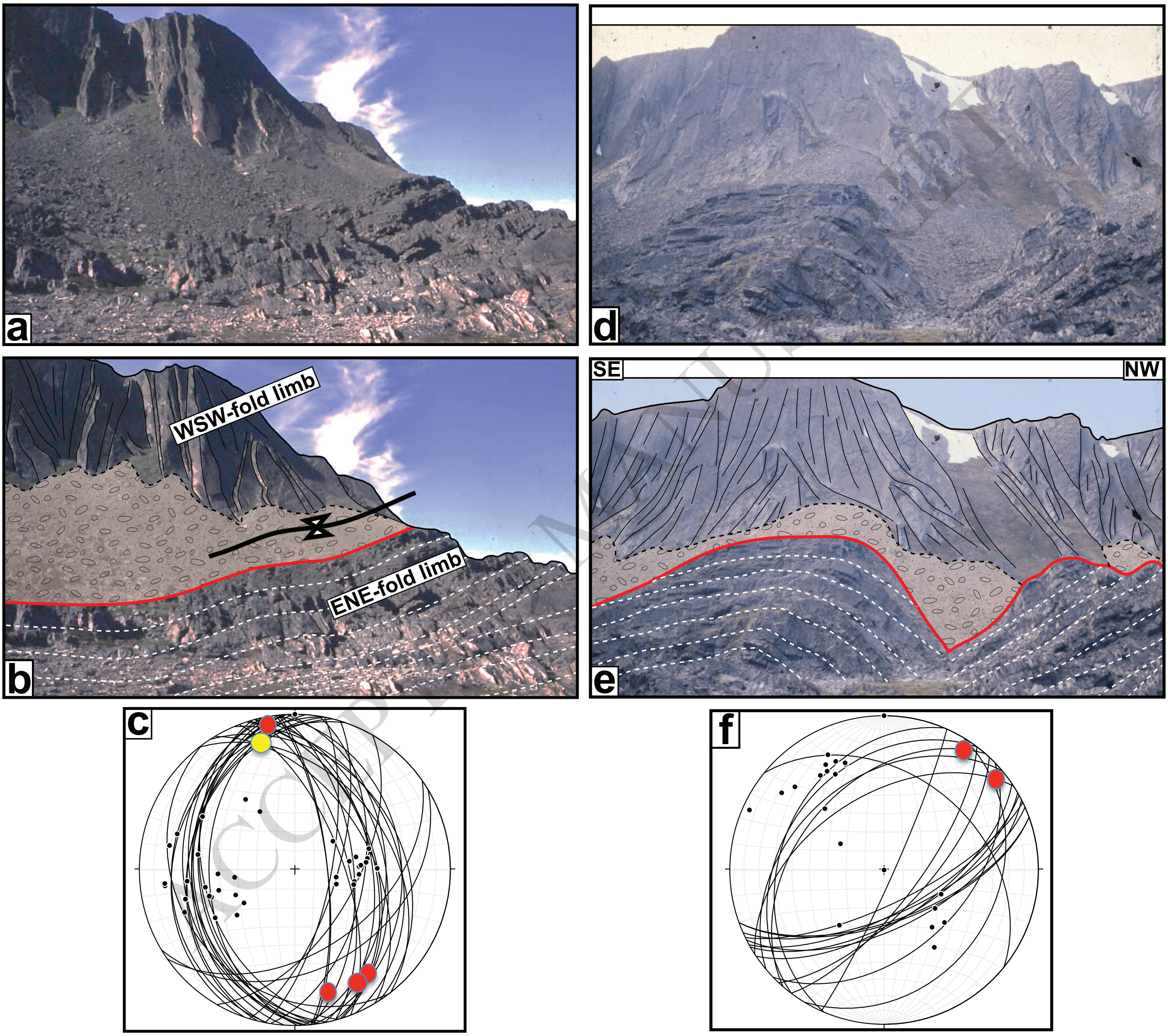


Figure 6

Figure 7

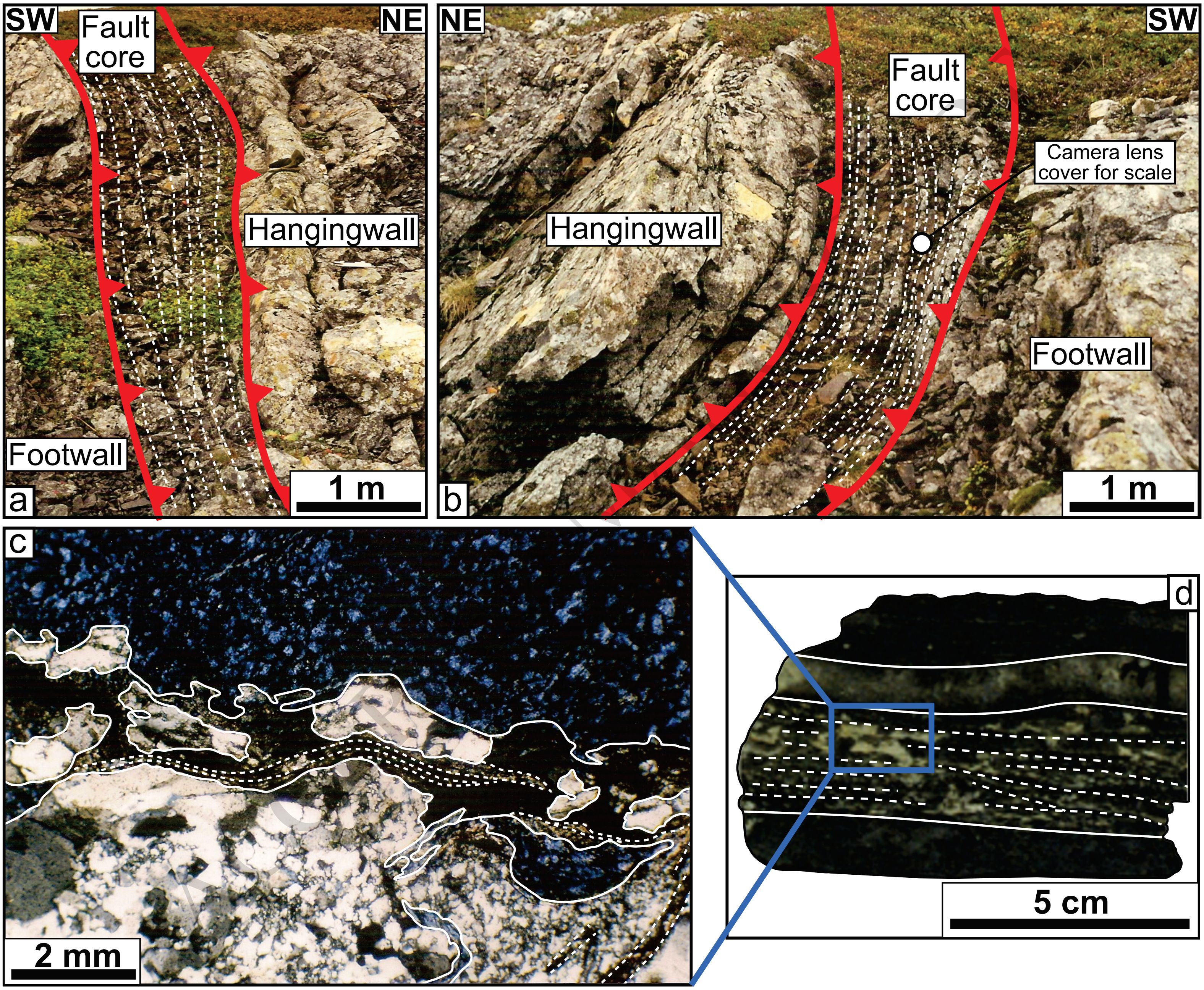

SW
Fault core
NE
Hangingwall
Footwall
a
1 m
NE
Fault core
SW
Camera lens cover for scale
Hangingwall
Footwall
b
1 m
c
2 mm
d
5 cm

Figure 8

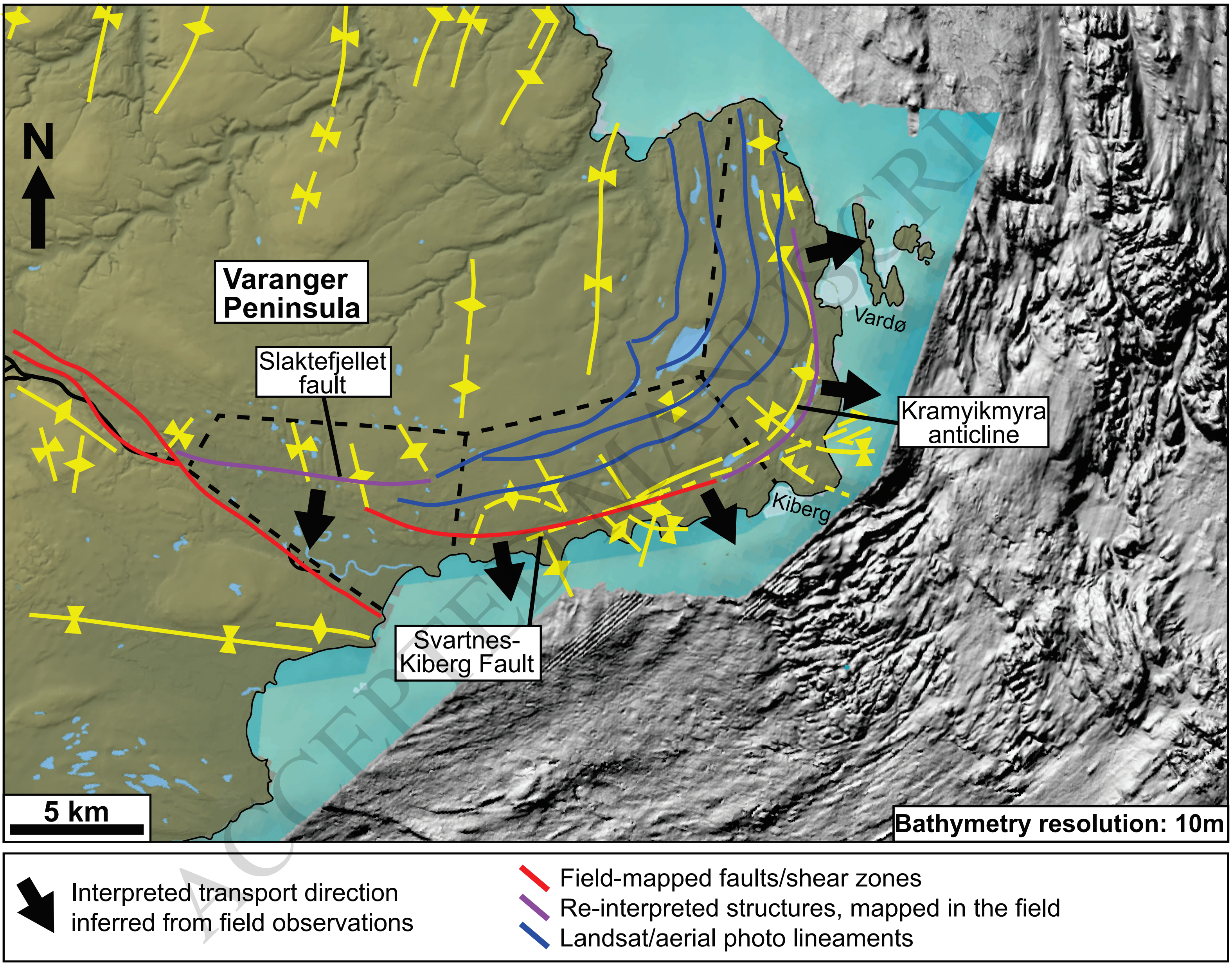

N
Varanger Peninsula
Slaktefjellet fault
Vardø
Kramyikmyra anticline
Kiberg
Svartnes-Kiberg Fault
5 km
Bathymetry resolution: 10m
Interpreted transport direction inferred from field observations
Field-mapped faults/shear zones
Re-interpreted structures, mapped in the field
Landsat/aerial photo lineaments

Figure 9

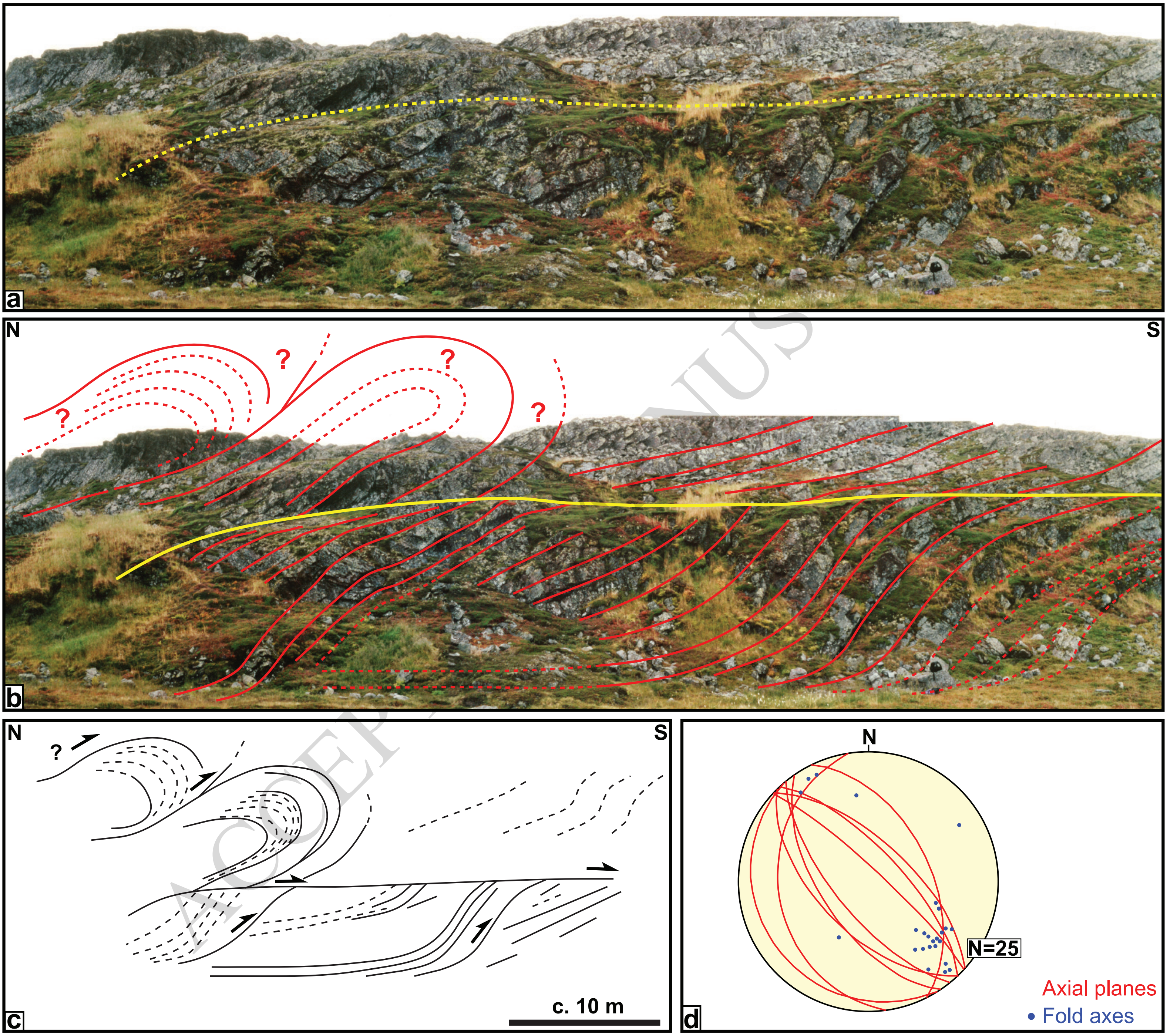


Figure 10

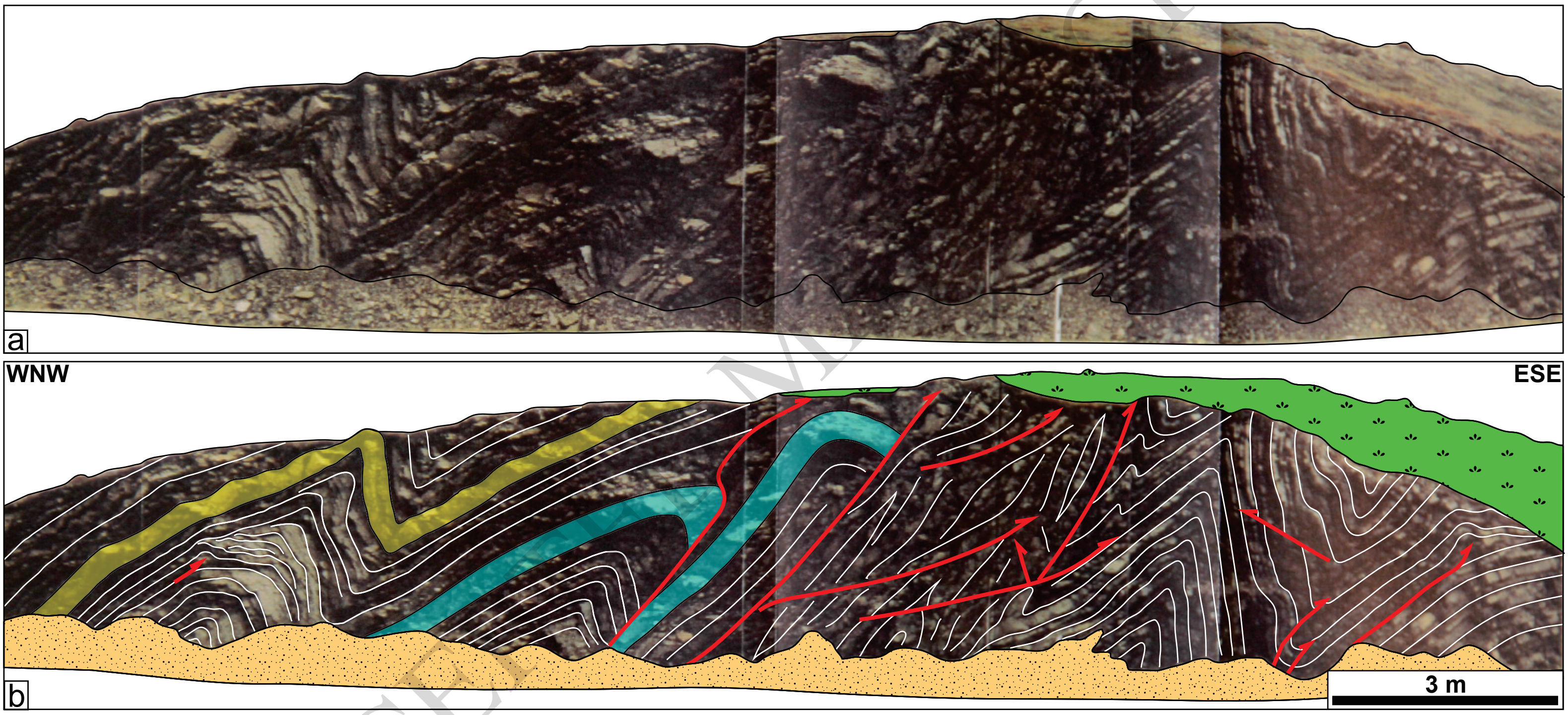


Figure 11

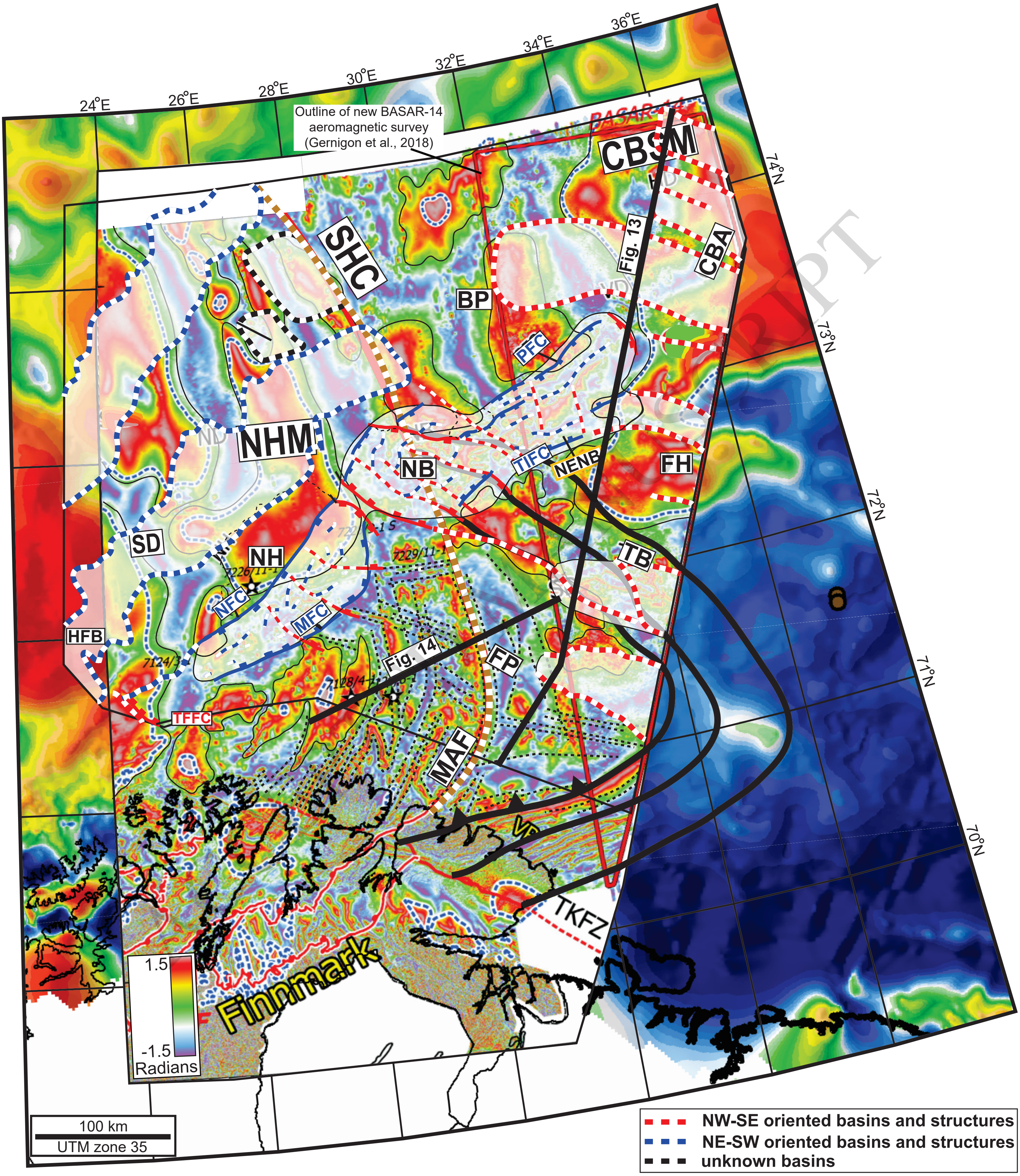

24°E
26°E
28°E
30°E
32°E
34°E
36°E
74°N
73°N
72°N
71°N
70°N
Outline of new BASAR-14 aeromagnetic survey (Gernigon et al., 2018)
BASAR-14
CBSM
SHC
BP
CBA
Fig. 13
PFC
NHM
ND
NB
TIFC
NENB
FH
SD
NH
7226/11-1
7229/11-1
TB
NFC
MFC
HFB
7124/3
Fig. 14
7128/4-1
FP
TFFC
MAF
VF
TKFZ
Finnmark
1.5
-1.5
Radians
100 km
UTM zone 35
NW-SE oriented basins and structures
NE-SW oriented basins and structures
unknown basins

Figure 12

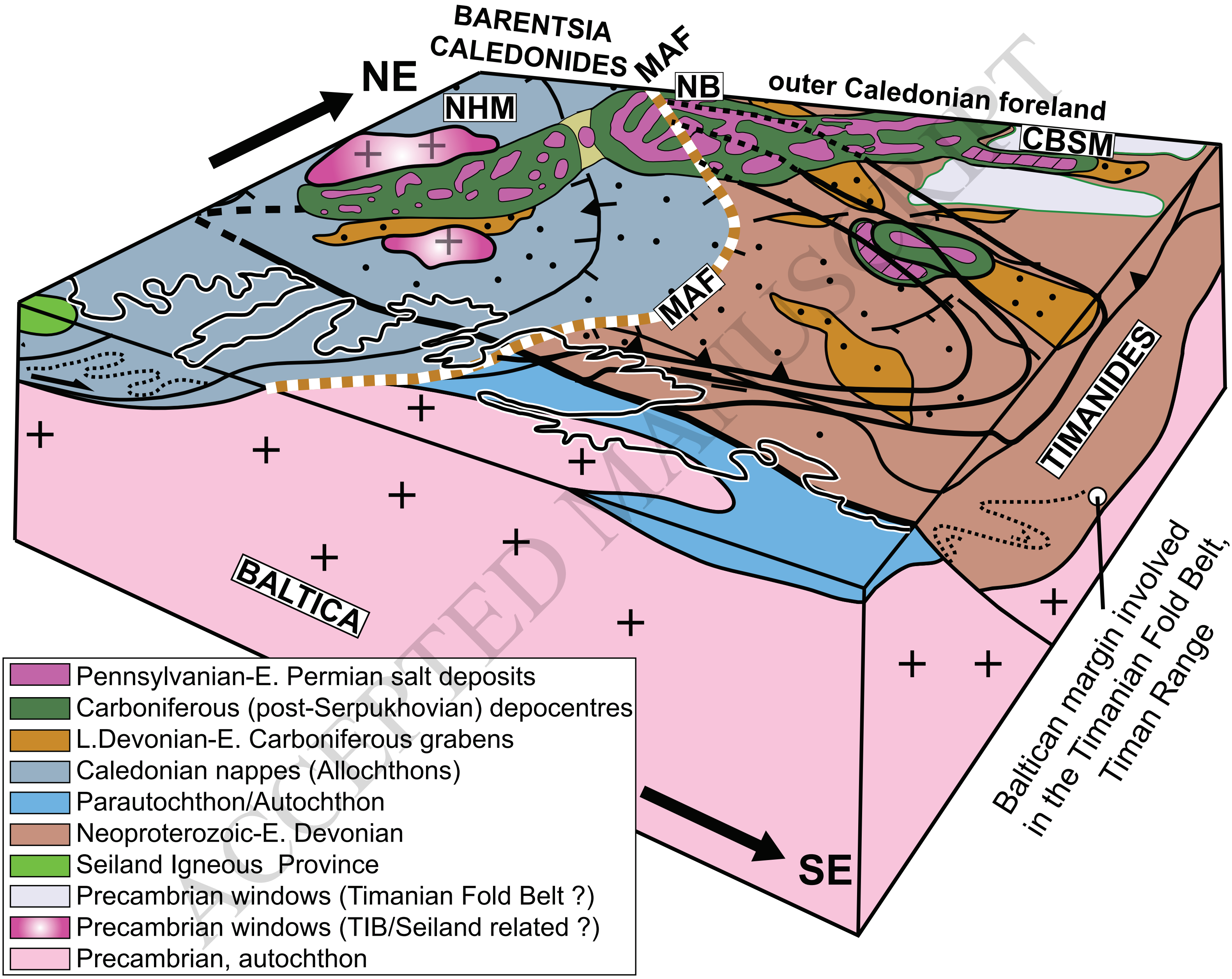

BARENTSIA
CALEDONIDES
MAF
NB
outer Caledonian foreland
NE
NHM
CBSM
MAF
TIMANIDES
BALTICA
SE
Baltican margin involved
in the Timanian Fold Belt,
Timan Range
Pennsylvanian-E. Permian salt deposits
Carboniferous (post-Serpukhovian) depocentres
L.Devonian-E. Carboniferous grabens
Caledonian nappes (Allochthons)
Parautochthon/Autochthon
Neoproterozoic-E. Devonian
Seiland Igneous Province
Precambrian windows (Timanian Fold Belt ?)
Precambrian windows (TIB/Seiland related ?)
Precambrian, autochthon

Figure 13

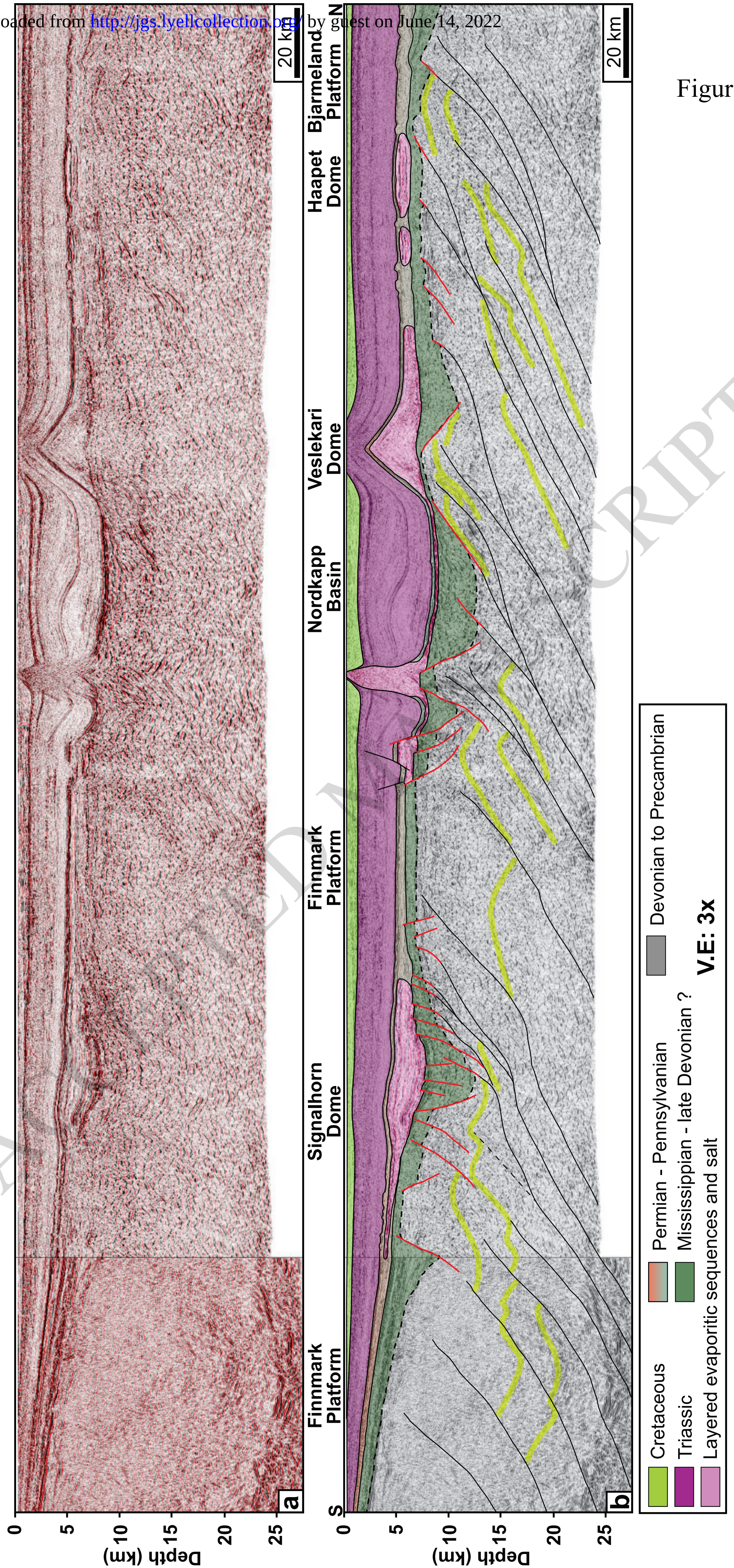
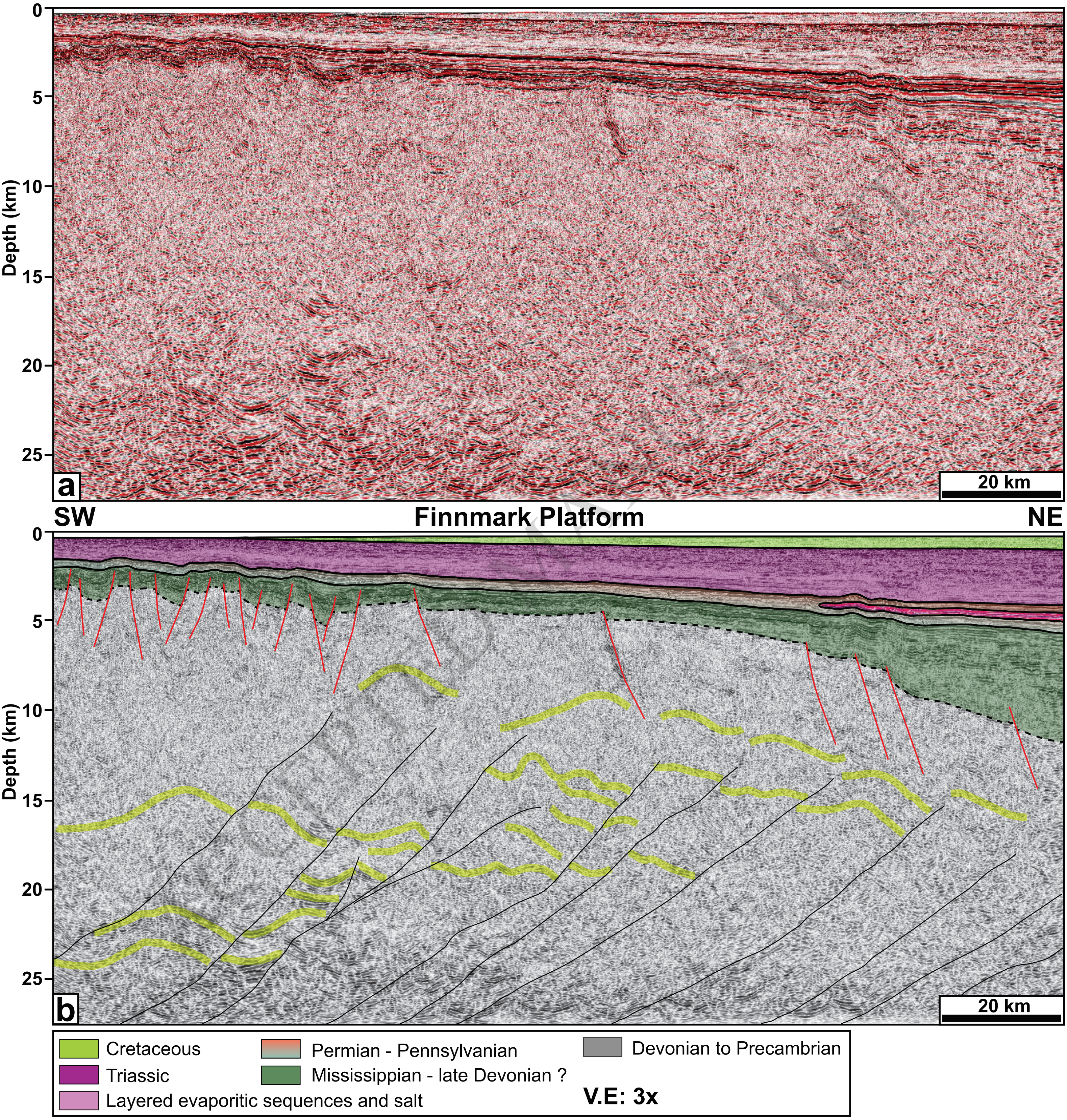

a
b
Depth (km)
0
5
10
15
20
25
20 km
S
N
Finnmark Platform
Signalhorn Dome
Finnmark Platform
Nordkapp Basin
Veslekari Dome
Haapet Dome
Bjarmeland Platform
Cretaceous
Triassic
Layered evaporitic sequences and salt
Permian - Pennsylvanian
Mississippian - late Devonian ?
Devonian to Precambrian
V.E: 3x

Figure 14


Depth (km)
0
5
10
15
20
25
a
20 km
SW
Finnmark Platform
NE
Depth (km)
0
5
10
15
20
25
b
20 km
🟩 Cretaceous
🟪 Triassic
🟪 Layered evaporitic sequences and salt
🟫 Permian - Pennsylvanian
🟩 Mississippian - late Devonian ?
⬛ Devonian to Precambrian
V.E: 3x