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Influence of subtle inherited basement structures on thin-skinned thrust systems: The Caledonian Thrust Front in Lapland (CaTFLap)

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ABSTRACT

Thin-skinned fold-thrust belts are defined by an extensive detachment surface, “the sole thrust’. The sole thrust is typically assumed to be sub-planar beneath the fold-thrust belt. The model of a planar sole thrust and, by inference, planar basement is often applied rather uncritically, whereas experimental and field studies show that basement topography is not only varied but crucial for the geometrical and kinematic evolution of fold-thrust belts. Basement topography controls on the thrust dynamics remains the least well understood parameter in fold-thrust belts, and more case studies are needed to underpin further understanding. We present field evidence from the well-exposed Caledonian Thrust Front in Lapland, showing the influence of inherited, orogen-perpendicular basement structures on the subsequent structural evolution of the Caledonian sole thrust and its underlying sedimentary rocks. Inherited orogen-perpendicular basement structures created open corrugations in the foreland that directed thrust allochthons and controlled the geometry and strain state of the sole thrust and associated rocks. We propose that even relatively small-scale structures can have a significant control on the geometry and strain state of an evolving thrust system, and that variations in thrust geometries are not simply explained by inversion or coincidental heterogeneous internal thickening (imbrication) of thrust-related units.

1. Introduction

Models of orogenic wedges (e.g. Coward, 1983; Dahlen, 1984, 1990; Davis et al., 1983) have underpinned many field, analogue and numerical studies exploring the mechanics and geometries of thrust belt development (see e.g. Suppe, 1983; Jamison, 1987; Suppe and Medwedeff, 1990; Erslev, 1991 for classical models for thrust system evolution; Buiter, 2012; Graveleau et al., 2012 for reviews on experimental studies). The external (foreland) parts of many orogenic wedges are marked by zones of low-angle thrusting where tectonised units have been carried over continental crust. The type examples of this style of so-called “thin-skinned” tectonics are provided by the foothills of the southern Canadian Cordillera (Bally et al., 1966; Hatcher, 2007). Early descriptions of allochthonous thrust sheets come from the Palaeozoic structures of Appalachia (e.g. Hayes 1891) and NW Scotland (Callaway 1883; Peach et al., 1888). In Scandinavia, Törnebohm (1888) recognised what is now known as the Seve allochthon (Gee, 2020) and that it had moved for over 130 km, establishing that thrust systems could accommodate very large horizontal displacements.

A general feature of thin-skinned tectonics is that thrust structures within them detach upon an extensive slip surface, generally termed the “sole thrust’. The sole thrust is typically assumed to be sub-planar and gently-dipping beneath the fold-thrust belt that it carries (see characterisation by Chapple 1978; and many others since). This conceptualisation is followed in most experimental recreations of thrust systems using analogue materials (Graveleau et al., 2012 for an extensive review). Even when variations in the sole thrust geometry are noted, they are often assumed to be simply a result of heterogeneous thickening (usually via imbrication) of material underneath a thrust sheet (e.g., Juhlin et al., 2016); but the underlying reasons for this heterogeneous thickening are not usually elaborated. Indeed, experimental and field studies show that the basement topography is not only varied but crucial for the geometrical and kinematic evolution of the sole thrust, and the structures above it (e.g., Sanderson, 1982; Calassou et al., 1993; Cotton and Koyi, 2000; Vidal-Royo et al., 2009; Poblet and Lisle, 2011; Jiménez-Bonilla et al., 2016; Schori et al., 2021). Even with these existing works, however, basement topography controls on the thrust dynamics remains possibly the least well understood parameter in fold-thrust belts; in particular, thrust transport-parallel (orogen-perpendicular) structures are rarely considered. Therefore, more case studies are needed to underpin further modelling work and to establish what types and scales of basement topographical variations can influence thrust evolution. In essence, how much do size and orientation matter?

In this paper, we present and discuss results from a short self-contained reconnaissance expedition to the Caledonian Thrust Front in

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Lapland (CaTFLap), near Kilpisjärvi, NW Finland. This exploratory fieldwork aimed to investigate the detailed geometry of the sole thrust and the basement below it. The thrust front is very well exposed here along its strike, but this remote wilderness area has largely been overlooked in both the regional syntheses and in more detailed field approaches. More widely, there is little modern research addressing the detailed structure of the thrust front and the sole thrust of the Caledonian Front. This contrasts sharply with the abundant research on the

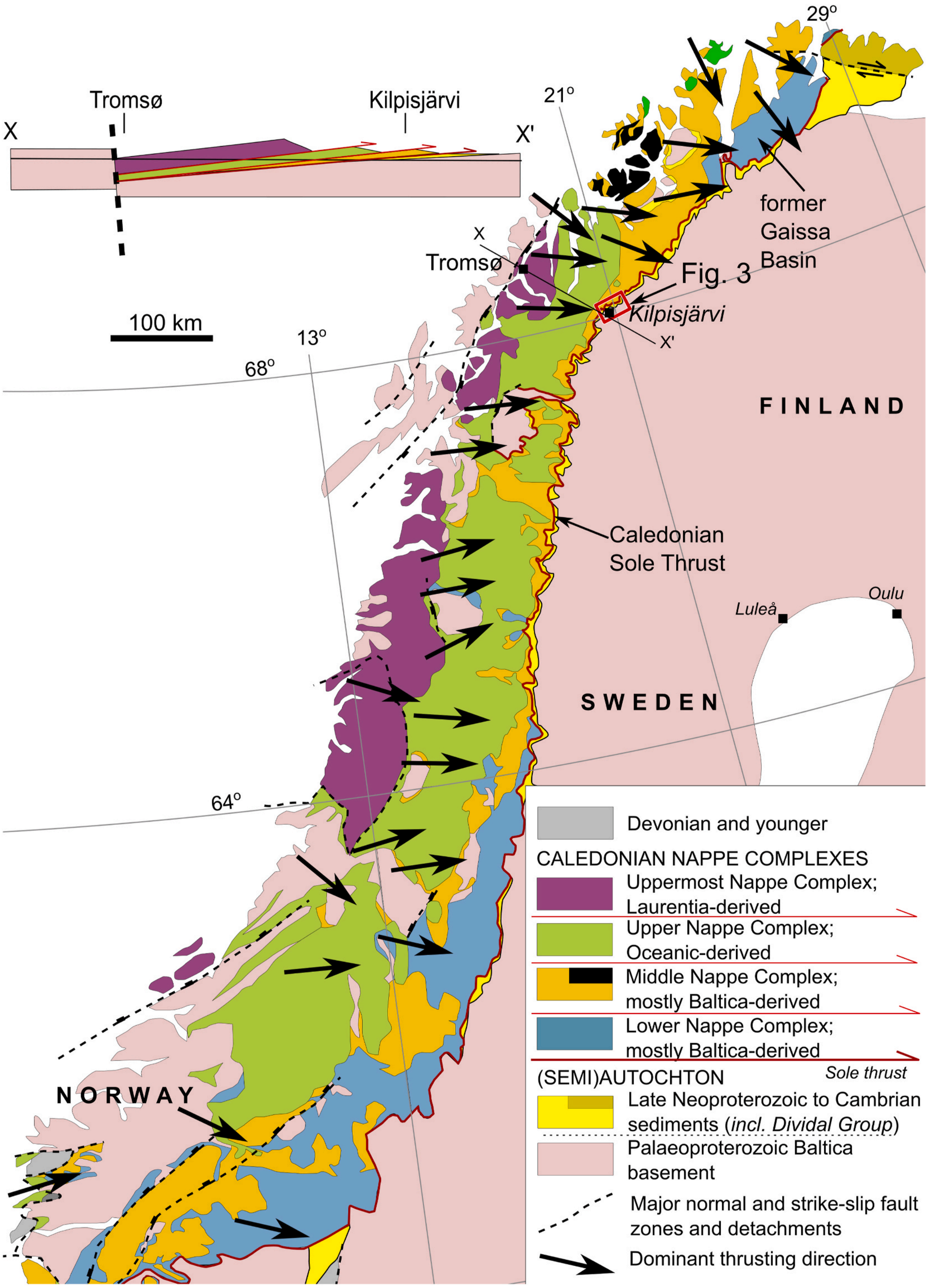

Fig. 1. Overview map of the Caledonides. The proximal parts of the orogen comprise units derived from the Laurentian margin and the Iapetus Ocean (the Uppermost and Upper Nappes); the distal parts comprise units affiliated mostly with the Baltica Margin (the Middle and Lower Nappes). The sole thrust and the underlying Late Neoproterozoic to Cambrian (semi)autochtonous sediments were initially deposited unconformably onto the Precambrian crystalline basement of Baltica: these are the units observed in the study area (red rectangle). A schematic cross section transecting the Caledonides and the study area is also shown. Geological map based on Corfu et al., (2014); thrust transport directions (representative stretching lineations) based mostly on Hossack and Cooper (1986); except in the north on Rice (2014) and the geological maps of N Norway and NW Finland. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

equivalent structures on the Laurentian side of the orogen, which includes the Moine Thrust Belt (e.g. Mendum et al., 2009; Law et al., 2010 and references therein). We discuss our observations on the interactions between the sole thrust and the Precambrian basement to demonstrate the impact of subtle inherited basement features on geometry and dynamics of the evolving thrust system. We compare these with recent insights on the structural evolution in the Moine Thrust Belt of Scotland, an equivalent front to the Caledonian orogen on the western margin of the Iapetus Ocean, and discuss more generally the role of basement structures in thin-skinned thrust systems.

2. Geological background

Before describing our observations in detail, we briefly describe the tectonic context and general features of the Scandinavian Caledonides and its foreland.

The Caledonian orogenic front against the Precambrian Fennoscandian shield can be traced for over 1500 km from the SW coast of Norway and the Oslo graben outlier to the Norwegian coast to Finnmark in the north (Fig. 1). Following pioneering plate tectonic interpretations (Strand and Kulling 1972) and Gee's (1975) tectonostratigraphic map, a succession of palaeogeographic reconstructions have been proposed (e. g., Abrahamsen, 1985; Kumpulainen and Nystuen 1985; Stephens and Gee, 1985; Torsvik and Rehnström 2001; Pisarevsky et al., 2003; Cawood and Pisarevsky 2006). The vast majority of these studies show that the western margin of Baltica was situated opposite to the eastern margin of Laurentia throughout the evolution of the Iapetus Ocean and that, upon closing of Iapetus, the Scandinavian Caledonides formed in a single, continuous deformation episode between 440 and 380 Ma (the "Scandian orogeny"; Fig. 2; reviewed by Corfu et al., 2014; Gee, 2020). The historical model of a "Finnmarkian orogeny", a Cambrian orogenic phase preceding the main Scandian collision, has been largely discredited: e.g. geochronological studies show that the pre-Scandian deformation in Finnmark is much older (Neoproterozoic; e.g., Corfu et al., 2007).

The Caledonian front, trending NNE-SSW through the Swedish sector to NE-SW in northern Norway, front marks the outer limit of Scandian deformation (Fig. 2; e.g. Gee et al., 2008). The general characteristics and location of the Caledonian front in Scandinavia are relatively well-established (e.g., Strand and Kulling, 1972; Gee, 1975; Hossack and Cooper, 1986; Lehtovaara, 1995; Pirrus, 2004; Corfu et al., 2014). The Swedish sector is characterised by large-displacement, relatively thin thrust sheets (e.g. Gee et al., 2010). In contrast, in Finnmark the thrust structures involve thicker sedimentary units, interpreted to have been deposited within a large palaeobasin (the Gaissa Basin) which lay on the rifted Baltica continental margin with the Ægir Ocean (Figs. 1 and 2; e. g., Gayer and Roberts 1973; Rice 1994, 2014). These two sectors show slightly different thrusting directions, from west to east along much of the central parts, to more NW to SE direction in the Gaissa Basin area. This change occurs near the Kilpisjärvi area in NW Finland, the location of our study (Figs. 1 and 3).

The Precambrian crystalline basement of the Fennoscandian shield of Baltica, now comprising the orogenic foreland to the east, is unconformably overlain by the Neoproterozoic to Palaeozoic "basal" sedimentary rocks (Gee and Stephens, 2020). (Fig. 1). In our study area, the type locality for these is at Dividal c. 30 km SW of Kilpisjärvi (Kathol, 1987; Gayer and Roberts, 1973; Pirrus, 2004). The Dividal Group here consists of fairly homogeneous quartz sandstones, together with fossiliferous fine sandstones and siltstones and local shallow-water limestones (Fig. 4a–d). The basins into which these and other syn-rift sediments were deposited were defined mostly by ~ NE-SW striking rift faults related to the Iapetus Ocean opening, but in the northern orogenic segments of Finnmark the rifting, including the formation of the Gaissa Basin, was dominated by the Aegir Ocean dynamics with its mostly ~ SE-NW striking rift faults (Figs. 1 and 2; e.g., Townsend et al., 1986; Rice, 1994).

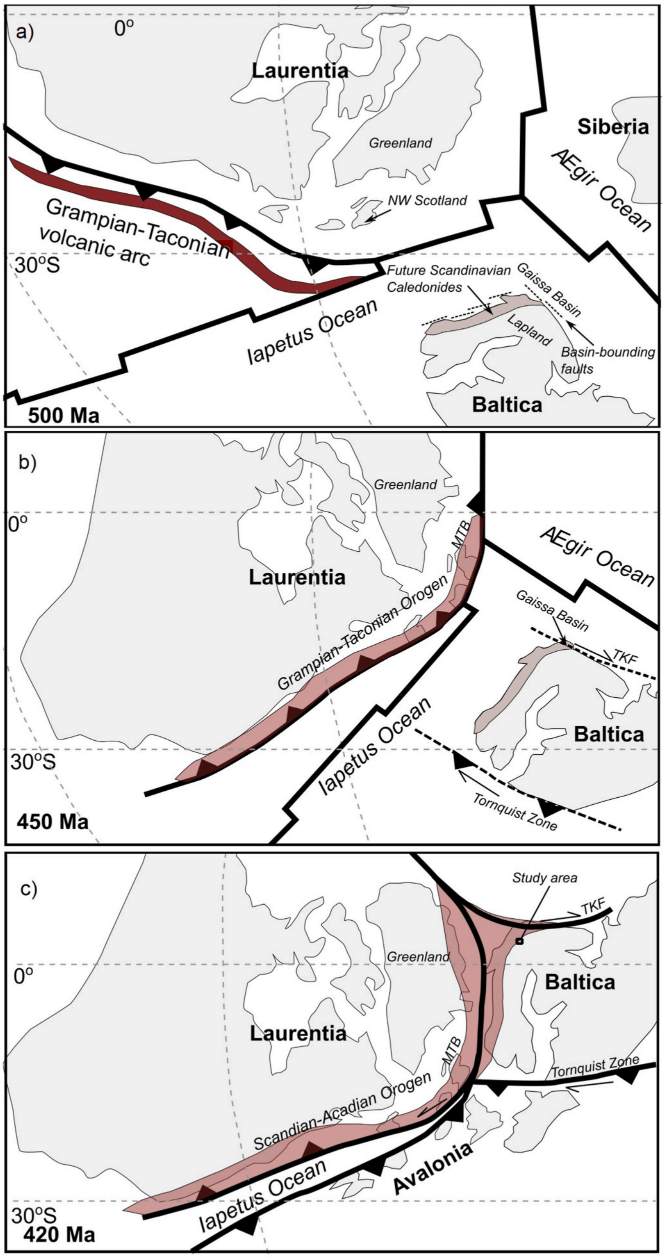

Fig. 2. Reconstruction of plate configurations during the protracted closure of the Iapetus Ocean that led to the formation of the Caledonides in Scandinavia and the British Isles and the Appalachian mountains in North America. a) Late Cambrian; b) Late Ordovician; c) Late Silurian. The deformation along the sole thrust of the Moine Thrust Belt (MTB) in Scotland affects Cambrian sedimentary rocks deposited on the Laurentian margin, whereas the Caledonides sole thrust, including CaTFLap, deform Cambrian sediments deposited onto the Baltica margin. The Trollfjorden-Komagelva Fault (TKF) in northern Scandinavia is probably a reactivated major basin-bounding fault of the Ægir Ocean rifted margin that includes the Gaissa Basin (Rice, 1994). Map based on e.g. Abrahamsen (1985); Rice (1994); Torsvik and Rehnström (2001); Chew and Strachan (2014).

During the Caledonian orogeny, the various allochthonous nappes were thrusted towards the east and east-southeast onto the basement and the Neoproterozoic to Cambrian basal sedimentary rocks (Fig. 1; e. g., Andréasson et al., 2003; Corfu et al., 2014; Gee and Stephens, 2020). The lower nappes along the eastern part of the orogen were derived mostly from the former rifted continental margin of Baltica, whereas the western (upper) nappes are oceanic or Laurentian in origin (e.g., Corfu

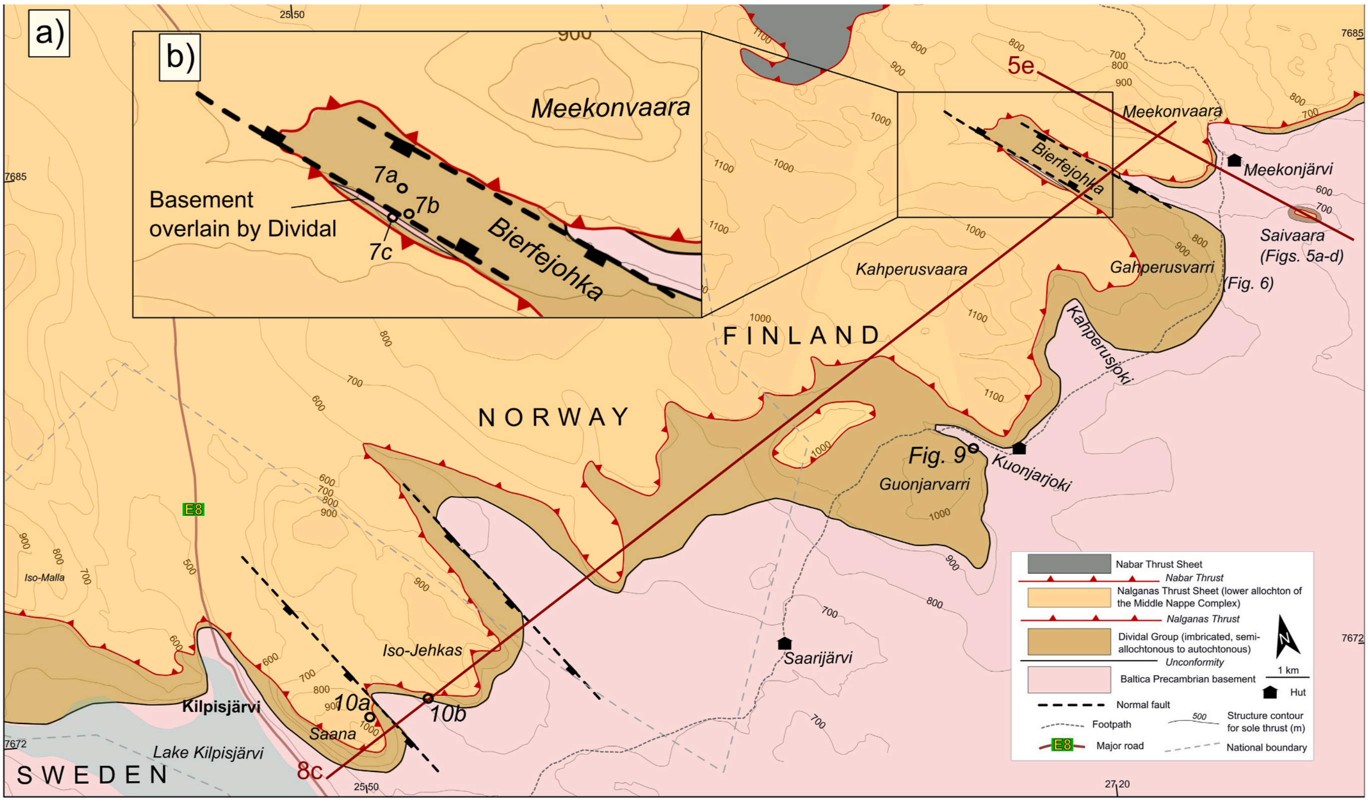

Fig. 3. a) Simplified geological map of the Kilpisjärvi-Meekonjärvi area and stratigraphy of the study area. Localities of Figs. 5–9 are indicated. Based on the Geological Survey of Finland and Geological Survey of Norway 1:50,000 map sheets (Lehtovaara, 1994a, b; see also Lehtovaara, 1995), refined after own observations and interpretations, except in the area between Kuonjarjoki and Iso-Jehkas due to time limitations. Coordinates EUREF, topographic elevation values in metres. b) Detail of the Bierfejohka valley.

et al., 2014). However, in the Finnmark sector in the north, once thought to be part of the ancestral continental margin of Baltica, more recent detailed radiometric dating allowed Corfu et al. (2007), Kirkland et al. (2008) and Andersen et al. (2014) to demonstrate that at least some metasedimentary rocks within these allochthons were not derived from Baltica but probably from the Timanian orogen in the NE. According to these authors, only the structurally lower parts of the orogen in Finnmark are derived from Baltica, including the thin veneer of basal sedimentary rocks below the sole thrust. The dominant thrust direction is west to east along most of the orogen, but in the Finnmark area the orientation changes into a more NW to SE orientation (Fig. 1; Corfu et al., 2014 and references therein). The original Ægir Ocean margin-related normal faults controlled the location and vergence of the thrust system and this role of inherited structures is important in Finnmark (Rice, 2014).

Major thrust sheets have been correlated from the studied areas along the length of the chain, implying large-scale lateral continuity of thrust displacements and the generality of dominantly thin-skinned tectonic styles (e.g., Gee 2020). However, typically for fold-thrust belts, the major tectonic units do show some lateral discontinuity, reflecting e.g. the original extents and thicknesses of individual units, structural complexity of the pre-existing basins, or the effects of syn-to postorogenic extension processes (e.g., Corfu et al., 2014). Gee and Stephens (2020 and references therein) provide further descriptions of the thrust system in Sweden. In addition, seismic reflection data from central Sweden, tied to the COSC-1 deep borehole, have been used to image the Baltic continental crust beneath the orogen (e.g. Juhlin et al., 2016).

Despite the general features of the structure of the orogen being reasonably well understood, there are many unanswered questions. For example, the more detailed structure of the foreland and the sole thrust is not well resolved. The assumption in the Swedish sector has been that the thrust sheets have been emplaced on a sole thrust that over-ran the basal sedimentary cover (as reviewed by Gee 2020). The sole thrust is generally depicted as a simple, planar surface that dips gently to the west, with any variations in the sole thrust geometry attributed to folding during progressive deformation above zones of heterogeneous thickening (Juhlin et al., 2016). It has, however, been recognised that the basal sediments, too, are deformed via local imbrication structures, including in the area of our study (e.g. Lehtovaara, 1995; Gee, 2020). There are no detailed, published studies on the lateral sole thrust morphology and strain variations along the thrust front, or on the exact nature of the interaction of the basal sediments, the underlying basement, and the sole thrust.

2.1. Study area and observed geological relationships

Our case study area lies NE of Kilpisjärvi, close to the Finnish-Norwegian border (Figs. 1 and 3). The Finnish sector of the thrust front lies in the wilderness NE of the highway that passes through Kilpisjärvi village. Access is entirely pedestrian. The terrain is sparsely vegetated and generally free of glacial drift, although modern erosion processes have formed scree slopes that can be extensive. The landscape has been streamlined by glacial erosion with NW-SE-trending ridges that terminate abruptly in SE-facing cliff-lines, giving good natural sections of the thrust front Fig. 4a).

Our work builds on the 1:100,000 existing geological mapping (Lehtovaara 1994a, 1994b) and its associated memoir (Lehtovaara 1995). These show Vendian to Cambrian siliciclastics and Ordovician carbonates of the Dividal Group, caught between the Archaean basement of the foreland and the over-riding rocks of the “lower allochthon”, i.e. the Nalganas Thrust sheet (Figs. 3 and 4). (Figs. 3 and 4). Existing

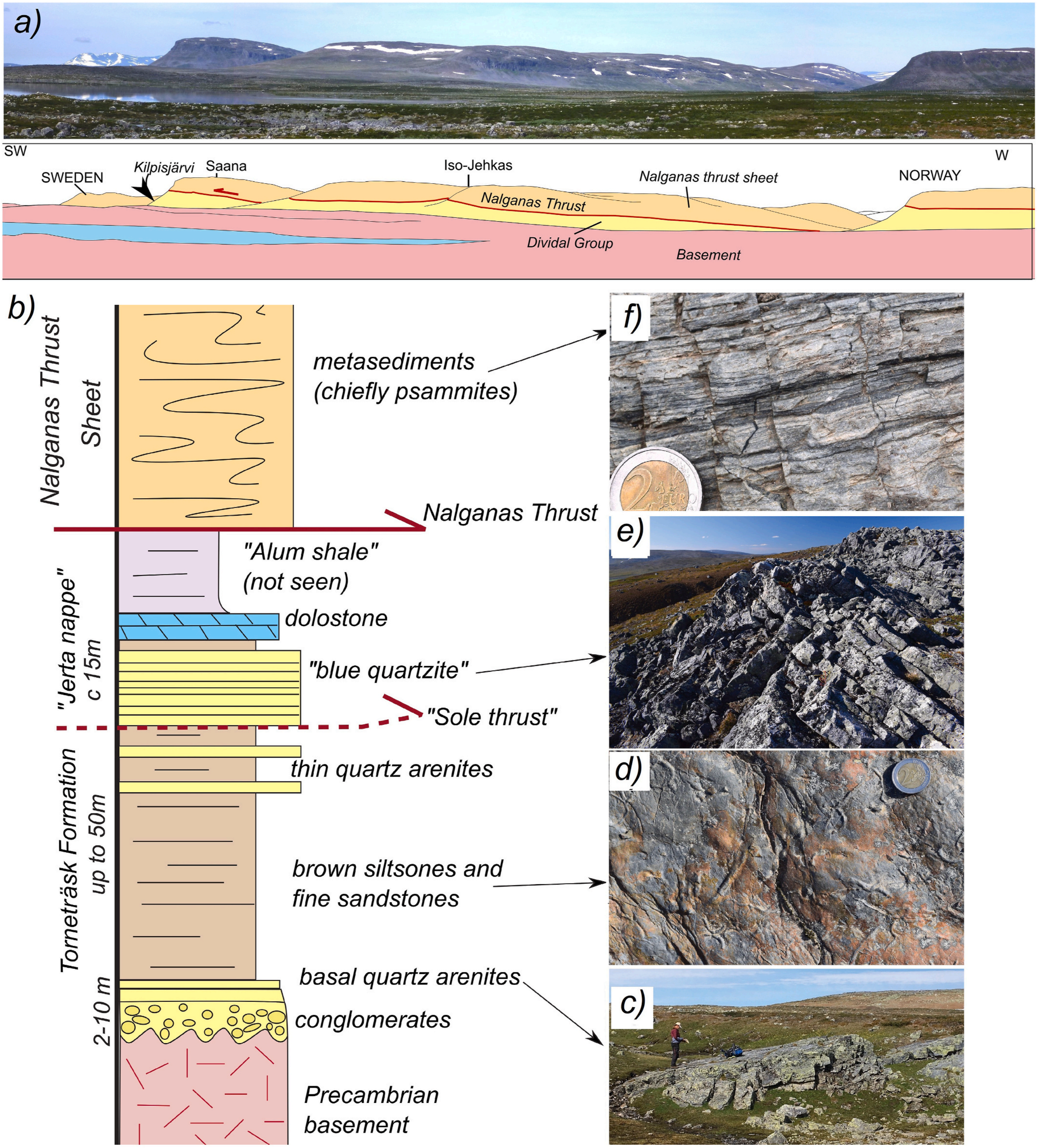

Fig. 4. Stratigraphy of the study area. a) A view of the thrust front looking west-southwest showing the general stratigraphic relationships. The Dividal Group sediments are grouped in the pale yellow unit between the Nalganas Thrust (orange) and the Archaean basement (pink); b) Stratigraphy of the study area. Modified from Lehtovaara (1995) based on own observations; c-f) Typical rocks in each part of the stratigraphy: c) quartz arenites of Torneträsk Formation; d) brown shales of Torneträsk Formation, with trace fossils; e) "blue quartzites" of the Jerta nappe; f) mylonitic quartz arenites of the Nalganas thrust sheet. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

research in the wider area has focussed on the igneous rocks of the Halti-Ridnitsohkka Igneous Complex within the allochthon (e.g. Sipilä, 1992) and on the stratigraphy and palaeontology of the Vendian-Cambrian Dividal Group sediments (e.g. Pirrus 2004). Beyond local mention of some minor structures and fabrics in published papers and the geological map memoir (Lehtovaara, 1995; Pirrus, 2004), there have been no structural studies. The Dividal succession here is broadly similar to that observed in the type locality at Dividal in Sweden (e.g. Jensen and Grant, 1998): i.e., the basement is in places overlain by basal conglomerate, which is in turn overlain by a thin quartz arenite unit, followed by a ~20 m package which is characterised by a brown-weathering siltstone-sandstone (the Torneträsk Formation of Jensen and Grant, 1998), resembling the Fucoid Beds of NW Scotland. Lehtovaara's accounts generally show this unit to contain 2-3 distinct, metre-thick layers of quartz arenite. The overlying, upper part of the Dividal Group is inferred to be tectonically detached (so-called para-allochthonous), constituting the "Jerta Nappe" of Lehtovaara (1989), although he recognises that the Jerta rocks have only been displaced a very short distance or locally not at all. The Jerta rocks include a prominent quartz arenite, several 10 s m thick, termed the "blue quartzite", above which lies a 1–2 m thick layer of dolomitic carbonates that according to Lehtovaara (1989) pass up into dark shales.

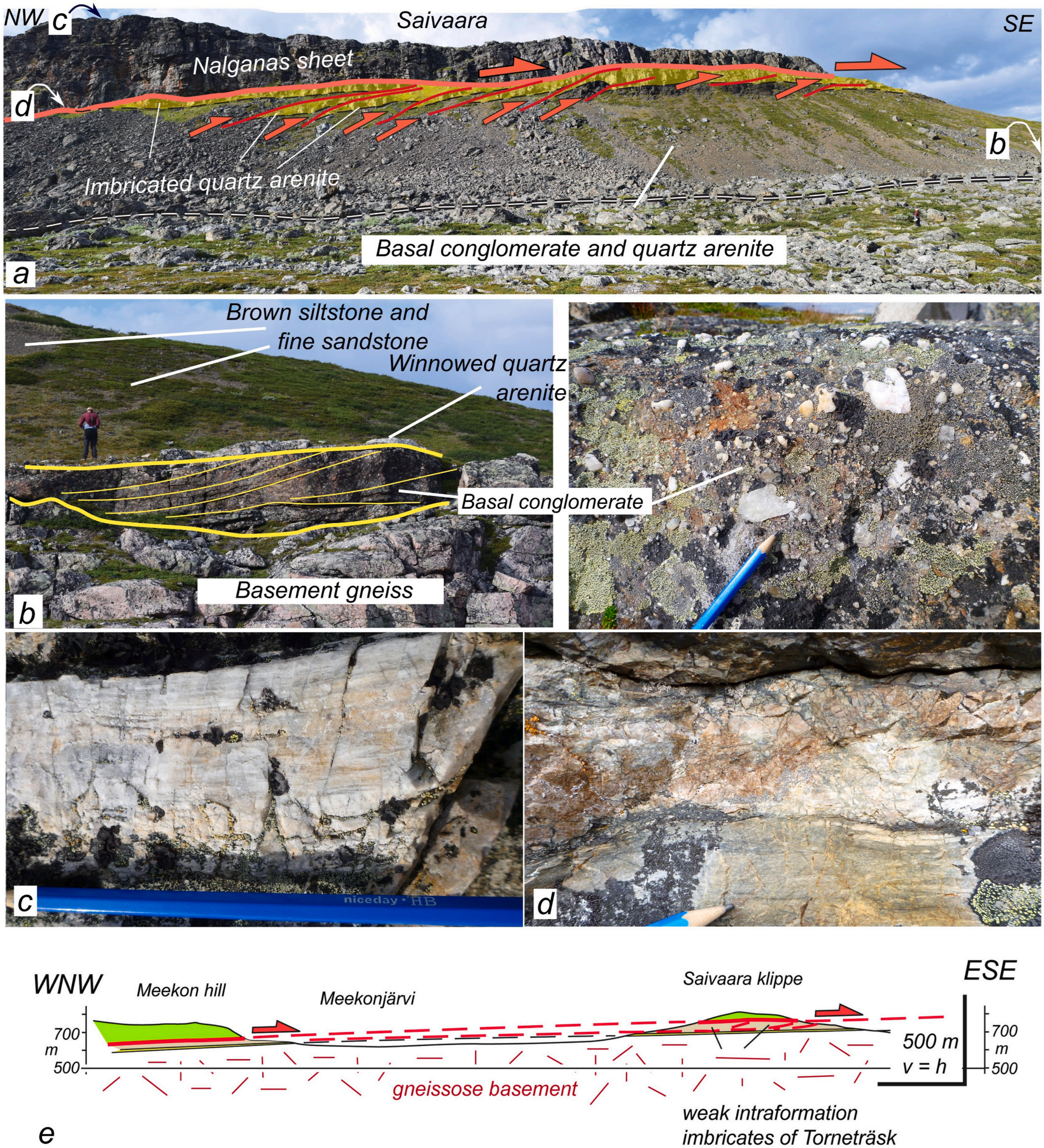

Fig. 5. Outcrop photos and structural data from the northern sector (Fig. 3 for reference). a) Structural and stratigraphic relationships at the Saivaara klippe; b) Detail of the sub-Cambrian unconformity and the overlying sedimentary rocks; c) Very well developed stretching lineation on top of the Saivaara klippe; d) Quartzo-feldspathic mylonites and cataclasites near the base of the Nalganas thrust sheet; e) Interpreted structural relationships and thrust geometry between the Meekonvaara hill and the Saivaara klippe.

Although our studies confirm these broad relationships, understanding the basement-sole thrust interactions demands disentangling the depositional sequence from structural repetitions. In building our interpretation, we discuss various locations in our study area from north to south, including sections with increased complexity.

2.2. Northern sector (Saivaara and Meekonvaara)

Within our study area, some of the clearest geological relationships are preserved at the spectacular inselberg of Saivaara (Figs. 3 and 5). At Saivaara, the Archaean basement rocks are unconformably overlain by c. 2 m of poorly sorted conglomerates, with the unconformity showing c. 1 m relief upon it over c. 100 m (Fig. 5a). The conglomerate clasts that at the base of the section match lithologies in the underlying basement, but higher up contain mostly quartzitic pebbles of variable roundness (Fig. 5b). We interpret these pebbly quartz arenites to have been derived by winnowing of the top of the conglomerates. The pebbly arenites pass abruptly up into brown siltstones and fine sandstones of the Torneträsk

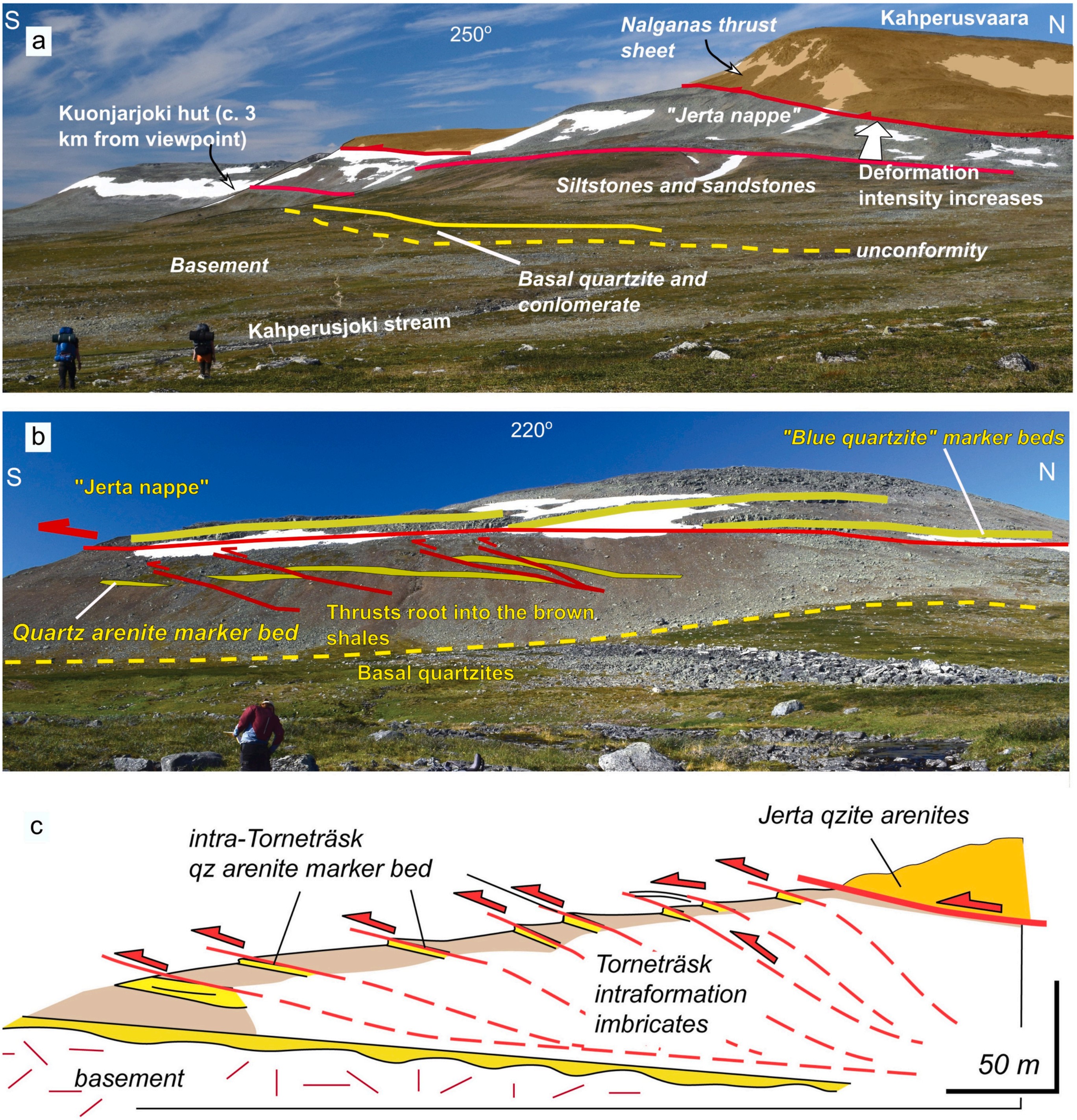

Fig. 6. Observations and interpretation from the central sector (Fig. 3 for reference). a) Overview of the structural and stratigraphic relationships; b) A detailed section showing the internal structural complexity within the Dividal Group sediments: the Torneträsk Formation is imbricated into an intra-formational duplex under a roof thrust carrying the para-autochthonous Jerta nappe SE-wards; c) Conceptual model of the relationships between the Precambrian basement, the Torneträsk Formation, and the Jerta nappe.

Formation, dipping gently to the NW (Fig. 4b; 5a-b). These are overlain by c 2–3 m of quartz arenite, forming the immediate footwall to the Nalganas Thrust (Fig. 5a). The upper quartz arenite is imbricated with the immediately underlying brown siltstones (Fig. 5a). Therefore, the Nalganas Thrust is underlain by an intraformational duplex of Torneträsk rocks, to which it forms the roof. The upper parts of the Dividal Group, the autochthonous to para-allochthonous "Jerta nappe", is missing.

The hilltop comprises quartzo-feldspathic mylonites with chloritic bands of up to a few cm thickness and very well developed stretching lineation fabrics (Fig. 5c). Occasional 10 cm-scale folds have thrust transport-oblique to transport-parallel fold axes. Overall the rocks have the appearance of L > S tectonites. We follow Lehtovaara (1989) in considering these rocks to be part of the Nalganas thrust sheet. The basal contact of the mylonites, interpreted to be the Nalganas Thrust, includes flinty cataclasites (Fig. 5d).

To the WNW of the Saivaara klippe, the main outcrop trace of the Nalganas Thrust lies on the wooded slopes overlooking the Meekonjärvi Hut (Fig. 3). Although rock exposure is limited on the lower slopes, they are consistent with a similar rock sequence and thicknesses to those found at Saivaara: gneissose basement overlain by a few metres of conglomerates with a veneer of quartz arenites followed by around 20m of brown siltstones and sandstones. The quartzo-feldspathic mylonites of the Nalganas thrust sheet are well-exposed higher up in cliff sections. Therefore, we simply infer that that Nalganas Thrust originally connected across to the klippe at Saivaara (Fig. 5e) and that its footwall shows only weak imbrication, restricted chiefly to the upper parts of the Torneträsk Formation. The floor thrust to these imbricates, which therefore forms the local Sole Thrust (strictly the lower edge of Scandian thrusting on this transect) lies within the brown siltstones that characterise the lower part of the formation.

2.3. *Central sector (Kahperusvaara, Gahperusvarri and Kahperusjoki)*

Farther SW from the Saivaara-Meekonvaara transect, the structures associated with the sole thrust get increasingly complex. We will first consider the section on the east side of Kahperusvaara which exposes a transect up from gneissose basement, through Dividal rocks and up into the Nalganas thrust sheet (Figs. 3 and 6a). As at Saivaara, the lower succession contains the basal coarse siliciclastics which pass upwards abruptly into the brown siltstones and sandstones of the Torneträsk Formation. The succession collectively dips c. 10° to NW. The Torneträsk units have contacts that are generally bedding-parallel, although in several cases, low-angle discordances can be found, and we consider the overall succession to be tectonically imbricated. Particularly the NE edge of the Gahperusvarri plateau, at the mouth of the Bierfejohka valley (Fig. 3), provides an informative profile, revealing thrust repetitions of a prominent unit of quartz arenites within the Torneträsk Formation (Fig. 6b). However, it is unclear if the Torneträsk Formation here has just one, or multiple depositional layers of quartz arenites, and so the number of imbricate thrusts in Fig. 6b is conjectural. These outcrops on the SE corner of the Biefe valley also reveal the contact at the base of the quartz arenites of the Jerta nappe ("blue quartzite" of Lehtovaara 1995, Fig. 6b). This unit consists of c. 25m of well-bedded mature quartz arenites with well-defined beds c. 10–20 cm thick. Cross-bedding is locally preserved. The blue quartzite unit is discordant to the imbricates in the Torneträsk Formation, and in some places the imbricate thrusts seem to climb across into the Jerta nappe. The base of the Jerta nappe, therefore, forms the local roof thrust to these imbricates: the contact, at least here, is not simply stratigraphic (Fig. 6c).

The Jerta blue quartzites appear to be overlain by a poorly-exposed interval of a few metres of rusty-weathering siltstones. Along strike the section also contains broken outcrops of dolostone, but overall the upper parts of the Jerta nappe are missing below the Nalganas thrust (where preserved). Above are further quartz arenites, with flat sedimentary clasts that define a S1 foliation dips c. 15° to NW. The foliation intensity increases up section. These rocks lie in the footwall to the Nalganas Thrust Sheet with strongly foliated quartzo-feldspathic rocks. Stretching and crenulation lineation is strong but varies in intensity, so that the lineation and crenulation are better developed in the southern pats of this section at Kahperusvaara than in NE parts of the section at Gahperusvarri. Rare 10 cm to metre-scale folds are east-verging and generally have thrust transport-perpendicular (NE-SW) trending fold axes. Generally the rocks can be classified as S = L to S > L tectonites.

2.4. *Linking structures across the bierfejohka valley*

The thrust systems shows significant variations between the northern and the central sector. The change in the structural style between the northern and central sectors occur within the Bierfejohka valley (Fig. 3). In the northern sector, the Jerta nappe rocks are not preserved in the Nalganas Thrust footwall and the Torneträsk Formation is relatively thin. The central sector contains 10s of metres of Jerta quartz arenites ("blue quartzite") between the much thicker Torneträsk Formation and the over-riding Nalganas Thrust Sheet. The Torneträsk Formation is imbricated, with the para-allochthonous Jerta nappe forming a roof to the imbricates. The unconformity along the top of the foreland basement is also topographically higher in the central sector than in the north. All of these observations imply that the Nalganas Thrust rapidly climbs up the stratigraphic section within the Bierfejohka valley, and branches into the base of the para-allochthonous Jerta nappe. We will now describe the detailed structures occurring in the Bierfejohka valley where the most rapid structural change occurs.

On the NE side of the Bierfejohka valley, along the Meekonvaara slope, the Nalganas Thrust sheet lies directly above a thin layer of highly deformed brown siltstones of the Torneträsk Formation. Moving southwards along the valley floor, the Dividal Group rapidly thickens with outcrops of both folded and strongly lineated Torneträsk rocks and imbricated blue quartzites of the Jerta nappe (Fig. 7a and b). The fold axes are generally SE-NW orientated, i.e. along the thrust transport direction (Fig. 7a). However, the Dividal rocks do not simply pass upwards into the Nalganas Thrust sheet mylonites like in the central sector. The SW wall of the valley contains a small window of basement gneisses, overlain by a few metres of brown siltstones and sandstones, overlain higher up the slope by a succession of deformed Dividal Group rocks underneath the Nalganas Thrust (Fig. 3b). Towards the centre of the valley, the gneisses show a sub-vertical abrupt contact with the Jerta rocks (Fig. 7c). These relationships and the structurally elevated position of the basement window shows it is not simply a product of erosion, nor a basement thrust slice: the NE side of the inlier is a faulted contact against Jerta quartz-arenites with at least 40 m of north-side down displacement. We interpret that the abrupt change in the thrust structure and the thickness of the Dividal Group, as well as the folding of the Dividal Group rocks, across the Bierfejohka valley were controlled by this inherited basement fault (Fig. 8a–c). The thickness changes and structure contours drawn across this area imply that the northern margin of the valley may follow an another, south-dipping fault, although this is not exposed (Fig. 8a–c).

2.5. *Southern sector (Kuonjarjoki valley)*

The lower walls of the Kuonjarjoki valley contains the brown siltstones and sandstones of the Torneträsk Formation, containing trace fossils (see also Systra and Jensen, 2009). The majority of the SW side of the valley is largely obscured by fallen blocks of quartz arenites but the NE side provides a good cross-section (Fig. 9). Above the basement lie c. 70m of brown siltstones of the Torneträsk Formation, capped in turn by the Jerta "blue quartzite" above which lies a prominent dolostone. All these units (Torneträsk and Jerta rocks) are imbricated together; it is unclear if, as in the central sector, the basal Jerta contact here is tectonic.

The structural variations between the central and the southern sector

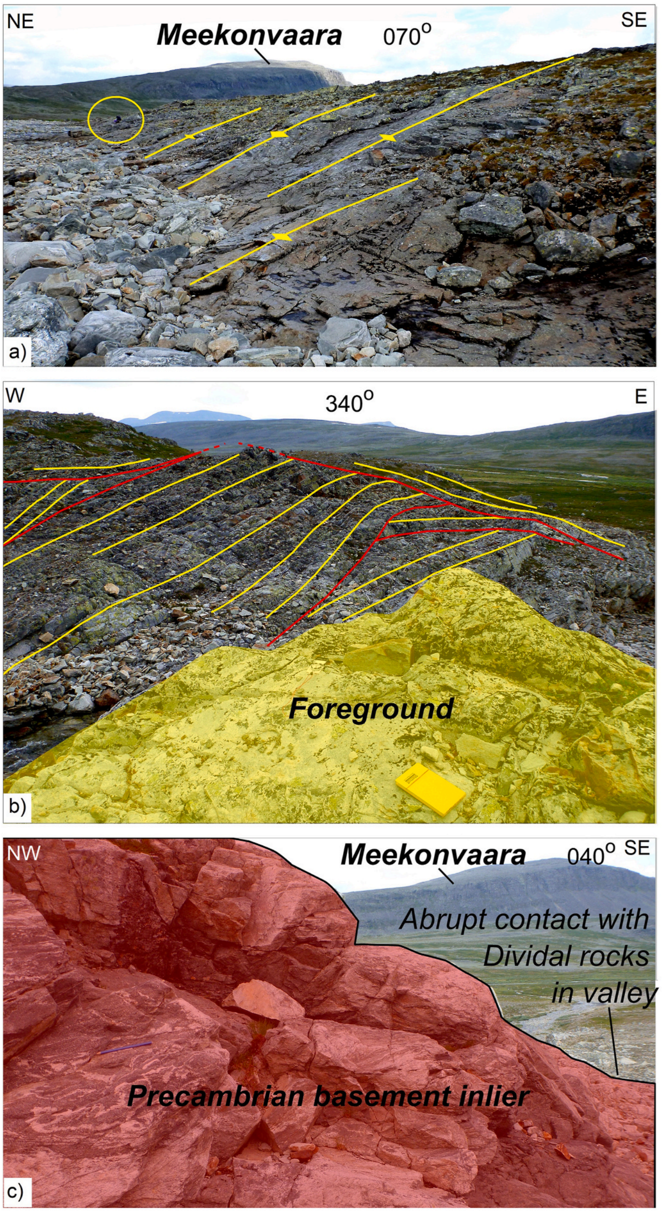

Fig. 7. Linking structures across the Bierfejohka valley. See Fig. 3b for reference. a) Folded Torneträsk Formation rocks with fold axial traces orientated c. SE-NW, i.e. along the valley axis; see also Fig. 8c. Person for scale; b) Imbricated Jerta blue quartzites in the immediate hanging-wall of a basement inlier (Fig. 7c). The yellow lines indicate bedding trace, the red lines are imbricate thrust traces; c) View from the basement inlier towards the Bierfejohka valley and Meekonvaara. The abrupt contact on the side of the valley is interpreted to represent a NE-dipping normal fault within the basement. See text for further discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

appear to be rather gradual, over the c. 8 km between the localities so that the Nalganas Thrust keeps climbing more slowly across this area. There is no evidence of basement faulting here.

2.6. *Saana – Iso-Jehkas*

The footpath between Saana and Kuonjarjoki traverses on the basement, away from the exposed thrust, and the timeline of this exploratory mission did not allow for detailed investigation of the thrust structures between Kuonjarjoki and Iso-Jehkas. However, further observations of the relationships between the thrust belt structure and palaeotopographic relief of the underlying crystalline basement can be made near the township of Kilpisjärvi (Fig. 3). The area includes the prominent hill of Saana and the adjacent plateau of Iso-Jehkas. These, together with outcrops around the shores of Saana lake, provide another excellent control not only on the structure of the Nalganas Thrust but also on the top-basement unconformity. Note that there are no rocks of the Jerta nappe here: the Nalganas Thrust lies directly upon Torneträsk Formation.

The basement unconformity here has a general northerly dip. However, across the valley on the east side of Saana hill, there is an abrupt change in its elevation, associated with a dramatic thickening of the Dividal Group sediments (Fig. 10): just c. 25m thick in the NE but over 250 m thick on the slopes of Saana hill. Within the valley floor, the Nalganas thrust sheet lies structurally much lower and the rocks here exhibit strong, thrust transport-parallel stretching lineations and fold axes. The changes in the Dividal Group thickness and the elevation of the thrust plane occur abruptly along the NE slope of Saana hill. We interpret this change to be controlled by an inherited basement fault, similarly to the relationships observed in the Bierfejohka valley (Fig. 8b and c).

3. Discussion

3.1. *Implications to basement controls on strain state within thin-skinned thrust sheets*

A key conclusion of our field research is that lateral variations in thrust belt structure coincide with structures in the foreland that offset the top of basement, and therefore are likely to have impacted on the behaviour of the floor thrust and the imbrication within Dividal Group rocks (Fig. 11). Furthermore, the "minibasins" controlled by the inherited basement faults, the overlying Dividal Group and, in the Saana area, Nalganas rocks show intense stretching lineations and folding with thrust transport-parallel axial traces (constrictional L > S tectonics; Fig. 7a and 8d), whereas elsewhere the deformation style is dominated by S = L tectonics (Fig. 8d). This suggests that not only did the basement palaeotopography influence the thrust geometry and the imbrication patterns, but also the strain state of the thrust sheet and the deformed Dividal Group rocks: the presence of extremely well-developed stretching lineations and folds with thrust transport-parallel axes within the fault-controlled "minibasins" indicates that the rocks here experienced strong constriction. Therefore, we propose that the strain state in thrust sheets, especially the development of constrictional strain, can be controlled by the forcing of thrust displacements into basement-governed corridors, analogous to stream-lines in ice sheets (e.g., Stokes, 2017). Inherited orogen-perpendicular basement structures may, in other words, create open corrugations in the foreland that serve to direct thrust allochthons. This explanation is reminiscent of Coward's (1994) "tram-lining" model for the western Alps, where crustal shortening is interpreted to have been guided by extensional fault systems inherited from earlier rift events. Substantial further work, including experimental modelling, is needed to test this hypothesis. Either way, the spatial relationship with the thickness changes, L-tectonites and transport-parallel folds suggest that the basement faults were indeed pre-existing features, rather than forming after the thrust sheet was emplaced. We cannot rule out the possibility of positive fault inversion causing some of the variations, particularly local thickening of Dividal and associated changes in thrust elevation, but we do consider that the thickness changes and, in particular, the prevalence of transport-parallel folds and L-tectonites within the minibasins (Fig. 8d) is more consistent with our interpretation of dominantly basement-influenced strain style distribution, than inversion.

It is feasible that the basement faults, sub-parallel to the thrust transport direction, represent structures associated with the opening of the similarly orientated Gaissa rift further north in pre-Caledonian times (Fig. 2). However, the fault and the rift orientation may be controlled by

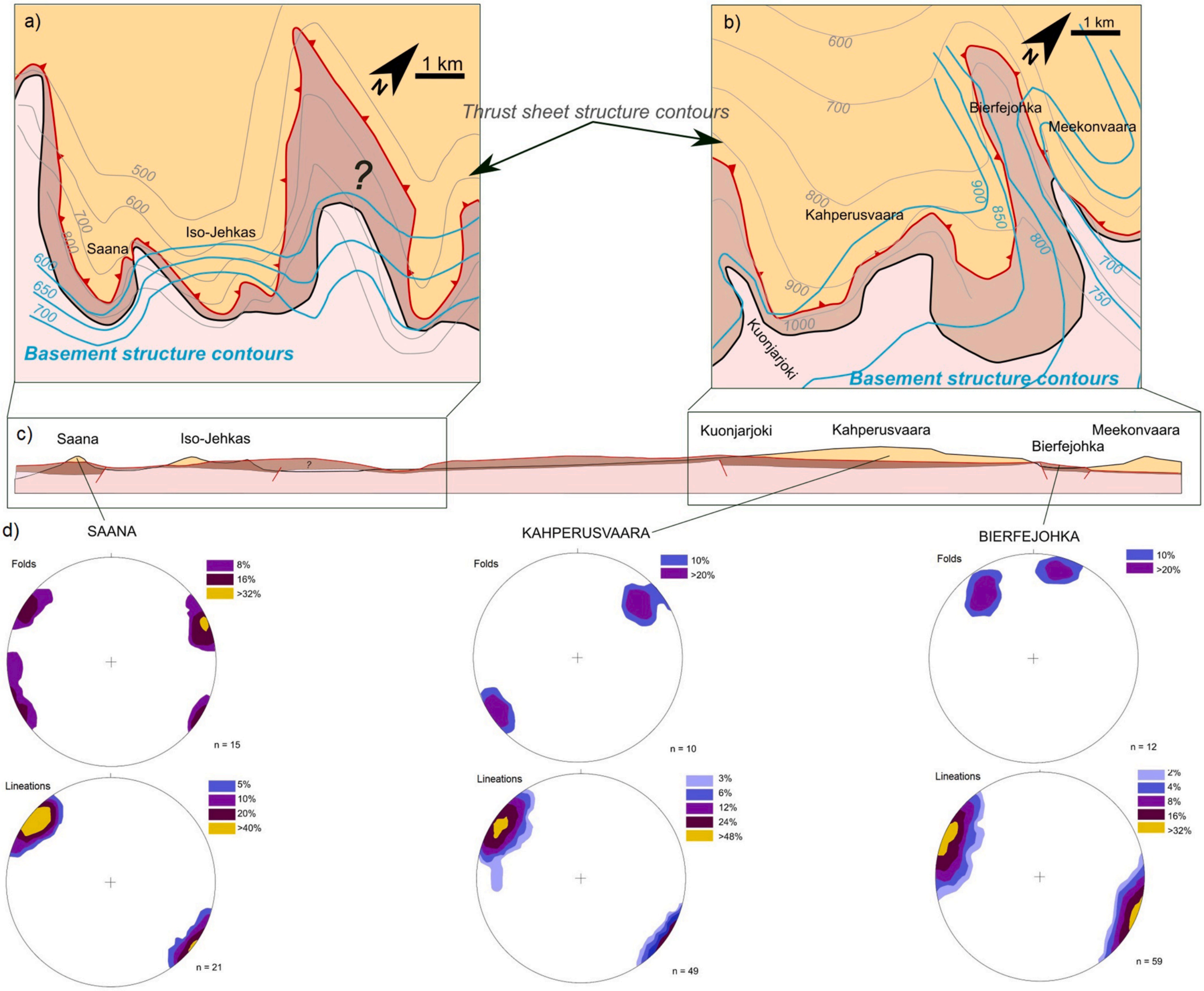

Fig. 8. Simplified detail maps of the a) Bierfejohka area and the b) Saana-Iso-Jehkas area with structure contours drawn in for the basement (blue) and the Nalganas Thrust (grey). Legend otherwise as in Fig. 3. Contour elevation values in metres; c) Simplified long section based on the basement and thrust plane structure contours across the area (Fig. 3 for reference). The inherited basement normal faults, interpreted from both the outcrop patterns and the basement structure contour patters, are seen to coincide with changes in thrust elevation and thickness of the Dividal Group rocks; d) Structural measurements in key localities, highlighting the changes in strain state across the area. Both Saana and Bierfejohka Valley where a presence of 'basement corrugations' are suggested, are dominated by L > S tectonites expressed by folds with thrust transport-parallel fold axes as well as the strong stretching lineations and thrust transport-perpendicular, SE-verging folds; whereas e.g. at Kahperusvaara the rocks are L = S tectonites the thrust transport-parallel folds seem to be absent. See text for further discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

even older events. Northern Fennoscandian shield comprises a collage of Archaean and Palaeoproterozoic terrains accreted through a series of orogenic episodes (e.g. Hölttä et al., 2008). These have left the crust of the foreland of northern Baltica with a complex geological structure, but the c. NW-SE to N–S trend of structural fabrics and magnetic anomalies is sub-parallel to the interpreted basement faults, as can be observed in the field, from the existing geological maps (Lehtovaara, 1994a, 1994b) and the compilation of aeromagnetic surveys for northern Fennoscandia (Nasuti et al., 2015). Therefore, we argue that this trend of Precambrian basement structure has had a long-lived influence on the subsequent structural evolution.

Future work in northern Finland and Norway could include extending the mapping area further north and north-east, following the basal thrust, in order to define any further basement-thrust interactions. On the other hand, two more thrust sheets/nappes exist in the wider area and investigation of these would be needed to enable wider discussion of the architecture of the Caledonian Front in this area, timing of the various thrusts, and their linkage to the inherited basement structures and the entire orogenic evolution. These may also yield more information on the strain state of thrust sheets. Other important research questions remains: what is the extent of the pre-Caledonian Gaissa rift, and how have both inherited geometries and possible inversion structures influenced the thrust sheet behaviour and orogenic evolution in the Arctic Caledonides. In addition, published literature implies that a significant change in stratigraphy, thrust sheet origins/lithologies, and transport direction occurs approximately in the Kilpisjärvi-Halti area of the wider Arctic Caledonides (Rice, 2014). The palaeorift and/or inherited rift structures are likely to have a significant role in this, but the extent of this influence in the south is unresolved.

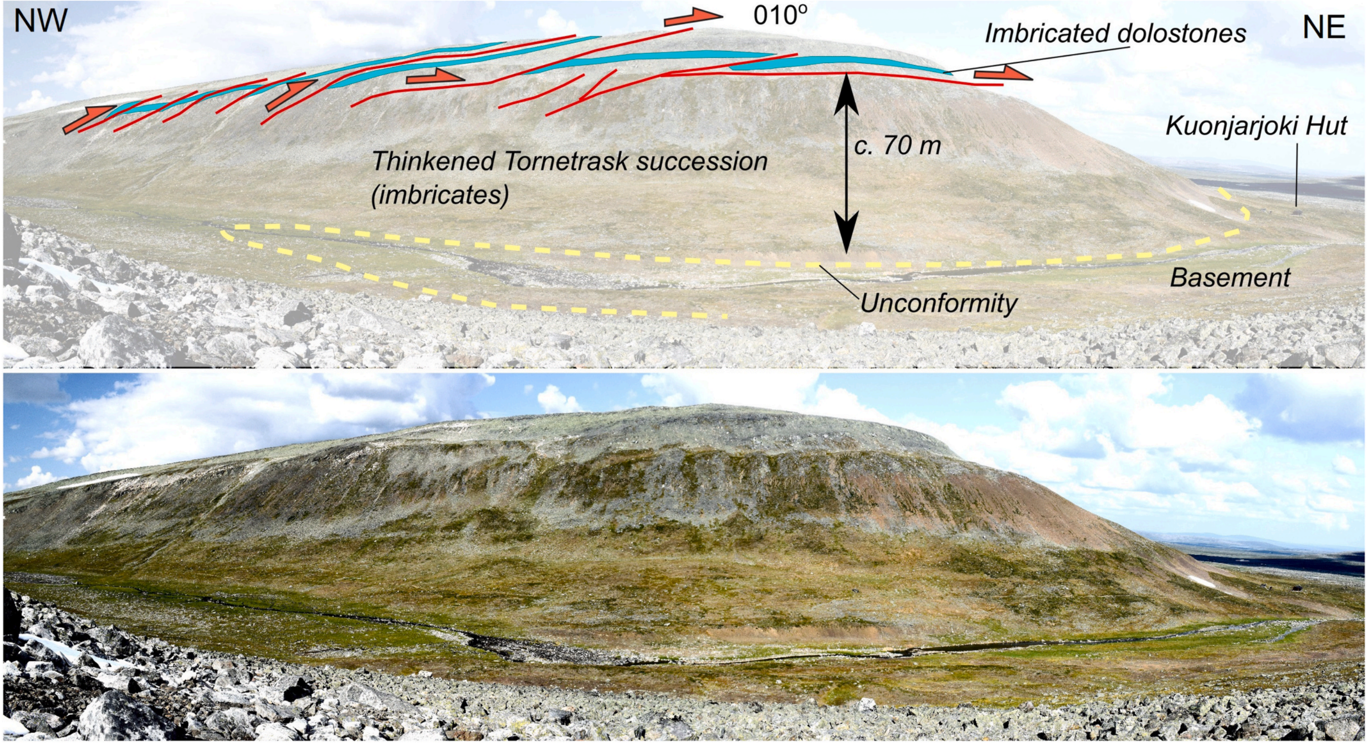

Fig. 9. Overview of the hillside at Kuonjarjoki (Fig. 3 for reference). The basement is overlain by a thick, highly deformed Dividal Group rocks, including the “Jerta nappe” units that are largely absent in other parts of the study area. The Dividal Group is here significantly thicker than farther north due to extensive imbrication.

3.2. Comparisons with the Moine thrust belt of NW Scotland

The thrust front equivalent to CaTFLap in mainland Scotland is the Scandian thrust front represented by the Moine Thrust Belt (MTB; Fig. 12a). The MTB corresponds to the Caledonian thrust front against the Fennoscandian shield, but on the opposite, Laurentian side of the orogen (Fig. 2). The MTB is commonly considered to be a “thin-skinned” tectonic regime (e.g. Elliott and Johnson 1980), but strictly speaking this characterisation only applies to its frontal structures. The thrust belt itself carries significant slices of crystalline basement, the incorporation of which into the thrust belt may indeed be influenced by pre-existing, deep-rooting structures (Butler 1997; Butler et al., 2006a). Our concern here is the behaviour of the regional Sole Thrust and the frontal structures of the MTB which are developed exclusively in the sedimentary cover beneath the Sole Thrust.

Regional accounts of the MTB and its adjacent foreland are provided by several extensive reviews (e.g. Mendum et al., 2009; Butler 2010). The Cambro-Ordovician sedimentary cover incorporated into the thrust belt is broadly a correlative of the Dividal Group of the Fennoscandian margin (e.g. Chew and Strachan, 2014, Fig. 12b). This succession lies unconformably upon the Late Archaean to Palaeoproterozoic crystalline basement (the Lewisian basement complex). However, unlike Fennoscandia, in NW Scotland there are successions of Proterozoic sedimentary rocks (the Torridon and Stoer groups, informally collectively termed the Torridonian). The distribution of the Torridonian preserved beneath the sub-Cambrian unconformity is variable, controlled by combinations of late Precambrian folding (e.g. Elliott and Johnson 1980) and normal faulting (e.g. Butler 1997).

In NW Scotland, the Cambro-Ordovician cover overlies a planar unconformity of regional extent and comprises the Ardvreck (older) and Durness (younger) groups (Fig. 12b). The Ardveck Group comprises a transgressive quartz arenite (the Eriboll Formation), followed by brown siltstones and sandstones (the Fucoid Beds Member) and thin quartz arenites (Saltarella Grit Member, collectively the An t-Sron Formation). Along the length of the Moine Thrust Belt, stratigraphic thicknesses of these Cambro-Ordovician rocks are remarkably constant, with the combined thickness of the Eriboll Sandstone and An t-Sron formations being around 200m. They are overlain stratigraphically by carbonates of the Durness Group. These have a stratigraphic thickness in excess of 800 m (Raine and Smith 2012) but, within the Moine Thrust Belt, commonly only a few tens of metres are incorporated into thrust structures. It is this long-range consistency in facies and depositional thicknesses of Cambro-Ordovician strata, a layer-cake stratigraphy, that has expedited structural interpretations within the MTB.

Despite the lateral simplicity of the stratigraphic template, the MTB shows dramatic lateral variations in its structure, as comprising thrust sheets and duplexes. Some of these variations have been ascribed to the influence of igneous intrusions (e.g. Elliott and Johnson 1980; Searle 2023) but these are only found in a small part of the thrust belt whereas lateral structural variations are much more ubiquitous. Furthermore, the larger intrusive bodies are restricted to structurally higher-level, more internal thrust sheets.

A general expectation of thrust systems is the trajectory of individual thrusts is controlled by the stratigraphic succession within which they are developed, i.e. ”with long flats in ductile horizons and short ramps through competent horizons” (Elliott and Johnson 1980, p. 70). However, like within CaTFLap, this expectation is not borne out in the MTB where thrust flats or imbricates/duplex systems can form in many parts of the Cambro-Ordovician succession, regardless of their competence (e.g. Coward 1980). The Sole Thrust and the associated structures (duplex systems) therefore show significant lateral variations in their position within this succession.

The lateral variations in stratigraphic level of the Sole Thrust and in the structure of the frontal duplex systems is summarised on a longitudinal section along the MTB (Fig. 12c). The most dramatic lateral change in the position of the Sole Thrust is found south of the Loch Maree fault (Fig. 12c) where the MTB is represented by a thick stack of relatively low-displacement imbricate thrusts that root down into Torridon Group rocks. The structural relationships here are described by Butler et al. (2006a) and we follow their interpretation here. This “Achnashellach

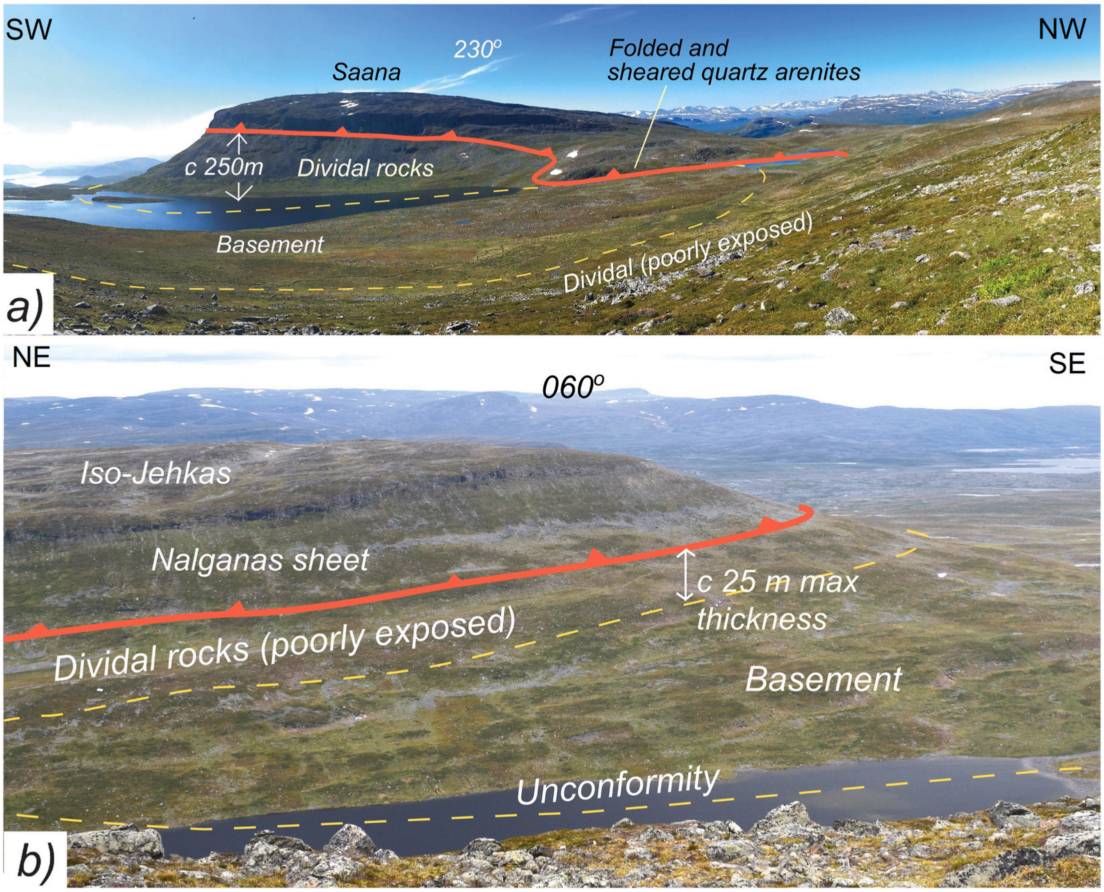

Fig. 10. Overview of the Saana – Iso-Jehkas area (Fig. 3 for reference). a) View towards the southwest. The relatively undeformed Dividal Group rocks are c. 250 m thick at Saana, whilst the valley contains highly deformed quartz arenites that probably belong to the Nalganas Thrust sheet; b) On the opposite side of the valley, the Dividal rocks are much thinner, indicating a pre-existing major topographic/structural change (fault) across the valley.

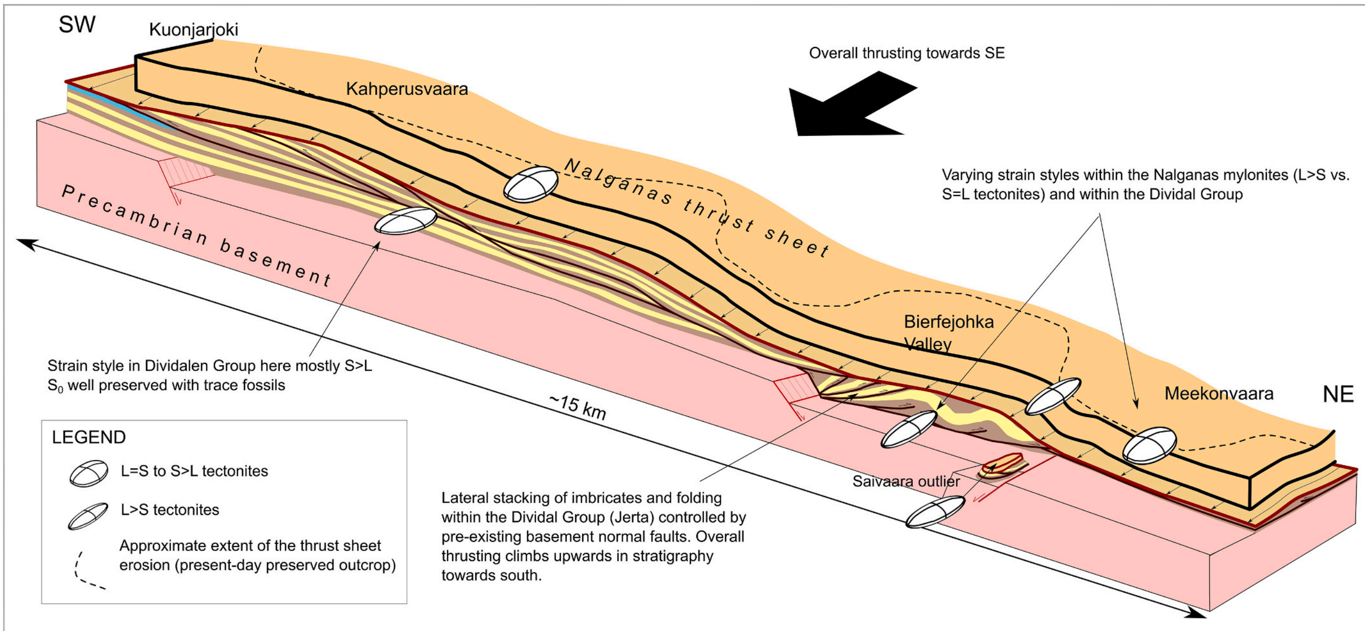

Fig. 11. A schematic long section of the structures and strain styles associated with the basement and the sole thrust. Rock type colour coding as in Fig. 4. See text for discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

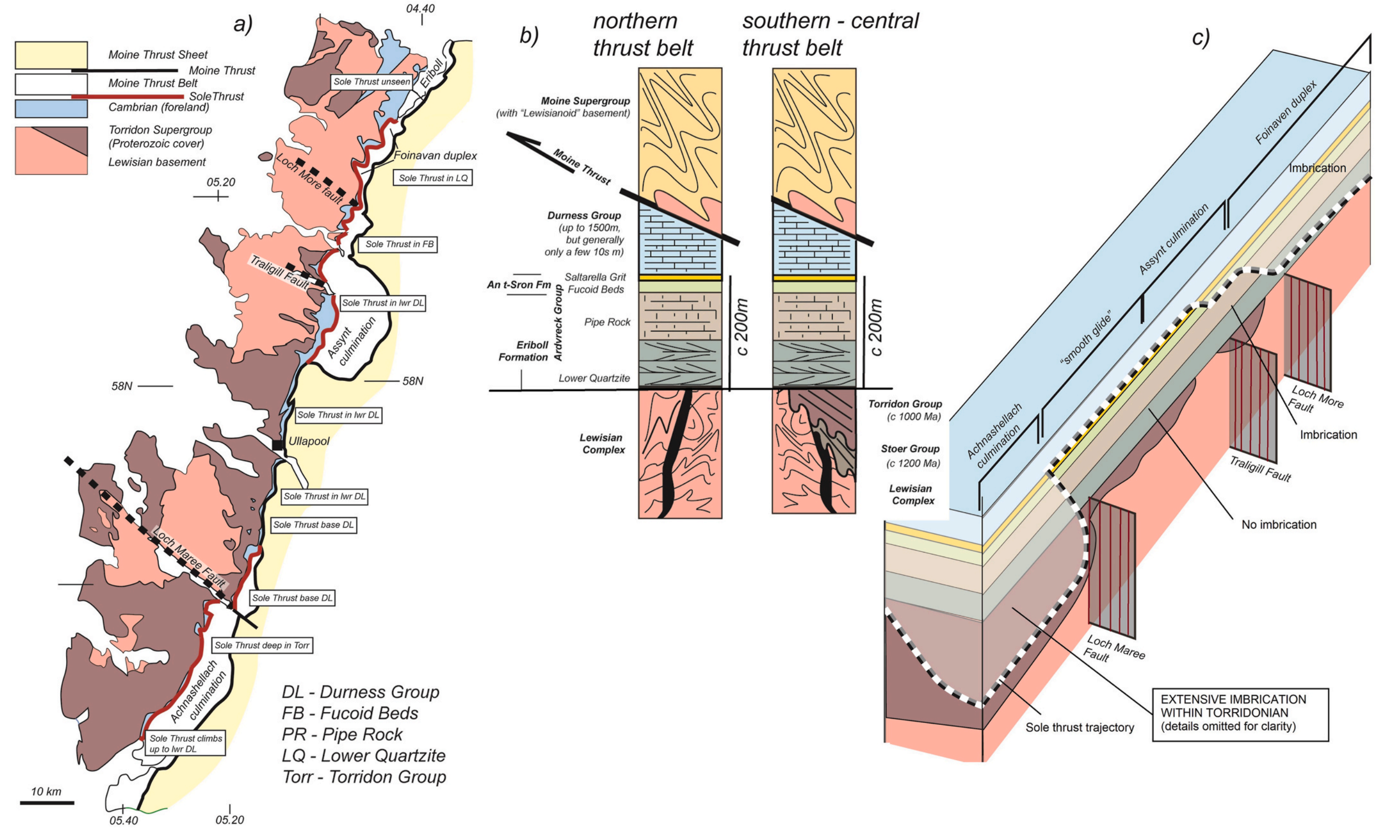

Fig. 12. A summary of structural geometry in the Moine Thrust Belt. a) simplified geological map of NW Scotland (after Butler 2010). b and c) stratigraphic columns for the units involved in the foreland and thrust belt (after Butler 2010). d) longitudinal section showing the lateral variations in the stratigraphic position of the Sole Thrust, tied to the location of Precambrian faults in the basement.

culmination" terminates abruptly at the valley containing Loch Maree, to the north of which these imbricate structures are not developed within the Torridonian and younger sediments. Rather, the MTB is represented simply as the Moine Thrust alone. This dramatic change in thrust belt structure, charting a lateral ramp in the Sole Thrust coincides with the Loch Maree Fault, a Precambrian structure that controls the distribution of Torridonian strata beneath the sub-Cambrian unconformity. Thus, an inherited structure (Loch Maree Fault) directly controls the position of the Sole Thrust and the structural style within the rocks associated with it.

Further north in the MTB, the Assynt culmination is a larger and significantly more famous analogue to the Achnashellach culmination (Fig. 12a–c). However, unlike Achnashellach, at Assynt the culmination is largely a result of stacking of basement thrust sheets, perhaps promoted by igneous intrusions (e.g. Elliott and Johnson 1980), rather than in variations in the Sole Thrust location. In southern and central Assynt the Sole Thrust glides near the base of the Durness Group and therefore the frontal part of this segment of the MTB is represented by imbricated carbonate formations. However, at Loch Assynt the stratigraphic content in the imbricates changes – to include both Fucoid Beds and Saltarella Grit along with carbonates of the Durness Group. This implies that the level of the Sole Thrust drops down to near the base of the Fucoid Beds (Fig. 12c). The change in thrust geometry coincides with the position of the Tralligill Fault. This structure was recognised by Elliott and Johnson (1980) as a compartmentalising thrust sheet geometry within the central Assynt segment of the MTB. However, the fault projects into the foreland where, as has long been recognised, it offsets Torridon Group rocks beneath the sub-Cambrian unconformity (see for example Krabbendam and Leslie, 2010).

North of the Assynt Culmination the MTB is characterised by a complex array of imbricate thrusts developed in quartz arenites of the Eriboll Formation (Fig. 12c). Therefore, the floor thrust to this Foinaven duplex, the regional Sole Thrust, lies towards the base of the Lower Quartzite (Butler, 2004). Elliott and Johnson (1980) show that at the southern edge of the Foinaven duplex, the Moine Thrust, which acts as a roof to the duplex, is cut by a transverse structure: the Loch More fault. They imply that this fault formed in response to differential thickening in the footwall to the Moine Thrust within the Foinaven duplex. However, the Loch More fault also offsets the sub-Cambrian unconformity demonstrating that it is a deep-rooting basement structure.

The synthesis shown in Fig. 12c demonstrates that the structure of the frontal part of the Moine Thrust Belt, similarly to the Caledonian Thrust Front in Lapland are both influenced by basement structures, albeit at very different scales. Influence of thrust transport-parallel inherited basement structures is unlikely to be a unique phenomenon to the Caledonian Orogeny; indeed, e.g. Cawood and Botsford (1991) argue for a cross-strike discontinuity in the basement of the Appalachian orogenic front, with potential implications for the evolution of the thrust-related structures there. We consider that considerable further work is warranted for a wider investigation of how inherited, thrust transport-parallel structures can influence both the geometries and the strain states of thin-skinned thrust sheets.

4. Conclusion

We have presented new field observations and interpretations of the Caledonian Thrust Front in Lapland, describing lateral variations in the structure of the thrust belt and their relationship to much older structures in the underlying crystalline basement. Our findings show that even relatively subtle variations in basement topography and particularly inherited basement structures (faults) can have a fundamental influence on the behaviour of the sole thrust and associated thrust-related structures. A comparison with the Moine Thrust Belt, an analogous tectonic regime on the opposite margin of the orogen, reveals similar influence on thrust belt structure by inherited basement faults. Therefore, the structure within an allochthonous thrust system, its spatial variations and possible dynamic controls may not be simply explained by considering processes operating *within* the thrust zone alone.

Investigations of structural inheritance in foreland fold and thrust belts commonly focus on the role of basement fault reactivating to either form or localise major thrust structures, particularly in the form of inversion of thrust transport-perpendicular structures (e.g. Butler et al., 2006b). While such interpretations may be appropriate elsewhere, these styles of tectonic reactivation are not necessarily applicable to frontal structures, particularly thrust transport-parallel structures as exemplified by the Caledonian thrust system of Lapland and its equivalent on the Laurentian side of the orogen in NW Scotland (the Moine Thrust Belt). As Elliott and Johnson (1980) note, the present-day outcrop of the Moine Thrust Belt provides access to structural levels in thrust belts, specifically of the Sole Thrust, that remain buried in many Cenozoic thrust systems; the same is evidently true for the Scandinavian Caledonides. Therefore, conventional field mapping and observations can reveal structures that otherwise can go unrecognised in younger tectonic settings where investigations rely on seismic imaging alone. We suggest that the structural relationships proposed here, particularly the influence of thrust transport-parallel inherited basement structures, and the implications for subtle controls on the kinematic evolution of thrust belts may be under-reported.

CRediT authorship contribution statement

Taija Torvela: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Robert W.H. Butler:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests Taija Torvela reports financial support was provided by Robert Scott Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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