RESEARCH ARTICLE

Provenance and sediment routing of Neoproterozoic formations on the Varanger, Nordkinn, Rybachi and Sredni peninsulas, North Norway and Northwest Russia: a review

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Provenances and sediment routing of Neoproterozoic, mainly low-grade, sedimentary successions on four large peninsulas in Northeast Norway (Varanger and Nordkinn) and Northwest Russia (Rybachi and Sredni) have been assessed using a combination of abundant palaeocurrent data, lithological and petrographic features, heavy-mineral accumulations, a plentiful geochemical database and initial results of a detrital mineral isotopic study. The palaeocurrent data from both platformal and basinal domains on all four peninsulas show a remarkable consistency, with sediment dispersal directed largely towards the north (between NW and NE). Together with evidence from the other parameters, it has thus been possible to suggest various mafic to felsic terranes of Neoarchaean to Palaeoproterozoic age on the Fennoscandian Shield as likely source regions for the bulk of the detritus. An exception is provided by detrital zircon analyses from one prominent, NE-prograding, deltaic formation in the allochthonous basinal succession on Varanger Peninsula, which shows a profusion of Mesoproterozoic grains. An older submarine-fan formation in this same basin has been reported by others to show a comparable enrichment in Mesoproterozoic zircon grains. Taking into account a palinspastic restoration of this particular basinal terrane, the source of the deltaic detritus is likely to be concealed beneath the Caledonian nappes and present-day continental shelf, and could conceivably represent a northward extension of the Sveconorwegian/Grenvillian orogen, as has been suggested in recent literature. An alternative source could be that of a Tonian-emplaced, sandstone-dominated thrust sheet derived from the margin of Rodinia.

Roberts, D. and Siedlecka, A. (2012) Provenance and sediment routing of Neoproterozoic formations on the Varanger, Nordkinn, Rybachi and Sredni peninsulas, North Norway and Northwest Russia: a review. *Norges geologiske undersøkelse Bulletin*, **452**, 1-19.

Introduction

Studies of the provenance of sedimentary successions have traditionally focused on the lithologies, petrography and geochemistry of the rocks under investigation, in addition to sediment dispersal patterns indicated by palaeocurrent flow. Over the last two decades, however, increasing attention has been given to more sophisticated methods such as isotopic dating of detrital mineral species, notably zircon, coupled with Lu–Hf analysis, and geochemistry of a variety of heavy minerals (e.g., Morton and Hallsworth 1994, Morton et al. 1996, 2005, Cawood and Nemchin 2001, Kosler et al. 2002), all of which are conducive to refining palaeogeographic reconstructions and regional tectonic analysis.

In this contribution we consider the provenance and sediment routing systems of thick, passive-margin, sedimentary successions of mainly Neoproterozoic age occurring on four peninsulas flanking the Barents Sea in NE Finnmark, northern Norway, and in Northwest Russia (Figure 1). This particular region is especially interesting in that it records evidence of both Timanian and Caledonian orogenic deformation (Tschernyschev 1901, Schatsky 1952, Siedlecka 1975, Roberts 1995, 1996, Roberts and Siedlecka 2002, Herrevold et al. 2009). In addition, the low-grade rock successions of this region have also been the subject of several sedimentological studies, with a detailed record of palaeocurrent data for many of the formations, which is an ideal starting point for any reliable provenance investigation.

The earliest studies of parts of these Neoproterozoic successions aimed specifically at provenance evaluation are those of Siedlecka (1995), Sochava (1995), Sochava and Siedlecka (1997) and Siedlecka and Lyubtsov (1997). The paper by Sochava and Siedlecka (1997) is based on an assessment of the major-element geochemistry of over 400 samples of diverse sedimentary rocks from the Varanger, Rybachi and Sredni peninsulas. The work of Siedlecka and Lyubtsov (1997) was a pilot investigation involving heavy-mineral populations in sandstones, where the authors noted three disparate provenance areas on the shield based on the predominance of certain minerals in specific formations. Two studies have investigated the age spectrum of detrital zircons in formations on Varanger Peninsula (Kirkland et al 2008, Roberts et al. 2008, abstract). A study involving sedimentary geochemistry and preliminary detrital zircon analyses from parts of Varanger Peninsula has also been presented by Nicoll et al. (2009, abstract), some aspects of which are reproduced in Orlov et al. (2011). In addition to these provenance studies, there are several contributions dealing with palaeocurrent flow and sediment dispersal patterns in various formations occurring on the Rybachi, Sredni, Varanger and Nordkinn peninsulas, references for which are given below.

It should be mentioned at the outset that all directional data noted in this paper refer to present-day coordinates.

Geological setting

Varanger Peninsula

Neoproterozoic to Cambrian, fairly low-grade, sedimentary successions characterise the bedrock geology of Varanger Peninsula, which is divided into southwestern *platformal* (also called pericratonic) and northeastern *basinal* (passive margin) domains by the c. NW–SE-trending Trollfjorden–Komagelva Fault Zone (TKFZ) (Siedlecka and Roberts 1992) (Figure 2). The *c.* 4 km-thick platformal successions of the Tanafjorden–Varangerfjorden Region (TVR) are largely autochthonous to parautochthonous

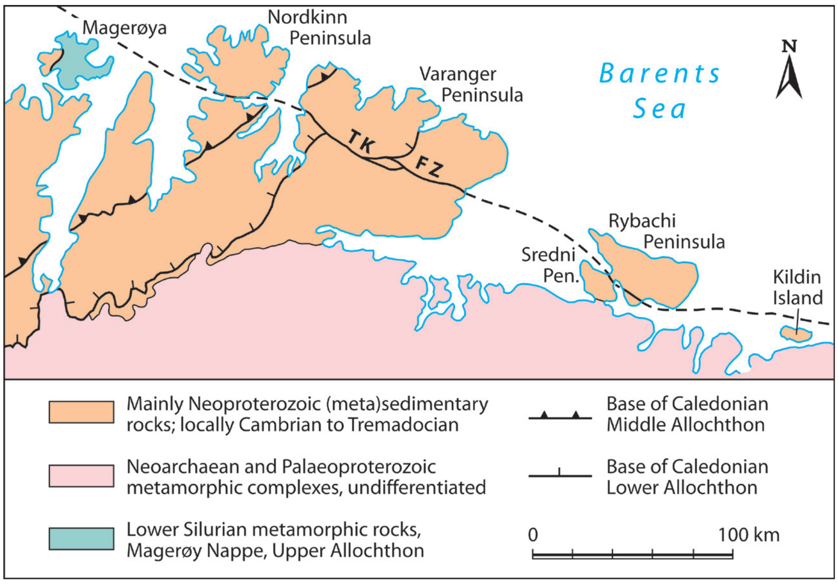

Figure 1. Outline map showing the locations of the Rybachi, Sredni, Varanger and Nordkinn peninsulas and Kildin Island. TKFZ – Trollfjorden–Komagelva Fault Zone.

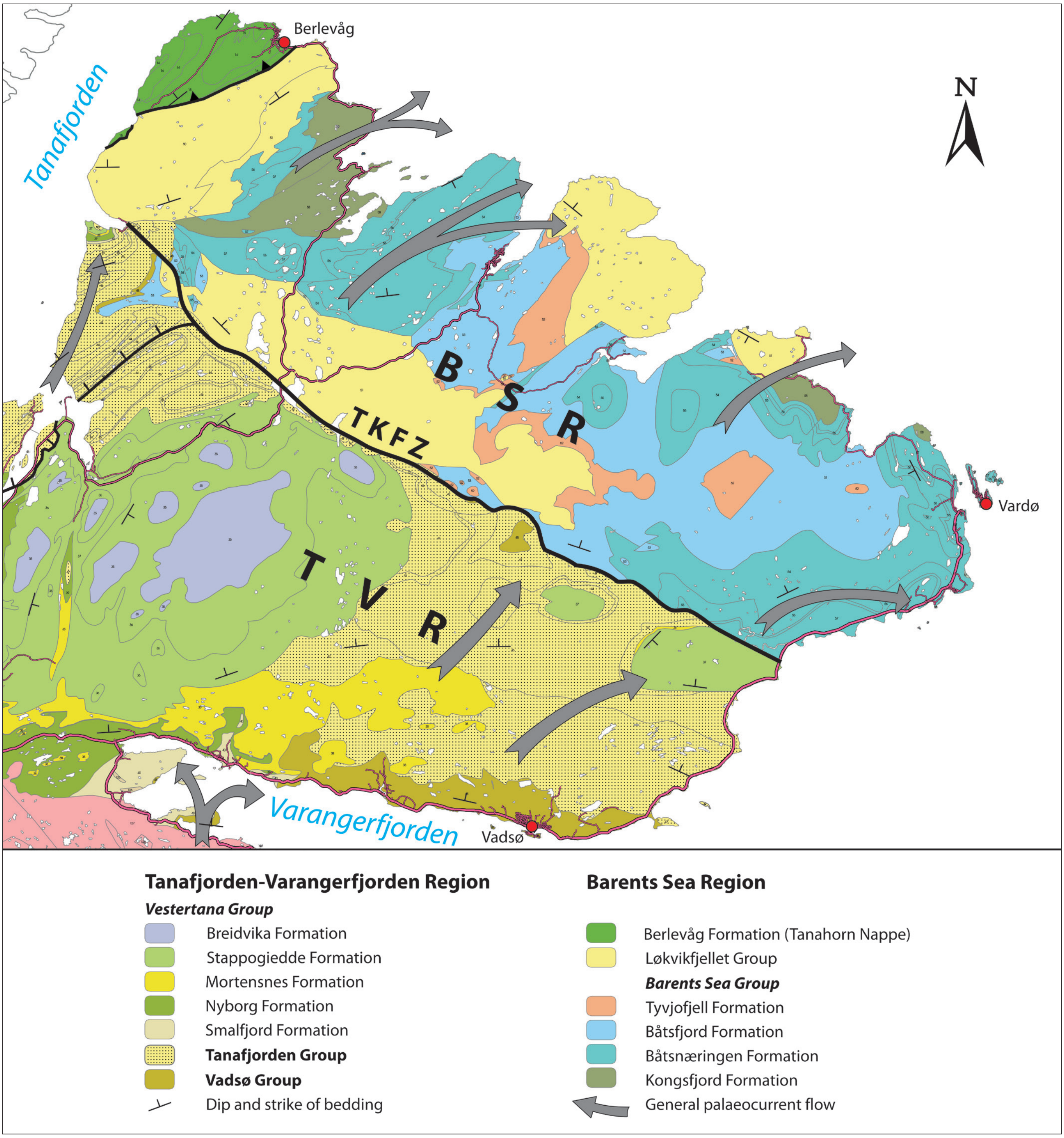

Figure 2. Simplified geological map of the Varanger Peninsula with the principal palaeocurrent flow indicated by the grey arrows. BSR – Barents Sea Region; TVR – Tanafjorden–Varangerfjorden Region; TKFZ – Trollfjorden–Komagelva Fault Zone. The base of the Tanahorn Nappe is marked by the thicker line with filled triangles. In the western part of the TVR, the thicker line with ticks marks the base of the Gaissa Nappe.

(diagenesis to anchizone grade) and comprise the fluvial (Figure 3a) to shallow-marine, Vadsø, Tanafjorden and Vestertana groups (Siedlecka 1985, Siedlecka and Roberts 1992). Rocks of the Vadsø Group, of inferred Tonian to early Cryogenian age, lie with angular unconformity upon Archaean granitic to granodioritic gneisses of the Fennoscandian Shield in the inner Varangerfjorden area (Banks et al. 1974, Rice et al. 2001). Three depositional sequences separated by important unconformities have been differentiated within the complete succession (Siedlecka et al. 1995a). The most significant break is the angular uncon-

Figure 3. Field photos of selected lithologies; photos by D.R. except where stated. (a) Foreset bedding in cross-bedded sandstones of the Fugleberget Formation, Vadsø Group, Vadsø, Varangerfjorden; looking northeast. (b) Groove casts, frondescent marks and other sole marks on the bottom surfaces of two beds of greywacke, Kongsfjord Formation, Barents Sea Group, c. *5 km north of Kongsfjord; looking* c. *northwest. (c) Cross-bedded sandstones of the Zemlepakhtinskaya Formation, western coast of Sredni Peninsula. The dark layer is a leucoxene- and rutile-rich placer. Photo: Valery Lyubtsov. (d) Basal breccia/olistostrome of the Motovskaya Formation, Cape Vestnik, Rybachi Peninsula. The blocks and fragments consist mainly of Neoarchaean granitoid and gneissic rock types. (e) Medium- to thick-bedded and cross-bedded, feldspathic sandstones with thin silty layers,* c. *1 km east of Mehamn, Nordkinn Peninsula; looking* c. *northeast. (e) Thin-bedded and cleaved, alternating greywacke and silty mudstone with deformed load casts, current-rippled layers and possible dewatering structures,* c. *2 km south of Gamvik, Nordkinn Peninsula; looking north-northeast.*

formity between the Vadsø and likely Cryogenian Tanafjorden groups. The Vendian[1] to Cambrian, Vestertana Group includes two diamictites of glacial origin (the Smalfjord and Mortensnes formations) which are thought to correlate with the worldwide Marinoan and Gaskiers glacigenic events, respectively (Halverson et al. 2005, Rice et al. 2011). In the far northwest of this particular region (still southwest of the TKFZ), the Tanafjorden Group reappears in the Gaissa Nappe Complex (Figure 2), which is a part of the Lower Allochthon of Caledonide tectonostratigraphy. Just to the west on Digermul Peninsula, the succession in the Gaissa extends up into the Tremadocian (Reading 1965). Details of the subdivisions into Lower, Middle, Upper and Uppermost allochthons in the Scandinavian Caledonides are contained in Roberts and Gee (1985).

The basinal successions northeast of the TKFZ (Barents Sea Region, BSR) are allochthonous, mostly part of the Lower Allochthon, and of slightly higher metamorphic grade (epizone), and have been involved in modest, Caledonian (Early Ordovician), dextral strike-slip translation along the fault zone (Rice and Frank 2003); a figure in excess of 200 km has been suggested, based on palaeomagnetic data (Bylund 1994a, b). The successions comprise the 9 km-thick, mainly Tonian to Cryogenian, Barents Sea Group (deep-water submarine fan (Figure 3b) through deltaic to shallow-marine assemblages), the unconformably overlying, fluvial to shallow-marine, 5.7 km-thick Løkviksfjellet Group, of uncertain but probable Cryogenian age, and the slightly higher-grade rocks of the Berlevåg Formation of the Tanahorn Nappe, part of the Middle Allochthon (Figure 2) (Siedlecka 1972, Siedlecka and Edwards 1980, Pickering 1981, Siedlecka et al. 1989, Drinkwater et al. 1996), in the far northwest of the peninsula. An important link between the stratigraphic successions on either side of the TKFZ occurs in the Manjunnas area *c.* 10 km south of Trollfjorden. There, the highest formation in the Vadsø Group, the Ekkerøya Formation, lies unconformably above one of the formations of the Barents Sea Group (Rice 1994, Roberts and Karpuz 1995).

Taking Varanger Peninsula as a whole, there have been many sedimentological studies of diverse formations or complete groups (e.g., Banks et al. 1971, 1974, Laird 1972, Siedlecka 1972, 1978, Banks and Røe 1974, Røe 1975, 2003, Siedlecka and Edwards 1980, Pickering 1981, 1982a, b, 1983, Edwards 1984). The palaeocurrent record on this peninsula is thus one of the most comprehensive in the entire Caledonide orogen, a feature which augurs well for detrital zircon studies and interpretations. In general, palaeocurrent data are indicative of sediment transport from the southwestern to southern quadrant in both the platformal and the basinal domains, but there are some interesting diversions from this general rule with changing source regions between the different depositional sequences.

Rybachi and Sredni peninsulas

As on Varanger, the platformal and basinal domains are represented on the Rybachi and Sredni peninsulas on either side of a prolongation of the TKFZ, named the Sredni–Rybachi Fault Zone (SRFZ) (Roberts 1995) (Figure 4). The *c.* 2 km-thick, diagenesis-grade succession on Sredni Peninsula comprises the fluvial to shallow-marine Kildinskaya and Volokovaya groups (Figure 3c) of late Stenian to Cryogenian age based mainly on K–Ar dating of glauconite but also on one Pb–Pb date from a pebble of phosphorite (Negruta 1971, Siedlecka et al. 1995a). The succession correlates broadly with the Vadsø Group and parts of the Tanafjorden Group on southwestern Varanger Peninsula (Siedlecka et al. 1995a). In terms of sequence stratigraphy, four depositional sequences have been recognised in the Sredni succession. A basal, unconformable contact against Palaeoproterozoic granite is present in southernmost Sredni Peninsula. There is no record of diamictites or other rocks of Vendian/Ediacaran age on Sredni (Negrutsa 1971, Lyubtsov et al. 1989, Samuelsson 1997). Rocks of the Kildinskaya Group also occur c. 100 km farther east on Kildin Island (Siedlecka et al. 1995a). Palaeocurrent data are based on a variety of criteria such as cross bedding, ripple marks, graded bedding, sole marks and slump structures, and indicate sediment transport mainly from sources located to the southwest, south and southeast. Some differences, however, are seen between the different depositional sequences (Siedlecka et al. 1995a).

On Rybachi Peninsula, northeast of the SRFZ, a *c.* 4 km-thick, anchizone-grade succession (Rice and Roberts 1995) is representative of a basinal turbidite system overlain by upper slope deposits (Siedlecka et al. 1995b, Drinkwater et al. 1996). The two main units, the Einovskaya and Bargoutnaya groups (Figure 4), are considered to be of Tonian to Cryogenian age, and include a spectacular olistostrome-breccia (Figure 3d) near the base in the hangingwall to the SRFZ (Siedlecka et al. 1995b). The Rybachi turbidite system has been compared to the

[1] The term **Vendian**, introduced by Sokolov (1952) for the youngest period of the Neoproterozoic, has been, and still is, used in Russian and some Nordic geological literature. In 2006, the IUGS International Commission on Stratigraphy decreed that the name Vendian should be replaced formally by **Ediacaran**, named after the Ediacara Hills in Australia where the soft-bodied Ediacara fossils were first discovered. However, the time ranges of the Vendian and Ediacaran are not identical. Whilst both terminate upwards at the base of the Cambrian, the base of the Vendian is taken at the base of the Smalfjord (Marinoan) diamictite/tillite whereas the base of the Ediacaran is placed at the *top* of the Smalfjord Formation, just below a carbonate layer that caps the glacial deposit. Thus, the Ediacaran period is of shorter duration than the Vendian. In spite of losing its formality, the term Vendian is not invalid and can still be used as a legitimate chronostratigraphic unit. As it encompasses *both* the Smalfjord and the Mortensnes diamictites, within the Vestertana Group, we continue to use it here, rather than relegate the Smalfjord Formation to the Cryogenian.

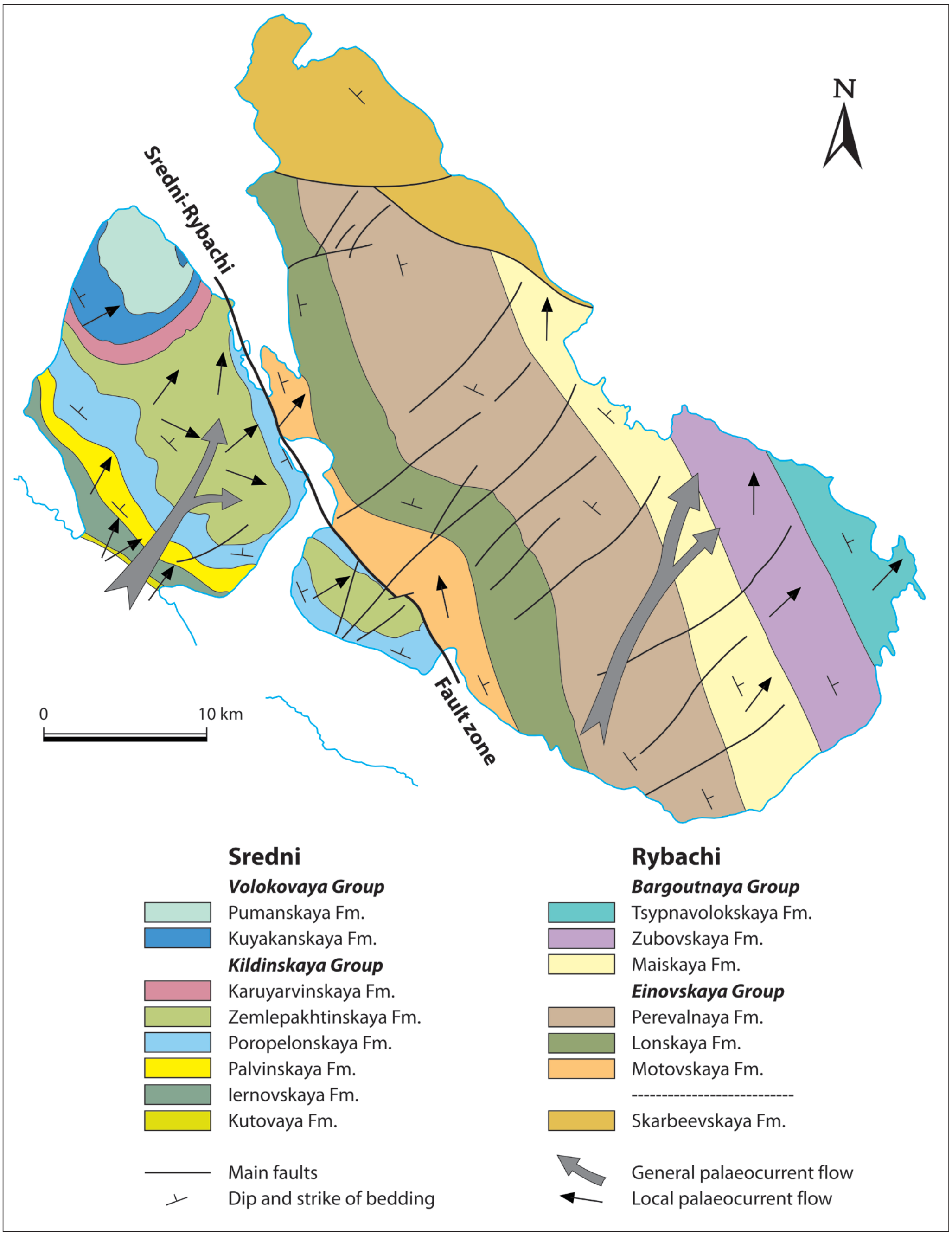

Figure 4. Geological map of the Rybachi and Sredni peninsulas, Northwest Russia, showing the general palaeocurrent flow and also local, formation-scale, flow vectors (taken from figures and information given in Negrutsa (1971) and Siedlecka et al. (1995a and b) supplemented by a few observations during fieldwork in 1990, 91 and 93).

Kongsfjord submarine fan in the basinal domain of Varanger Peninsula (Siedlecka et al. 1995b, Drinkwater et al. 1996), both developing across the shelf-slope break between the platformal and basinal domains marked by the major TKFZ/SRFZ fault system.

Nordkinn Peninsula

The metasedimentary rocks on the Nordkinn Peninsula (Figure 5) constitute a lower part of the Kalak Nappe Complex, which is generally assigned to the Middle Allochthon (Roberts and Gee 1985, Rice and Frank 2003, Gee et al. 2008). The greenschist-facies lithologies form a coherent succession and range from thick-bedded arkosic sandstones through interbedded sandstones and phyllites (Figure 3e) to more pelitic units containing porphyroblasts of biotite and garnet (Rice and Roberts 1988). In addition, orthoquartzite units >200 m in thickness occur in western and some eastern parts of Nordkinn. Because of lithological repetitions and sedimentary facies changes it has not yet been possible to establish a formal lithostratigraphy on this peninsula. Based on correlations with similar successions occurring immediately to the south and southwest, the siliciclastic rocks of Nordkinn are probably of latest Mesoproterozoic (Stenian) to Early Neoproterozoic (Tonian) age (Kirkland et al. 2007). This

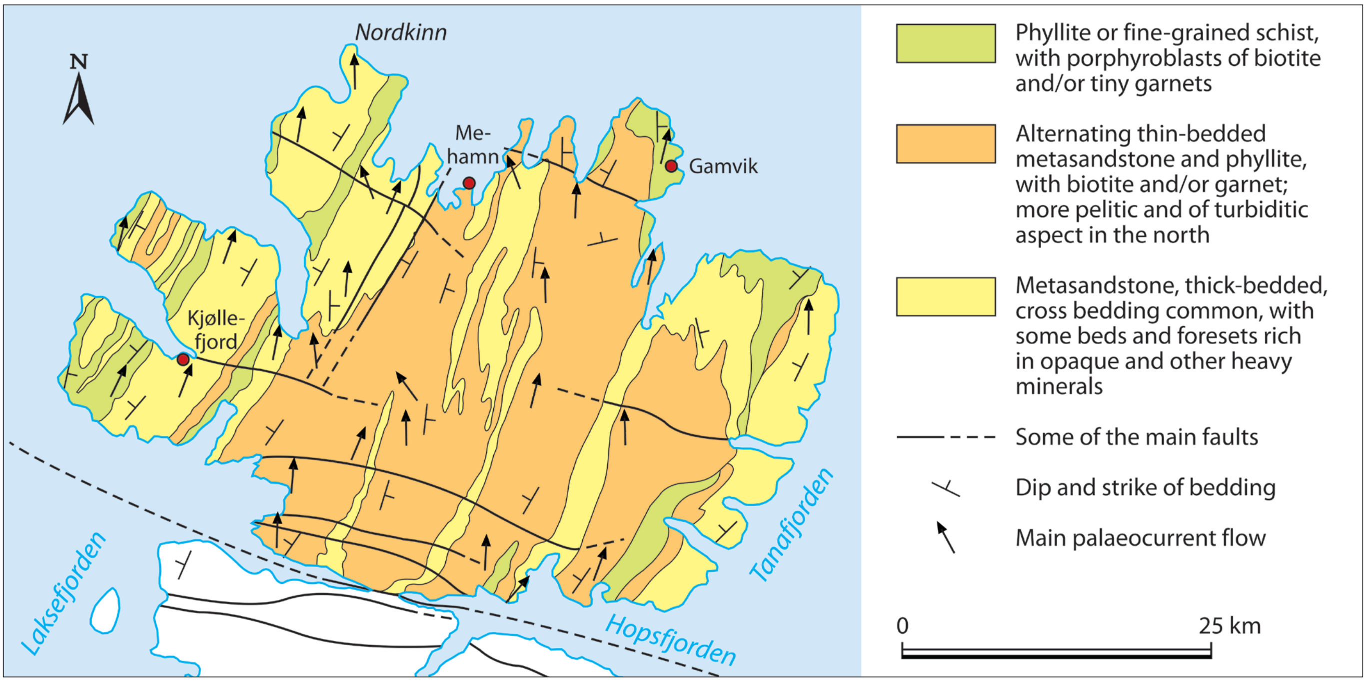

Figure 5. Simplified geological map of Nordkinn Peninsula showing palaeocurrent flow as measured in cross-bedded sandstones (corrected for dip of bedding and fold plunge).

age assignment relies on the detrital zircon U–Pb dating of one sample from Sværholt Peninsula by the aforementioned authors, and should therefore be considered as preliminary.

Cross-bedding is a common feature of the thicker sandstones with basal layers and foreset strata showing striking enrichments in a variety of heavy minerals, producing a distinctive black-and-white striping of the rock (Roberts 2007, figure 3). Many such cross-beds show penecontemporaneous deformation of the foresets (Roberts and Andersen 1985), a feature which has also been described from sandstones in the area directly south of Nordkinn Peninsula (Williams 1974) and in the subjacent Laksefjord Nappe Complex (Chapman 1980). In the more thinly interbedded and partly pelitic units, there are many examples of graded bedding, ball-and-pillow structures and sole marks (Figure 3f), typical of turbidites, together with chaotic sediment slide and slump structures, especially in northern areas. Considering the Nordkinn Peninsula as a whole, it appears that there is a gradual facies change from south to north from a dominantly fluvial to prodelta regime to a marine, turbidite association, reflecting a palaeobasin deepening roughly northwards (Roberts 2007).

Precambrian basement

In the Varangerfjorden–Kola region, the crystalline basement forming the substrate to the autochthonous formations of the Vadsø and Kildinskaya groups is dominated by Archaean complexes which range in age from 2.9 to 2.5 Ga (Levchenkov et al. 1995, Koistinen et al. 2001) and form part of the Murmansk Terrane. Some 50–200 km farther southwest, across NW–SE-trending suture zones, follow the Neoarchaean Inari Terrane and the 2.0–1.9 Ga Lapland Granulite Belt. Rocks in both these terranes were variably reworked during the diachronous, 1.95–1.87 Ga, Lapland–Kola orogeny (Daly et al. 2001, 2006). This collisional event is regarded as an early phase of the composite, Palaeoproterozoic, Svecofennian orogeny (1.95–1.77 Ga), the rocks and structures of which occur extensively farther southwest in northern Finland, Norway and Sweden (Gaál and Gorbatschev 1987, Korja et al. 2006, Lahtinen et al. 2008). Finally, rocks of suspected Mesoproterozoic age are inferred to be present farther west beneath the Caledonian nappes (Roberts 2007, Kirkland et al. 2011, Lorenz et al. 2012).

Basement to the basinal successions of the northeastern Varanger and Rybachi peninsulas northeast of the TKFZ/SRFZ is nowhere exposed. However, accepting that this major fault functioned as an extensional, shelf-edge structure during Neoproterozoic and even Late Mesoproterozoic time, then it is highly likely that the basin is underlain by Archaean complexes akin to those exposed in the Murmansk Terrane.

Main structural features of the Neoproterozoic successions

Rocks of the Parautochthon and Lower and Middle Allochthons on the Varanger and Nordkinn peninsulas are part of the Caledonide fold-and-thrust belt and were clearly involved in Caledonian deformation. Fold axes, an associated schistosity and thrust-faults trend approximately NE–SW ± 20° (Roberts 1972, Siedlecki 1980, Rice et al. 1989, Herrevold et al. 2009). Geochronological evidence is suggesting that the main structures and schistosity in northwestern Varanger Peninsula date to Early Ordovician time, with a more brittle event in the Mid to Late Silurian (Rice and Frank 2003), possibly extending into the Early Devonian (Kirkland et al. 2008). The main, dextral, strike-slip translation along the TKFZ occurred during Early Ordovician time (Rice and Frank 2003). Only limited data are so far available for the Nordkinn Peninsula. A sample of biotite phyllite subjected to laser-ablation Ar–Ar dating yielded an age of c. 500 Ma (Kirkland et al. 2008), interpreted by these authors as dating the greenschist-facies tectonometamorphic event as well as the main thrust emplacement of the Kalak Nappe Complex.

On the Rybachi and Sredni peninsulas, folds and an associated, steep, slaty cleavage trend NW–SE and are considered to relate to the Timanian orogeny, the type area for which is farther southeast in the Timans of the Komi Republic (Olavyanishnikov et al. 2000, Roberts and Siedlecka 2002, Gee and Pease 2004). The main phase of this orogenic event dates to approximately 600–560 Ma, i.e., of Vendian/Ediacaran age (Olovyanishnikov et al. 2000, Larionov et al. 2004, Roberts and Olovyanishnikov 2004), but orogenesis extended up into Early Cambrian time in some peripheral areas (e.g., Beckholmen and Glodny 2004, Pease and Scott 2009, Orlov et al. 2011). Comparable NW–SE- to NNW–SSE-trending folds and associated axial-planar cleavage occur in northeasternmost Varanger Peninsula (Roberts 1995, 1996, Herrevold et al. 2009), and the NW–SE trend is also registered on the seabed in outer Varangerfjorden (Roberts et al. 2011) as well as in aeromagnetic data (Gernigon et al. 2008, Brönner et al. 2009).

Provenance and sediment routing indicators

In this section we present the various evidence that has a direct bearing on the provenance of the Neoproterozoic successions occurring on the different peninsulas, and also on the sediment dispersal patterns or routing systems of these deposits. As this is a summary of the data and observations, we cite the many publications where readers can access the full details in their particular area of interest. For each indicator, we describe the peninsular areas from east to west.

Palaeocurrent data

In the autochthonous succession of *Sredni Peninsula*, palaeocurrent data derive mainly from cross-bed foresets in several sandstone formations recorded by Negrutsa (1971) and summarised in figure 4 in Siedlecka et al. (1995a). In general, a fairly unimodal flow from a SW to SE source characterises the succession as a whole (Figure 4), indicative of derivation of the sediment probably from the nearby Neoarchaean to Palaeoproterozoic complexes of the Fennoscandian Shield. However, there are noticeable differences of flow vector between the four depositional sequences (Siedlecka et al. 1995a), which may relate to tectonic activity and changing source areas in the hinterland or to fluctuating coastline configuration.

Information on current flow during deposition of sandstone formations on *Rybachi Peninsula* is minimal, but again a sediment dispersal towards a northerly point has been indicated by measurements from near the base of the Einovskaya Group (flow towards NW) and in the Bargoutnaya Group (flow between N and NE) (Negrutsa 1971, in Siedlecka et al. 1995b). The entire Rybachi submarine-fan system is considered to have accumulated by basinward progradation away from the shelf-slope break (Siedlecka et al. 1995b, figure 20), with a slight clockwise swing which may have been associated with down-slope currents turning into the axial elongation of the deep-marine basin.

On *Varanger Peninsula*, the autochthonous to parautochthonous Vadsø and Tanafjorden groups south of the TKFZ have yielded a large amount of data on palaeocurrent flow by many authors (Reading and Walker 1966, Banks 1971, Banks et al. 1971, 1974, Siedlecka and Siedlecki 1971, Banks and Røe 1974, Hobday 1974, Røe 1970, 1975, Edwards 1984). In this shallow pericratonic basin, with 8 or 9 transgressive/regressive cycles and with intertidal environments recognised in several formations, the directional variance of the currents is comparatively high, yet overall we again see a predominance of sediment dispersal towards the NE to NW quadrant (Siedlecka et al. 1995a) (Figure 2). A more complex palaeogeographical scenario marked the start of Vendian time and deposition of the Vestertana Group, following tectonic uplift and erosion, with the glaciogenic diamictite formations showing ice-sheet advances and sediment infill into a shallow epicontinental basin from both the south and the north (Edwards 1984). A southwesterly sediment source characterised the inter-glacial Nyborg Formation (Banks et al. 1971, Edwards 1984). Interestingly, the immediate postglacial era (Stappogiedde Formation) records a major input of detritus from a northeasterly source, based on the sedimentological studies of Banks et al. (1971), a feature which has been considered by Roberts and Siedlecka (2002) to relate to erosion of the rising deformation front of the Timanide orogen and deposition in a small foreland basin. In this regard, a burial diagenesis age of *c.* 560 Ma for Stappogiedde shales (Gorokhov et al. 2001) is in accord with this interpretation. Farther to the southeast, in the White Sea area of Russia, the Vendian succession of the Mezen Basin has also been interpreted as relating to Timanian orogenesis (e.g., Schatsky 1952, Grazhdankin 2004), with the sediment input into the foreland basin sourced from the northeast.

The geology of the BSR, northeast of the TKFZ, is dominated by the Barents Sea Group with its prominent, deep-water, Kongsfjord submarine fan (Siedlecka 1972, 1985, Pickering 1981, 1982a, b, 1983, 1985) which records current flow towards NE–E, away from the shelf edge (Figure 2). This was superseded by deltaic to shallow-marine environments, with the deltaic sediments showing a general ENE progradation (Siedlecka and Edwards 1980, Pickering 1982a, Siedlecka et al. 1989). Overlying formations of the shallow-marine to locally fluvial Løkviksfjellet Group show a fairly unimodal pattern of sediment dispersal and current flow directed towards the NNE to ENE quadrant (Laird 1972, Levell 1978). It is appropriate here to note that although the Løkviksfjellet Group has been loosely correlated chronostratigraphically with the largely Vendian, Vestertana Group succession of the TVR (Vidal and Siedlecka 1983), the poor acritarch taxa recovered from this group by these authors are in no way time-diagnostic. Thus, the precise age of the Løkviksfjellet Group is unknown. The character and chemistry of the deposits (see below) and the palaeocurrent evidence, however, do not accord with features typical of the Vestertana Group; and there is no evidence of a northeasterly source for any of the sediment input. Moreover, Kirkland et al. (2008) have noted that a Sm–Nd model age for a psammite from the Løkviksfjellet Group is similar to model ages from metasedimentary rocks of the Kalak Nappe Complex. The various evidence therefore points toward a pre-Vendian and most likely Cryogenian age for this group.

Structurally overlying the Løkviksfjellet Group, the Berlevåg Formation of the Tanahorn Nappe (interpreted as part of the Middle Allochthon) has not provided any reliable palaeocurrent data, but there are clear facies changes indicative of finer-grained, more distal elements towards the north where diverse sole marks and flute casts are quite common on the bottom surfaces of greywacke beds.

Palaeocurrent data from the thick, late Stenian to Tonian, sandstone units on *Nordkinn Peninsula* are based on abundant cross bedding, ripple marks and parting lineations and document a fairly unimodal flow towards NW–NNW with a minor azimuth directed NNE (Roberts 2007) (Figure 5). Coupled with the regional facies change noted earlier, this accords with the presence of a palaeobasin situated towards the 'north' at the time of sediment accumulation. Since the rocks on Nordkinn are allochthonous, the fluvial system and distal basin would have been located at some unknown distance to the northwest prior to Caledonian thrusting (cf. Gayer et al. 1987).

Lithological indicators

Lithology and petrography of sedimentary rocks can provide important clues regarding provenance, particularly where blocks, boulders and small rock fragments in breccias and conglomerates can be identified with relative confidence. On *Sredni Peninsula*, there is little documented evidence in this regard, although conglomerates at the bases of the four depositional sequences are reported to contain extrabasinal pebbles of granitic rock types derived from southerly sources (Negrutsa 1971, Siedlecka et al. 1995a). Clasts of phosphorite in a 30 m-thick bed at the base of the Volokovaya Group have been interpreted by Negruta (1971) and Negrutsa et al. (1995) to derive from bedded phosphorite horizons in the subjacent Kildinskaya Group (Negrutsa 1971, Negrutsa et al. 1995).

Rybachi Peninsula, on the other hand, exposes an olistostrome-breccia at the base of the Einovskaya Group (Motovskaya Formation) containing angular blocks and fragments of diverse granitoid rocks and gneisses (Siedlecka et al. 1995b, Lyubtsov et al. 1999) (Figure 3d). According to Negrutsa (1971), one exotic block of granite measures over 100 m across. The fragmentary clast material in the breccia is clearly of local derivation, probably ripped away from the Neoarchaean crystalline basement (Levchenkov et al. 1995, Koistinen et al. 2001) of the Murmansk Terrane below the edge of the Sredni platform in the footwall of the SRFZ. Other conglomerates higher up in the Rybachi succession are also polymict and contain a variety of granitic and gneissic clasts, interpreted to be derived from known Neoarchaean and Palaeoproterozoic terranes in the shield area to the south (Siedlecka et al. 1995b). Lenses of a well-sorted boulder conglomerate are present in one formation, with rounded boulders of granite (Lyubtsov et al. 1999).

In southern *Varanger Peninsula* and inner Varangerfjorden, the autochthonous succession lies with an angular unconformity upon Neoarchaean granitic and tonalitic gneisses, and clasts within the braided fluvial and prodelta sandstones and conglomerates signify derivation from both external and intraformational sources (Banks et al. 1974, Rice et al. 2001, Røe 2003) (Figure 3a). In several places, the basal Smalfjord Formation diamictite of the Vendian/Ediacaran Vestertana Group lies directly upon the crystalline Archaean basement (Føyn & Siedlecki 1980, Edwards 1984). Clasts in this formation include both granitic gneisses of local derivation (from the south) and more common dolomitic and arenaceous rocks from the Tanafjorden Group (from diverse sources) (Edwards et al. 1973, Edwards 1984, Rice et al. 2011).

The succession in northern Varanger Peninsula provides comparatively few clues regarding the actual provenance of the original sediments, but rock fragments and small clasts in the Kongsfjord fan have been interpreted as deriving mostly from felsic plutonic and volcanic rocks as well as gneissic complexes (Siedlecka 1972, Pickering 1981). As both the submarine fan and the succeeding Båtsnæringen Formation delta prograded northeastwards, this is again suggestive of a sediment source on the shield. As the delta was originally located farther to the northwest (p. 13), then the source rock terrane (prior to dextral translation along the TKFZ) is likely to have been one now concealed beneath the Caledonian nappes (Roberts 2007, Lorenz et al. 2012). The Båtsnæringen Formation also contains phosphorite fragments, considered to be redeposited from bedded phosphorites akin to those in the platformal succession on Sredni Peninsula (Negrutsa et al. 1995). The unconformably overlying, feldspathic sandstones of the Løkviksfjellet Group show a marked change towards textural and mineralogical maturity. This points to sediment transport from a completely different, but southwesterly, source region following an event of uplift, tilting and erosion prior to deposition of the Sandfjorden Formation.

On *Nordkinn Peninsula*, no detailed petrographic study of the sandstones and small-clast conglomerates has yet been carried out. Accordingly, at this stage, lithology alone cannot contribute to the discussion of sediment provenance.

Heavy-mineral accumulations

Assemblages of heavy minerals are considered to be important and sensitive indicators of sediment provenance (Morton and Hallsworth 1994, 1999), even though the original provenance signal may have been disturbed, to some extent, by processes such as weathering, diagenesis and hydrodynamics. Studies of such mineral accumulations and individual mineral chemistry have proved valuable in linking sediment to source, also in present-day rivers in Norway (Morton et al. 2004).

On the *Sredni* and *Rybachi* peninsulas, concentrations of heavy minerals have been reported from the Zemlepakhtinskaya Formation of the Volokovaya Group on Sredni, where palaeoplacer deposits occur at two stratigraphic levels in this same formation (Negrutsa 1971, Siedlecka et al. 1995a). These consist mainly of titanomagnetite and zircon concentrates, but dark-grey to black sandstones with high contents of leucoxene and rutile have also been reported (Lyubtsov et al. 1999) (Figure 3c). Several formations of the Kildinskaya Group on Kildin Island also contain layers rich in zircon, rutile, apatite, titanite, tourmaline and opaque minerals (Lyubtsov et al. 1999) and small placers of titanomagnetite have been reported (Sochava 1995).

On *Varanger Peninsula*, a pilot study of heavy-mineral assemblages in thirteen different formations in both the autochthonous and the allochthonous successions has been reported by Siedlecka and Lyubtsov (1997), aiming specifically to provide evidence on provenance. The mineral concentrations studied were those of zircon, tourmaline, garnet, rutile and apatite (Figure 6) with >100 counts per sample. The results showed that at least three provenance areas in the crystalline shield contributed to the Neoproterozoic sedimentary successions; one, with a dominance of zircon in the heavy fraction and inferred by Siedlecka and Lyubtsov (1997) to derive from granites and granodiorites, is fairly widespread (Figure 6); a second, wherein tourmaline predominates, probably sourced from granites, gneisses and possibly pegmatites, is restricted to the Tanafjorden Group (Figure 6, lower part); and a third, with common garnet, which provided material to the interglacial Nyborg Formation. Whereas the zircon and tourmaline are likely to derive from Neoarchaean rocks, the garnet source (to the southwest, from palaeocurrent data) was quite possibly within the Palaeoproterozoic Lapland Granulite Belt (Siedlecka and Lyubtsov 1997). As well as these features, there are also fairly marked differences in heavy mineral content between samples in the two separate regions of Varanger Peninsula (Figure 6).

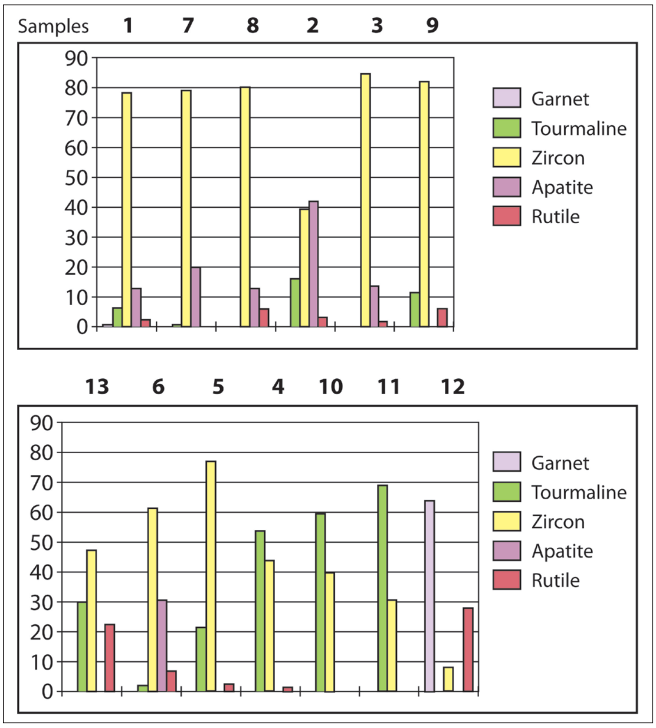

Figure 6. Heavy-mineral distributions in samples of sandstones from thirteen formations on Varanger Peninsula. Lower panel – formations in the platformal Tanafjorden–Varangerfjorden Region; upper panel – formations in the basinal Barents Sea Region. The formations are as follows (lower panel first): 13 – Veidnesbotn: 6 – Fugleberget: 5 – Golneselva: 4 – Dakkovarre: 10 – Gamasfjellet: 11 – Hanglečærro: 12 – Nyborg: 1, 7 & 8 – Kongsfjord: 2 & 3 – Båtsnæringen: 9 – Sandfjorden. The figure is modified from Siedlecka and Lyubtsov (1997, figure 3).

The feldspathic metasandstones of the Kalak Nappe Complex on *Nordkinn Peninsula* (Figure 3e) are in many places characterised by heavy-mineral accumulations, marked by dark-grey to black intercalations rich in titanomagnetite and/or magnetite. These occur either as thin beds (up to 2 cm), lensoid deposits or as enrichments in foreset strata in cross-bedded units (Roberts and Andersen 1985, Roberts 2007, figure 3). Closer inspection has revealed the common presence of titanite, rutile, apatite and monazite in these layers and foresets, with accessory garnet and tourmaline. Coupled with the palaeocurrent data, indicative of a broadly north- to northwestward sediment dispersal, we consider that these heavy-mineral concentrates are likely to have derived from the diverse basement terranes on the Fennoscandian Shield.

Geochemistry

The geochemistry of diverse lithologies in the Neoproterozoic successions on the *Sredni*, *Rybachi* and *Varanger peninsulas* was investigated in great detail in the 1990s, though at that time based wholly on major-element analyses (Siedlecka 1995, Sochava 1995, Sochava and Siedlecka 1997). Nevertheless, no fewer than 461 samples were analysed by XRF, 231 from Sredni and Rybachi and 230 from Varanger, and the complete analytical data were evaluated by classification diagrams and cluster dendrograms (Sochava and Siedlecka 1997).

A principal result of this study is that there is a clear compositional distinction between the platformal and basinal domains on either side of the major TKFZ/SRFZ, with K_2O > Na_2O south of the fault whereas high contents of Na_2O, MgO, FeO and CaO predominate in rocks of the turbiditic to deltaic, basinal successions. A similar conclusion was reached by Nicoll et al. (2009). Compositions of the basinal successions were interpreted by Sochava and Siedlecka (1997) as relating to a tectonically active source region with likely derivation from the mafic to intermediate rocks of the Palaeoproterozoic Pechenga Greenstone Belt. Sources of unknown age, but possibly Mesoproterozoic, farther west in the basement beneath the Caledonian nappes, but not exposed today, are also likely to have been involved.

The Sandfjorden Formation of the Løkviksfjellet Group shows a distinctive geochemical signature that differs from formations of the Barents Sea Group in having higher K_2O and SiO_2 contents (Sochava and Siedlecka 1997). This is indicative of derivation from a different source area to the south following the tectonic event that gave rise to the uplift, tilting and unconformity at the base of the Løkviksfjellet Group.

The geochemistry of shales showed interesting changes, even within the same formation, indicative of a changing provenance and/or climatic variations. Sandstones and siltstones of the Ediacaran Stappogiedde Formation show compositions which differ quite markedly from those of underlying formations and, along with the evidence of changing palaeocurrent flow, may relate to derivation from the rising topographic front of the Timanian orogenic belt.

Rare-earth element (REE) analyses exist from 24 shales from different formations on Rybachi Peninsula (K.T. Pickering, unpublished data). The REE patterns in these particular shales are quite variable and are thus indicative of rapidly changing sources and river catchments for the sediment influx onto the platform and its redistribution via deltas and submarine fans into the basinal regime.

For *Nordkinn Peninsula*, there is as yet no published documentation on the geochemistry of rocks in the Kalak Nappe Complex.

Isotopic studies on detrital minerals

Until recently, the only published isotopic studies on detrital minerals in rocks from the investigated peninsulas were those of Gorokhov et al. (2001, 2002) and Kirkland et al. (2008). An additional study, on six formations from Varanger Peninsula, has just become known to us (Orlov et al. 2011; a translation of an original Russian text), and provides important information regarding the provenance of these sandstones.

Rb–Sr dating studies on illite from shales on *Sredni* and *Varanger* (Gorokhov et al. 2001, 2002) have shown that the coarser grain-size, 2M1, illite polytype is clearly detrital with minimum ages of 830 Ma (Sredni) and *c.* 930 Ma (Varanger), and derives from the source area or areas of the sediments, which are inferred to have lain somewhere to the south of the sites of deposition of these autochthonous formations. Other, very low-grade, authigenic, illite polytypes relate to burial diagenesis and other events in Ediacaran and Siluro–Devonian time (Gorokhov et al. 2001, 2002).

Preliminary results of a provenance study employing U–Pb (LA–ICP–MS) analyses of detrital zircons from four formations from *Varanger Peninsula* were presented by Roberts et al. (2008) and Slagstad et al. (2011). For the interglacial Nyborg Formation of the Vestertana Group, one population group dominates the probability plot at 2.0–1.85 Ga with a minor spread between 3.0 and 2.5 Ga (Figure 7b). No Mesoproterozoic zircon grains were analysed. This frequency plot contrasts markedly with that of the deltaic Båtsnæringen Formation, from north of the TKFZ, which shows a multimodal spread from *c.* 2.1 to 1.0 Ga with spikes at 1.80–1.65, 1.45–1.40 and 1.25–1.0 Ga (Figure 7a). There are also subsidiary peaks at 2.1–2.0 and 2.9–2.6 Ga. Zircons from this formation vary greatly from short prismatic grains to well rounded, elongate forms (B.Davidsen and T.Slagstad, unpublished data). Zircons from the Sandfjorden Formation show two groups at 2.0–1.75 and 2.9–2.6 Ga with a few grains in the range 1.6–1.0 Ga (Figure 7c). For the Berlevåg Formation of the Tanahorn Nappe, the probability plot depicts one main group at 1.9–1.7 and a minor spread at 2.9–2.6 Ga (Figure 7d). A comparable plot for the Berlevåg Formation has been presented by Kirkland et al. (2008) who also reported an oldest zircon grain of 3136 ± 13 Ma.

In general, the detrital zircon data are thus indicative of derivation from Archaean to Palaeoproterozoic basement terranes that lay roughly to the south of where the Neoproterozoic formations occur today. The Cryogenian Båtsnæringen Formation is the prime exception here, containing much Mesoproterozoic detritus from a source not exposed in northern Fennoscandia at the present time but possibly concealed beneath the Caledonian nappes and adjacent continental shelf (Roberts 2007, Be'eri et al. 2011, Lorenz et al. 2012). Considering the pre-Caledonian location of the Barents Sea Region (see discussion), this is not an unreasonable suggestion. However, accepting the proposition that some initial thrusting of the Kalak sedimentary rocks onto older basement is likely to have occurred in Tonian time, associated with a late-Sveconorwegian event (Kirkland et al. 2006), then the Mesoproterozoic zircons of the Båtsnæringen delta, particularly those that are well rounded and most likely recycled, may have been sourced from this early allochthon.

The work of Orlov et al. (2011) depicts probability plots for four formations from the pericratonic domain on Varanger and two from the basinal Barents Sea Group. Their plot of detrital

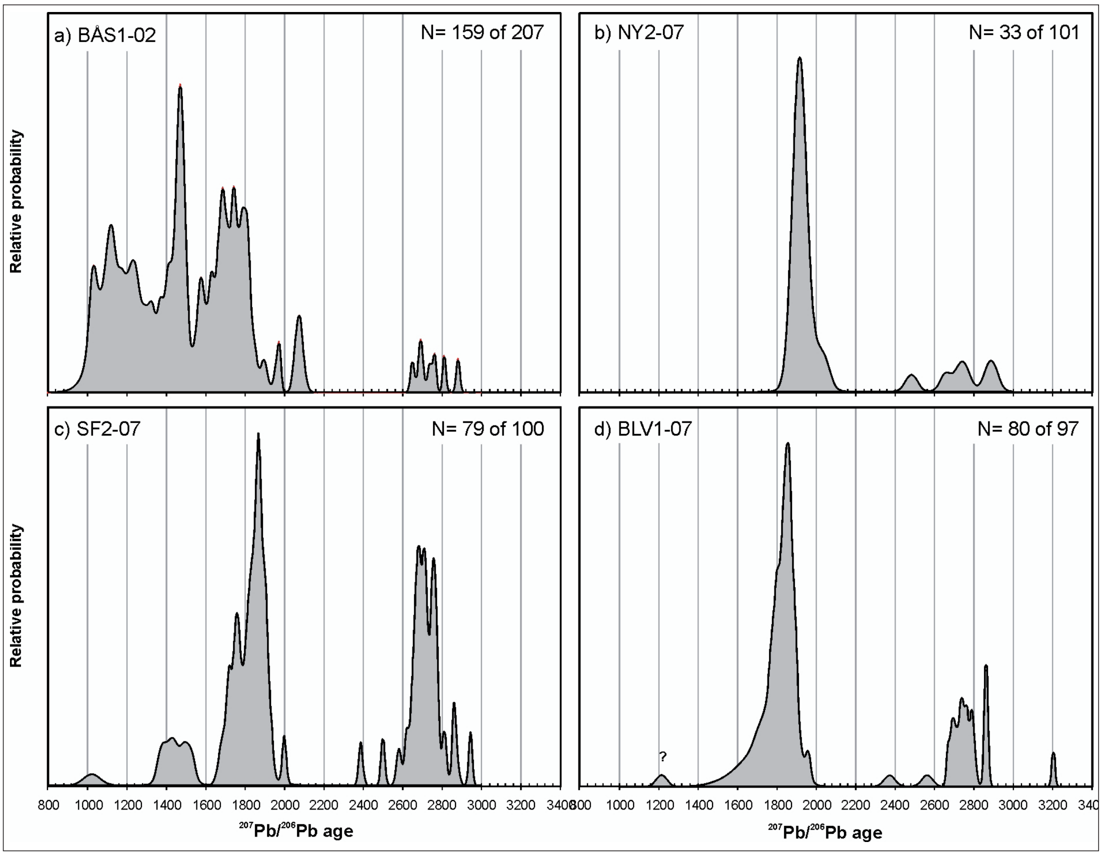

Figure 7. Probability density versus age (common-Pb corrected, $^{207}Pb/^{206}Pb$) plots of detrital zircons from very low-grade metasandstones of the (a) Båsnæringen Formation, Barents Sea Group, (b) Nyborg Formation, Vestertana Group and (c) Sandfjorden Formation, Løkviksfjellet Group; and (d) greenschist-facies metasandstone of the Berlevåg Formation, Tanahorn Nappe. The probability density plots include ages with <10% discordance. The number of grains that are <10% discordant and the total number of analysed grains are indicated. The figure is modified from one depicted in Roberts et al. (2008). The zircons were analysed by Børre Davidsen and Trond Slagstad at NGU, Trondheim. Precise sample locations can be obtained from the first author upon request.

zircon analyses from the Båtsnæringen Formation is comparable to ours (in Figure 7a); and interestingly, a sample from the Kongsfjord Formation shows a very similar pattern, with a dominance of Mesoproterozoic and Late Palaeoproterozoic grains. Samples from the Andersby (Vadsø Group), Dakkovarre (Tanafjord Group) and Mortensnes (Vestertana Group) formations also show a series of peaks between 2.0 and 1.0 Ga. It therefore seems clear that a Mesoproterozoic source (or possibly successions containing recycled Mesoproterozoic zircons) was available for erosion and fluvial and marine-current dispersal during the deposition of these platformal Tonian–Cryogenian successions on southern Varanger Peninsula. Moreover, the Mesoproterozoic source, or sources, is even more prominent in the case of the allochthonous, basinal, Båtsnæringen and Kongsfjord formations.

As yet there are no detrital zircon data from rocks on the *Nordkinn Peninsula*. However, along strike to the southwest, zircon analytical data have been reported by Kirkland et al. (2007) from two samples of psammite and one of pelite from the lower thrust sheets of the Kalak Nappe Complex, with the oldest zircon grains in the range c. 2.88 to 2.67 Ga. These various data were interpreted by Kirkland et al. (2007) to suggest that sedimentation of these rocks was confined to the period c. 1030 to 980 Ma, Late Stenian to Early Tonian. The upper constraint for deposition was based on a U–Pb zircon age of 981 ± 7 Ma for a strongly foliated granite in a thin thrust slice within the lithostratigraphy in the eastern part of the Porsanger Peninsula (Kirkland et al. 2006).

Discussion

To produce a truly comprehensive picture of provenance and sediment dispersal patterns of depositional systems in any region requires the interpretation of a variety of sedimentological, lithological, geochemical and isotopic age data. On their own, these parameters provide just one facet of the sediment source terrane puzzle, but in combination they constitute a powerful tool in assessing the likely source regions, their location, composition and age, and sediment dispersal pathways of the successions under scrutiny.

In the case of the lithological successions considered here we are fortunate in having a robust sedimentological database founded on detailed geological maps, both of which have led to diverse studies in a variety of disciplines. Taking the platformal or pericratonic domain on both Sredni and Varanger, sediment source areas clearly lay mainly to the south but there are significant variations in palaeocurrent flow directed between northwest and northeast which correlate to some extent with specific depositional sequences floored by important unconformities. These in turn relate to changes in erosion level, relief rejuvenation at the source or likely ephemeral ponding within the catchments, a response to repetitive epeirogenic events and tilting that affected the shield throughout Neoproterozoic time.

Confirmation of these diachronous changes in provenance are seen in the geochemical and heavy-mineral data, notably from granite- and zircon-dominated source regions to areas of the shield underlain by garnetiferous metamorphic rocks, e.g., the Lapland Granulite belt. As yet we have limited information from detrital mineral isotopic data but source ages are mainly Late Palaeoproterozoic and Neoarchaean, conforming to the present-day exposed terranes of the Fennoscandian Shield (Levchenkov et al. 1995, Koistinen et al. 2001). However, the work of Orlov et al. (2011) has signified that Mesoproterozoic source terranes, or successions containing recycled Mesoproterozoic grains, were also available to erosion during Tonian–Cryogenian and Early Vendian time. Departures from the otherwise consistent southerly source story appear only in Vendian time on Varanger Peninsula where diamictites of the Vestertana Group show local derivation from the north. More significant is the evidence of a northeasterly source for sediments deposited in the immediate post-glacial era (Stappogiedde Formation), effectively implying the presence at that time of a small foreland basin ahead of the rising Timanian deformation front (Gorokhov et al. 2001). This accords with the evidence of a foreland basin (Mezen Basin) situated immediately southwest of the Timans (Grazhdankin 2004).

Assessment of the provenance or provenances of the basinal successions on Rybachi Peninsula and on the Varanger Peninsula northeast of the TKFZ has to take into account their dextral translation of more than 200 km during the Caledonian cycle. Thus, the Timanian-deformed Rybachi succession, comprising an early shelf-edge olistostrome and a subsequent greywacke-dominated submarine fan, probably accumulated roughly where the Nordkinn Peninsula is situated today (Figure 8). Similarly, the Barents Sea Group of northern Varanger, with its complex submarine fan and younger delta, would have been deposited even farther to the northwest. Rocks of the Vardø district, for example, with Timanian structures, are likely to have been located just north of Magerøya, and the Kongsfjord area at least 100 km farther to the northwest on today's continental shelf (Figure 8). The Timanides are considered to have extended even farther to the northwest, to an inferred Balto–Timanian triple junction (Siedlecka et al. 2004, Figure 15), in the vicinity of which the Ediacaran magmatic complexes of the Seiland Igneous Province are thought to have originated (see also Burke et al. 2007). One particular terrane in southernmost Spitsbergen, with Mesoproterozoic protolith ages and carrying evidence of Ediacaran metamorphism, has also been suggested to represent an isolated outlier of the Timanide orogenic belt (Mazur et al. 2009). As the Seiland plutonic rocks now occur in the highest and outermost, Seiland–Sørøy Nappe of the Kalak allochthon, penetrating psammites of Tonian age (Kirkland et al. 2007), then it is not inconceivable that Timanian structures may be found in these thrust sheets, in addition to evidence of possible deformation and metamorphism relating to the *c.* 710 Ma 'Snøfjord event' of Kirkland et al. (2006).

The most westerly segment of the basinal *and* platformal successions on Varanger Peninsula is exposed in one particular area in the Gaissa Nappe southwest of the TKFZ. There, the contact between the Båtsfjord Formation of the Barents Sea Group and the uppermost, Ekkerøya Formation of the Vadsø Group was first considered to be primary (Siedlecka and Siedlecki 1971) but later reinterpreted as tectonic (Johnson et al. 1978, Siedlecki 1980). Subsequently, in 1991, an examination of this contact by a group of geologists from the Geological Survey of Norway and the Russian Academy of Sciences supported the primary contact interpretation. Shortly afterwards, Rice (1994) produced a convincing field documentation of the boundary as being an unconformity. As it is the lower part (Annijokka Member) of the Båtsfjord Formation that is unconformably overlain by the Ekkerøya Formation, this indicates that a large part of the upper Barents Sea Group has either not been deposited in the northwesternmost areas of the Timanian basin

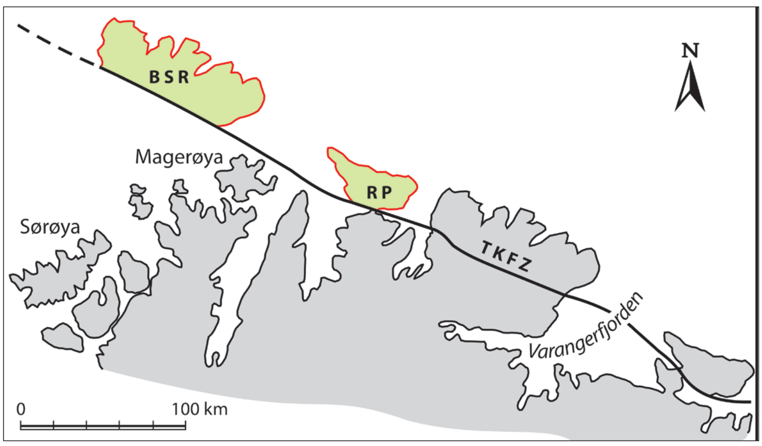

Figure 8. Outline map showing the approximate inferred locations of the Rybachi Peninsula (RP) and the Barents Sea Region (BSR) of Varanger Peninsula prior to their dextral translation along the Trollfjorden–Komagelva and Sredni–Rybachi fault zones in Caledonian (earliest Ordovician) time. Detritus feeding the Båtsnæringen delta from the southwest would have derived from a now concealed, Late Palaeoproterozoic to Mesoproterozoic terrane or a previously transported (Tonian) thrust sheet located some few tens of kilometres to the west or northwest of where Sørøya is situated today.

or has been removed by uplift, tilting and erosion prior to deposition of the prograding, platformal Ekkerøya strata.

The geochemistry of the basinal successions on Rybachi and northern Varanger shows significant differences as compared with the platformal domain. Higher contents of, e.g., Na, Mg, Fe and Ca and a relative deficiency of K point to source terranes dominated by mafic Na-rich complexes of likely volcanic origin (Sochava and Siedlecka 1997). Detrital zircon data from the deltaic Båtsnæringen Formation show a predominance of Mesoproterozoic and Late Palaeoproterozoic detritus and only a minor Neoarchaean component. The same is the case for the subjacent Kongsfjord Formation (Orlov et al. 2011). Accepting that the Båtsnæringen delta was originally situated well to the northwest of Magerøya, the geochemical and zircon data clearly suggest that a Mesoproterozoic, mainly volcanic terrane was exposed to erosion and provided much of the infill of this particular delta. This Mesoproterozoic terrane is not exposed in Finnmark today, and thus likely to be concealed beneath the Caledonian nappes and younger Late Palaeozoic and Mesozoic successions on the continental shelf of the southwestern Barents Sea (Roberts 2007). Alternatively, some of the Mesoproterozoic detritus may have derived from the inferred Tonian-emplaced thrust sheets (Kirkland et al. 2006). Work is in progress on detrital zircon analyses from other formations in both the basinal and the platformal domains, and it is quite conceivable that more evidence of a substantial Mesoproterozoic input may come to light.

Geochemical data from the unconformably overlying Løkviksfjellet Group show a markedly different signature to that in the subjacent Barents Sea Group with high SiO_2 and K_2O contents in mainly quartz-arenitic lithologies (Sochava and Siedlecka 1997), signifying a return to a felsic-magmatic source terrane on the shield to the south or southwest. Detrital zircon data from the Sandfjorden Formation show Late Palaeoproterozoic and Neoarchaean peaks, but also with a minor Mesoproterozoic component.

In summary, taking the full complement of parameters necessary for a comprehensive assessment of the provenances of the latest Mesoproterozoic to Neoproterozoic successions on these four peninsulas, the principal source regions for the fluvial to shallow- and deeper-marine deposits clearly lay at diverse locations to the south (i.e., southwest to southeast). Before post-Caledonian and later denudation events, the platformal sedimentary successions probably extended much farther 'inland' across the Fennoscandian Shield and were most likely fed by several major river systems that dispersed debris northwards from both Neoarchaean and Palaeoproterozoic terranes, and in some cases from Mesoproterozoic sources. Farther to the west or northwest, terranes comprising Mesoproterozoic complexes were also evidently involved in providing debris to the allochthonous, submarine-fan and deltaic formations in northern Varanger Peninsula, as well as to successions in early (Tonian) thrust sheets in the Kalak Nappe Complex farther west (Kirkland et al. 2007). These Mesoproterozoic terranes are inferred to be an integral part of the Precambrian basement concealed beneath the Caledonian Nappes and continental shelf (Roberts 2007, Lorenz et al. 2012). Interestingly, detrital zircons of Mesoproterozoic age sourced on the Fennoscandian Shield are also registered in certain Neoproterozoic sandstone formations in the Timanides of Northwest Russia (Kuznetsov et al. 2010). Some of these zircons were probably recycled from successions in a vast graben and river system that once extended across much of the central Fennoscandian Shield (Kuznetsov et al. 2012).

The thick, submarine fan systems of Rybachi and northern Varanger form the northwestern onshore termination of the 1800 km-long Timanian passive margin, but it has long been speculated as to how much farther northwest the Timan basin actually extended (Siedlecka 1975 and references therein). On Varanger Peninsula, Timanian structures are restricted to the northeasternmost area northeast of the TKFZ (Roberts 1996, Herrevold et al. 2009), but can be traced offshore in aeromagnetic data (Gernigon et al. 2008, Brönner et al. 2009, Gernigon and Brönner 2012) and seabed bathymetric features (Roberts et al. 2011). However, both onland and offshore the Timanian structural grain is quickly overprinted towards the northwest by Caledonian thrusts and folds. Simple restoration of the Barents Sea Group places these Timanian basinal rocks well to the northwest of Magerøya (Figure 8) but since the Neoproterozoic sedimentary wedge attains a thickness of almost 15 km just north of Rybachi Peninsula it is more than likely that the Timanian basin can be found at depth beneath the western Barents Sea.

Conclusions

Assessment of the provenances of Proterozoic successions occurring on four peninsulas flanking the Barents Sea in NE Norway and NW Russia has been carried out based on an evaluation of five disparate parameters. The results indicate the following:-

1. Palaeocurrent data in the pericratonic, platformal areas (Sredni and the Varanger TVR) indicate a principal sediment dispersal from fluvial systems directed between roughly north and northeast, from sources in the Archaean and Palaeoproterozoic terranes of the Fennoscandian Shield. Unconformities beneath specific depositional sequences signify epeirogenic events in the source regions and commonly mark transient changes in current flow. Local input of detritus from a northeasterly source in Mid Vendian time is considered to reflect erosion from the rising deformation front of the Timanide orogen and conversion of the pericratonic shelf into a small foreland basin which is likely to have existed into Early Cambrian time. This synorogenic, foreland basinal feature has also been recognised in the White Sea–Mezen Basin area of

Northwest Russia, immediately southwest of the Timans. Data from the allochthonous basinal realm of Rybachi and Varanger BSR are also indicative of a general transport towards the northeast, mainly in submarine fans and shelf-edge deltas. These thick successions, representing an extension of the Timanides, were originally located farther to the northwest of where they occur today, with the sources of their detritus now lying concealed beneath the Caledonian nappes and the present-day continental shelf. The Løkviksfjellet Group, which was originally suggested to be of possible Vendian age, was also sourced in the southwest and is likely to be of Cryogenian age. Palaeocurrent data from the Nordkinn Peninsula, part of the Kalak Nappe Complex, also show fairly consistent flow vectors towards N–NW in mainly fluvial to shallow-marine sandstones, but with deeper-water turbidites appearing in the far north.

2. Lithological indicators, including interpretation of depositional systems and their distribution, largely accord with the sediment dispersal patterns on the Rybachi, Sredni and Varanger peninsulas, signifying various sources to the south on the shield. On Rybachi, a spectacular olistostrome-breccia at the base of the succession represents a disintegration and collapse of the fault-bounded shelf-edge footwall.
3. Accumulations of heavy minerals representing palaeoplacer deposits are particularly common on the Sredni and Rybachi peninsulas. A pilot study of such mineral assemblages on Varanger Peninsula showed that at least three provenance areas on the shield, with markedly different abundances of zircon, tourmaline and garnet, have contributed to the Neoproterozoic sedimentary successions. Clear differences are also seen in the heavy-mineral contents of formations on either side of the Trollfjorden–Komagelva Fault Zone. On Nordkinn, concentrations of diverse heavy minerals and notably Ti- and Fe-rich opaques are common as thin beds, foreset strata or lensoid deposits, with probable sources in basement terranes on the shield.
4. A geochemical study of more than 460 samples from the Rybachi, Sredni and Varanger peninsulas has revealed a clear compositional distinction between the basinal and platformal domains, the former with element compositions indicative of likely derivation from mafic to intermediate sources in, e.g., northwestward extensions of the Palaeoproterozoic greenstone complexes, or in terranes farther west in the basement beneath the Caledonian nappes. The transgressive, felsic and silica-rich Løkviksfjellet Group, on the other hand, derives from a markedly different, potassic-granitoid, source region.
5. Detrital mineral isotopic studies (illite and zircon) are few, but those so far available for zircon from Varanger Peninsula denote population peaks in the Mesoproterozoic, Late Palaeoproterozoic and Neoarchaean for sandstones from the platform and from the Tanahorn Nappe, both of which derive from southerly sources. The deltaic Båtsnæringen and submarine-fan Kongsfjord formations in the BSR, however, are quite different in showing a multimodal spread of zircon grains from *c.* 2.1 to 1.0 Ga with only a minor Neoarchaean component. This dominance of Mesoproterozoic detritus, seen in relation to the original location of the delta somewhere to the northwest of Magerøya, argues for the presence of source rocks of this age beneath the Caledonian nappes and continental shelf. These sources could be representative of magmatic or metamorphic complexes which may once have formed part of a northward extension of the Sveconorwegian/Grenvillian orogen, as has been suggested in recent literature, or alternatively represent Tonian-transported sedimentary rocks derived from the margin of Rodinia prior to its ultimate break-up.

Acknowledgements
The authors are grateful to Johan Petter Nystuen and Chris Kirkland for their helpful and constructive comments, as reviewers, and also to Kevin Pickering for his equally helpful suggestions and comments on the manuscript. All these comments helped greatly in allowing us to expand and improve the manuscript. We also thank professors Nikolay Kuznetsov and Elizabeth Miller for providing files of translated publications of papers originally published in Russian, which are valuable additions to our knowledge of the Timanide orogen. We are grateful to Professor Malgorzata Moczydlowska for her written comments on aspects of biostratigraphy. Irene Lundquist is thanked for producing most of the figures, and a special thanks goes to the editor, Trond Slagstad, for allowing us to include Figure 7.

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