The Late Neoproterozoic Smalfjord Formation of the Varanger Peninsula in northern Norway: a shallow fjord deposit

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The Smalfjord Formation in the Varangerfjorden area of northern Norway was deposited as valley fill during an interglacial period of the Varangerian (Marinoan) glaciation. The paleovalley was initially cut by glacial erosion and braided rivers. Subsequent marine transgression due to glacial eustasy entered through the fjord valley mouth located to the present WNW and advanced across an irregular valley floor. As the initial transgression slowed down, the shallow fjord acted as a normal storm-dominated estuary and was filled by a prograding bay-head delta and flood-tidal delta prograding from opposite ends of the paleovalley. The final stage of fjord fill was completed by tidal sandflats and braided-river deposits. The latter was due to isostatic rebound in the hinterland. Renewed transgression resulted in a return to marine conditions in the succeeding Nyborg Formation, which spilled out of the paleovalley onto the surrounding areas.

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Introduction

A common feature of the contemporary post-Pleistocene world is the occurrence of marine drowned valleys, either as fjords in formerly glaciated regions or as incised river valleys in more temperate regions. Three major glaciations occurred during the Neoproterozoic (Halverson et al. 2003), but until now Neoproterozoic incised valleys have been described only from the Caddy Canyon Formation of Idaho and Utah and the Johnnie Formation of California (Abolins et al. 1999) as well as the Wonoka Formation (Christie-Blick et al. 1995) and the Seacliff Sandstone (Dyson & von-der-Borsch 1994) in South Australia. None of these lithological units feature depositional fill of a glacial origin.

The Varangerfjorden area of northern Norway is one of the first places that Neoproterozoic glaciations were recognized. Reusch (1891) described the base of the Smalfjord Formation at Oaibáhčannjárga (formerly named Bigganjargga) as a pre-Pleistocene glacial deposit sitting on a striated basement. Most workers (Holtedahl 1918, 1930; Rosendahl 1931; Reading & Walker 1966; Bjørlykke 1967; Edwards 1975, 1984, 1997; Føyn & Siedlecki 1980; Rice & Hofmann 2000; Laajoki 2001, 2002, 2004 and Røe 2003) concur with a glacial origin for the basal Smalfjord Formation at this locality, although Crowell (1964), Jensen & Wulff-Pedersen (1996) and Arnaud & Eyles (2002) advocate a mass-flow origin without glaciation. Laajoki (2001, 2002, 2004) provide additional support for the glacial theory, although he also recognizes local deposits of mass-flow origin. The bedded sandstones in the overlying parts of the Smalfjord Formation have received much less attention.

The goal of this study is to provide a sedimentological and paleoenvironmental overview of the Smalfjord Formation in the Varangerfjorden area. Detailed stratigraphical measurement and analyses of the bedded sandstones overlying the classical Oaibáhčannjárga locality were undertaken, and current directions in strata from the surrounding area were measured. These data are combined with stratigraphic information collected from nearby localities and paleoflow information recorded stratigraphically below and above by earlier workers such as Edwards (1984), Arnaud & Eyles (2002) and Laajoki (2001, 2002, 2004).

Regional stratigraphic history and paleogeography

The Late Neoproterozoic Smalfjord Formation of the Vestertana Group was deposited in the Tanafjorden-Varangerfjorden area (Fig. 1). Røe (2003) reviewed the regional and local tectonic interpretations for this area and suggested some revisions. During the Mesoprote-

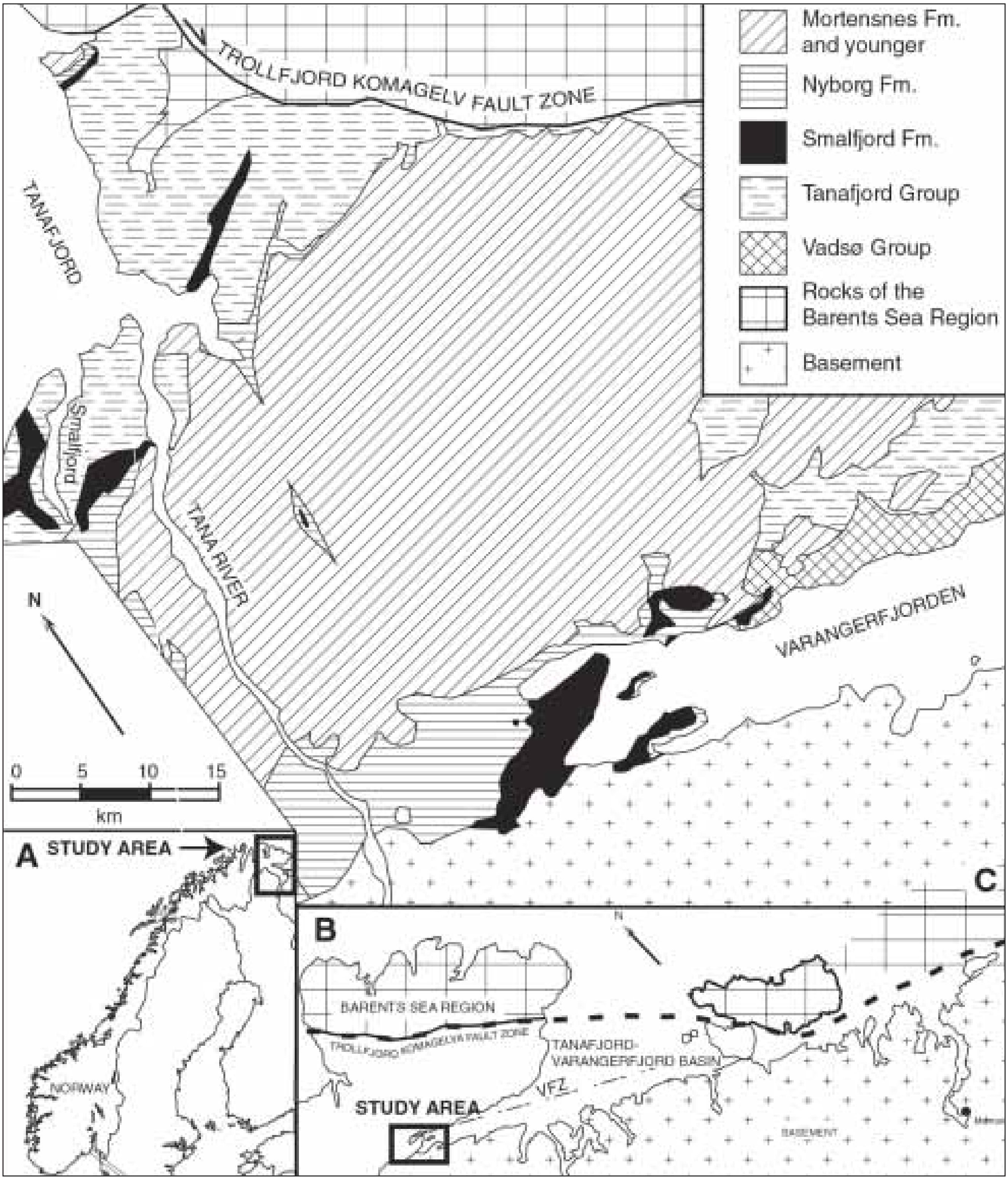

Fig. 1. Map of Scandinavia (A) showing the study area. Map (B) showing the Tanafjorden-Varangerfjorden and Barents Sea regions. VFZ – the inferred Varangerfjorden Fault Zone. Modified after Torsvik et al. (1995). Geological map (C) of area between Tanafjorden and Varangerfjorden. Modified after Siedlecki (1980).

rozoic to Neoproterozoic, a long-lived oceanic basin off the margin of the Fennoscandia Shield extended SE to Rybachi Peninsula in Russia and NW to the outer Porsangerfjorden (Siedlecka 1985; Torsvik et al. 1995, Olovyanishnikov et al. 2000). The Tanafjorden-Varangerfjorden area was located on the southwestern margin of this ocean within the pericratonic zone (Roberts & Siedlecka 2002; Røe 2003). Røe (2003) suggested that there were two phases of extensional activity during the Riphean. The first phase occurred during the middle

AGE	GLACIATIONS	LITHOSTRATIGRAPHIC UNITS/DATES	
		GROUP	FORMATION
CAMBRIAN		VESTERTANA	Breivika
EDIACARAN	GASKIERS 595-565 Ma		Stappogiedde 560-530 Ma
			Mortensnes
			Nyborg 560-530 Ma
	MARINOAN 650-600 Ma		Smalfjord
CRYOGENIAN		TANAFJORD	Grasdalen
			Haglecærro
			Vagge
			Gamasfjellet /Veinesbotn
			Dakkovarre
			Stangenes ~ 650 Ma
			Grønneset
	STURTIAN 748-713 Ma	VADSØ	
		OLDER PROTEROZOIC BASEMENT	

Fig. 2. Stratigraphy of Neoproterozoic sediments in the study area. Reference to chronological data from Gorokhov et al. (2001) and Halverson et al. (2003).

Late Riphean and reactivation occurred during the second phase at the close of the Riphean. To accommodate her model, Røe (2003) inferred the presence of a major fault zone beneath the Varangerfjorden. During the deposition of the Smalfjord Formation, the northern margins of Baltica, including the Varanger Peninsula, seem to have been part of a passive margin (Vidal & Moczydlowska, 1995; Olovyanishnikov et al. 2000; Roberts & Siedlecka 2002).

The Smalfjord Formation is the basal unit of the Vestertana Group which overlies continental and shallow-water deposits of the Vadsø and Tanafjord groups (Fig. 2). The Smalfjord Formation is overlain by the Nyborg Formation, composed largely of deep-water shales with a thin basal shallow-water dolostone succession (Edwards 1984). This is followed by the Mortensnes Formation, predominantly diamictites of inferred glacial origin. When the underlying Vadsø and Tanafjord Group underwent a second, Late Riphean uplift, there was also a slight tilting towards the north, interpreted by Røe (2003) as due to reactivation of the inferred basin margin fault below the Varangerfjorden and rotation of structural blocks. The Veinesbotn Formation that underlies the Smalfjord Formation in the central parts of the Varangerfjorden area, was previously considered to belong to the Vadsø Group (Banks et al. 1974). Røe (2003), however, proposed that the Veinesbotn Formation is even younger (Fig. 2) and that it onlapped the basin margin during the post-rift phase. This event was followed by an episode of erosion before deposition of the succeeding Vestertana Group. The erosion created an angular unconformity so that the Smalfjord Formation locally rests unconformably on the older gneiss and granites of the Fennoscandian Shield and the onlapped Tanafjord Group to the south and on sedimentary rocks of the Vadsø Group to the north (Fig. 1C).

The Smalfjord Formation is exposed in the Smalfjord and inner Varangerfjorden areas (Fig. 1C). It also occurs farther to the west on Laksefjordvidda. Paleovalleys of the Varangerfjorden and Laksefjordvidda areas contain thick deposits with facies that differ considerably from those in intervening areas (Edwards 1984). This study concentrates on the Smalfjord Formation in the inner Varangerfjorden area, where the outcrops are found in an east-west belt that follows the orientation of the present fjord (Fig. 1C). The maximum thickness of the formation here is about 130 m. Bjørlykke (1967) pointed out that the outcrop belt occupies a paleovalley with a steep, uneven topography on the south side and a gentler, but still substantial slope on the north side. Glacial striations are widespread across the base of the paleovalley (Laajoki 2002). Laajoki (2004) inferred Late Neoproterozoic ice movements from east to west along the axis of this paleovalley. The basal unconformity surface was scoured both by glacial and post-glacial erosion resulting in very uneven topography demonstrated by gneiss monadnocks that protrude through the Smalfjord Formation at Lárajeaggi (Laajoki 2004). Thus, the paleovalley has a complex origin. It is pos-

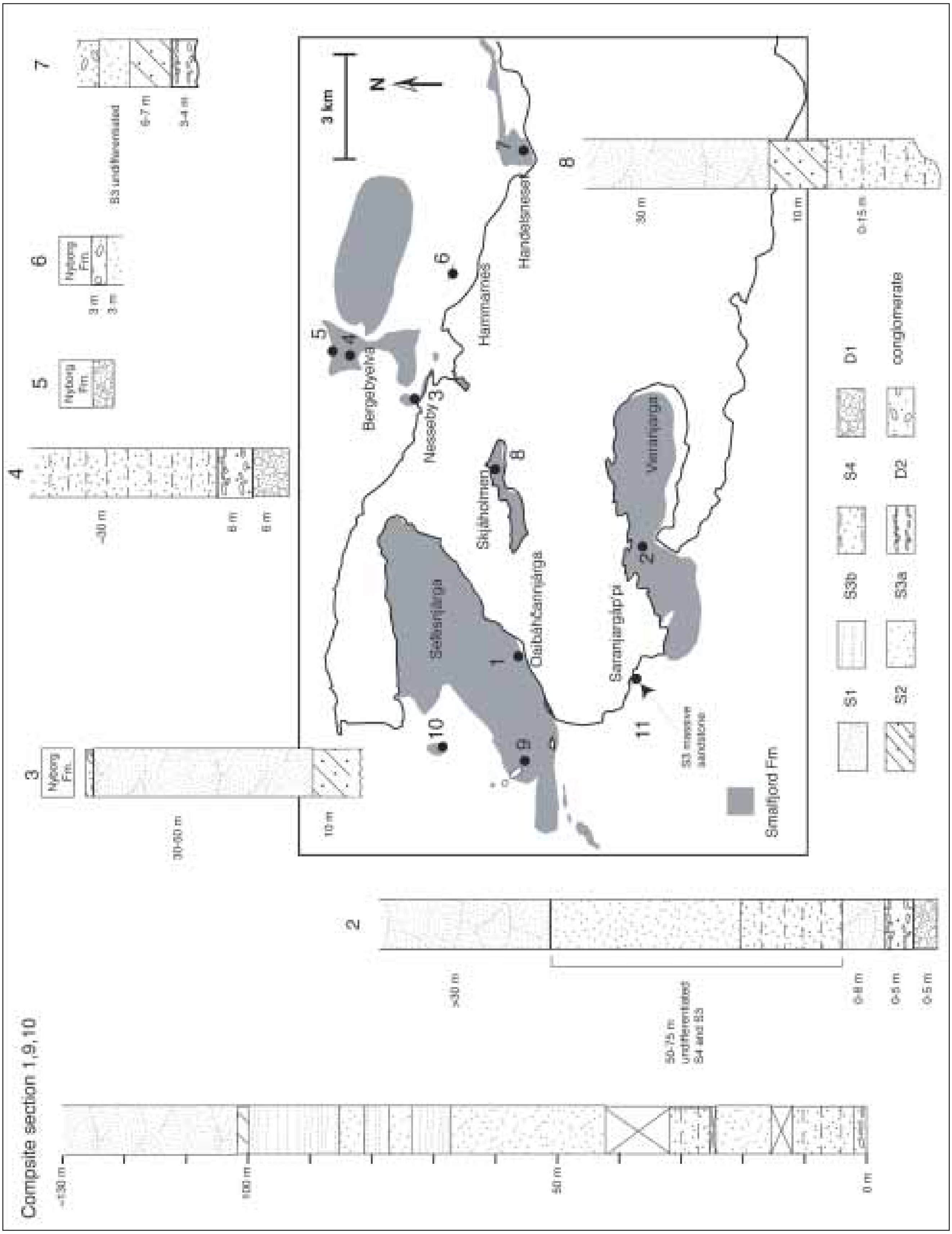

Fig. 3. Map of the inner Varangerfjorden area showing outcrop distribution of the Smalfjord Formation and locations of the stratigraphi sections used in this study. Sections 2-5 and 7-8 are modified after Edwards (1984); Section 6 is modified after Rice & Hofmann (2001b).

sible that glacial and post-glacial agents further enlarged a pre-existing fault-related depression.

The age of the Smalfjord Formation is constrained by Rb-Sr dating of the clay sub-fractions from sediments in the Stangenes Formation near the base of the underlying Tanafjord Group (Fig. 2), from strata of the directly overlying Nyborg, as well as the succeeding Stappogiedde formations within the Vestertana Group (Gorokhov et al. 2001). The Late Riphean Stangenes Formation yielded a burial diagenesis age of about 650 Ma, and the others are dated at around 560 Ma (Fig. 2). Knoll (2000), Hoffman & Schrag (2002) and Halverson et al. (2003) proposed that three glaciation events occurred during the Neoproterozoic: the Sturtian, the Marinoan and the Gaskier glaciations. There is no evidence of the earlier, Sturtian glaciation in Norway. The name Varangerian is generally applied to the ice age, or ages, encompassing both the Smalfjord and Mortensnes formations. The earlier glacial episode connected with the Smalfjord Formation has been suggested by Halvorsen et al. (2003) as being equivalent to the Marinoan glaciation, whereas the overlying Mortensnes Formation between the Nyborg and Stappogiedde formations (Fig. 2) features glacial deposits that may correspond with the latest Gaskier glaciation. Halverson et al. (2003) used carbon isotopes to correlate and date the different glacial episodes worldwide. He found that the Marinoan glacial episode must be younger than 650 Ma and older that 600 Ma, which falls well within the age limits for the Smalfjord Formation proposed by Gorokhov et al. (2001).

Earlier work on the Smalfjord formation in the Varangerfjorden area

Most studies regarding the Smalfjord Formation in this area have focused on the diamictites near the base of the formation. Bjørlykke (1967), who referred to the massive sandstones in the Varangerfjorden area as the Kvalnes Quartzite, made a short description of the entire Smalfjord Formation in the Varangerfjorden area. He also showed a map with a few current directions from the formation. Only Edwards (1984) looked at the entire Smalfjord Formation in the Varangerfjorden area in detail. In the inner Varangerfjorden area, he described 6 stratigraphic profiles (sections 2-5, 7 and 8; Fig. 3), and recorded current-flow directions. Edwards (1984) divided the Smalfjord Formation into 6 facies, D1-2 and S1-4, which are followed in this study. Among other recent workers, Arnaud & Eyles (2002) measured sections on Vieranjarga peninsula and at Oaibáhčannjárga (Fig. 3). On Vieranjarga, they compiled stratigraphic logs with a maximum thickness of 30 m, although their description cites up to 54 m of sandstone strata above the diamictites. At Oaibáhčannjárga, they measured about 90 m of strata and produced a simple profile. The diamictites are treated in detail but only a summary description of the overlying sandstones is provided (Arnaud & Eyles 2002). Rice & Hofmann (2000) described a new locality at Karlebotn, where a thin cover of the Smalfjord Formation overlies striated basement (Fig. 3, Section 11). Laajoki (2001, 2002) extensively reexamined the diamictites, while Rice et al. (2001a) described the petrography of the basal beds at Oaibáhčannjárga and Karlebotn. Rice & Hofmann (2001) studied the strata of the overlying Nyborg Formation at Hammarnes (Fig. 3, Section 6).

Methods of study

This study examines the thick succession of mainly quartzite strata at Oaibáhčannjárga (map reference 803 633 NGU map series 2335, 1: 50 000, NOR4) on the Selešnjarga Peninsula (Fig. 3, Section 1; Fig. 4). Additional sections from the upper parts of the formation (Fig 3, Section 9 and 10; Fig. 4) were measured at map reference 818 598, at Sélešnjáralás about 3 km west of Oaibáhčannjárga, and at map reference 827 595 farther north near Aune. It is possible to follow individual beds along strike for up to several kilometers, thus enabling correlation with some degree of certainty between Oaibáhčannjárga, (Section 1) and Sélešnjáralás (Section 9). The short section near Aune (Section 10, Fig. 3) is located on an isolated knoll surrounded by brush and bog.

Samples for thin sections were collected from sites at map reference 822 593 and at 816 598 near Section 9. Rare current directions were recorded from ripple marks within an area with map reference 81 58 - 83 60. Stratigraphic sequences recorded in earlier studies as well as the new stratigraphic data are summarized and placed in a geographic context (Fig. 3).

Facies descriptions

Edwards (1984, p. 7-8) divided the Smalfjord Formation into diamictites, Facies D1 and D2, and sandstones, Facies S1-4. His facies designations and interpretations are retained, but Facies S3 is subdivided into S3a and S3b and new descriptions are provided as summarized below in Table 1. Edwards (1984) also described Facies S2 where it crops out as delta foresets, but this unit was not investigated by us. Earlier workers inconsistently labeled Facies S as quartzites or sandstones. Following Edwards (1984) and Laajoki (2002), the term sandstone is used to distinguish it from the harder quartzite below.

The outcrops of the Smalfjord Formation in the

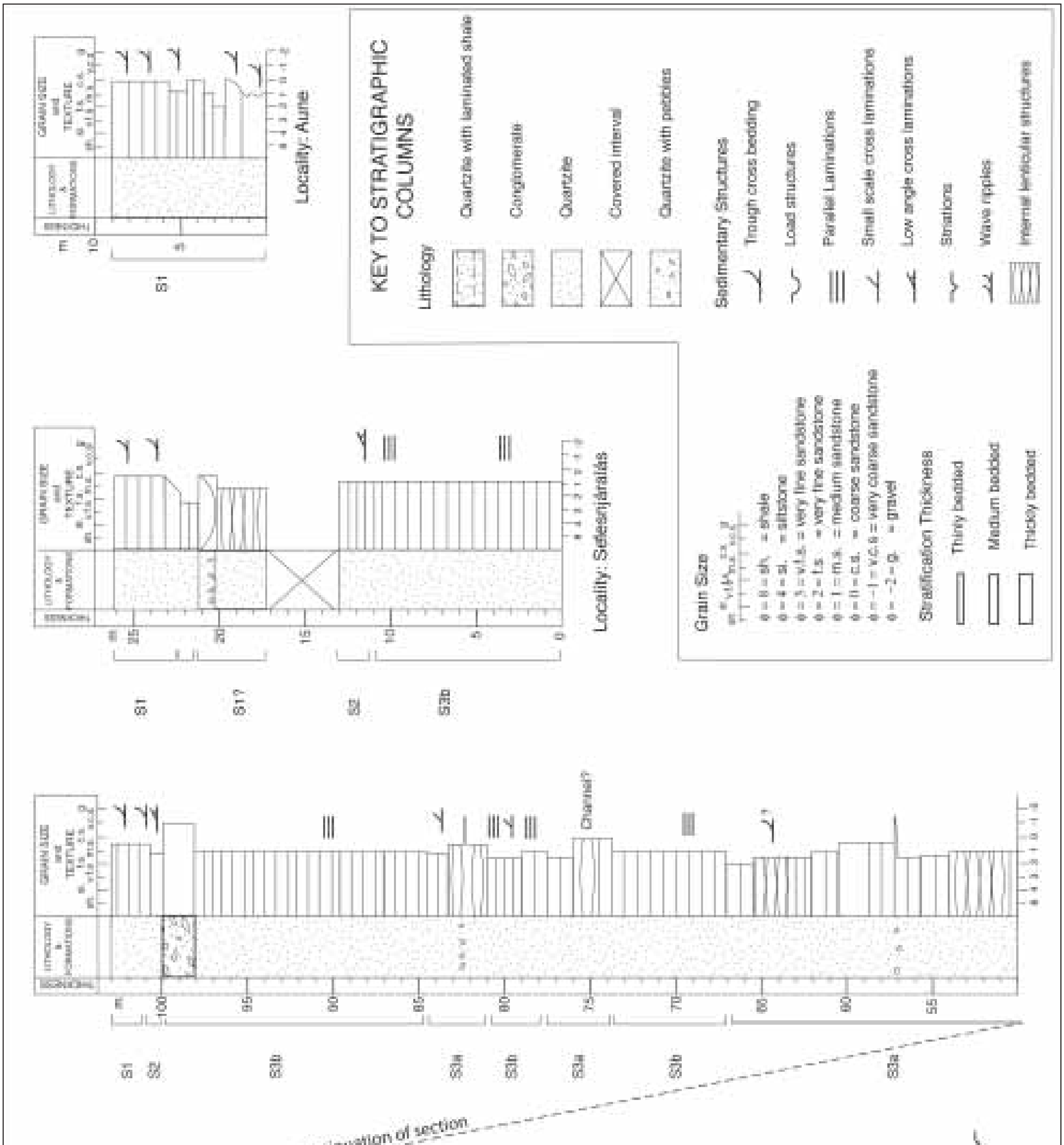

Fig. 4. Stratigraphic logs from the Smalfjord Formation showing lithology, grain-size and sedimentary structures.).

Table 1. Model parameters for estimation of fluid-flow in and out of a sandstone reservoir

Facies	Lithology and grainsize	Sorting	Bedding	Internal structures
S1	A: sandstone; coarse to medium in fining up cycles B: pebble conglomerate;	A: poor to medium B: relatively well	A: medium to thick B: lenticular bodies with erosive base	A: Trough cross bedding; parallel lamination B: imbricated clasts
S2	A: pebble conglomerate B: fine to medium sandstone	A: Poor B: Medium to well	A: thick B: thin to medium Both laterally continuous	A: large scale foresets 5-10 m thick B: gently dipping parallel lamination
S3a	Sandstone very coarse to fine, in fining up cycles; scattered pebbles may occur at base of cycle	Medium	Medium to thick, Parallel to slightly lensoid Erosive base	"bundling" at base of cycle; no clear structures above; current ripples on bedding planes
S3b	A: sandstone; medium B: sandy conglomerate	A: medium well B: poor	A: medium; laterally parallel and continuous B: lenses up to 30 m laterally	A: occasional faint parallel lamination; rare small-scale ripple lamination B: massive
S4	A: sand; fine to medium, often graded B: minor mudstone C: occasional matrix supported diamictite	A: poor to medium C: poor	A: thin to medium; laterally continuous; infrequently convolute B: very thin C: lenses	A: loading; parallel lamination and small scale-cross ripple lamination near top

Varangerfjorden paleovalley occur over a maximum measurable width of approximately 11 km and a minimum length of 30 km (Fig. 1C). To the south, the formation onlaps the older basement where the present topography is fairly rugged and high. The present landscape is gentler to the north, although Edwards (1984) found an unconformity eroded about 140 m into the underlying strata. The thickness measured at Selešnjárga from the base of the Smalfjord Formation to the base of Facies S1 is 101 m. Edwards (1984) estimated Facies S1 to be 30 m thick at this locality. Therefore, the total thickness of the formation is on the order of 130 m. Gneissic monadrocks protrude through and are overlapped by the Smalfjord Formation close to the measured section 9 (map reference 816 598, Fig. 3). These overlapping beds can be correlated to a level about 80-90 m above the base of the formation. Thus, the thickness of the formation varies significantly over short lateral distances.

Facies D1 and D2

Edwards (1984), Laajoki (2001, 2002, 2004) and Arnaud & Eyles (2002) treated the diamictites in great detail. No new observations are added here. Edwards (1984, p. 8) distinguishes between two types of diamictite facies: D1 - massive diamictite as opposed to D2 - stratified diamictite.

Facies D is normally at the base of the Smalfjord Formation and is widespread in the paleovalley. Laajoki (2002), however, noted that massive sandstones of Facies S3 also may form the basal beds of the Smalfjord Formation. At Vieranjarga, he found Facies D2 directly on a scoured surface containing slabs of the overlying Facies S4 and clasts of the underlying Veinesbotn quartzite. At Skjåholmen, Edwards (1984) reported diamictites between Facies S4 and S2 that he interpreted as Facies D1 based on incorporation of underlying sediments. Laajoki (2002) reinterpreted this as Facies D2.

Facies S1

This facies occurs near the base of the section between Facies D and S4 at Vieranjarga (Edwards 1984; Laajoki, 2002). Deposits of this facies are widespread in all but the most marginal areas above Facies S3 and S2 (Fig. 3). The sandstones are medium-fine to coarse and poorly to medium sorted in medium to thick beds. The beds display cross-bedded trough sets or, less commonly, are parallel laminated. In places the sandstones display a reddish hue. Relatively well-sorted pebble conglomerates with erosive bases occur throughout.

Facies S2

This facies consists of two subfacies. Both are laterally continuous and consist of large-scale foresets. The subfacies at Skjåholmen and Nesseby was not examined in this study, but Edwards (1984, p. 10, Fig. 8) described it as 10 m thick with large-scale foresets that dip 5-10º to the west consisting of parallel-laminated brown sandstone and scattered lenses of pebbles. The second subfacies crops out as a continuous bed along Selešnjárga, and is 3 to 4 m thick with low-angle cross-sets of medium to fine sandstone above Facies S3 (Fig. 4). The light-colored sandstone is medium to well sorted, well

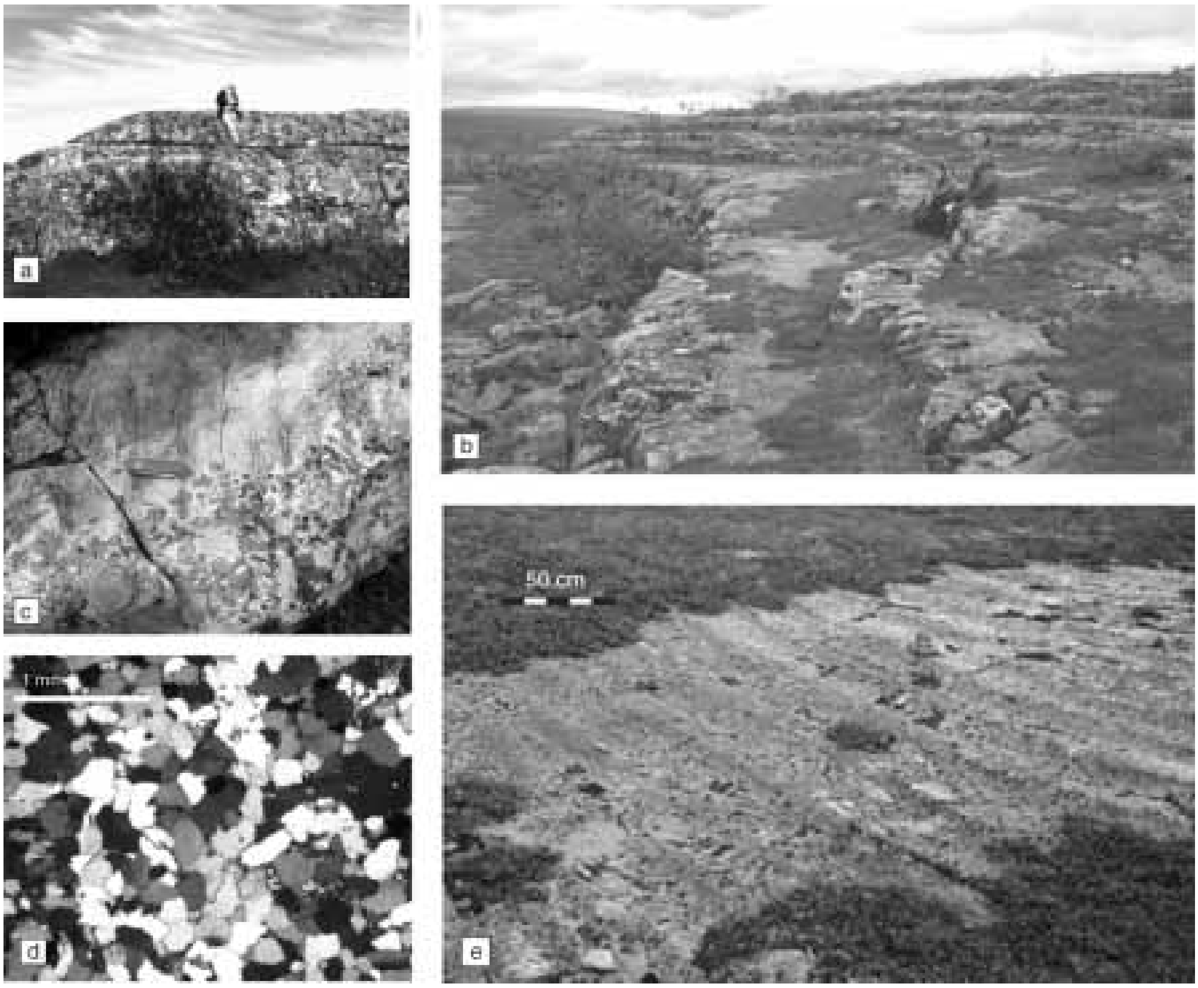

Fig. 5. Typical structurless beds (a) from Facies S3b near Section 9. Continuous beds of Facies S3b (b) near Selésnjáralás. Straight crested and asymmetrical current ripples (c) of Facies S3b near Section 9. Petrographic thin section (E-38) from Facies S3b (d) near Lárajeaggi. Bedding plane with asymmetrical ripples of combined flow (e) of Facies S3a, 1 km SW of Section 9.

rounded and parallel laminated. Laajoki (2002) also mentions Facies S2 below Facies S3 and 4 at east Vieranjarga.

Facies S3a

Facies 3 is composed of the 'massive sandstones' or Kvalnes Quartzite of Bjørlykke (1967) and observed by earlier workers (Fig. 5a). This facies is widespread throughout the region, although absent at Skjåholmen. The sandstones are often lichen covered and internal structures are difficult to detect.

Facies S3a occurs above the graded beds of Facies S4 and below the succeeding Facies S3b, although interfingering with both at the transitions. It occurs through 60 m of section at Oaibáhčannjárga. The light sandstones are moderately rounded, very coarse to fine grained and occur in fining-up cycles (Fig. 4). The erosive bases of the cycles in places contain scattered pebbles and the sorting is poor near the base of the cycle but moderate through the rest. Indistinct internal 'bundling' was observed in beds, generally near the base of the cycles. These are probably remnants of trough cross stratification. The beds in this facies may display a lensoid shape and uneven, possibly hummocky upper surfaces. A few scattered small pebbles were observed towards the top of a thick, otherwise structureless bed. A fist-sized lone stone was observed at one locality SE of Lárajeaggi.

Facies S3b

This facies interfingers with and occurs on top of Facies S3a and below Facies S2. It consists of light-colored sandstones with conglomerate lenses towards the top. The sandstones are medium-coarse, medium to well sorted, well rounded, and the medium-thick beds are

Table 2. Current directions in the Smalfjord Formation recorded by earlier workers.

Facies	Locality	Type of agent	Direction	Reference
Facies S4	Skjåholmen	Channel	SE-NW	Bjørlykke (1967)
	Varangerfjord Area	Soft sediment folding and faulting	To NW and W	Edwards (1984)*
Facies S3	Hammarnes	Cross-bedding	To N	Rice & Hofmann (2001)
Facies S2	Nesseby	Crossbedding in conglomerate	From SE or E	Bjørlykke (1967)
Facies S1	Selešnjárga	Crossbedding**	From SE	Bjørlykke (1967)
Facies D	Oaibáhčannjárga	Striations old set	NW-SE 322.5° –325°	Laajoki (2002)
		Young set	NW-SE 283° 304°	
	Handelsneset	Striations	NW-SE 287° -293°	
	Skjåholmen		NW-SE 288°	
	Veinesbotn		NW-SE 288°	
	Ruossaivi		NW-SE 306°	
	Saranjargåp'pi	Striations	Mean NW-SE set 325° Meam NW-SE set 342 °	Rice & Hofmann (2000)
	Vieranjarga		NW-SE ~330 °	Bjørlykke (1967)

* Edwards (1984) refers to soft sediment folding in facies S3 and S4 and current directions to NW and West for both facies. Soft sediment deformation and folding occurs only in the lower 30 m of the section that mainly is Facies S4. Therefore, his directions probably came from S4.

**Bjørlykke mentions numerous cross-beddings in the Karlebotn Quartzite which equal the sandstones of the Smalfjord Formation. He interprets the entire section of sandstones as braided river deposition. Since cross-bedding is very rare in facies S3 that make up the majority of the sandstones but very common in Facies S1 near the top of the section. The assumption is that he took his measurements in Facies S1.

laterally continuous (Figs. 4, 5b). Parallel laminations are fairly common with rare, small-scale cross laminations and ripples on bed tops. Conglomerate lenses are up to 2 m thick, but usually considerably thinner. The lenses have a lateral extent of up to 30 m and increase in frequency upwards. The cobbles and pebbles are heterolithic, well rounded and poorly sorted. A channel with an ESE-WNW orientation was found near the top of the facies at map reference 818 598, near Lárajeaggi.

Facies S4

Facies 4 is widespread in the paleovalley in all but the most marginal sites (Fig. 3). It occurs at the base of the Smalfjord Formation where it may rest directly on the unconformity, above D1 or above and interfingered with D2. The mix of sandstones, mudstones and rare matrix-supported diamictites is brownish and darker in color than the overlying sandstones. The thin to medium-thick and laterally continuous bedded sandstones are coarse to fine grained and commonly graded. The sorting and rounding are poor to moderate. Loading near the base, parallel lamination and rare ripple lamination are present near the tops of the beds. Erosive bases are common, as are ball-and-pillow structures. The mudstones are very thin, while the conglomerates are restricted to poorly sorted lenses with scattered pebbles up to 3 cm in diameter.

Paleoflow directions

Few of the facies in this scheme, except Facies S1, provide many structures indicative of paleoflow. Information provided in earlier papers is listed in Table 2 and new finds from this study in Table 3. Combined results are shown in Fig. 6. Laajoki (2002) found glacial striations with slightly different directions: NW-SE 323-325 and WNW-ESE 283-304 (Fig. 6). Based on interpretation of inherited roches moutonnées, Laajoki (2004) suggested that the glacier flowed from the SE to NW.

The Smalfjord Formation clearly records two predominant current directions. In Facies S1, S2 and S4, the main direction from channels, soft sediment folding

Table 3. Current directions from Facies S3 at Selešnjárga.

Location	Direction	Current ripples: Mean wave length	Mean wave height (cm)	Ripple index	No	Symmetry	Note
808 586	N 57° E	34	2.0	17	7	Asym.	Fig. 5e
808 588	N 40° E					Asym?	Poor preserv.
813 598	N 67° E					Asym?	"
814 597	N 37° E					Asym	"
817 596	N 52° E	29	2.2	14	2	Asym	
813 600	N 82° W	6	0.7	9	6	Asym	Fig. 5c
		Palaeo channel data					
818 598	N 62° E	Epsilon cross-beds dipping in an easterly direction					

and faulting, cross bedding (restricted to Facies S1), and large foresets (restricted to Facies S2) is from SE/E to NW/W (Table 2, Fig 6). In the intervening Facies S3 there are indications of two current directions, from the ESE to WNW and from the SW to NE with the latter predominating (Table 3, Fig. 6). Most of these are from Facies S3b, while the two at grid reference 808 586 are from Facies S3a. The large ripple sets with current directions from the SW have a ripple index indicating combined flow (Table 3). In one instance (Fig. 5e), a larger bedding plane shows that the ripple sets are slightly arcuate over about 2m of exposure. There is also a channel in Facies S3b near Lárajaeggi (Table 3), where epsilon cross-beds indicate flow from the WNW to ESE. The small ripple sets (Fig. 5c) are typical current-generated ripples and the direction agrees with that observed in the underlying and overlying beds. Paleoflow measured at the base of the Nyborg Formation at Section 6 (Fig. 3 and Table 1) is directed northwards (Rice & Hofmann 2001).

Petrographic thin-sections

Three petrographic thin-sections were made from Facies S3. All samples were collected stratigraphically close to the basal unconformity of the protruding gneiss monadnacks or inherited roches moutonnées at Lárajaeggi. The exact position in the stratigraphic section is difficult to specify, but they are all from Facies S3b. Comparing the modal analyses of these three samples with an analysis done by Rice et al. (2001a) from Facies S4, shows that the sandstones in Facies S3 are more mature (Fig. 5d, sample E-38) than those found in Facies S4. The amount of quartz grains varies between 92 and 97% in Facies S3b, while Facies S4 has only 67-74% of quartz grains. Most of the difference lies in a high clay mineral content and a somewhat higher amount of feldspar in Facies S4 compared with S3. Only negligible amounts of calcite cement were observed in Facies S3.

Interpretation

Valley genesis and origin of basal beds

A relatively shallow and broad paleovalley opened towards the WNW. During the Marinoan glaciation, glaciers scoured the valley and left behind a veneer of Facies D1. Most of Facies D1 was subsequently stripped away by the erosive overlying facies. The valley floor, itself, was further incised by Facies S2 to S4. We follow the interpretation of Edwards (1984) of Facies D2 as pro-glacial, because it occurs between glacial and fluvial deposits at Vieranjarga.

Facies S1 and S2

The basal Facies S1 was fluvially deposited by braided rivers in a periglacial setting during early glacial retreat (Edwards, 1984). Current directions were towards the WNW. The basal topography of the valley at that point was very rugged and rivers would have run through the valley bottom around gneissic hills.

As the glacier retreated, glacial eustasy ensued. The basal Facies S2 most likely was a marginal facies in an open fjord, although a marginal facies in a lake dammed by a fjord sill cannot be excluded. As found at Skjåholmen and Nesseby (Fig. 3), Facies S2 was deposited in a bayhead delta in front of Facies S1. This delta prograded towards the WNW and probably eroded much of the underlying facies.

When Facies S1 was deposited at the top of the Smalfjord Formation, the paleovalley was nearly filled and the accumulated sediments created a smooth, broad surface with rivers flowing across most of the valley.

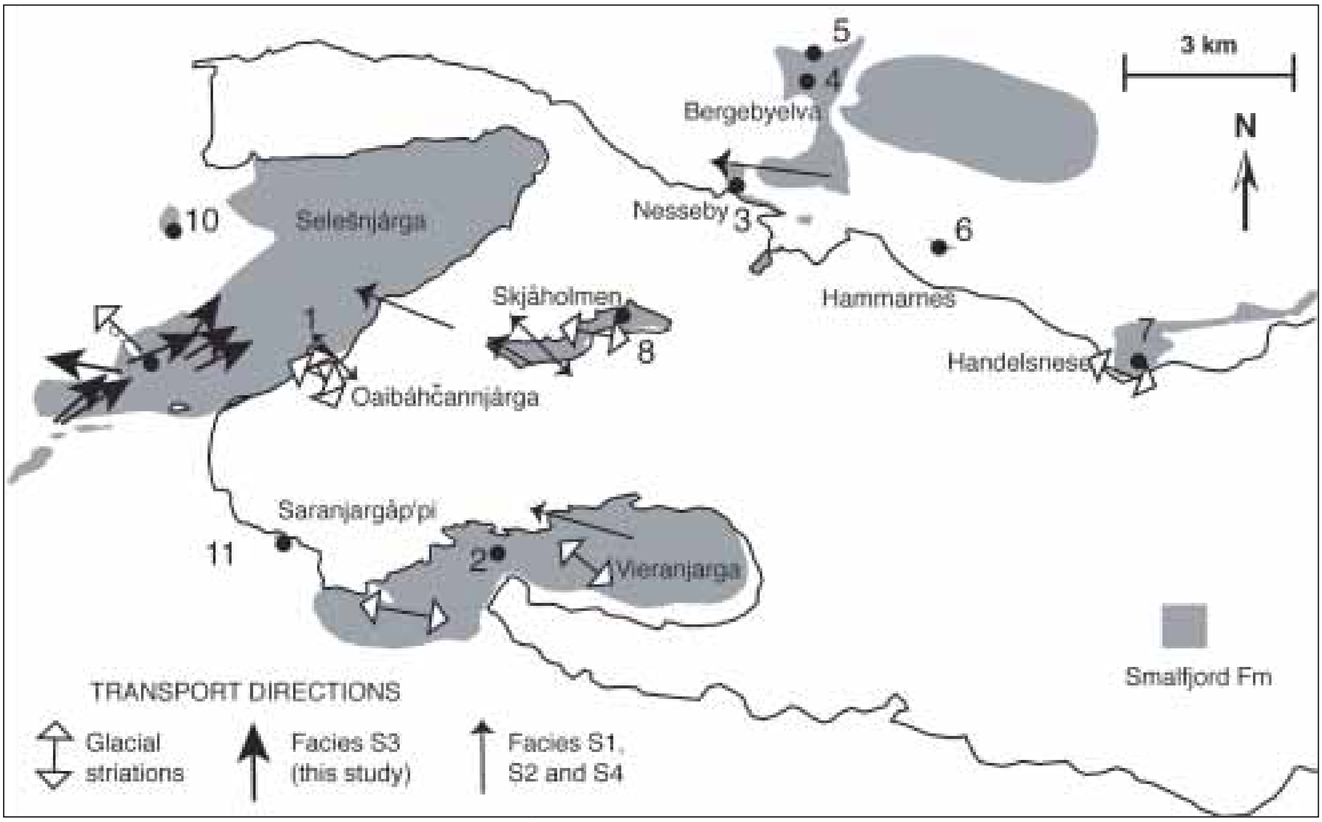

Fig. 6. Transport directions recorded in the Smalfjord Formation from the Varangerfjorden area. See tables 2 and 3 for detail.

The return of continental facies was due to the valley filling up (progradation), isostatic rebound after the end of the glaciation, or most likely a combination thereof.

Facies S4

Facies S4 was deposited as turbidites (Edwards 1984; Arnaud & Eyles 2002). Much of it was prodelta deposits, but some also might have originated as slumps from steep valley sides creating density currents following the general WNW trend of the valley. This facies suggests further deepening.

Facies S3

Facies S3a was deposited above wavebase in a marine setting in tidal channels. The tidal channels were associated with a flood-tidal delta as the shallow fjord either lacked a sill or was filled to the sill and changed from a restricted fjord-type circulation to a more open estuary-type circulation. This alternative is shown in Fig. 7A and B based on the stratigraphic cross-sections as represented in Fig. 7C. Some of the beds are due to grainflows from slope failure in local islands or valley sides. This facies is succeeded by Facies S3b, which was deposited in shallow, high-energy sand flats. Mass flows from land became more common as the fjord shallowed.

Transition to the Nyborg Formation

The valley was more or less filled at this point. Deposition of the Nyborg Formation was due to a renewed transgression. The direction of sediment transport shifted from WNW to due north, because there were no restricting valley slopes.

Discussion

Valley genesis and origin of basal diamictites

Glacially incised valleys are common today, but incised fjords with glacial fill from older deposits are fairly uncommon. Examples of incised fjords with glacial fill are known from Upper Ordovician rocks in Mauritania (Ghienne & Deynoux 1998), Algeria (Hirst et al. 2002) and Jordan (Powell et al. 1994), and from terminal Paleozoic rocks in the Chaco basin of Bolivia and Argentina (Winn & Steinmetz 1998; Minicucci et al. 2000), as well as Western Australia (Eyles & de-Broekert 2001). The end-Ordovician Tamadjert Formation of Algeria (Warme & Hussein 1997) also was deposited in an incised valley but glacial deposits are found only in lateral facies outside the valley.

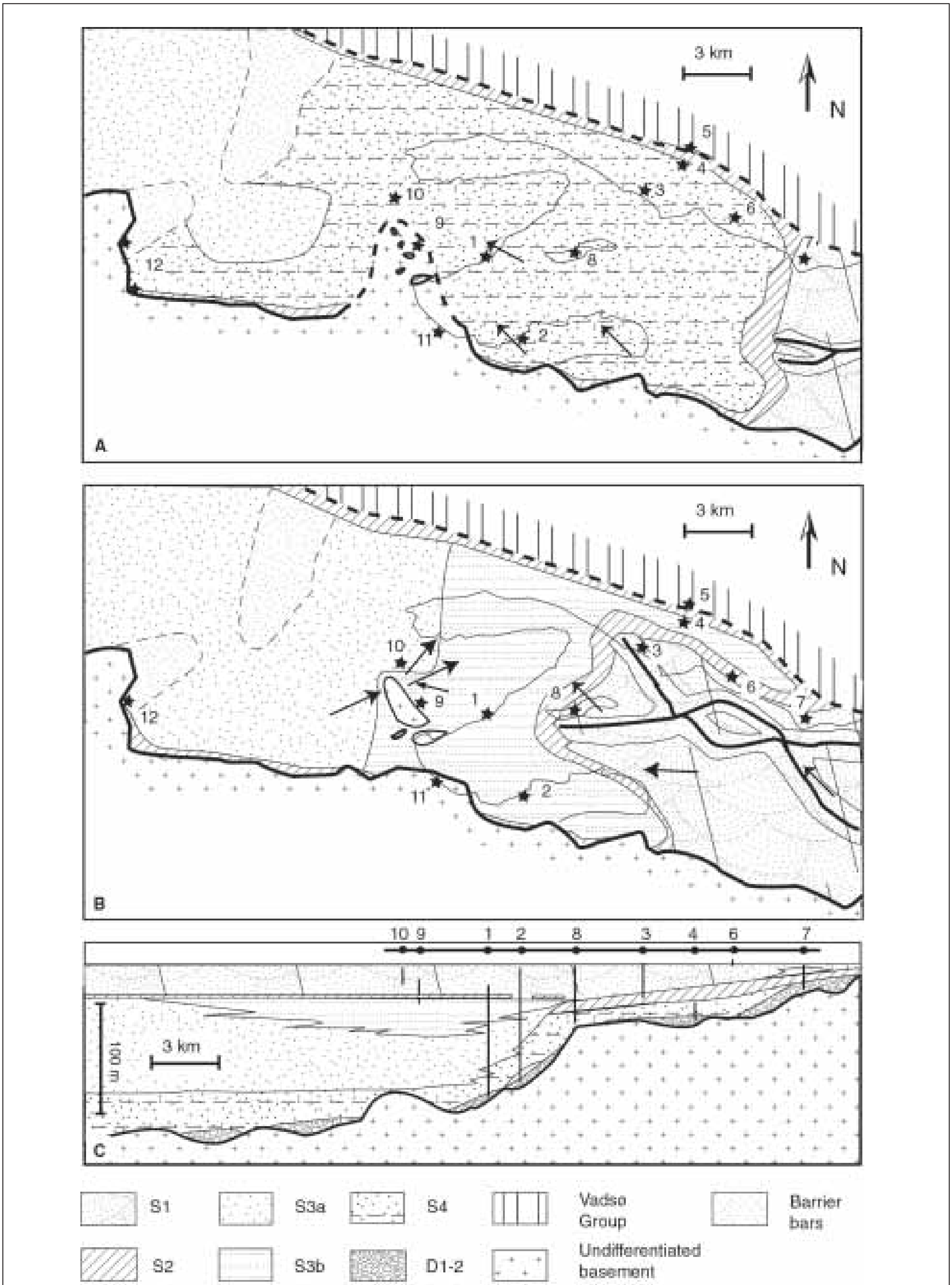

Fig. 7. Reconstructed palaeoenvironment (A early and B late) and geological cross-section (C) of the Varangerfjorden Palaeovalley.

The definition of a fjord given by Syvitski et al. (1986) is "a deep, high latitude estuary which has been excavated or modified by land-based ice." The Varangerfjorden paleovalley was broad and shallow and therefore not a typical glacial fjord valley. The typical Norwegian fjord valley might have up to 1000 m relief and very steep slopes. Broad, shallow glacial valleys or glacially influenced estuaries, like the one in the Varangerfjorden area, do occur on the east coast of Canada and also along the coast of Scotland (Syvitski et al. 1986). For lack of a special term for these variants, the Varangerfjorden paleovalley is called a fjord valley.

The river Facies S1 and delta Facies S2 prograded towards the WNW. This, together with the finding by Edwards (1984) and Laajoki (2004) that the glacier moved towards the NW, lead us to conclude that the valley opened towards the WNW. Edwards (1984) also states that all the formations of the Vestertana Group that he studied are thickest in the Vestertana region to the W and NW. This relationship implies that the fjord opened into a depositional and structural basin of that orientation.

Arnaud & Eyles (2002, Fig. 9) do not regard the Smalfjord Formation of the Varangerfjorden area as having been deposited in a paleovalley. They show the Smalfjord Formation of the Varangerfjorden area as marginal deposits in a larger active rift basin that deepened towards the Smalfjord area and farther to the northwest. The relatively small thicknesses of the diamictites and conglomerates of the Smalfjord Formation together with the fairly mature sandstones of Facies S3 and lack of evidence for volcanic activity make an active rift setting unlikely. Arnaud & Eyles (2002, Fig. 3) also disregard the newer dates for the Smalfjord Formation of 630 to 600 Ma proposed by Gorokhov et al. (2001) and more recently supported by Halverson et al. (2003). A Cryogenian age, possibly 725 Ma, is favored by Arnaud & Eyles (2002). At that time, the Tanafjorden-Varangerfjorden Region was part of an active rift basin, but not so from 650 to 600 Ma.

Most workers hold the view that a glacier eroded the valley and that Facies D is of glacial origin (see above). A few workers have adopted an opposing view, that all the diamictites (Facies D) originated by mass-flow (Crowell 1964; Jensen & Wulff-Pedersen 1996; and Arnaud & Eyles 2002). Among these, the two former studies are limited to the classical locality of Oaibáhčannjárga, where the diamictite is of obscure origin. Laajoki (2001, 2002, 2004) has amassed a wealth of information leaving little doubt that the valley was influenced by a glacier and that Facies D1 appears as a relict glacial deposit. However, Laajoki (2002) also points out that, in places, Facies D2 includes large clasts of the turbiditic Facies S4. This supports a lateral deposition of Facies D2 and S4 in a deeper sub-aqueous environment, in agreement with the proposal by Arnaud & Eyles (2002) who favor sub-aqueous debris aprons. However, Facies D2 is also found sandwiched between the continental facies D1 and fluvial deposit (S1), indicating that the Facies D2 is of mixed origin from proglacial and sub-aqueous debris aprons.

Many present-day Norwegian fjords are terminated by sills and show former dammed lakes between the sill and the retreating glacier before onset of post-glacial marine deposition (Aarseth 1997). It is possible this was true in the early development of the Varangerfjorden paleovalley. However, there are no signs of varves as would be expected in this early stage of paleovalley development.

Facies S1 and S2

The deposition of Facies S1 near the top of the section is pervasive and thick (Fig. 3) compared with the total thickness of the formation. Considering the paleorelief, the Smalfjord Formation at this point must have nearly filled the paleovalley. Meandering rivers are most common in infilled estuaries (Dalrymple et al. 1992), but here braided rivers with strong carrying capacity were active. Isostatic rebound in the hinterlands most likely led to renewed erosion and higher gradients.

Facies S4

Holtedahl (1967) found that up to 50% of the fill in some Norwegian fjords originated from slope failure and gravity flows. Syvitski et al. (1986) noted that mass transport processes dominate fjords with rugged bottom topography and high rates of sedimentation. These criteria fit the available data for the Varangerfjorden paleovalley. Braided rivers generally have high rates of sediment transport and failures in the bayhead delta would have been common. Much of the sediment load would have been deposited in the prodelta. The sandstones of Facies S4 are immature with relatively poor sorting and angular grains, indicating little reworking. At this stage in the valley's history, tidal or storm reworking must have been of little importance.

The steep slope on the south side and the associated monadnocks would be likely sources for additional slumps and slides that later became density currents following along the lower part of the valley. Arnaud & Eyles (2002), who favored this type of deposition for both Facies D and Facies S, concentrated their study on Vieranjarga, closest to the steep south side of the Varangerfjorden paleovalley, where deposits from wall slope failure would be expected to occur.

Facies S3

Some earlier correlations between the Krokvatn paleo-

Table 4. Modal analyses (%) of petrographic thin-sections from the Smalfjord Formation.

	After Rice et al (2001) Facies S4			This study Facies S3		
Sample	5/96 Karlebotn	12b/99 Oaibáhčannjárga	2/99 Karlebotn	E-37 Lárajeaggi	E-38 Lárajeaggi	Br1 S3b
Quartz grains	74.3	67.3	66.9	92.1	93.4	97.4
feldspar	2.7	3.8	3.8	2.3	1.5	0.6
LF shale	-----	1.8	-----	------	-----	-----
LF-polycr. quartz	2.0	2.7	2.9	0.7	-----	0.2
Heavy minerals	0.2	0.02	2.4	-----	-----	-----
Detrital mica	-----	-----	1.1	1.7	1.8	-----
Clay	15.3	12.2	6.0	2.0	1.8	0.9
Quartz cement	3.9	6.7	0.9	1.0	1.5	0.6
Calcite-cement	1.6	3.8	13.3	-----	-----	-----
FE-oxides	-----	1.6	2.7	-----	-----	-----

N = 450 in all cases.

Two samples from Lárajeaggi were collected adjacent to a palaeoisland about 15 m apart (map reference 814 598) surrounded by S3b; sample Br 1 is from facies S3b at map reference (819 595).

valley at Laksfjordvidda to the west and the Varangerfjorden paleovalley are based on the assumption that the light colored sandstones deposited in both areas are similar (Bjørlykke 1967), the most significant comparison being lack of structures. The composition of the Krokvatn sandstones differs from the seemingly structureless Facies S3 sandstones in the study area. Facies S3 is very pure, up to 97% quartz, and the grains are medium-well to well sorted and rounded (Table 3), wheras the Krokvatn sandstones show around 20% feldspar and are angular and unsorted (Føyn & Siedlecki 1980, Fig. 6c). The composition of these sandstones is more similar to Facies S4 of the Varangerfjorden area than to the dominant Facies S3 (Table 3, Fig. 5d). To correlate the sandstones is meaningless, because they are local facies in two different paleovalleys.

Both basal Facies S1 and S2 have a very limited occurrence in the paleovalley (Fig. 3). Good preservation of these facies is not expected because most of the overlying facies are erosive in character (turbidites, S4, and tidal channels, S3a). In addition, the river at that stage probably did not extend across the entire valley floor but skirted around the monadnock hills.

Facies S3 differs from Facies S4 in having a lighter color, better sorting and better rounding. Thin sections show a major change from subarkose and feltspathic greywacke in Facies S4 to quartz arenite in Facies S3. (Table 3). Facies 3 sandstones have been reworked to a higher degree than the sandstones of Facies S4, either by wave or tidal currents. Current ripples from oscillatory wave combined flow show this facies, at least in its stratigraphic upper levels, was deposited above wave base.

Facies S3 displays 3-10 m thick fining-upwards sequences and bi-directional currents. The predominant transport was from the SW to NE (Table 2) with minor transport from the ESE, as distinct from unidirectional transport from the ESE to E as observed in Facies S4 (gravity flow), Facies S2 (delta) and Facies S1 (braided river deposits). Facies S3a is tentatively interpreted as tidal channel deposits, although there are no typical bi-directional structures. Kreisa & Moiola (1986) observed that mainly flood currents are preserved in flood tidal channels due to strong time and velocity asymmetry. Also, Cloyd et al. (1990) and Nio et al. (1983) note that storm-enhanced flood tidal deposits commonly lack mud drapes and tidal bundles, also missing in Facies S3a. Flood tidal channel facies are typically thin and laterally widespread (Reading & Collinson 1996).

Edwards (1984) noted the sparseness of internal stratification in Facies S3 and proposed deposition by fluidized or liquefied sediment gravity flow. Some of the sandstones show characteristics of grainflows in being mainly structureless and, in a few places, having floating clasts dispersed throughout. Grainflows are common in fjord environments with steep bottom topography (Syvitski et al. 1986; Cowan et al. 1999). The sections measured are deposited close to a pronounced topographic high of the basement in the valley represented by the roche moutonnée at Lárajaeggi. Limited amounts of grainflows from reworked beach deposits around these islands might be expected. The current direction of large-scale ripples found on top of the beds, however, reveals the same direction of movement both on the SW and the E sides of the roche moutonnée, and thus did not follow the slope away from the islands on opposite sides. Grainflows have a short transport distance, only move down slope and normally are not erosive. The transport direction together with erosive bases and the wide lateral continuity of many of the beds argue that few of the beds originated as grainflows.

Tidal deposits, including tidal deltas, typically display ample internal structures, whereas the sandstones of the Smalfjord Formation lack such structures. Structures are common both in the underlying Veinesbotten Formation and in the overlying Facies S1. Elliott (1993) noted that deltas have a wide range of controls so that each delta tends to be unique. He also claimed that there were non-actualistic ancient deltas. One of his examples, the Middle Jurassic Etive Formation from the northern parts of the Brent Delta in the United Kingdom sector of the North Sea, is similar to the tidal channel sandstones (Facies S3a) of the Smalfjord Formation. It displays massive sandstones with only rare, indistinct structures in stacked, fining-up units, as described by Brown & Richard (1993). Their interpretation points to an origin as distributary channel-fill deposits. The extensive and unstable nature of the former channels is similar to what is found in the Smalfjord Formation, but unlike any modern delta system (Elliott 1993).

Facies S3b exhibits indistinct laminar, small-scale ripple marks and better-sorted sediment than found lower in the sequence. Also, the beds are thinner and more laterally continuous. The position of Facies S3b above and partly interbedded with the tidal channels, and below beach foresets, may indicate filling of a shallow lagoon where the sands brought from the flood or bayhead delta were distributed in sand flats.

Regional depositional model for Facies S3

The following scenario is proposed. Tidal channels were associated with a flood tidal delta as the shallow fjord experienced a transgression, possibly filling to the sill and shifting from restricted fjord-type circulation to more open estuary-type circulation.

Dalrymple et al. (1992, p. 1132) define an estuary as "the seaward portion of a drowned valley system which receives sediments both from fluvial and marine sources, and which contain facies influenced both by tide, wave and fluvial processes." According to this definition, open fjords are estuaries. The ideal profile of the central basin in a storm-dominated estuary starts and ends with fluvial facies. Bayhead delta deposits with the finest prodelta sediment are followed by coarser flood-tidal delta or washover sediments in the middle (Dalrymple et al. 1992). In the Varangerfjorden paleovalley, fluvial deposition occurs near the base at Vieranjarga (Facies S1, Fig. 3). A tidal-dominated facies with the dominant flood tides coming from the SW to NE, combined with the presence of a bayhead delta to the east, conforms to a model of a storm-dominated estuary (Fig 6a-c) as defined by Dalrymple et al. (1992). The paleoestuary was capped and filled in by a braided river system in the central parts. High sediment supply due to isostatic rebound is probably the reason for the thick sequence of braided river facies found above Facies S3. It might also be the explanation for the nearly structureless sandstones.

The Nyborg Formation

The full transition between the continental upper Smalfjord Formation and the marine Nyborg Formation is not exposed. At Hammarnes, the basal Nyborg Formation shows sandstones similar to the Smalfjord Formation that interfinger with marine shales and carbonates of typical Nyborg Formation facies over an interval about 6 m in thickness (Rice & Hofmann 2001). This indicates erosion of the Smalfjord Formation during deposition of the basal Nyborg Formation and suggests the occurrence of an unconformity between the two formations. How large a gap this unconformity represents is unknown. However, Rice et al. (2001b) documented that the basal Nyborg Formation carbonates have the same negative $\partial^{13}C$ values as recognized in other coeval Upper Neoproterozoic capstone carbonates. This suggests that the Marinoan glacial episode ended during deposition of the Smalfjord Formation prior to deposition of the basal Nyborg Formation carbonates.

The Smalfjord Formation during the Marinoan glaciation

The Marinoan glaciation was associated with a major draw down of sea level and the Varangerfjorden paleovalley was one of a number of recognized incised valleys dating from that time (Abolins et al. 1999; Christie-Blick et al. 1995; Dyson & von-der-Borsch 1994). The change in sea level was probably due to growth of vast polar ice sheets (Halverson et al. 2003).

The intra-glacial sandstones of the Smalfjord Formation in the Varangerfjorden area thus attest to sea-level oscillations and retreats of major icefields. In a Late Neoproterozoic reconstruction of the polar-wander path for Baltica, Torsvik et al. (1996) suggest a geographic position at 630 to 600 Ma for Finnmark and the Tanafjord-Varangerfjord basin around 60o south of the equator. This means that even at the fairly high latitudes proposed for the Varangerfjorden area, the polar caps must have receded farther south when the Smalfjord Formation was deposited.

Conclusions

A Neoproterozoic valley coincides with the present-day Varangerfjorden in northern Norway. During the Marinoan glaciation this valley was eroded by a combination of glacial, periglacial and transgressive erosive facies. The resulting paleovalley opened to the NNW onto the shelf of the Baltica paleocontinental margin, which at that time, occupied high latitudes in the Southern Hemisphere. The valley was relatively shallow and broad with sidewalls as much as 140 m high and a length and width of at least 30 km by 11 km, respectively. Only remnants of the original glacial cover were left. This is followed by 30 m thick sandstone strata mainly of turbiditic prodelta origin deposited during a transgressive phase related to melting of the ice caps. Subsequently, the middle and upper parts of the Smalfjord Formation accumulated during an interglacial episode in transition from marine-associated deposits to dominantly fluvial deposits.

The following model may be used to account for the infill of the Varangerfjorden paleovalley. The fjord either had a small sill or lacked a sill and behaved much as an open system similar to the model described by Dalymple et al. (1992) for storm-dominated estuaries. Isostatic rebound in the hinterland finally filled the paleovalley with braided-river sediments before renewed transgression led to deposition of the capstone carbonates in the succeeding Nyborg Formation.

The following are more specific conclusions regarding deposition of the Smalfjord and Nyborg formations in the Varangerfjorden area.

1) Structureless sandstones in the Smalfjord Formation dominate approximately two-thirds of the formation and have been lumped together as sediment gravity-flow deposits by many previous investigators. A careful search for more sedimentary details within these sandstones indicates that only approximately the lower 30 m of the formation conform to turbidite deposits.
2) The central and thickest part of the Smalfjord Formation consists of sandstones about 60 m in thickness that are very pure, better rounded and well sorted in comparison with underlying facies from the basal part of the formation. Rare combined-flow current ripples in Facies S3 indicate that the central part of the formation was deposited above wave base. Tidal deposits within this facies are implied by bi-directional current indicators and stacked fining-upwards sequences that vary between 3 to 10 m in thickness.
3) The bottom topography of the Varangerfjorden paleovalley was highly irregular, as attested by monadnocks of basement gneiss that protrude through sandstone strata belonging to the middle part of the Smalfjord Formation. Conglomeratic mass-flow deposits that originated from these monadnocks or from valley walls occur locally interspersed in the upper part of strata from the central and thickest part of the Smalfjord Formation.
4) Pervasive, thick braided river deposits at the top of the Smalfjord Formation indicate isostatic rebound in the hinterlands with renewed erosion and high sediment supply.
5) During initial deposition of the succeeding Nyborg Formation, current directions changed from the SSE –to-NNW trend prevalent for the Smalfjord Formation to a S-to-N pattern. This suggests that the Varangerfjorden paleovalley was filled and that currents related to Nyborg deposition were no longer confined by valley walls.

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