Glacial and rocky-shore dynamics of the Karlebotn monadnocks: late Neoproterozoic of northern Norway[1]

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Abstract: Located near the village of Karlebotn in East Finnmark, Norway, a cluster of six gneissic monadnocks is unconformably surrounded by weakly metamorphosed sandstone strata of late Neoproterozoic age in the Smalfjord Formation. Differentiated by faults, the monadnocks were further sculpted by a glacier that flowed through a coastal valley concordant with the present-day Varangerfjorden. The largest of the monadnocks is 337 m long and 167 m wide. There remains ample evidence of glacial activity associated with this feature. Relict lodgement tillites are preserved on the west side of the monadnock, flowtillites on the steep surfaces of the north and southwest sides, and a small esker directly on top. The valley was later inundated due to glacial eustacy, and the Karlebotn monadnocks became an archipelago in a shallow estuary of a broad fjord. Interpretation of exposed versus sheltered rocky shores on opposite sides of the largest monadnock island is supported by mineralogical variations in basal strata along the unconformity and evidence of paleocurrents. Greater water energy was concentrated on the southeast side, where a small sandy beach developed. Water energy must have been minimal on the north side because of a general lack of reworking and winnowing of till when the rocky shore was inundated.

Résumé : Situé à proximité du village de Karlebotn dans l'est de Finnmark, en Norvège, un ensemble de six monadnocks gneissiques est entouré de manière discordante par les strates de grès, faiblement métamorphisées, de la Formation de Smalfjord (Néoprotérozoïque tardif). Différenciés par des failles, les monadnocks ont été entaillés encore plus par un glacier qui s'écoulait dans une vallée côtière, laquelle concorde avec l'actuel Varangerfjorden. Le plus gros des monadnocks mesure 337 m de long sur 167 m de large. De nombreuses évidences d'activité glaciaire sont encore bien visibles. Des reliques de tillites de fond sont préservées sur le côté ouest, des tillites d'écoulement sur les pentes abruptes des côtés nord et sud-ouest et un petit esker directement sur le dessus. Plus tard, la vallée a été inondée en raison de l'eustasie glaciaire et les monadnocks de Karlebotn sont devenus un archipel dans l'estuaire peu profond d'un large fjord. L'interprétation des rivages exposés par rapport aux rivages protégés sur les côtés opposés de la plus grosse île monadnock est appuyée par les variations minéralogiques des strates de base le long de la discordance et des évidences de paléocourants. La plus forte énergie de l'eau était concentrée sur le côté sud-est, où une petite plage sablonneuse s'est développée. L'énergie de l'eau devait être minime sur le côté nord car le till n'a pas été retravaillé ni trié lorsque le rivage rocheux a été inondé.

[Traduit par la Rédaction]

Introduction

Ancient islands with rocky shores may be recognized by an unconformity between a geological inlier or monadnock, surrounded by younger strata deposited in an aqueous environment. Relatively few ancient archipelagos are described (Dott 1974; Johnson 2002), although paleoislands can be important for the interpretation of coastal paleogeography and related patterns of marine and atmospheric circulation. Until now, paleoislands have not been described in any detail from rocks of Precambrian age or from a fjord setting during an interglacial period.

The late Neoproterozoic Smalfjord Formation in East Finnmark, Norway, has been the topic of numerous studies since Reusch (1891) described the glacially striated pavement on which the unit is deposited. Most of the attention has been devoted to basal diamictites in the Smalfjord Formation (e.g., Holtedahl 1918, 1930; Rosendahl 1931; Crowell 1964; Reading and Walker 1966; Bjørlykke 1967; Edwards 1975, 1984, 1997; Føyn and Siedleckie 1980; Jensen and Wulff-Pedersen 1996; Rice and Hofmann 2000; Laajoki 2001, 2002; Arnaud and Eyles 2002). By comparison, the rest of the overlying Smalfjord Formation has received less attention.

Holtedahl (1918) described the Karlebotn monadnocks as "granitic islands" expressing original topographic relief. Sandstone patches that lay directly on the granite were found to include conglomerate with angular clasts of varied

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lithology. Holtedahl mentioned additional monadnocks at Skiippagurra, about 12 km west of the Karlebotn monadnocks (Fig. 1*a*). Bjørlykke (1967) also observed patches of quartzite on the gneiss and concluded through thin-section studies that the gneiss surface below the quartzite was unweathered. Laajoki (2004) studied the largest monadnock at Lárajeaggi mainly in the context of its being an earlier landform during the Neoproterozoic glaciation. He interpreted the monadnock as having been sculpted by Neoproterozoic and Pleistocene glaciers moving in opposite directions. The western side was found to be the original Neoproterozoic lee side, where ice plucked and eroded material from the rough incline. Neoproterozoic diamictite occurs at the base of the steep lee side in fractures and hollows in the basement gneiss. Laajoki also recognized sandstone relicts on the smooth stoss side of the gneiss monadnock.

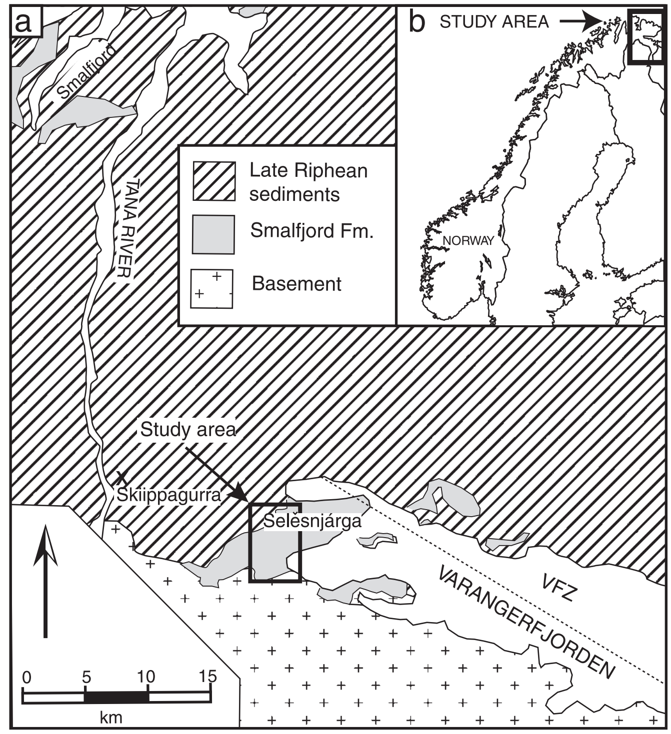
Baarli et al. (2006) considered the monadnocks only briefly as paleoislands in the context of a broader study on the Smalfjord Formation. This companion study is focused on the monadnocks as rocky shores prior to and during deposition of the Smalfjord Formation. The monadnocks were mapped and paleocurrent data collected from the surrounding Smalfjord Formation. Sedimentological signatures along the perimeter of the largest monadnock were carefully checked to determine facies variation of coastal sediments.

Geographic setting of monadnocks in the Varangerfjorden area

The monadnocks occur near Karlebotn, at the terminal end of the Varangerfjorden on the Selesnjárga peninsula (Fig. 1). Five of the monadnocks are aligned in a south-southeast to north-northwest direction between the beach at Karlebotn and a small quarry 0.4 km west of Highway 6 (Fig. 2). They are composed of gray and pink gneisses of granitic and tonalitic composition. The gneisses belong to the metamorphosed basement of the Fennoscandian Shield, which is Neoarchean to Paleoproterozoic in age. A part of this shield is exposed on the south side of the Varangerfjorden. It is overlain by the Neoproterozoic sedimentary Tanafjord and Vestertana groups on the north side of the fjord (Figs. 1*a*, 3). Thus, the monadnocks are inliers near the boundary between the shield and overlying sedimentary units. All five monadnocks are directly onlapped by the Smalfjord Formation, the basal stratigraphic unit of the Vestertana Group (Fig. 3).

The larger paleogeographic setting was reviewed recently by Laajoki (2002), Røe (2003), and Baarli et al. (2006). In short, sedimentary strata were deposited on the margin of an oceanic basin situated on the Baltic Shield (Olovyanishnikov et al. 2000). Røe suggests there were two episodes of extensional activity earlier during Cryogenian time which led to development of a major fault zone beneath the Varangerfjorden (marked as VFZ in Fig. 1*a*). During deposition of the Smalfjord Formation in a paleovalley running along this fault zone, the margin was passive (Røe 2003). The valley was initially incised by a glacier and later further eroded by braided rivers and other erosive facies in a shallow fjord estuary (Baarli et al. 2006). Occurrence of diamictites at the base of the Smalfjord Formation is associated with the Marinoan glaciation (Halverson et al. 2003), which occurred between 650 and 600 Ma (Fig. 3).

Fig. 1. Geological map of the Varangerfjorden area with inset map of Norway.



At the classical locality of Oaibáhcannjárga on the coast 1 km northeast of the nearest monadnock, the Smalfjord Formation overlies a striated surface on the Veinesbotn Formation marking a disconformity that cuts out three other formations known elsewhere in the Tanafjord Group (Fig. 3). Laajoki (2002) documented comparable striated surfaces below the Smalfjord Formation at several other localities. The basal Smalfjord Formation displays a variety of facies (Edwards 1984; Laajoki 2004; Baarli et al. 2006), although diamictites of varying composition are most common.

The Smalfjord Formation reaches a minimum known thickness of 130 m at Selesnjárga, where the monadnocks occur. The lithology consists largely of weakly metamorphosed sandstones with minor conglomerates and diamictites. The diamictites occur near the base where a maximum 2 m thick exposure is found on the Selesnjárga peninsula. Edwards (1984) divided the sandstone strata above the diamictites into four facies (S1–S4), all of which display conglomerate lenses more or less prominently. Facies S1 and S3 occur near the monadnocks, although only facies S3 is in direct contact with them. Facies S3, which entails most of the Smalfjord Formation, has been called a “structureless sandstone” by earlier authors, although some structures are present. Baarli et al. (2006) subdivided facies S3 into S3a and S3b. Both are light-colored sandstones, but facies S3a displays cycles of coarser to finer sandstone with medium to thick, sometimes lensoid bedding with no conglomerate lenses. Facies S3b is better sorted in medium thick, parallel-bedded layers with a few sandy, paraconglomeratic lenses that increase in frequency upward. Baarli et al. tentatively interpreted facies S3a as tidal-channel deposits and facies S3b as tidal-flat deposits in a shallow fjord estuary. The conglomerates were attributed to mass flow off the valley sides

Table 1. Physical dimensions of the Karlebotn monadnocks.

Monadnock	Circumference (m)	Long axis (m)	Long axis trend	Short axis (m)	Short axis trend	Max. elevation (m)
Little Island	~70	22	N3°W	20.3	N87°E	3.8
Sister Island	~370	142.6	N3°W	111.0	N87°W	19.2
Egg Island	688.5	225.9	N10°W	164.7	N80°E	22.3
Long Island	1029	336.5	N75°W	167.1	N18°E	19.6
Sheep Island						
West Sheep	na	37.3	—	24.3	—	4.2
East Sheep	na	98.8	—	73.5	—	9.6

Note: Elevation and circumference are defined by gneiss exposure, not by contour topography. na, not available.

Fig. 2. Geological map of the study area near Karlebotn, showing distribution of the gneiss monadnocks.

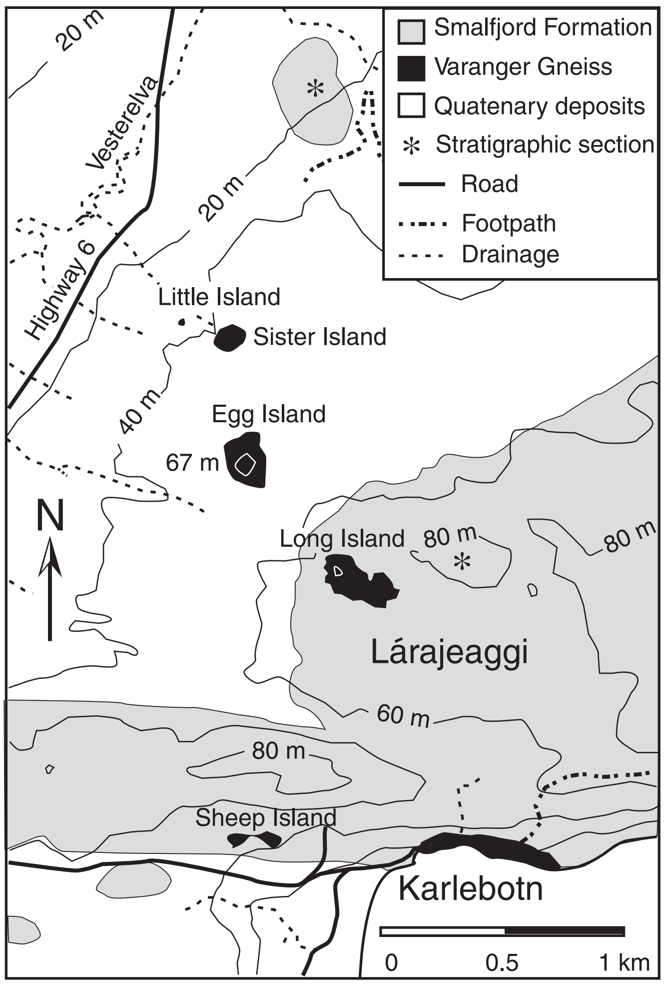


Fig. 3. Stratigraphy of Neoproterozoic strata in the study area. Reference to chronological data is from Gorokhov et al. (2001) and Halverson et al. (2003).

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

and local topographic highs in the valley bottom. The tidal-flat facies show a transition to braided-river deposits (facies S1), commonly with intervening shoreface facies.

Results

Size and placement of the monadnocks

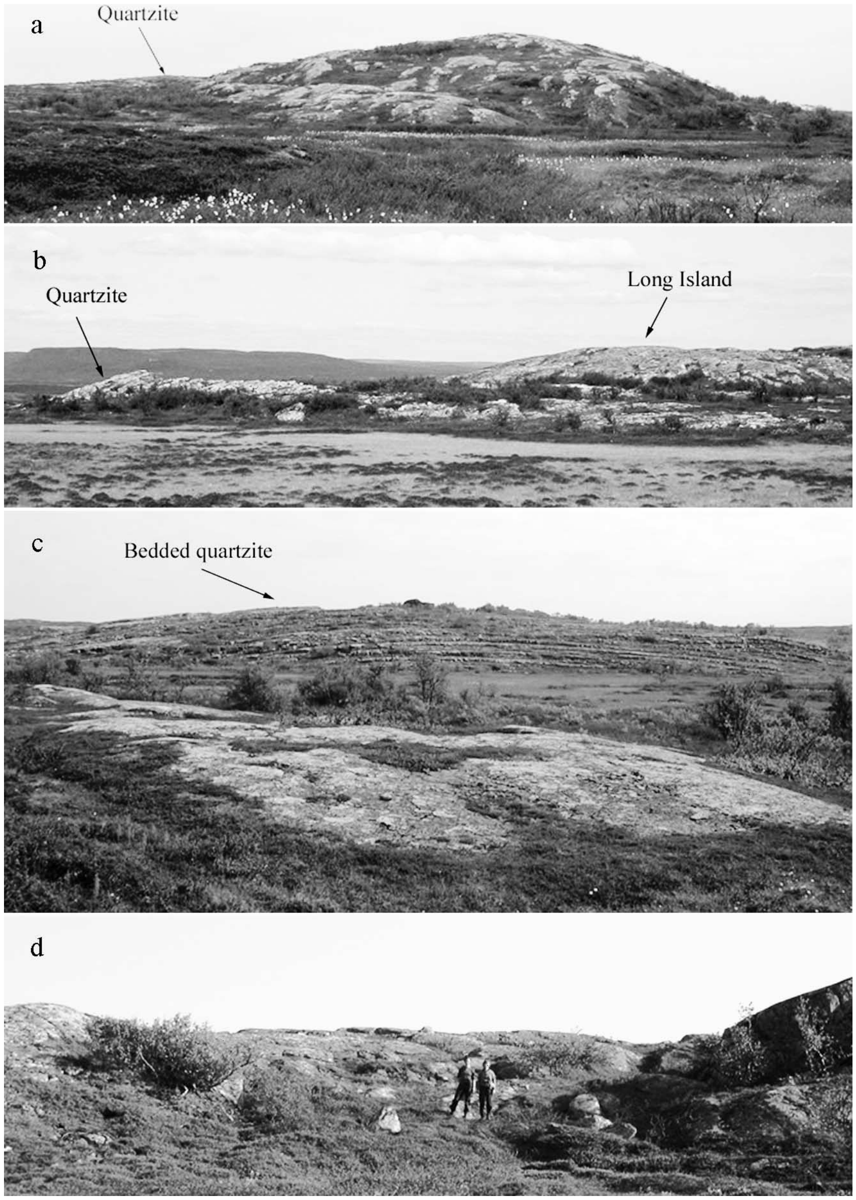
Map references to the approximate center of five monadnocks are derived from Norges geologiske undersøkelse (NGU) 1 : 50 000 scale map series 2335, NOR4: Sheep Island in Karleboth (map reference 804 595), Long Island (814 596), Egg Island (819 593), Sister Island (825 592), and Egg Island (826 590). Another gneiss inlier occurs along the shore east of Karlebotn (804 600 to 803 607). Because it partly occupies the tidal zone, this monadnock was not investigated in detail. The physical dimensions of the island monadnocks are summarized in Table 1.

Egg Island rises 67 m above sea level and, with 22 m of topographic relief, has the greatest elevation above the surrounding landscape of all the studied landforms (Fig. 4*a*). The elevation of Long Island is 80 m above sea level, and the monadnock has a relief of nearly 20 m above the surrounding area (Figs. 2, 4*b*). It is followed by Sister Island at about 60 m above sea level with a relief of 19 m above the surrounding landscape. Little and Sheep islands both reach close to 40 m above sea level, with an exhumed relief of about 4 and 10 m above their surroundings, respectively.

Monadnocks related to local fault patterns

The geological map of the region (Siedlecka 1990) was used to search for possible trends in fault orientation. Fault orientations from the map are plotted on a rose diagram and

Fig. 4. Landscapes near Karlebotn in the Varanger area. (*a*) Egg Island rising out of the boggy landscape that surrounds it. The rock visible to the left (see arrow) lies south of the monadnock and is composed of quartzite. (*b*) Long Island as seen from the southwest. Notice how the quartzite outcrop (see arrow) dips away from the monadnock. (*c*) View from Long Island (in the foreground) looking towards the northeast and the bedded quartzites (see arrow) of facies S3b that transition into facies S1. (*d*) View of the draw near transect Sb–Nb. Notice how it continues upwards towards the middle of the monadnock.

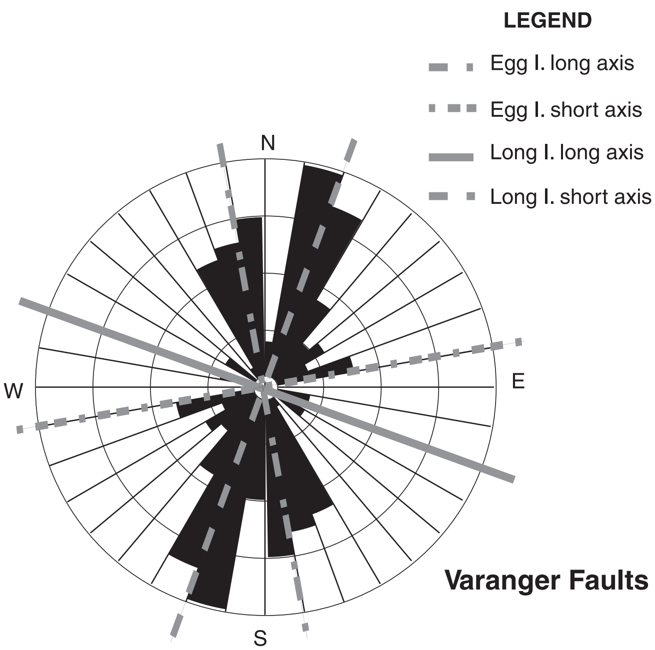


compared with the axes of the monadnocks (Fig. 5). There are two primary fault directions, one at approximately N20°W and the other at N25°E. The outcrop alignment of monadnocks follows a general trend that coincides with one of the primary fault directions at N20°W (Fig. 2). Plotting the long and short axes of the monadnocks also fits well, as one axis is always consistent with one of the major fault trends.

In addition, there is evidence of two minor fault directions normal to the two primary fault trends (Fig. 5). One of these minor fault directions coincides with a postulated fault zone below Varangerfjorden (Røe 2003) trending about N70°W, and this also corresponds to the long axis of Long Island (Fig. 5). Therefore, faulting has played at least some role in framing the shape and geographic orientation of the monadnocks.

It is important to emphasize the considerable topographic relief expressed by the monadnocks. Today, they stand about 20 m above the landscape as typified by Long Island (Fig. 6*b*). Prior to burial, the gneiss topography may have had a maximum relief of at least 100 m in some locations on Selesnjárga (Edwards 1984). Paleotopography was not due to faulting alone. Laajoki (2004) showed that some of the monadnocks were eroded by glaciers, both during the Pleistocene and during the Marinoan glaciation before deposition of the Smalfjord Formation.

Fig. 5. Orientation of faults in the Varanger Gneiss Complex with the short and long axes of Egg and Long islands superimposed (n = 130).



Relation of monadnocks to their surrounding strata

Five monadnocks were inspected for direct contact between the basement gneiss and the adjoining sedimentary succession of the Smalfjord Formation. Where contact was found, strike and dip were measured and lithological samples were collected. In cases where the overlying basal strata displayed clasts, a 30 cm × 30 cm grid was laid out and all clasts having a long axis greater than 5 mm were recorded as to composition and drawn to scale. The orientation and length of the long axis of each clast were also measured. It was possible to measure a continuous stratigraphic section from the contact through successive sedimentary layers at only one locality.

Both the Little and Sister islands are surrounded by bog and thick brush with no visible contact with surrounding strata. The former is located about 500 m south of the Vesterelv outcrop (Fig. 2), which features facies S1 of the Smalfjord Formation. There are several sandstone outcrops from the Smalfjord Formation situated in close proximity to Egg Island, but none in direct contact. The closest outcrop is about 1 m away from the gneiss. The strike of these beds in outcrop is N13°W, and the dip is 25°E following the dip and strike of the underlying gneiss surface.

Sheep Island is situated in a pasture about 150 m north of the access road from Highway 6 to Karlebotn (Fig. 2). The outcrop entails two bodies of gneiss separated by about 30 m. Both express very irregular shapes. No direct contact with the surrounding sandstone is evident. On the western monadnock, however, there occurs a thin quartzite layer that sits directly on the gneiss. There is also a depression in the gneiss, where a thicker sedimentary deposit accumulated. The rocks consist of a paraconglomerate with larger pebbles in the bottom fining up through a 8 cm thick succession. Another lens of conglomeratic material extends 7.5 m eastwards along the top of the monadnock.

Long Island is the largest and most elongate of the monadnocks (Figs. 4*b*, 6*a*; Table 1). Parts of the paleoisland are surrounded by bog or drier brush, but direct contacts between the gneiss and the surrounding strata of the Smalfjord Formation are found at numerous localities as marked in Figs. 6*c* and 6*d*. Facies S3b with a transition to facies S1 is well exposed about 300 m to the north across a bog (Fig. 4*c*). A more detailed description of the nonconformity around this monadnock is given in the next section.

Microenvironments on and around Long Island

Contacts around the Long Island monadnock are fairly evenly distributed (Fig. 6) and facilitate analysis of different paleoenvironments around the circumference of the monadnock. Combining the local results with the larger setting of the Smalfjord Formation as interpreted by Baarli et al. (2006), it is possible to interpret a detailed history from the onset of sedimentation until the island monadnock was buried.

Description of rock contacts

Grids (30 cm × 30 cm) for clast counts were laid out around the circumference of the monadnock (Fig. 6*c*) except for parts of the south and east sides where sandstones without large clasts are plastered against the gneiss. Data from nine grids were collected for basal clast counts, with grid 8 located within the interior of the monadnock (Fig. 6*c*). All grids show a predominance of gneiss clasts or smaller mineral clasts of feldspar and quartz originally derived from the gneiss (Table 2). Sandstone and quartzite fragments are a minor component in grids 1–5 on the northwestern part of the monadnock. This component is absent in grids 6–9 towards the southeastern end of the monadnock.

Diamictites previously described by Laajoki (2004) occur at the northwest end of the monadnock. We recorded grids 1–3 (Fig. 6*c*) with diamictite content. The diamictites occur commonly as thin layers on top of the gneiss or as fill in shallow depressions and fractures, revealed where the overlying strata were stripped away. It was possible to measure diamictite deposits 20 and 9 cm thick at grids 2 and 3, respectively. The clasts vary from boulders to pebbles, with cobbles and pebble sizes about equally common (Figs. 6*c*, 7*a*). The clasts themselves are angular to subrounded and very poorly sorted. Bullet- and blade-shaped clasts are fairly common. In grids 1–3 there is some degree of orientation expressed among the elongated clasts, with one major group of clasts oriented with axes parallel to the long axis of the monadnock, and the other major group with axes perpendicular to the long axis (Fig. 8). Gneiss clasts dominate, whereas sandstone and quartzite clasts are common (Table 2). A few fragments of a dark igneous rock also were encountered in grid 3. The matrix in the three grids is rust red in color, and grid 1 includes cement of iron oxide (Fig. 9*a*). In thin section, the matrix is a sublitharenite, whereas the grains are poorly sorted and include a mix of angular and subrounded grains. There is a weak orientation of grains that mimics the pattern observed in the grid sample. Quartz grains dominate, but lithic fragments are prominent (Table 3). Compaction is moderate. Samples for thin

Fig. 6. Details and references to orientation, development of clastic rocks, and mineralogical composition. (*a*) Long Island reconstruction with transects, quartzite strike and dip, current directions, and stratigraphic sections marked. The southernmost arrow for current directions has been taken from a locality outside of this map. (*b*) Profiles across the long and short axes of Long Island. Note the difference in vertical and horizontal scales. (*c*) Size classes represented in clast data from grids around Long Island. (*d*) Composition of rocks in direct contact with Long Island gneiss as determined by thin section analysis (number of count points in each thin section is 450).

Table 2. Rock composition of clasts from the grid samples.

Clast count	Grid 1	Grid 2	Grid 3	Grid 4	Grid 5	Grid 6	Grid 7	Grid 8	Grid 9
Feldspar	1	0	2	2	0	0	1	1	3
Quartz	5	0	1	5	5	2	4	2	0
Gneiss	84	34	26	37	44	22	63	23	2
Sandstone	5	16	3	3	2	0	0	0	0
Quartzite	3	0	2	2	0	0	0	0	3
Unidentified	2	1	7	2	0	0	0	0	0

sections were not collected from grids 2 and 3, but the matrix is equally bright red.

Grids 4–7 were recorded from the north side of the Long Island monadnock. All are close to or come from a cove in the gneiss that follows a small topographic draw until it terminates near grid 8 (Fig. 4*d*). Clasts observed both in the grids and in thin sections are mainly subrounded to rounded (Figs. 7*b*, 9*f*). The majority of clasts in grids 4 and 5 on the west side of the draw are pebble size, sparse and floating in the matrix. In both cases, the paraconglomerate is plastered directly against the gneiss surface. These samples were recorded at levels 9 and 5 cm above the gneiss surface, respectively, at a dip of about 42°. The conglomeratic layer has two sets of orthogonal joints parallel to the dip direction (Figs. 7*b*, 7*c*). In grids 6 and 7, the clasts are much larger, mainly of cobble size (Fig. 6*c*). Grid 6 was placed about 50 cm above the gneiss surface at a dip of 16°. Grid 7 comes from a slightly displaced block that had shifted about 20 cm down the gneiss surface. In this sample, clasts mainly of cobble size dominate, although they remain matrix supported. The matrix is reddish colored in grids 4–7, but much paler in tone than that in grids 1–3. Thin sections from grids 4 and 5 show a slightly bimodal grain-size distribution, involving subrounded to rounded, coarse to medium sublitharenite to litharenite (Fig. 9*f*). The compaction of grains is moderate. Larger elongate grains tend to orient themselves subparallel to the gneiss surface. Quartz grains dominate, whereas lithic clasts are the next most common lithology. Iron oxides are rare (Table 3).

In the middle of the monadnock where the draw ends, there occurs a 6 m long, 1.45 m high, and 2.85 m wide, upward-tapered ridge formed by cemented boulders (Fig. 7*d*). Grid 8 was recorded from an exposed cross section through this ridge. The ridge rests on the gneiss surface and at one time was clearly covered by sandstone strata of the Smalfjord Formation which still remains 1.5 m in front of the crest overlying boulders and cobbles. Boulders found at the base of the sandstone section may represent a flank of the extended ridge. The surface of the ridge is obscured by a thick layer of lichen and vegetation that make lithological identification of the boulders difficult. The boulders are partly eroded out of the finer matrix. The remaining matrix is very hard. Many of the boulders are faceted and ellipsoidal in shape. These large clasts have a preferred orientation perpendicular to the direction of the ridge (Fig. 7*d*). This is the only example of clast-supported lithology on or around the monadnock. The matrix is reddish-colored, and clasts make up 58% of the grid surface (Fig. 6*c*). The majority of clasts are rounded to subrounded gneiss cobbles to boulders. Some internal sorting of clasts is evident because the uppermost crest of the ridge displays smaller, cobble- to pebble-sized clasts and measurement of the long axes of clasts in the grid indicates some level of preferred orientation (Fig. 8). A thin section of the matrix shows a poorly sorted, coarse feldspathic litharenite, in which quartz grains account for 43% and clay minerals about 22% of the composition (Fig. 9*c*; Table 3). Lithic grains of mainly gneiss are very common, as are feldspar and mica grains. The grains are subangular to rounded in shape and moderately compacted. The elongate grains commonly show the same orientation. Many of the larger grains have a thin iron oxide crust (Fig. 9*c*, see arrow).

Two samples from the south side (Sb-44 and Sb-47) are similar, except that the latter sample includes a few clasts (Fig. 6*c*). They are both light pink, fine sublitharenites to litharenites (Fig. 9*b*; Table 3) with moderate compaction, so the grains float in a finer matrix. Sample Sb-44 shows moderate sorting and the clasts are subrounded to angular, whereas Sb-47 exhibits poor sorting and the larger grains are rounded. There is a clear bimodal composition. The matrix in sample Sb-44 has a quartz content of 84%, whereas sample Sb-47 has 75% quartz content and clay minerals are more predominant (Table 3). Site Sb-47 is interesting, because the 6 cm thick sandstone seems to flow down the gneiss surface (Fig. 7*f*) and displays clear flow lobes.

On the north side, between the diamictites and the draw, light-colored sandstone occurs directly on the gneiss surface. Sample Na-10 is located midway between the diamictites and the embayment, whereas Na-12 is at the outer western mouth of the embayment, 10 m from grid 4 (Fig. 6*d*). Sample Na-10 consists of a slightly pink, fine-grained subarkose that is subrounded and well to very well sorted. Compaction is high and the contact between grains is commonly sutured. Total quartz content is 83%, whereas clay minerals, feldspar,

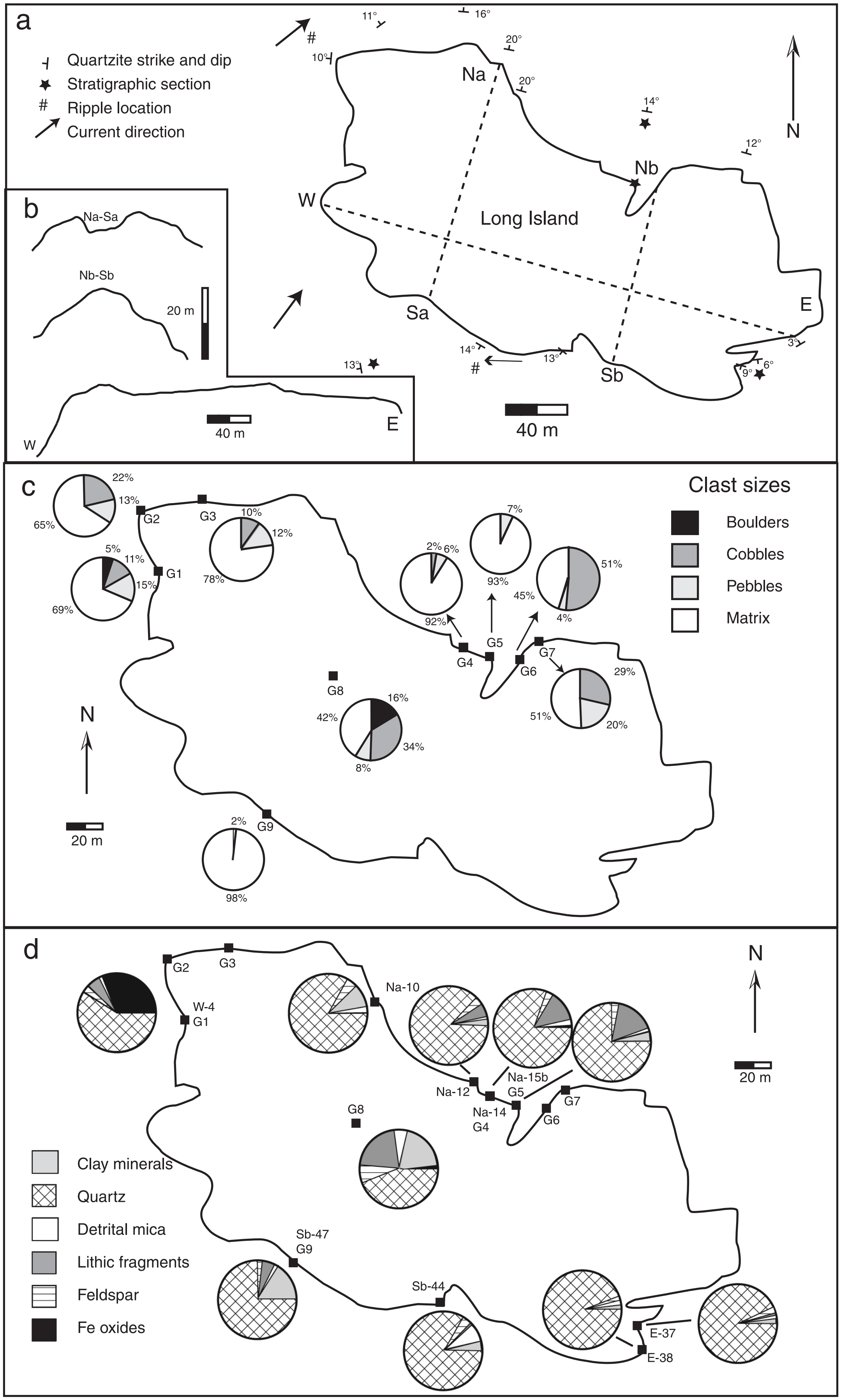
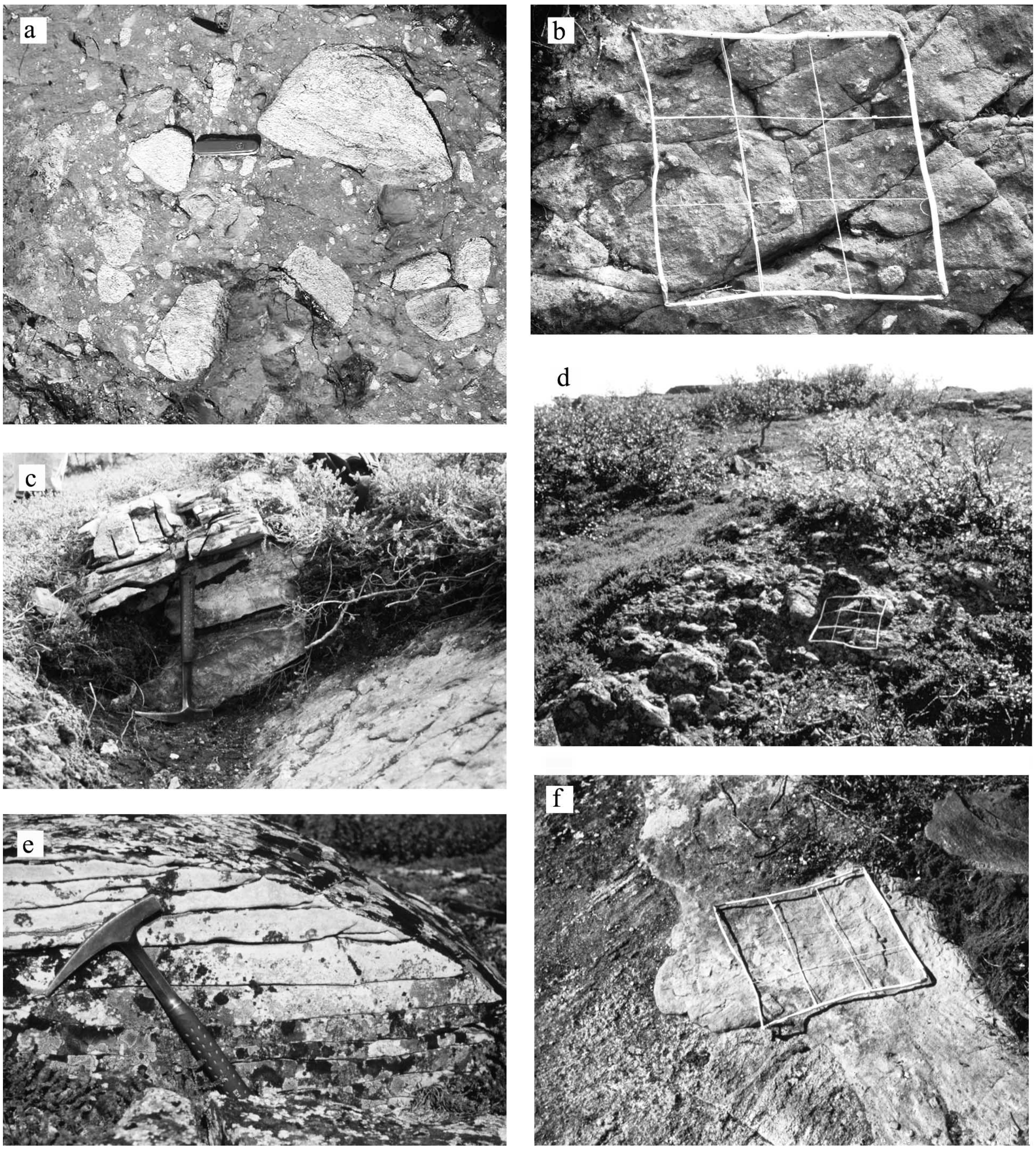

a
Quartzite strike and dip
Stratigraphic section
Ripple location
Current direction
Na
Nb
W
Long Island
Sa
Sb
E
N
40 m
b
Na-Sa
Nb-Sb
20 m
40 m
W
E
c
Clast sizes
Boulders
Cobbles
Pebbles
Matrix
G1
G2
G3
G4
G5
G6
G7
G8
G9
20 m
d
Clay minerals
Quartz
Detrital mica
Lithic fragments
Feldspar
Fe oxides
W-4
Na-10
Na-12
Na-14
Na-15b
Sb-47
Sb-44
E-37
E-38
20 m

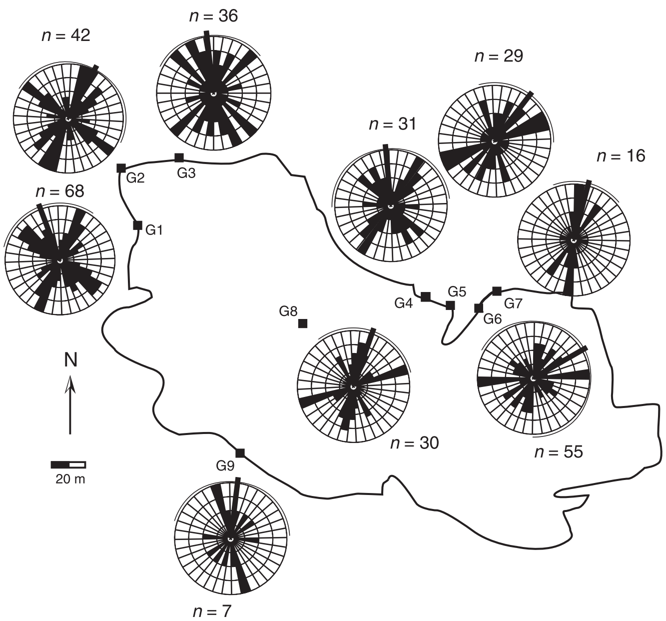
Fig. 7. Outcrop exposures along the periphery of the Long Island monadnock. (*a*) Photograph of locality at grid 1 (knife for scale is 9 cm long). Notice the bullet-shaped larger clasts. (*b*) Photograph of grid 5 (grid for scale is 30 cm across). Notice the joints in the tillite surface. (*c*) The stratigraphic section at grid 5 (hammer for scale). The paraconglomerate at the base is plastered directly against the gneiss, whereas the top portion is well-sorted sandstone. (*d*) Cross section of fossil esker at grid 8 (grid for scale is 30 cm across). Notice the orientation of the larger boulders. (*e*) Thin bedded sandstone interpreted as foreshore deposits on the east side of Long Island (hammer for scale). (*f*) A thin paraconglomerate on the gneiss surface on the south side of Long Island (grid for scale is 30 cm across). Notice the flow lobes of the tillite.



and mica are common (Table 3). Thin-section study of sample Na-12 reveals a coarse subarkose to sublitharenite with grains that are medium to poorly sorted and subrounded to rounded. Compaction is medium to high (Fig. 9*d*). The rock contains 88% quartz and 5.5% lithic fragments (Table 3).

There are no contacts exposed along the perimeter on the northeast side of the monadnock, but there are several localities with sandstone plastered directly against the gneiss along the east and south flanks of the monadnock (Fig. 6*a*). Laajoki (2004, figs. 1*c*, 4*a*, 4*b*) reports a quartzite relict from the south side of the monadnock. It is difficult to know

Fig. 8. Orientation of the long axes of clasts from each grid plotted on a map of the Long Island monadnock.



for certain if that coincides with one of our localities because of the generalized nature of his map. The locality may be from a higher elevation and not observed by us.

Thin sections from the two east-facing localities (E-37 and E-38) are similar (Fig. 9*e*). They consist of a light, fine-grained, arenite to subarkose that is subrounded, highly compacted, and very well sorted (Fig. 9*e*). They exhibit total quartz contents of 93% (E-37) and 95% (E-38), with minor amounts of clay minerals, feldspar, and mica (Table 3).

Vertical stratigraphic sections

A 58 cm thick section from the gneiss surface through the Smalfjord Formation was excavated at locality Na-15 on the north side of the Long Island monadnock (Fig 7*c*). This section was measured in detail (Fig. 10), and samples for thin sections (Figs. 9*f*–9*i*) were collected from the gneiss and from each distinct bed, as marked. The basal bed is 5 cm thick, light reddish in color, and consists of coarse sandstone with larger clasts oriented parallel to the bedding surface, which follows the steep incline of the gneiss surface at 42°. A thin section from this level shows a texturally immature litharenite to sublitharenite with moderate compaction (Table 4; Fig. 9*f*). The succeeding 15 cm thick layer consists of dark gray sandstone with pebbles floating in the matrix. This layer pinches out towards the gneiss surface, so the upper surface dips almost parallel with the overlying sandstone beds at 18° (Fig. 7*c*). The bed is graded from coarse to fine sand over a thickness of 15 cm. Thin sections show a change from moderate compaction near the base (Fig. 9*g*) to high compaction near the top (Fig. 9*h*), as well as a corresponding decrease in clay minerals and an increase in mica content through subarkose and sublitharenite towards arenite (Table 4). Clasts are oriented parallel to bedding. They have a maximum diameter of 2.5 cm near the base and decrease in size upwards. A small percentage of gneiss clasts is present at the top of the bed, but is only as seen in thin section (sample Na-15d; Fig. 9*h*; Table 4). No lithics occur near the top or above that bed in outcrop or thin section (Fig. 9*i*). At the top of the section, quartz content in thin section is 89% and the bed resembles typical facies S3b of the Smalfjord Formation (Fig. 9*i*). Worthy of note, however, is the steady increase in mica content through the section (Table 4).

Two outcrops of sandstone strata near the monadnock may be used to relate the immediately surrounding strata to the facies scheme of the Smalfjord Formation. One outcrop is exposed 40 m north of transect Nb–Sb (Fig. 6*a*). The second section occurs on the southwest side about 60 m from the perimeter of the gneiss. Beds from these two localities dip in near-opposite directions, with dips of 13° and 14° (Fig. 6*a*). The first is a 4 m thick succession composed of medium-grained sand of medium thick and laterally continuous bedding. The grains in the sandstone are well sorted and rounded. The other succession consists of a similar facies, although grain size is mainly fine sand and thin beds are more common. No structures are visible. In both cases, this corresponds to facies S3b of the Smalfjord Formation.

A third section occurs close to locality E-37, about 1.5 m away from the gneiss surface. The 35 cm thick section consists of strongly compacted, very light colored, fine sandstone with rounded, very well sorted grains. The sandstone shows very thin to thin bedding without any measurable dip (Figs. 6*a*, 7*e*). This is probably a foreshore deposit where compaction close to the gneiss basement altered the original dip.

Paleocurrent directions

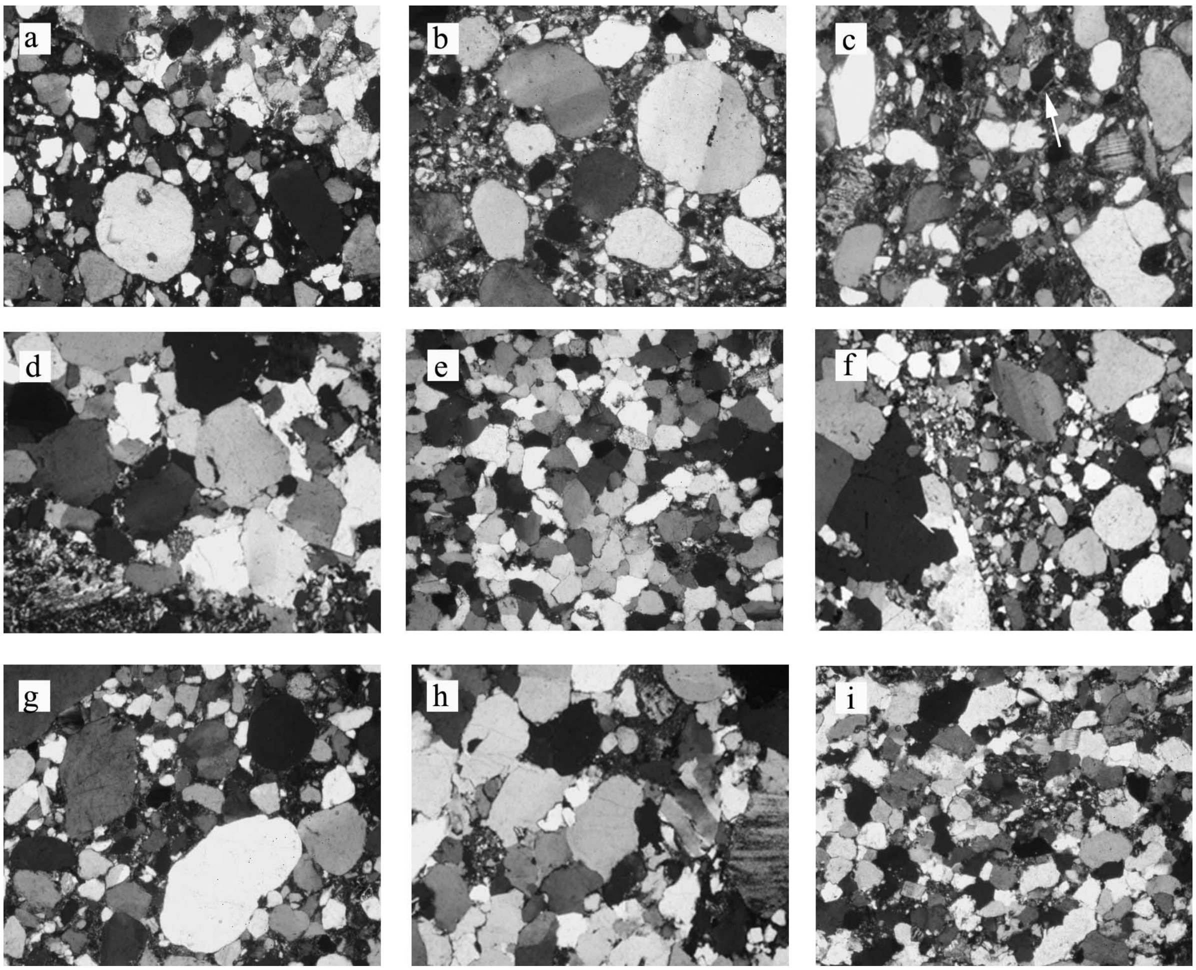
Facies S3 of the Smalfjord Formation onlaps the Long Island monadnock (Fig. 4*b*). Sedimentary structures are rare in this facies, which represents tidal channels and tidal flats. Bedding planes with well-preserved ripple marks occur at two places near the gneiss monadnock (Fig. 6*a*). A bedding plane on the south side features a set of small-scale current ripples. Another near the northwest end shows ripple marks derived from combined flow. These and a few additional ripple sets were reported by Baarli et al. (2006). The prevailing current direction in facies S3 is from the southwest to the northeast. This direction is different from the current directions observed in facies S1, S2, and S4. The one small-scale current indicator from the south side of the monadnock corresponds to the east-southeast to west-northwest direction found in facies S1, S2, and S4.

Interpretations

The chain of monadnocks exhumed at the termination of the Varangerfjorden was first differentiated by the primary fault pattern in the area. When the Varangerfjorden paleovalley was sculpted by ice during the Marinoan glaciation, this chain stood out obliquely as a ridge from the valley wall. Glaciers moving through the valley further eroded and sculpted the monadnocks as indicated by the roche moutonnée profile of the Long Island monadnock and the congruence of one of the axes of the smaller rounded monadnocks with the general direction of glacial movement.

The unsorted, deep red deposits found on the western, lee side of the roche moutonnée of Long Island are relict lodgement tillites left behind in cracks and as a thin crust atop the gneiss. The boulder ridge on the top of the monadnock was

Fig. 9. Petrographic features of the sandstones and tillites in the basal layers above the gneiss surface of the Long Island monadnock. Each photograph represents a 3 mm wide segment of a thin section and is taken with crossed polars. (*a*) Tillite from grid 1 on the west side of Long Island. Notice the wide variation in sorting and rounding and the dark iron oxide cement. (*b*) Paraconglomerate from grid 9 on the south side of Long Island. Notice the bimodal size distribution and rounding of larger clasts. (*c*) Thin section from the esker at grid 8. Notice the iron oxide rim around clasts (arrow). (*d*) Coarse sandstone from Na-12 directly on the gneiss surface as seen in the left corner. Notice the high degree of compaction compared with the tillites. (*e*) Fine, well-sorted sandstone from E-38 on the east side of Long Island. (*f–i*) Photographs of thin section taken throughout the stratigraphic section at Na-15 on the north side of the island. The samples are in stratigraphic order from Na-15b, Na-15c, Na-15d, and Na-15g (Fig. 10). Notice the change in compaction between the two lowest samples and the two highest samples.



most likely deposited below the ice on dry land in a tunnel with high-velocity meltwater just before the glacier retreated from the area. The iron oxide rim on many of the clasts, seen only in the oldest lodgement tills and in the boulder ridge, indicates that some of the material may have been eroded out of an earlier lodgement till. Some of the coarse material was flushed down the draw either as a washout fan or perhaps as a downward continuation of the esker.

The basal material plastered against the steep gneiss surface on the north and south sides of the monadnock is interpreted as subglacial flowtillite. The tillites from the south side further demonstrate this by preservation of terminal flow lobes preserved draped over the sloping gneiss surface (Fig. 7*f*). The tills associated with the north and southwest sides are dark tan in color and lack the iron oxide matrix observed on the western side of the monadnock. These localities are situated at higher elevations and were transgressed at a later stage when the ocean waters were well oxygenated.

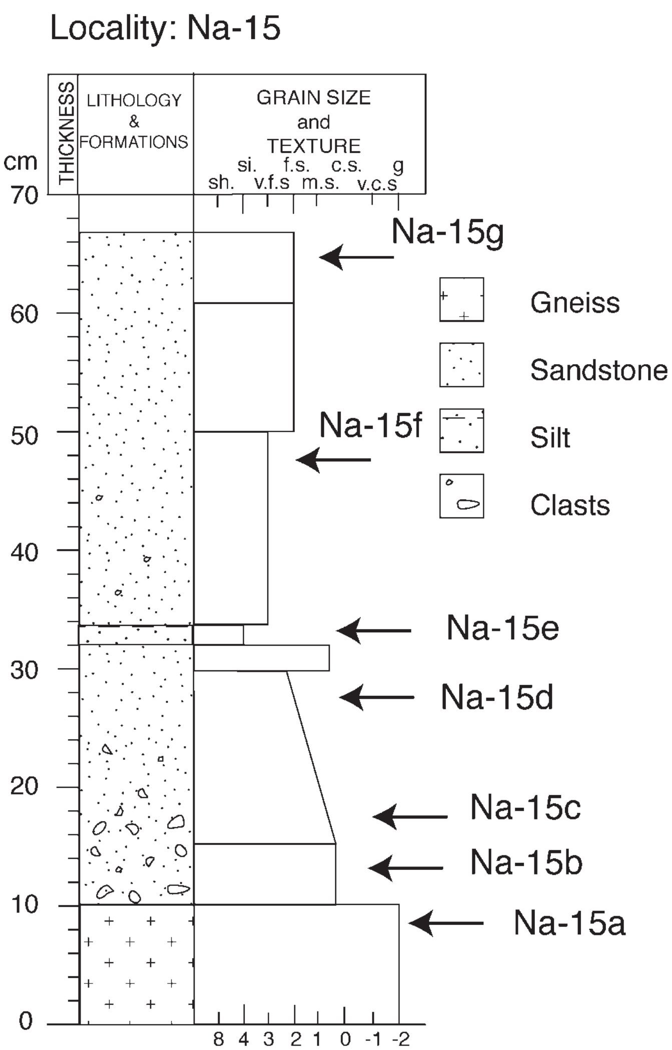
The sandstones plastered directly against the gneiss on the north and east sides are very compacted without much cement. These sands were transported by water around the rocky shore of the island in a tidal-flat setting. There is a clear difference in maturity and sorting among these samples. Samples collected from the north side are less mature and less well sorted than those on the east side. Erosion of the tills at the beach and slumped till from the sides of the island influenced the composition of the sandstone around the islands. This factor can be integrated with current directions based on data from ripple marks (Fig. 6*a*) and the presence of foreshore deposits on the east side. The main conclusion to be reached is that the north side was sheltered, whereas some level of current activity led to deposition of a well-sorted beach deposit on the southeast side. Thus there

Table 3. Point-count data (%; n = 450 counts in all cases) from petrographic thin sections around the perimeter of Long Island monadnock.

Sample	E-37	E-38	Sb-44	Sb-47	G-8	W-4	Na-10	Na-12	Na-14
Quartz grains	92.1	93.4	71.0	71.7	43.0	58.8	80.7	85.1	68.0
Feldspar	2.3	1.5	4.1	2.2	7.5	2.8	4.1	3.5	2.9
LF shale	—	—	—	—	—	—	—	—	1.3
LF polycrystalline quartz	0.7	—	0.7	0.8	2.6	0.9	0.4	1.7	1.3
LF gneiss	—	—	—	4.8	18.4	5.2	—	1.3	10.4
LF schist	—	—	—	—	—	—	—	2.4	—
Heavy minerals	—	—	0.2	—	1.0	—	—	—	—
Detrital mica	1.7	1.8	7.4	1.4	4.3	0.4	2.7	0.9	2.4
Clay minerals	2.0	1.8	4.1	15.2	19.7	—	9.8	2.6	—
Quartz cement	1.0	1.5	12.7	3.4	1.3	—	2.3	2.6	12.7
Fe oxides	—	—	—	—	2.3	31.8	—	—	0.9
Total quartz	93.1	94.9	83.7	75.1	44.3	58.8	83.0	87.7	80.7
Total LF	0.7	—	0.7	5.6	21.0	6.1	0.4	5.4	13.0

Note: LF, lithic fragments.

Fig. 10. Stratigraphic section from locality Na-15 on (Fig. 6*a*) the north side of the Long Island monadnock. sh, clay; si, silt; vfs, very fine sand; fs, fine sand; ms, medium sand; cs, coarse sand; vcs, very coarse sand; g, granule.



existed a protected and more exposed side on opposite flanks of the island.

Tidal currents could not have been very strong, because reworking was negligible on the north side, leaving a silt layer above the reworked tills intact and high mica content in the succeeding sandstone layers. The southeast side would have been fully exposed to the outgoing northwesterly tracking tidal current, which probably was reinforced by currents from fluvial discharge. Periodically, storms entered the valley and reinforced the weak incoming tide to produce combined-flow ripples from the southwest.

Discussion

There is a long-lived controversy regarding the origin of diamictites found at the base of the Smalfjord Formation. The majority of researchers advocate a glacial and fluvioglacial origin (Holtedahl 1918, 1930; Rosendahl 1931; Reading and Walker 1966; Bjørlykke 1967; Edwards 1975, 1984, 1997; Føyn and Siedlecki 1980; Rice and Hofmann 2000; Laajoki 2001, 2002, among others), whereas a minority favor a subaquatic mass-flow origin (Crowell 1964; Jensen and Wulff-Pedersen 1996; Arnaud and Eyles 2002). At this point, knowledge derived from the basal diamictites of the Smalfjord Formation near Karlebotn is considerable. The striated basement at Oaibáhcannjárgais is well known. Laajoki (2002) noted several other localities where the basement was similarly striated. At Vieranjarga, braided river deposits directly overlay the diamictites (Edwards 1984; Laajoki 2002). Laajoki (2004) convincingly demonstrated that the Long Island monadnock was an original landform or roche moutonnée left by glaciers of Neoproterozoic and Pleistocene age. He also suggested that the diamictites preserved at the base of the west side are glacial deposits. Menzies and Shilts (2002, p. 193) pointed out that tillites rarely are distinguished by only a few characteristics. Rather, it is the combination of properties, lithofacies associations, and stratigraphy that must be used. This study adds several other likely glacial facies associations to what already is understood about the basal diamictites.

The deep red diamictites described by Laajoki (2004) do not, by themselves, merit a strict interpretation as lodgement

Table 4. Point-count data (%; *n* = 450 counts in all cases except *n* = 200 for Na-15e) from petrographic thin sections from the stratigraphic section at grid 5.

Sample	Na-15b	Na-15c	Na-15d	Na-15e	Na-15f	Na-15g
Quartz grains	57.6	65.2	75.9	60.5	79.9	85.7
Feldspar	3.1	8.4	6.9	0.5	1.4	2.2
LF shale	—	—	0.7	—	0.2	—
LF polycrystalline quartz	4.4	0.7	—	—	—	—
LF gneiss	11.3	0.9	0.9	—	—	—
LF schist	—	—	—	—	—	—
Heavy minerals	—	0.2	—	—	—	—
Detrital mica	1.1	1.1	3.1	6.0	11.1	8.2
Clay minerals	4.4	7.5	3.3	31.5	5.2	—
Quartz cement	18.0	16.0	8.8	1.5	2.9	3.6
Fe oxides	—	—	0.4	—	0.7	—
Total quartz	75.6	81.2	84.7	62.0	82.8	89.3
Total LF	15.7	1.6	1.6	—	0.2	—

Note: LF, lithic fragments.

tillites; however, they share many characteristics with that facies. They are extremely poorly sorted with a high content of fine material and a diverse lithology among the clasts. Many of the clasts are smooth and bullet shaped, whereas others are blade shaped. Both kinds of clast shape are characteristic for basal till (Hambrey 1994, p. 125). The orientation of elongate clasts as recorded both in grid samples and thin-section samples is common for lodgement tillites. Laajoki (2004) suggested that the diamictites were formed through plucking of the gneiss by ice and that the sharp fractures where some deposits are preserved were caused by freezing. The presence of a considerable amount of quartzite and sandstone in the diamictites indicates that some material also was transported over a longer distance. Preservation of lodgement till is especially likely in the lee of obstructions.

The paraconglomerates found plastered against the gneiss surface in beds dipping up to 40° show many of the same characteristics as the aforementioned diamictites. In addition, they exhibit a clear vertical joint system that is typical of lodgement tillites due to deformation by the weight of overlying ice (Menzies and Shilts 2002, p. 195). The larger clasts, however, are better rounded in these deposits and tend to be orientated parallel to the gneiss surface. The matrix of these deposits retains a weak bimodal size distribution. In one case, the matrix is graded (Fig. 10), indicating some degree of sorting.

Flowtillites are commonly enriched in fine sediments compared with the primary till from which they may have been derived. They may display flow lobes, as seen in grid 9 (Fig. 7*f*), or grading (Menzies and Shilts 2002, p. 197). Flowtillites are commonly associated with later stages of glaciation on an ice margin in a non-aquatic setting, although the jointing indicates deposition below a moving glacier.

Glacial deposits normally show a grain-size distribution that is polymodal. In this study, bimodal grain-size distribution is displayed weakly in some of the lodgement tillites and stronger in the flowtillites. Rattas and Kalm (2001) found bimodal grain-size distribution in tills immediately overlying bedrock in east-central Estonia. They attribute the finest fraction to abrasion of the bedrock and the coarser grain size to preweathered quartz grains. A similar mechanism is a likely explanation in this case. Eolian deposits are common in denuded periglacial environments. Alternatively, it is possible that ice readvancements towards the end of the glaciation also incorporated eolian sediments to account for some of the fine-grained fraction.

Red, iron-rich tillites are commonly associated with the Marinoan glaciation (Hoffman and Schrag 2002). According to Kirschvink (1992), there was little exchange between the air and the oceans during the glaciation because of extensive sea ice, leading to buildups of ferrous iron in the deep sea. When the glaciation ended, extensive deposition of iron oxide occurred. These oxides consist mainly of Fe^{3+} and are related to rapid sea-level rise during interglacial periods (Klein 2001). A rapid rise in sea level seems to be corroborated by this study. There is a gradual transition from the tillites to the sandstones of the Smalfjord Formation. Therefore, the tillites were not lithified at the time they were transgressed. Unlithified flowtillite lobes were unlikely to be preserved unless the transgression was very rapid or the sedimentation rate was very high.

The boulder ridge preserved on the top of the monadnock is interpreted as a small fossil esker. The clear, tapering-upward shape is unique to eskers (Menzies and Shilts 2002, p. 267). The conglomerate from this ridge represents the only facies that is clast supported. This aspect is consistent with an esker model, because turbulent subglacial streams tend to carry away much of the fine material (Hambrey 1994, p. 168). The material is very coarse, and most of the contained boulders are faceted, a clear sign of a glacial origin (Hambrey 1994, p. 125). The corners are well rounded and not bullet shaped, however, indicating that they have been transported by water. The predominant orientation of the larger clasts perpendicular to the direction of the ridge is unusual for eskers. Clast transport was probably by rolling along the ground under high-energy conditions. Eskers develop below active glaciers, although they generally mark the final stage of ice advance and tend to be located close to the ice margin. Fossil eskers are rare, but examples are described from the Ordovician of Mauritania (Mangold 2000) and the Sahara (Beuf et al. 1971); the Carboniferous of the Parana Basin, Brazil (Frakes and Cromwell 1967), and the Falkland Islands (Frakes et al. 1968); and the Permo-Carboniferous of South Africa (Visser et al. 1987).

Geological inliers that represent former archipelagos are not widely reported in the literature. Precambrian quartzite hills surrounded by Cambrian sandstone are described as paleoislands in the Baraboo district of Wisconsin (Dott 1974). Examples of Ordovician–Silurian islands in the Hudson Bay area of Manitoba, Cretaceous islands in Baja California, and Pliocene islands in Baja California Sur entail geological inliers made of quartzite, granodiorite, and andesite, respectively (Johnson 2002). The Neoproterozoic Karlebotn archipelago of northern Norway is the oldest of its kind yet to be described.

Conclusions

The general outcrop path of several gneiss monadnocks that protrude through the sedimentary Smalfjord Formation is aligned with one of the primary fault directions in the Varanger region, northern Norway, at N20°W. Some axes of monadnock orientation also line up with the primary fault trends of the Varanger Gneiss Complex. A glacier followed the lineament below the present Varangerfjorden and eroded out a paleovalley during the Marinoan glaciation sometime between 650 and 600 Ma. The monadnocks were influenced by the major fault systems and subsequently eroded by that glacier and by marine and continental processes. The full relief of the monadnocks reached more than 100 m above the valley bottom.

The largest of the monadnocks preserves contacts with the surrounding and overlying strata. Four kinds of deposits are recognized with respect to basal sedimentary layers investigated in the field and in laboratory through thin-section analysis:

(1) A very poorly sorted diamictite with iron oxide cement and bullet- and blade-shaped clasts occurs on the west side of the largest monadnock. The clasts show a weak but clear orientation and reflect high lithological diversity. This diamictite is interpreted as lodgement tillite.

(2) Conglomerate enriched in fine material compared with the lodgement tillite is plastered against the gneiss surface, which dips up to 40°. These deposits possess a bimodal distribution of grain sizes and better rounding of grains than the lodgement tillite. They are interpreted as subglacial flowtillite, as corroborated by terminal flow lobes preserved draped over the sloping gneiss surface.

(3) A tapered ridge occurs on top of the largest monadnock. It is clast supported and composed mainly of boulders. These boulders are faceted but rounded at both ends, and many of them are oriented perpendicular to the ridge. This ridge is interpreted as a fossil esker that formed during the final stage of the Marinoan glaciation in the area.

(4) There are well-bedded sandstone layers of the Smalfjord Formation directly deposited against the gneiss surface on the north and east sides of the largest monadnock. These sandstones are well sorted, strongly compacted, and increasingly pure up through the stratigraphic succession away from the nonconformity. These are interpreted as sediments deposited in water when the monadnocks became islands in a tidal-flat setting.

Preservation of an esker and tillite layers with original flow lobes on the largest monadnock below the sandstones of the Smalfjord Formation indicates rapid island transgression with high depositional rates. The tills were not consolidated at the time they were drowned because there is a gradual change in lithological fabric from typical flowtillites to water-laid sediments within the same bed.

Slumps and gravity flows from the sides of the monadnock island and current or wave erosion of the primary till layer at the rocky shore influenced composition of the sandstones in nearshore areas. High mica content throughout and a thin layer of silt 20 cm above the unconformity on the north side indicate that currents were weak and wave reworking negligible on that side. Texturally and compositionally supermature quartz arenite interpreted as a beach deposit occurs on the southeast side. This association fits well with current indicators preserved as ripple marks in the area. Beach deposits were created by the outgoing tide, possibly combined with fluvial flux from the valley head to the east-southeast. Combined flow ripples indicate currents from the southwest to south-southwest that influenced the south and possibly west sides of the largest island. These current ripples were created by a combination of weak incoming tide and an occasional storm. Therefore, contrasting sheltered and exposed rocky shores around this paleoisland are recorded by deposits of the adjoining Smalfjord Formation.

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