RESEARCH ARTICLE

Geology of the Båtsfjordfjellet drillcore, Varanger Peninsula, Finnmark, northern Norway

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Logging of >800 metres of drillcore from a borehole on Båtsfjordfjellet, Varanger Peninsula, revealed a succession of very low-grade, metasedimentary rocks which are assigned to specific Neoproterozoic formations recognisable from regional mapping. The lowest 320 metres of the core consist largely of laminated, maroon to greenish-grey mudstones with thin sandstone beds and some dolomite, characteristic of the Skovika Member of the Båtsfjord Formation. A weak spaced cleavage is present in the mud- and clay-rich lithologies. This pelitic unit is overlain across an inferred unconformity by *c.* 230 m of coarse-grained sandstones with small-clast conglomerates, representing the Sandfjorden Formation of the Løkviksfjellet Group. The upper *c.* 240 m of the drillcore comprise a repetition of the Skovika Member mudrocks, with the basal contact against the Sandfjorden Formation sandstones marked by a thrust fault which appears to have been reactivated by normal fault movements.

Introduction

In mainland Norway, boreholes drilled solely for scientific purposes are a rarity. In recent years, however, two such holes have been drilled in Finnmark as part of a collaborative NGU–Statoil project – termed the 'HeatBar Project' – aimed at quantifying the heat production and flow from diverse basement rocks which are known to occur beneath the Late Palaeozoic to Cenozoic sedimentary basins of the western Barents Sea. The two drillholes are located (a) on Båtsfjordfjellet, a few kilometres southwest of the small town of Båtsfjord, in the northern part of Varanger Peninsula; and (b) at lake Vuoddašjavri, on Finnmarksvidda, *c.* 50 km northeast of Kautokeino (Pascal et al. 2008, 2010).

The Vuoddašjavri hole was drilled vertically in 2008 in Neoarchaean to Palaeoproterozoic gneisses and amphibolites down to a depth of *c.* 767 metres. By contrast, the drillhole on Båtsfjordfjellet (Figure 1), drilled in 2005, penetrated low-grade metasedimentary rocks of the Neoproterozoic, Barents Sea and

Siedlecka, A. and Roberts, D. (2012) Geology of the Båtsfjordfjellet drillcore, Varanger Peninsula, Finnmark, northern Norway. *Norges geologiske undersøkelse Bulletin*, **452**, 20-29.

Løkviksfjellet groups, initially reaching a vertical depth of 800 metres, but later collapsing at c. 620 m depth. The two boreholes and the extracted drillcores were subsequently logged for a variety of parameters, e.g., lithologies, thermal conductivity and diffusivity, rock density, gamma countings, temperature profile, etc., full details of which are contained in a NGU report (Pascal et al. 2010).

The purpose of the present contribution is to record the geology and some of the sedimentological and microstructural features resulting from our lithological logging of approximately 800 m of drillcore from the Båtsfjordfjellet site, and examination of thin-sections of eighteen representative rock samples from the core. As this is the first borehole to have been drilled on Varanger Peninsula and, in fact, in the northern Norwegian Caledonides as a whole, the logged data are clearly exclusive and thus worthy of documentation – moreso as details of our comprehensive logging and petrographic study were, by pure oversight, not included in the above-cited NGU reports.

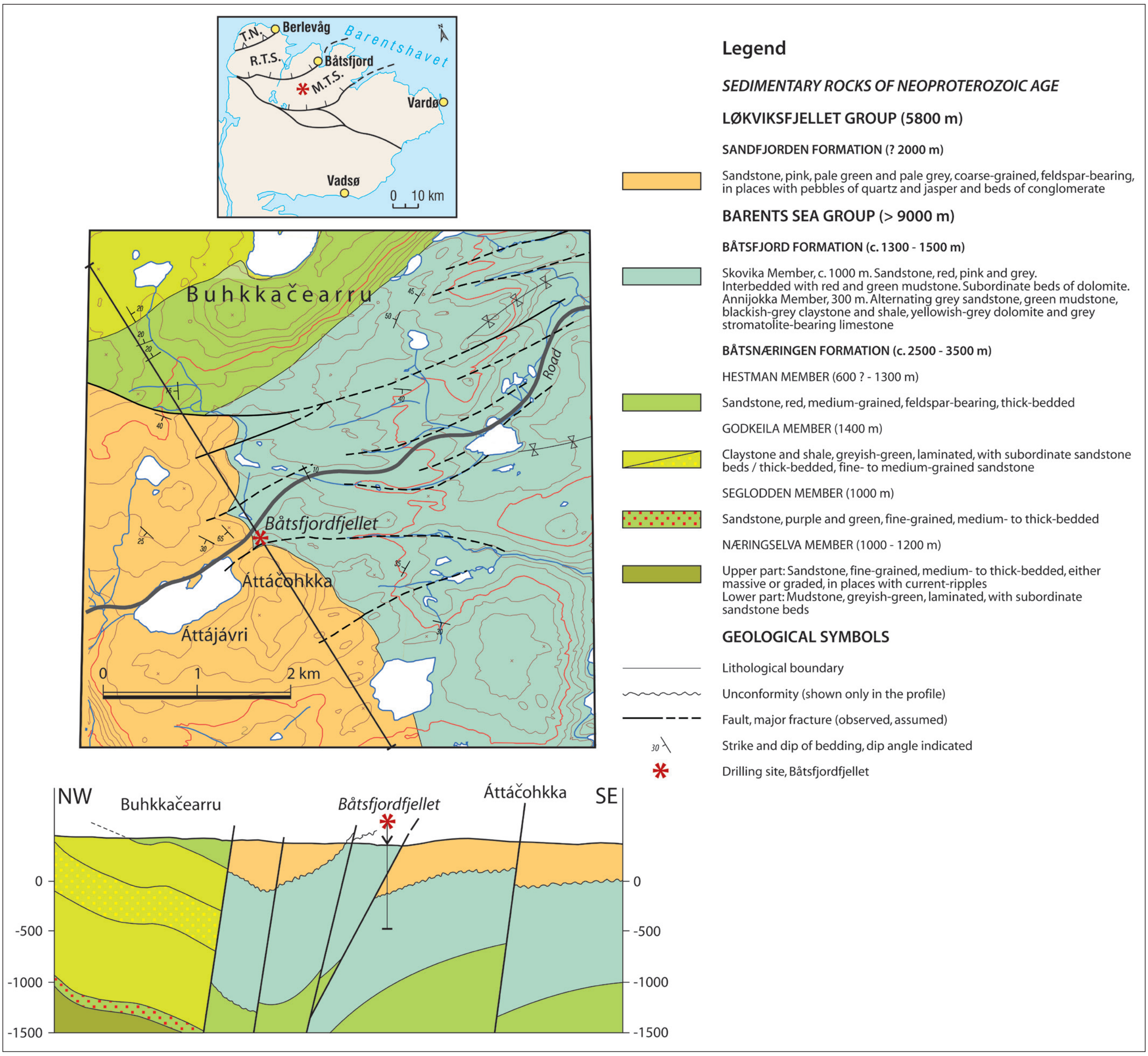


Figure 1. Location of the Båtsfjordfjellet borehole, and simplified map and profile of the local geology, Varanger Peninsula. In the inset map, M.T.S – Máhkirčearru thrust sheet; R.T.S. – Rákkočearru thrust sheet; T.N. – Tanahorn Nappe.

The Båtsfjordfjellet drillcore

Most of the drillcore is of good quality but some parts have been reduced to rubble. In some intervals, parts of the core are missing. In addition, the depths marked on the wooden drillcore boxes are in some cases incorrect, judging from our own measurements of continuous lengths of drillcore. Because of this, the intervals indicated in our description should be regarded only as our best estimates.

Lithologies and lithostratigraphy

The borehole penetrated parts of two, Neoproterozoic, lithostratigraphic units which are known to occur over large areas of northern Varanger Peninsula: the *Skovika Member* of the Båtsfjord Formation (part of the Barents Sea Group) and the *Sandfjorden Formation* (part of the Løkviksfjellet Group). The general lithostratigraphy of the Barents Sea Region of Varanger Peninsula is indicated in Figure 2, modified from Siedlecka and Roberts (1992). The following units have been measured and identified, in descending order, summarised in Figure 3:

Båtsfjord Formation, Skovika Member
c. 240 m with average dip 70°, equivalent to *c.* 100 m of stratigraphic section.
Sandfjorden Formation
c. 240 m with average dip 30°, equivalent to *c.* 210 m of stratigraphic section.
Båtsfjord Formation, Skovika Member
c. 321 m with average dip 25°, equivalent to *c.* 290 m of stratigraphic section.
Sum 801 m, = *c.* 600 m of stratigraphic section.

It has not been possible to indicate precisely which parts of the named lithostratigraphic units have been penetrated by the drillhole.

The intervals of the drillcore where contacts between the recognisable lithostratigraphic units occur are unfortunately either incomplete or partly represented by rubble (see the core log description, Appendix 1). The lower of the two contacts, between the Sandfjorden Formation and the subjacent Skovika Member, is considered to represent an unconformity, based on the fact that there is a well known, regional, low-angle, angular unconformity separating the Barents Sea Group from the Løkviksfjellet Group (Siedlecki and Levell 1978). The upper contact, between the Sandfjorden Formation and the overlying but older Skovika Member, is marked by a clay gouge and is interpreted as an original thrust-fault of unknown geometry and age. However, there are reasons for believing that this thrust-fault is most likely a Caledonian structure (p. 26) which was later reactivated in a more brittle, and probably extensional regime, thus generating the gouge.

The **Skovika Member** is lithologically heterogeneous, consisting of sandstones, mudstones, clay-rich rocks and dolomite metamorphosed at very low grade (Rice et al. 1989) (Figure 4a, b, d). The rocks are fine- to very fine-grained and in several places their textures extend across the classification boundaries of siliciclastic terrigenous rocks based on grain size, e.g., mud, clay or sand. Porosity varies, however, as in many places in the core the sand-rich varieties are comparatively porous. The pelitic rocks are characterised by a variegated coloration – greenish-grey, maroon or dark pink (Figure 4). The maroon and pink varieties contain disseminated hematite, whereas the grey sediments do not and are usually dolomitic.

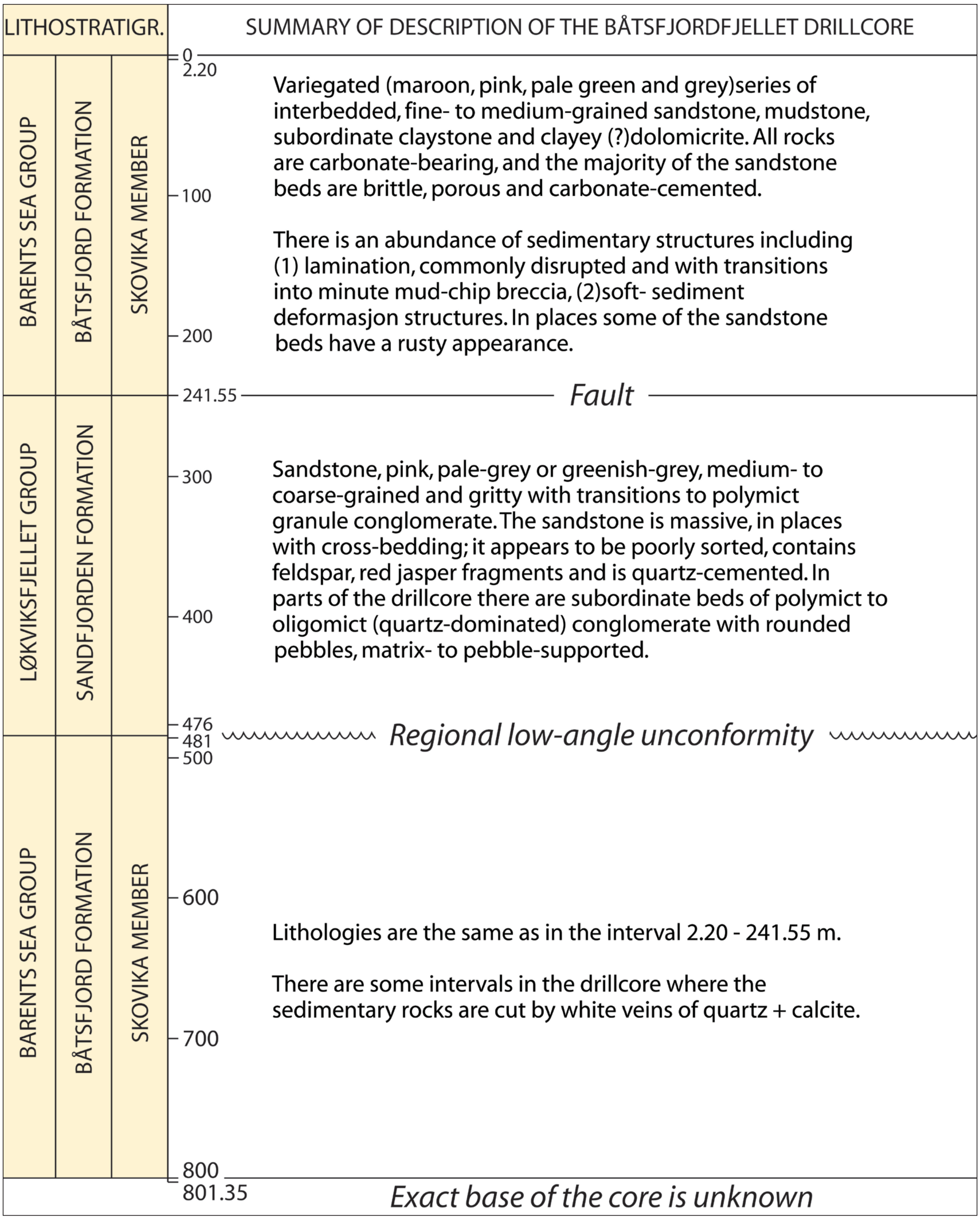
Some fairly homogeneous sandstone beds are present but, in general, the rocks are finely laminated where sand-, mud- or clay-sized particles or dolomite form a predominant component. Microscopic examination shows that silt and fine- to medium-grained sand are primarily represented by quartz with only subordinate grains of feldspar and sporadic flakes of chlorite (Figure 5). Clay-sized particles are a mixture of muscovite-like phyllosilicates described here as sericite, but some could be illite. This is a clastic material and a weathering product of silicate minerals derived from different source rocks. The dolomite is very fine-grained to micritic and is authigenic, either primary or a diagenetic replacement product of a calcium-carbonate mineral (calcite and/or aragonite).

In many of the finer-grained layers and laminae there is a weak spaced cleavage developed at a very low angle (normally 5–20°) to the primary layering. Where the cleavage folia cut

Age	Lithostratigraphy		
		Formation	Member
Ediacaran (Vendian)	LØKVIKSFJELLET GROUP 5710 - 5810 m	Skidnefjellet >800 m	
		Stordalselva 1200 m	
		Skjærgårdsneset 210 m	
		Styret 1500-1600 m	
		Sandfjorden 2000 m	
	BARENTS SEA GROUP 8900 - 10 000 m	Tyvjofjellet 1500 m	
		Båtsfjord 1400-1600 m	Skovika 1100-1300 m
Cryogenian			Annijokka 300 m
		Båtsnæringen 2500-3500 m	Hestman 600-1300 m
			Godkeila 490-1450 m
			Seglodden 100-350 m
			Næringselva 500-1200 m
		Kongsfjord >3500 m	Nålneset 2000 m; Risfjorden 1000-1500 m

Figure 2. Lithostratigraphy of the Barents Sea and Løkvikfjellet groups, Barents Sea Region of Varanger Peninsula. N.B. – see Addendum, p. 27.

Figure 3. Summary description of the Båtsfjordfjellet drillcore.



obliquely through quartz-rich laminae, the quartz grains show clear evidence of dissolution on the sides in contact with the cleavage surfaces, and tails or beards of microcrystalline material are developed in the pressure-shadow areas around the quartz grains. In other cases, very fine-grained layers or laminae show features indicative of layer-normal compaction. The oblique spaced cleavage is assumed to be axial planar to small folds that can be seen in outcrop in many parts of the Båtsfjord Formation; but no folds have been observed in our thin-sections. A summary description of the thin-sections is given in Appendix 2.

The **Sandfjorden Formation** is lithologically fairly homogeneous, consisting of coarse- to very coarse-grained, well sorted sandstones with subordinate granule- and small-pebble conglomerates (Figure 4c), also metamorphosed at very low grade. In spite of the largely oligomict character of the conglomerates and the apparently feldspathic character of the sandstones (Figure 5), the rocks in fact consist mostly of quartz with some grains or small clasts of quartzite, sandstone, chert, red jasper and sporadic feldspar. Some horizons contain enhanced contents of K-feldspar. The quartz grains are subrounded to well

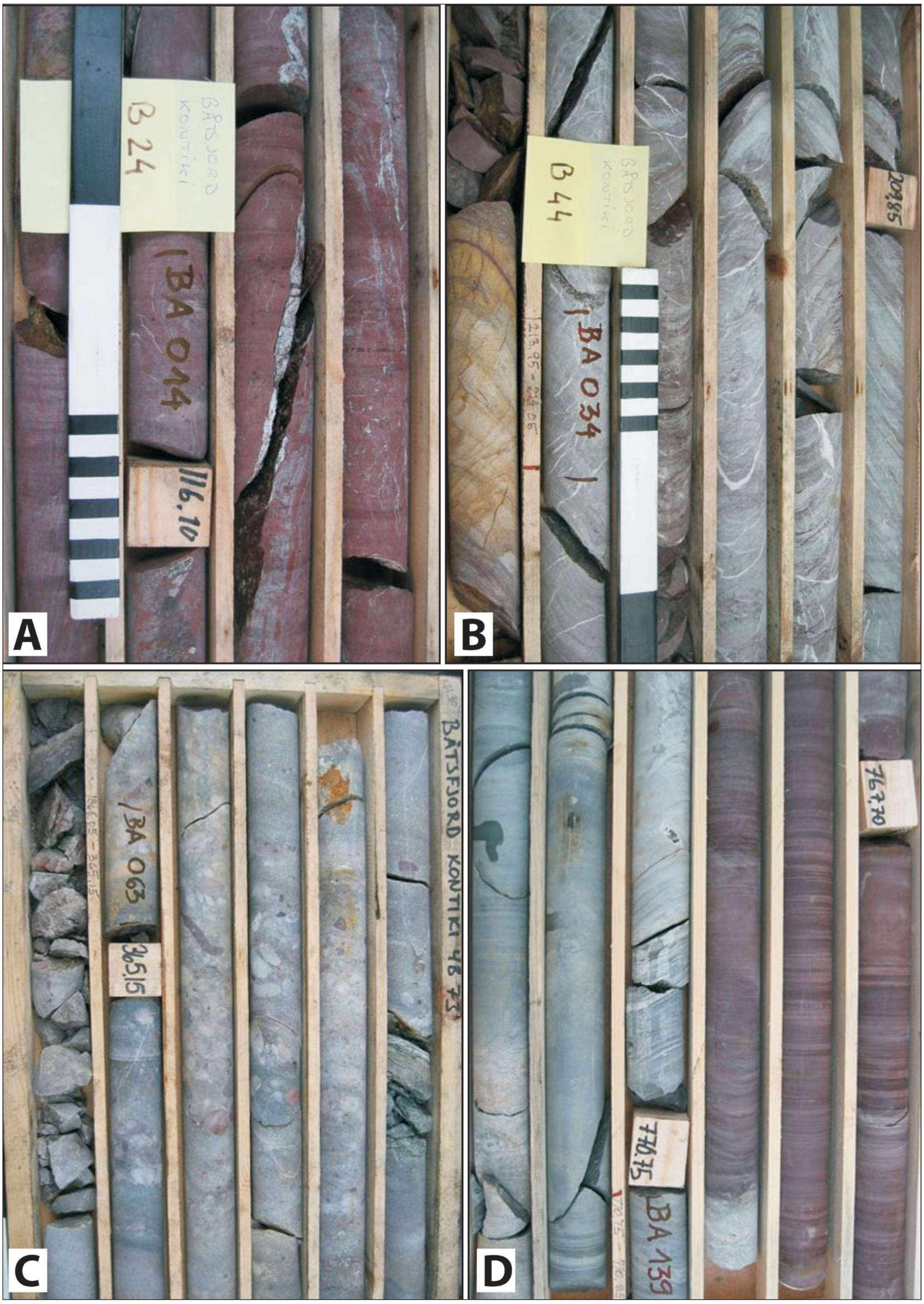
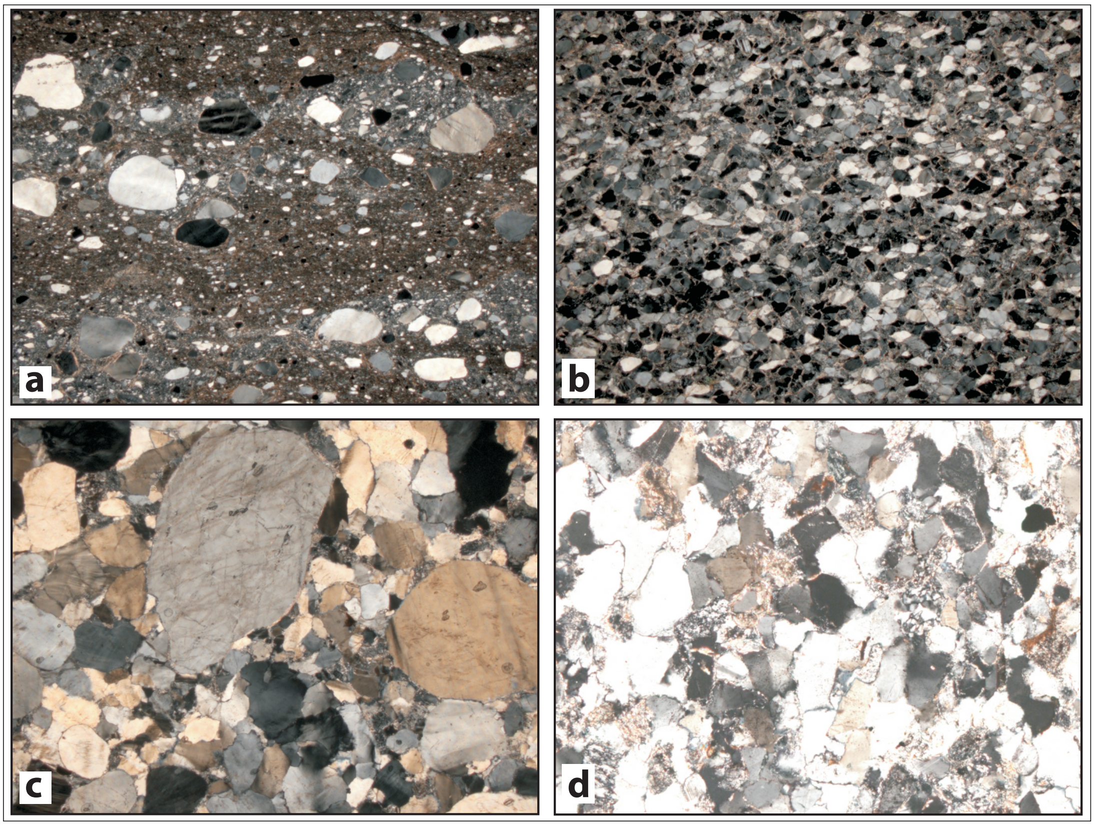


Figure 4. Selected core sections from different boxes. See Appendix 1 for logged descriptions. (a) Laminated maroon mudstones of the Skovika Member; part of box B24. (b) Laminated, grey, silty sandstone and intercalations of mudstone, with yellowish-grey limonitic sandstone to the left; Skovika Member, box B44. (c) Conglomerate, mostly oligomict with quartz pebbles, but also small scattered clasts of jasper; Sandfjorden Formation, box B73. (d) Maroon laminated mudstone in the three core sections to the right. The three cores to the left consist mostly of grey fine-grained sandstone and mudstone; Skovika Member, box B150.

rounded and in places exhibit quartz overgrowths (Figure 5). These overgrowths are probably more common than is possible to observe in small thin-sections (because of the clean grain surfaces) and have evidently contributed to the tightly packed texture of the sandstones. Some of the quartz grains, however, have thin skins of a sericitic cement.

Figure 5. Photomicrographs of selected thin-sections. Brief descriptions of each thin-section are given in Appendix 2. (a) BA 033, mudstone with large subrounded quartz grains of probable eolian origin. Skovika Member. Magn. x10. (b) BA 033, fine-grained sandstone; Skovika Member. Magn. x5. (c) BA 047, coarse-grained, gritty, quartz sandstone, Sandfjorden Formation. Magn. x5. (d) BA 005, fine-grained quartz sandstone with sericitic matrix, Skovika Member. Magn. x10.



Lithology, thermal conductivity and gamma radiation

It is interesting to compare the logged lithologies with profiles of thermal conductivity and gamma radiation recorded in the Båtsfjordfjellet borehole. Rocks of the **Skovika Member** show a thermal conductivity in the range 2–5.5 W m^{-1} K^{-1}, the lowest values being typical for the mud-dominated lithologies (Figure 6b) (Pascal et al. 2010). The subordinate fine-grained sandstones, which also yield fairly low thermal conductivity values, are either mud-enriched or contain mud laminae. The mudstones with the fairly high conductivity values are most probably silt-rich varieties. The presence of dolomite does not seem to have had any effect on the thermal conductivity values. These opinions, however, are based on only eighteen samples examined in thin-section out of a total of 146 samples taken for conductivity measurements. The overlap between the conductivities of rocks coded as 'sandstone' or 'mudstone' reflects the commonly observed transitional character between these two rock types. Sandstones and silt-rich mudstones are rich in quartz, and in addition to the texture and grain size this appears to be the reason why the sandstones and some of the mudstones exhibit values mostly between 3 and 4 W m^{-1} K^{-1}.

With few exceptions, the rocks of the **Sandfjorden Formation** show thermal conductivity values from 5 to slightly above 6 W m^{-1} K^{-1} (Figure 6b) (Pascal et al. 2010). This is a reflection of the quartz-dominated mineralogy combined with grain size, and perhaps also of the low porosity of these rocks. Four samples classified as sandstones show considerably lower conductivities and the same is noted in three mudstone samples close to the base of the formation. The four anomalous sandstone samples are, in fact, associated with mudstones and may perhaps contain slightly more mud than in the remainder of the examined, quartz-dominated, core section of the formation. The presence of mudstones close to the base of the formation may be explained by the regional, erosional character of the contact against the underlying, finer-grained and mud-rich Skovika Member.

A gamma log shows higher radiation values for the pelite-dominated Skovika Member as compared with the quartz-rich Sandfjorden Formation (Figure 6a). This clear distinction is taken to relate to the abundance of K-rich clay minerals in the Skovika mudstones. Whilst low values of gamma characterise the Sandfjorden sandstones, increased values towards the middle of the unit may correlate with an increased content of K-feldspar or proportionally more mudstone intercalations.

In summary, it is apparent that the high thermal conductivity values are characteristic of the coarse, 'clean', quartz sandstones and conglomerates with tightly packed, rounded grains and a restricted, comparatively low porosity. This feature goes hand in hand with low values of gamma radiation. On the contrary, the lower conductivity values seem to be more typical for the finer-grained, polymineralic, mud-enriched rocks where,

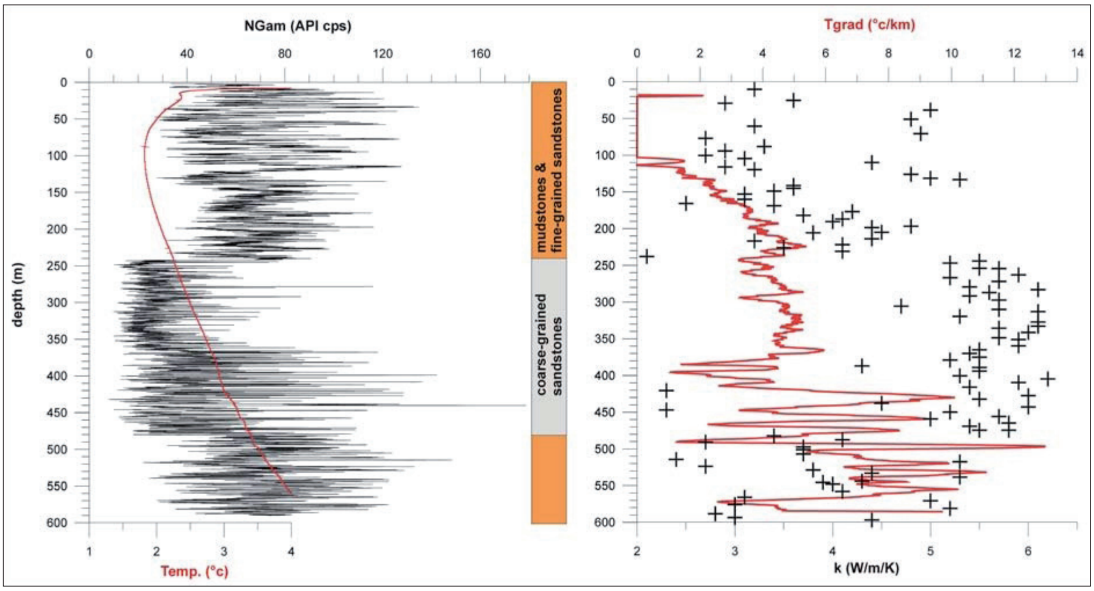


Figure 6. Left: *Gamma log from the Båtsfjordfjellet borehole with superimposed temperature profile and simplified lithostratigraphic column.* Right: *Thermal conductivities as measured on the drillcore, with the computed thermal gradient. For details, see Chapter 3 in Pascal et al. (2010).*

again, the quartz content has had a decisive effect in causing locally increased conductivity values.

Regional context of the borehole geology

In this northern part of Varanger Peninsula, rocks below the level of the Tanahorn Nappe (part of the Middle Allochthon of Scandinavian Caledonide tectonostratigraphy) (Figure 1) are involved in minor, syn-metamorphic, imbricate thrusting and form part of the Lower Allochthon. In this regard, the thrust emplacement of older Båtsfjord Formation rocks upon the Sandsfjorden Formation, as recognised in the Båtsfjordfjellet borehole, is not unexpected. The presence of gouge along the contact, representing a comparatively brittle component of fault movement, does, however, suggest that the thrust-fault was later reactivated during a phase of extension. Episodes of normal, extensional fault movement of Late Palaeozoic to Mesozoic age are well known from adjacent offshore areas (Gabrielsen & Færseth 1989, Bugge et al. 1995, Samuelsberg et al. 2003) and are suspected to have occurred onshore (Herrevold et al. 2009) and in Varangerfjorden (Roberts et al. 2011). Thinner gouge zones recorded in other parts of the drillcore may also represent brittle faults.

The actual location of the borehole is in the lowermost of two imbricate thrust sheets, the upper one known as the Rákkočearru thrust sheet (Herrevold et al. 2009, Roberts 2009) (Figure 1). The lower tectonic unit is here informally named the *Máhkirčearru thrust sheet* (Figure 1), the basal contact of which passes into Syltefjorden and can be followed offshore on recent aeromagnetic data (Gernigon et al. 2007).

The spaced, crenulation-type cleavage noted in some of the thin-sections is quite likely to correspond to the one reported from the nearby Kongsfjord area, in the Kongsfjord Formation, and the subject of a ^{40}Ar–^{39}Ar dating investigation (Rice and Frank 2003). This cleavage post-dates the main schistosity (which developed before 470 Ma) and most of the thrusting, and yielded a plateau age of *c.* 443 Ma (Rice and Frank 2003). This age corresponds to the Ordovician–Silurian boundary, and has not been recorded previously in Finnmark. Rice and Frank (2003) considered this pulse of deformation to have occurred approximately midway between the main, Early Ordovician (Finnmarkian) phase and the late-Caledonian, Siluro–Devonian (Scandian) event.

Conclusions

Logging of over 800 metres of drillcore from a borehole on Båtsfjordfjellet, Varanger Peninsula, revealed a succession of very low-grade, metasedimentary rocks which are assigned to two, specific, Neoproterozoic formations well known from regional mapping. The lowest c. 320 m of the core consist mostly of laminated maroon to greenish-grey mudstones, clay-rich rocks, thin sandstone beds and some dolomite ascribed to the Skovika Member of the Båtsfjord Formation. A weak spaced cleavage is seen in thin-sections of the mud- and clay-rich lithologies. This pelitic unit is overlain across an inferred unconformity by *c.* 230 m of coarse-grained sandstones with subordinate small-clast conglomerates, representing the Sandfjorden Formation of the Løkviksfjellet Group.

The upper *c.* 240 metres of the drillcore comprise a repetition of the Skovika Member mudrocks, with the basal contact against Sandfjorden sandstones marked by a thrust-fault that was later reactivated in a more brittle, and probably extensional regime.

Acknowledgements
Harald Elvebakk, NGU, carried out the logging of thermal conductivity and gamma-ray radiation. We thank him for his comments on these results and on an early version of the manuscript, and for allowing us to reproduce a figure (our Figure 6) from the Pascal et al. (2010) report. Cécile Barrère took photographs of the core at the time of logging, and Kirsti Midttømme is thanked for discussions of the geophysical results with the first author. Odleiv Olesen read and commented on the final manuscript, which was reviewed by Stephen Lippard. Irene Lundquist helped in preparation of the figures.

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Addendum

Based on a recent reconsideration of the age of the Løkviksfjellet Group, this lithostratigraphic unit is now regarded as most likely Cryogenian (see the companion paper by Roberts and Siedlecka in this same Bulletin volume).