The transition from Neoproterozoic glacial to interglacial sedimentation near Hammarnes, East Finnmark, North Norway

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A profile through the boundary between the Neoproterozoic Smalfjord (glacial; *sensu-lato)* and Nyborg (post-glacial) Formations at Hammarnes, East Finnmark, shows lithologies of the two units are intercalated, with rocks diagnostic of the Nyborg Formation (cap-dolostones, red shales) underlying Smalfjord-type clastic sediments (conglomerates, dark grey shales, pale grey sandstones). Since these latter rocks are almost certainly post-glacial, identical rocks underlying the lowest Nyborg-type lithologies must also be post-glacial. Thus the base of the Nyborg Formation cannot be unequivocally taken as the onset of post-glacial sedimentation; a small, but unknown amount of the Smalfjord Formation is probably also of post-glacial age, reflecting localized reworking of older, glacial sediments.

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Introduction

The basal part of the Vestertana Group (Cryogenian-Neoproterozoic III; time-scale of Plumb 1991) in Finnmark, N. Norway, comprises rocks generally interpreted as glacial *(sensu-lato;* here taken to include all rocks laid down contemporaneously with the presence of ice in the region) and inter-glacial sediments. An early glacial event (Smalfjord Formation; generally 0-50 m thick, locally up to 243 m) is separated from a later one (Mortensnes Formation; 10-60 m) by the inter-glacial strata of the Nyborg Formation (0-400 m; thicknesses from Føyn & Siedlecki 1980, Edwards 1984). These rocks have been studied by several authors (Reading & Walker 1966, Bjørlykke 1967, Edwards 1975, 1979, 1984, Edwards & Føyn 1981, Føyn & Siedlecki 1980, Rice & Hofmann 2000), although not all authors have agreed with a glacial or dominantly glacial facies interpretation for the Smalfjord Formation (Crowell 1964, Schermerhorn 1974, T. Warman pers. comm. 1993, Jensen & Wulff-Pedersen 1996, Arnaud & Eyles 1999).

The boundary between the Smalfjord and Nyborg formations has always been taken to represent the glacial-interglacial boundary (see references above and Johnson et al. 1978, Hambrey 1988, Nystuen & Siedlecka 1988, Gayer & Rice 1989, Siedlecka & Roberts 1992). In effect, the lithostratigraphic boundary has been inferred to also be a palaeoclimatic marker. An atypical development of this boundary, suggesting that this inference is not strictly valid, forms the basis of this note.

The Smalfjord & Nyborg Formations

In the Varanger area, Edwards (1984) divided the Smalfjord Formation into two parts; pale coloured sandstones-conglomerates and rarer diamictites. The former were divided into four facies (S1-S4):-

S1 – *braided stream*
S2 – *prograding delta-beach*
S3 – *submarine-fan and sediment gravity flows*
S4 – *turbidites*

Logged sections from the western end of Varangerfjord (Vieranjar´ga, Skjåholmen and Oaibaccannjar´ga) all show S4 at the base of the succession and S1 at the top, reflecting basin shallowing during sedimentation (Edwards 1984). Lodgement tillite (facies D1) and stratified diamictite from several glacially related environments (facies D2; Edwards 1984) usually occur at the base of the succession.

Between Per Larsvik and Handelsneset (Fig. 1), where the sub-Smalfjord unconformity cuts ca. 140 m down-section in an exposed distance of ca. 800 m, the lithologies "differ somewhat… including poorly sorted conglomerates and conglomeratic sandstones that resemble glacial outwash, well sorted conglomerates with well rounded pebbles that resemble beach deposits, layers of diamictite that may represent debris flows, large-scale foresets formed by prograding deltas and sandstones deposited by turbidites or sediment gravity flows." (Edwards 1984, p. 12).

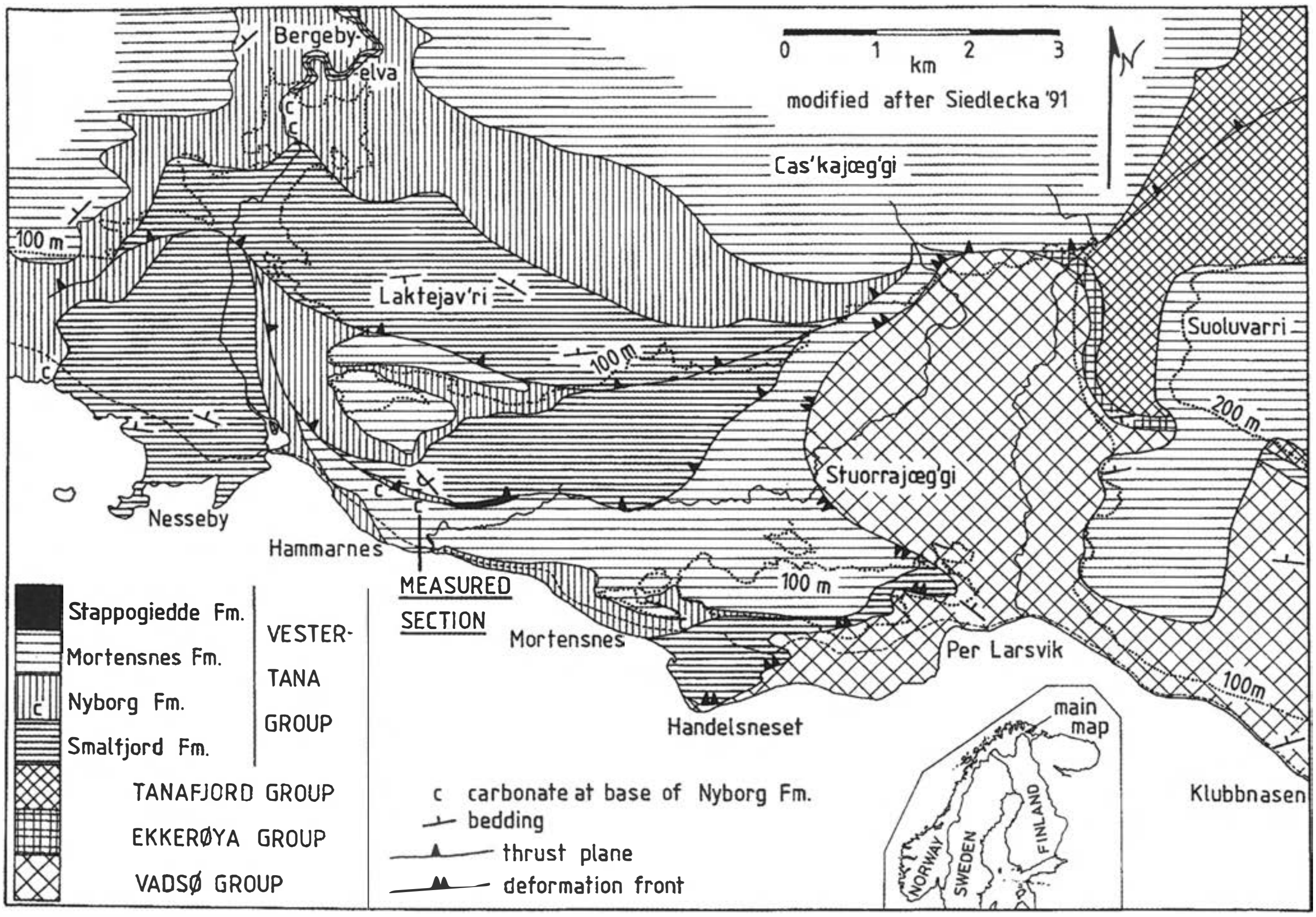

Fig 1. Geological map of the Varangerfjord area; modified from Siedlecka (1991).

In the Smalfjord area, immediately west of Varangerhalvøya, the formation comprises massive diamictite layers with intervening mudstones/sandstones, representing serial glacial advance and retreat deposition during both early valley-glacier and later ice-sheet phases (Føyn & Siedlecki 1980, Edwards 1984), although recently a debris-flow interpretation has once again been proposed for the diamictites (T. Warman pers. comm. 1993, Jensen & Wulff-Pedersen 1996, Arnaud & Eyles 1999). Critically, Edwards (1984, p.26) correlated the predominantly fluvial/marine succession in the Varangerfjord area with the early valley-glacier phase in the Smalfjord region, the latter phase being generally absent, indicating that the base of the Nyborg Formation around Varangerfjord must be an unconformity.

In the Nyborg Formation, five members were recognized by Edwards (1984). The lowest (Member A) comprising facies NA1-NA5:-

NA5 – *facies uncertain* - rare fine grained, structureless sandstone; several metres thick.

NA4 – *periodic high energy flows* - intraformational dolostone breccias in NA2/3; each up to 60 cm thick (edgewise breccia of Edwards 1984).

NA3 – *shallow marine* - red mudstone/shale; up to 25 m thick.

NA2 – *quiet shallow marine* - alternating dolostone and red mudstone laminae; up to 25 m thick.

NA1 – *peritidal* - massive buff weathering dolostone, rare gentle mound structures; up to 10 m thick.

This succession was interpreted as reflecting a postglacial transgression, with dolostone deposition gradually replaced by fine and then coarser (Member B) clastic deposits, which were derived from the Baltic Shield to the south (Edwards 1984). Facies NA1 formed around topographic highs within the transgressing sea (cf. Føyn & Siedlecki 1980), whilst purple muds and sands accumulated in intervening areas. In the Varangerfjord region, facies NA1 occurs only at Ruos´soai´vi, west of Varangerfjord (Siedlecka 1990) and at Hammarnes (see below). The dolostone succession is broadly comparable to cap-carbonates above other late-Proterozoic glacial successions (Kennedy et al. 1998, Hoffman et al. 1998, Myrow & Kaufman 1999, Prave 1999, Brasier & Shields 2000), in having negative $\delta^{13}C$ values (Rice et al. 2001).

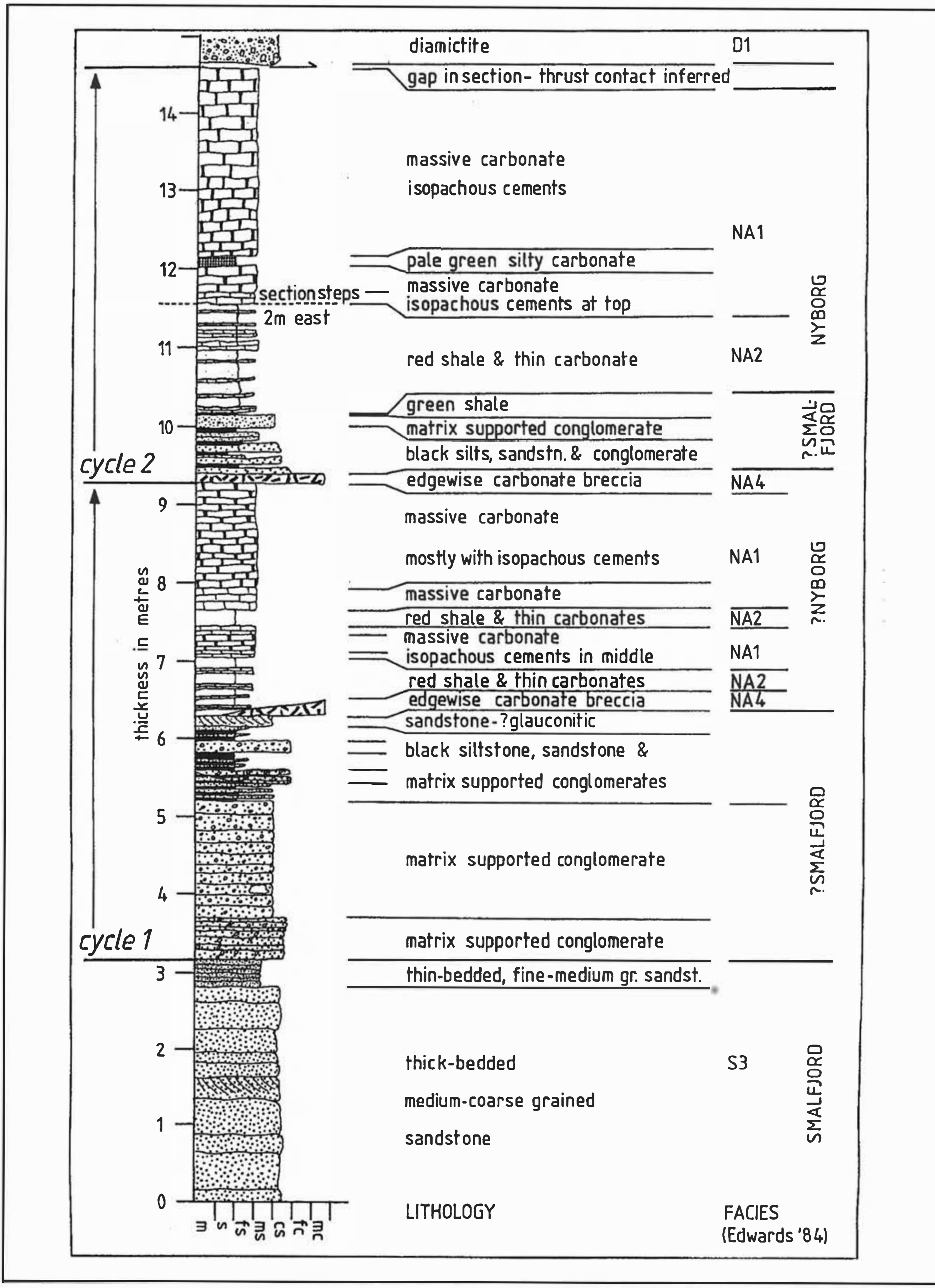

Fig 2. Logged section from outcrop near Hammarnes.

The Nesseby-Suoluvarri area

The structure in this region comprises two southerly directed thrusts in the Vestertana Group, which Siedlecka (1991) interpreted as klippen (movement direction inferred from structural data of Townsend 1986). However, this interpretation is impossible, since no root zone for the klippen thrusts lies to the north (cf. Siedlecki 1980). The structure is here reinterpreted in terms of two relatively minor thrusts, which link and die out to the west (Fig. 1); there are several small-scale southwards-directed thrust faults in Bergebyelva where the Smalfjord Formation is strongly folded (Rice, unpubl. data). To the east, they have been inferred to link with a zone of deformation recorded in the lower part of the Tanafjorden Group (Stangenes Formation) between Jakobselv and Vadsø (Røe 1986, Siedlecka 1991). Most probably, the thrusts splay from a basal thrust cutting through the sub-Smalfjord and sub-Mortensnes Formations unconformities. How this southwards directed deformation relates to the eastwards directed deformation of the Lower Allochthon (Gaissa Thrust Belt) in easternmost Varanger (Townsend 1986) is unclear.

In the lower imbricate, the Smalfjord and Nyborg formations lie in an E-W trending, south facing hanging wall anticline (Fig. 1), cut by contemporary very minor thrusts, and now exposed in a cliff north of Hammarnes (from GR732855 to GR739833; map sheet 2335 2 Nesseby; Siedlecka 1991). About 70 m east of a small quarry at GR73508340, the contact between the Smalfjord and Nyborg Formations is exposed in the cliff; this is described below.

Hammarnes section

The logged section (Figs. 1 & 2) is 13.65 m thick, with a bedding orientation of 281°/54°N. The bottom lies in the Smalfjord Formation, whilst the top is cut off by a thrust. The basal part of the section comprises 3.19 m of pale weathering well-bedded, slightly lensoid sandstones. Rare cross-bedding, which shows the succession is the right way-up, dips northward. In the lower part, beds are 14–45 cm thick, but thinner (2.5-7.0 cm) in the upper, somewhat finer grained, part.

The section above this basal part comprises two fining-upwards siliciclastic-carbonate *sedimentary cycles* (hereafter *cycle*; defined as a repeated succession of three or more lithologies; Einsele 1992), each passing from either conglomerate or breccia at the base, through to massive dolostones at the top. Cycle 1 is 6.23 m and Cycle 2 is 4.40 m thick.

Sedimentary Cycle 1:

The base of the cycle (Fig. 2) consists of 2.05 m of pale brown/greenish matrix supported conglomerates in beds 8-16 cm thick, with a medium to coarse grained sandstone matrix. The sub-rounded to angular vein quartz and carbonate clasts in the conglomerates are of variable size, but generally around 2.5 cm, and are commoner towards the top. In the overlying 0.98 m, similar matrix supported conglomerates in beds up to 0.22 m thick are interlayered with thin laminated (0.5-3.5 cm) black to dark grey siltstones and thin pale brown to white sandstones. Sandstones in this part of the succession also contain small rounded outsize pebbles, comparable to the matrix supported conglomerate below. This is overlain by 10 cm of faintly cross-bedded sandstone.

Above this lies 0.73 m of laminated red silts and shales with thin cream weathered dolostones (laminae from 0.1 cm to 10 cm thick) and then 2.20 m of thicker cream weathered massive pale grey dolostones, but including 0.22 m of red shale with thin dolostones. The massive dolostones are finely laminated and are mostly characterized by sheet-cracking, in which the fragments are rimmed by an isopachous cement and remaining larger cavities infilled with a rusty brown cement, although some parts are without such cements, particularly adjacent to the red mudstones; the sheet-cracking and isopachous cementation are typical of many cap-carbonates (Kennedy et al. 1998).

Sedimentary Cycle 2:

Directly above the top of Cycle 1 is 0.13 m of intraformational dolostone breccia, clearly of sedimentary origin, with 1 cm sized angular dolostone fragments. This is overlain by 0.65 m of thin-laminated dark grey shales, with pale sandstones and matrix supported conglomerates. The conglomerates contain rounded to angular fragments of carbonate and vein quartz. These pass up through yellow-green shale (4 cm) to 1.47 m of red shales with thin dolostone laminae (generally 0.5 to 1.5 cm thick, but some 5 cm thick) and thence to 2.08 m of massive dolostones, locally with slight domal structures. Most of the dolostones have isopachous cements.

At the junction between the red shales and massive dolostones, the logged section is displaced 2 m to the east, to better exposure. However, little or no material is missing from the log. The top of the succession is tectonically overlain by diamictites of the Smalfjord Formation.

Discussion

Although thinner, Cycle 2 essentially repeats Cycle 1; the red shale-massive dolostone rocks are similar in thickness in the two cycles (3.55 & 2.93 m respectively), although proportions of the two lithologies vary, and the two successions of finely laminated black silts and sandstones are also similar (0.65 & 0.98 m respectively). In view of the local structure, this repetition could be interpreted as a tectonic feature. However, the critical contact, between the intraformational dolostone breccia at the base of Cycle 2 and the overlying coarse siliciclastic succession, shows no evidence of tectonic displacement. The transition from sedimentary breccia to conglomerate is rapid and sharp in sedimentary terms, but is not tectonic.

The two fining-upwards cycles contain successively lower energy sediments; the basal parts of both are coarse grained (high energy) deposits – ca. 2 m of matrix supported conglomerate in Cycle 1 and 0.13 m of intraformational dolostone breccia in Cycle 2. These are both overlain by a succession of thin laminated black siltstones and sandstones with some thicker beds of matrix supported conglomerate, followed by red shales with thin dolostones and finally the supply of siliciclastic material effectively ceased and pure carbonate mud was deposited.

The dolostone rocks can be assigned to facies NA1, NA2 and NA4 of the Nyborg Formation. However, if both dolostone-red shale successions are assigned to the Nyborg Formation, then the intervening 0.77 m of siliciclastic sediments in Cycle 2 must also lie within the Nyborg Formation. In this case, the palaeogeographic implications of the similar rocks in Cycle 1 become significant.

The cyclicity in the profile can be modelled in two ways, the only relatively certain constraint being that the interpretation of the siliciclastic basal parts of both cycles should be the same. In one model, these rocks are inferred to be post-glacial, in which case the base of Nyborg Formation lithologies cannot be unequivocally taken as the onset of post-glacial sedimentation. In the alternative, they are taken as being glacial *(sensu lato)*, and the section reflects a short-term return to glacial conditions (base Cycle 2) after an initial short `post-glacial' interval (top Cycle 1). A few points suggest that the former alternative is more likely.

First, if the correlation of the bedded sediments of the Smalfjord Formation in the Varanger area with the base of the unit in the type area is accepted (Edwards 1984), then the lower part of Cycle 1 should be significantly older than the lower part of Cycle 2. This seems very unlikely in view of their lithological similarity, suggesting that there is an unconformity somewhere below Cycle 1, between the early part of the Smalfjord Formation and the rocks at Hammarnes, rather than between the Nyborg and Smalfjord Formations.

Second, in other Neoproterozoic successions the contact between glacial sediments and a post-glacial cap-carbonate is sharp rather than gradual and usually with little or no post-glacial sediments under the cap (Brookfield 1987, Fairchild et al. 1989, Aitken 1991, Kennedy 1996, Hoffman et al. 1998a, Myrow & Kaufman 1999, Prave 1999). This is comparable to the Finnmark situation. Third, a return to glacial conditions after the onset of cap carbonate deposition has not generally been recorded (see references above), although the Port Askaig Tillite remains an anomaly in many respects (Spencer 1971, Stephenson & Gould 1995). The first two features outlined above are consistent with a snowball Earth model (Hoffman et al. 1998b) in which the turnover from icehouse to greenhouse conditions was rapid and, in the short term, irreversible.

Although the uppermost part of the Smalfjord Formation should be considered post-glacial, exactly how much and how extensively this is developed is unknown. At Hammarnes, only ca. 3 m are almost certainly post-glacial. Similar lithologies crop out in the quarry directly west of the logged section and also in Bergebyelva (Rice unpubl. data; Fig. 1).

The interleaving of Smalfjord and basal Nyborg formation type rocks is not unexpected, since dolostone deposition occurred around topographic highs bordering the marine basin, allowing re-sediment of older glacial deposits within the cap-carbonate sequence. However, around Varangerfjord it is observed only at Hammarnes, since only this area exposes the contact close to a significant end-glacial palaeotopographic region (Per Larsvik; Fig. 1), from which older, weakly consolidated Smalfjord Formation sediments could be reworked; further east (Suoluvarri), erosion on the sub-Mortensnes Formation unconformity has removed the contact. In the Lap´puluokoai´vi – Ruos´soai´vi – Selesnjar´ga area, west of Varangerfjord, there is also evidence of a Neoproterozoic palaeorelief (Bjørlykke 1967, Siedlecka 1990), but here the stratigraphy is poorly preserved.

Conclusion

The Hammarnes profile shows that in some areas post-glacial conditions developed prior to Nyborg Formation deposition. Thus the usually held view that the boundary between the Smalfjord and Nyborg Formations marks the palaeoclimatic boundary between glacial (sensu-lato) and post-glacial conditions is untenable in the Hammarnes area. An unknown, but probably small, amount of the Smalfjord Formation is post-glacial.

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