Geology and structural evolution of pre-Caledonian rocks and the ?Devonian Sutorfjella conglomerate, northern Prins Karls Forland (Svalbard)

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Piepjohn, K., Griem-Klee, S., Post, H., Post, J. & Thiedig, F.: Geology and structural evolution of pre-Caledonian rocks and the ?Devonian Sutorfjella conglomerate, northern Prins Karls Forland (Svalbard). *Norsk Geologisk Tidsskrift,* Vol. 80, pp. 83–96. Oslo 2000. ISSN 0029-196X.

On northern Prins Karls Forland, Early Vendian metasediments (Glenbegdalen and Taylorfjellet units) were thrust over conglomerates, quartz-carbonate schists, quartzites and phyllites of the Macnairrabbane unit. Remnants of microfossils in dolomite clasts of the conglomerates indicate an Early Paleozoic age of the Macnairrabbane unit. The Glenbegdalen, Taylorfjellet and Macnairrabbane units were affected by two ductile phases of isoclinal folding (D1, D2), followed by a third ductile to brittle stage (D3) of NE-vergent folding. This polyphase deformation post-dated the deposition of the Early Paleozoic Macnairrabbane unit, indicating a Caledonian age of D1 to D3. The Sutorfjella conglomerate on the west-coast of Prins Karls Forland contains clasts which are characterized by two stages of ductile folding and foliation (D1, D2), whereas the matrix is unaffected by any ductile deformation. The Sutorfjella conglomerate unconformably overlies the vertical short limb of a F3-fold. These observations suggest that the Sutorfjella conglomerate represents a post-Caledonian sediment which could be related to the ?Late Silurian to Early Devonian molasse basins in NW Spitsbergen. The occurrences of some reddish beds and red-weathered clasts indicate an ?Early Devonian age. The youngest convergent deformation (D4) is characterized by thrust-faulting and nappe-stacking in the basement rocks and by the formation of a F4-fold in the Sutorfjella conglomerate. Compared with the structures on Brøggerhalvøya, this deformation could be assigned to the formation of the Tertiary West Spitsbergen Fold-and-Thrust Belt.

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Introduction

In the study area on northern Prins Karls Forland (Fig. 1), pre-Devonian basement rocks and the Sutorfjella conglomerate of uncertain age are exposed. First lithological classifications were given by Tyrrell (1924), Atkinson (1956, 1960) and Major et al. (1956).

The pre-Devonian rocks in this area were divided into the Barents, Scotia and Fuglehuken groups by Atkinson (1960) and later into the Late Vendian/Ediacaran Scotia Group and the Early Paleozoic Grampian Group by Harland et al. (1979, 1993), Manby (1986) and Harland (1997). Hjelle et al. (1979) divided the succession into the Black shale, Quartzite-sandstone and Calc-argillo-volcanic formations. Because the Scotia Group or Black shale Formation overlies the Grampian Group or Quartzite-sandstone Formation, the sequence was interpreted as being inverted (Fig. 2). Knoll & Ohta (1988) interpreted the basement succession as being in upright position and divided it into the Psammo-pelitic-volcanic unit (PPV), the Psammo-pelitic unit (PP) and the Black carbonate-pelitic unit (BCP) (Fig. 2).

The age of the Sutorfjella conglomerate is still a matter of debate: Hoel (1912) and Craig (1916) compared it with the Devonian Old Red conglomerates of the Raudfjorden area in NW Spitsbergen. Tyrrell (1924) described similarities to the Tertiary Thompsonfjella conglomerate, whereas Atkinson (1960), Harland et al. (1979) and Harland (1997) suggested a pre-Caledonian age (see Fig. 2). Conversely, the conglomerate was suggested as being post-Caledonian (Manby 1986) or Devonian or Tertiary (Hjelle et al. 1979; Knoll & Ohta 1988) in age.

In this paper, the pre-Devonian rock units on northern Prins Karls Forland are divided into the Glenbegdalen unit (Hjelle et al. 1999) (equivalent to the PP unit, the Quartzite-sandstone Formation, or the Grampian Group), the Taylorfjellet unit (Hjelle et al. 1999) (equivalent to the BCP unit, the Black shale Formation, or the Scotia Group) and what is here named the Macnairrabbane unit (equivalent to the PPV unit, or the Calc-argillo-volcanic Formation) (Fig. 2).

Lithology and age relations

Glenbegdalen unit

The Glenbegdalen unit (Hjelle et al. 1999) (Fig. 2) is characterized by siliciclastic, flyschoid metasediments (Harland 1997). The unit consists of a monotonous succession of light-grey to grey-green, light-brown weathering, medium- to coarse-grained quartzites intercalated with cm- to 10 m-thick beds of fine-grained, grey quartz phyllites and grey-green phyllites (Klee 1990; Mersmann

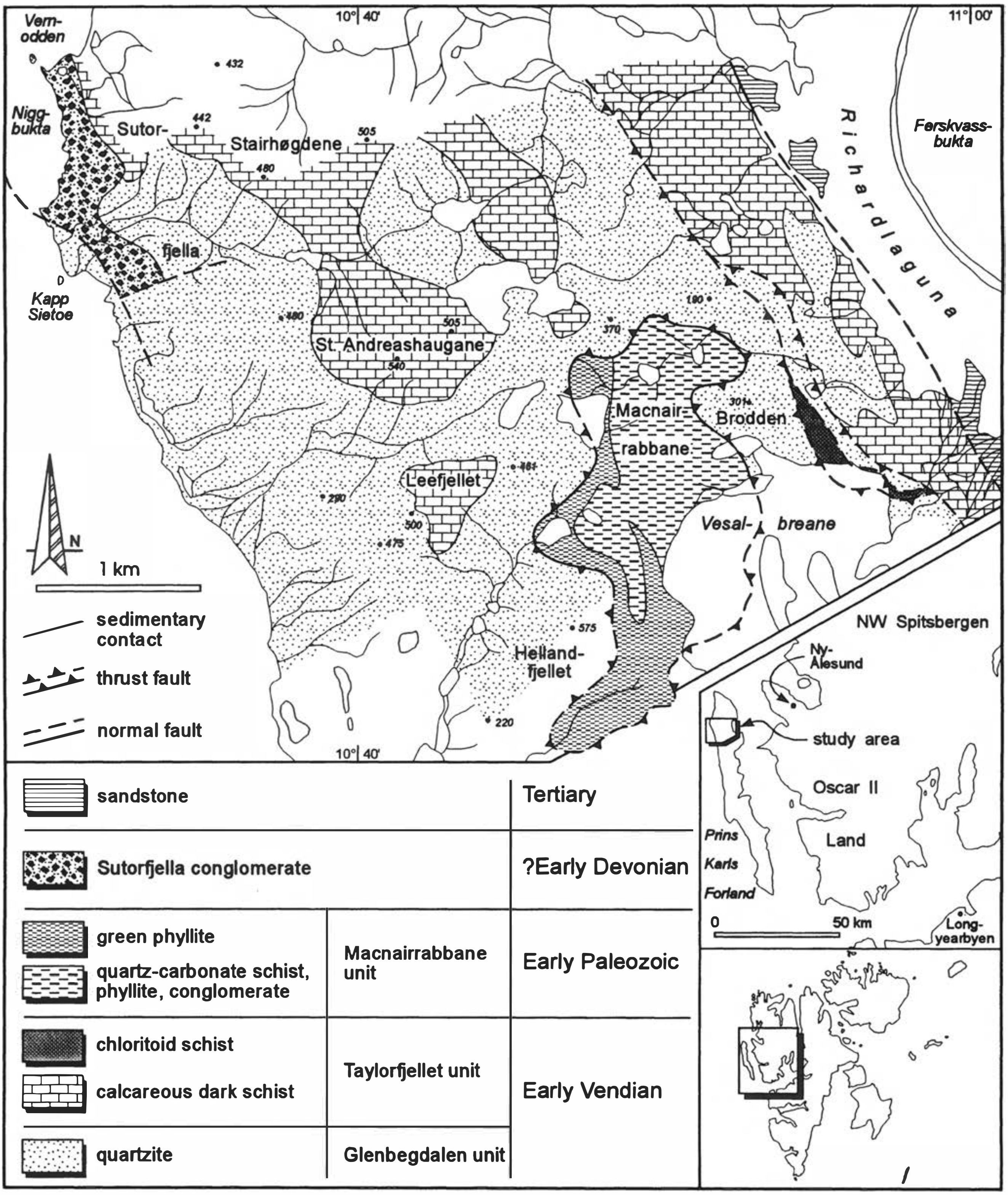

Fig. 1. Geological map of the study area, northern Prins Karls Forland, compiled and redrawn from Klee (1990), Mersmann (1990) and Post (1990).

1990; Post 1990). Upward, increasing portions of cm- to dm-thick graphitic schists and blue-grey, greenish weathering quartz-carbonate schists can be observed. The latter represent the transition of the clastic Glenbegdalen unit to the carbonate facies of the overlying Taylorfjellet unit.

Within the quartzites, metre-thick lenses of light-grey conglomerates are embedded; these are poorly sorted and clast-supported. The clasts are predominantly represented by quartzites, but some carbonate pebbles and reworked, intraformational quartz-phyllite clasts also occur. The mostly 5–15 cm scale, but max. 80 cm-large pebbles are subangular to well rounded.

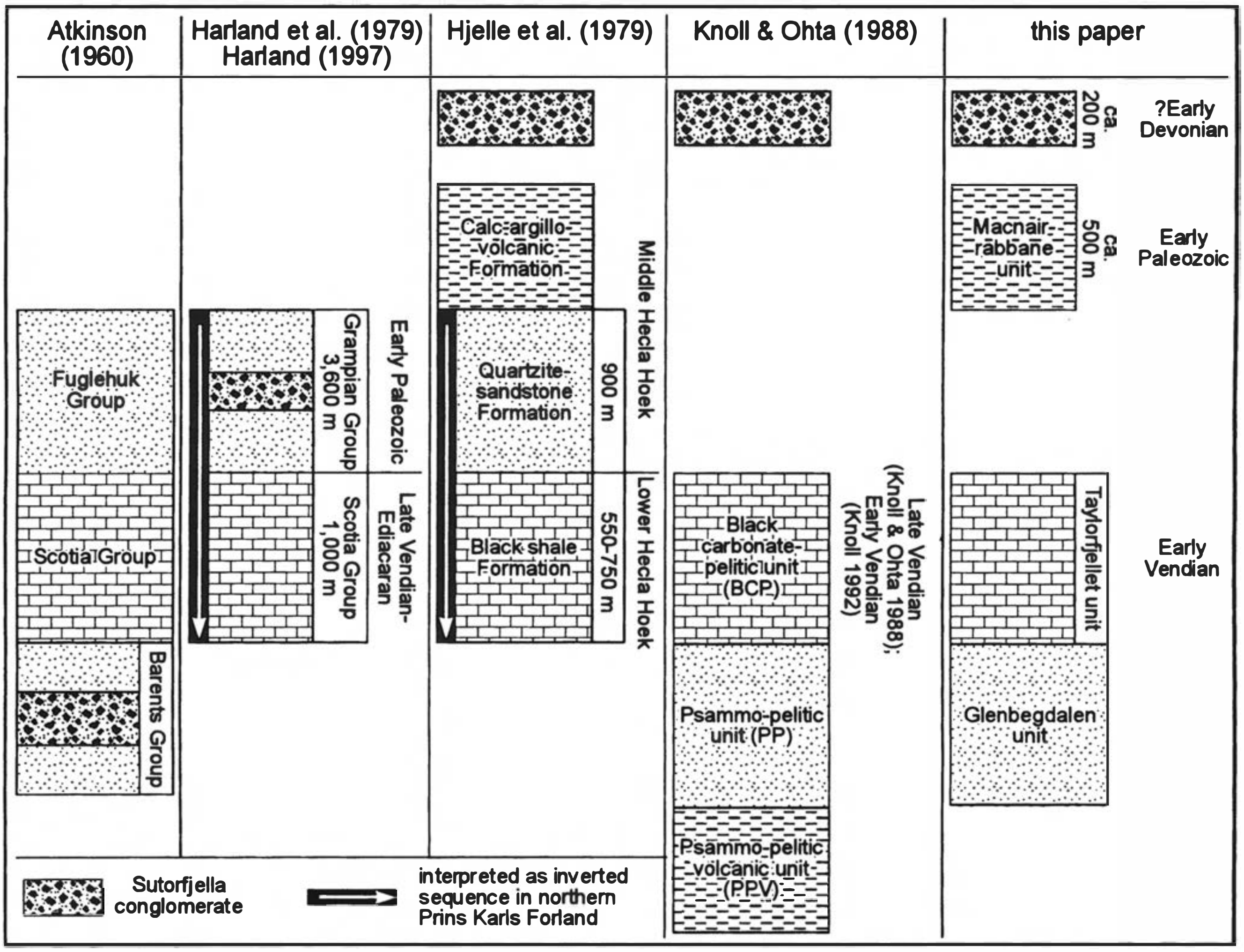

Fig. 2. Comparison of different stratigraphic interpretations of the pre-Devonian basement rocks and the Sutorfjella conglomerate in northern Prins Karls Forland, after Atkinson (1960), Harland et al. (1979, 1993), Hjelle et al. (1979), Manby (1986), Knoll & Ohta (1988), Knoll (1992), Harland (1997), Hjelle et al. (1999) and this paper.

The thickness of the Glenbegdalen unit is reported to be 3600 m by Harland et al. (1979), however, in the northern part of Prins Karls Forland the estimate of 900 m by Hjelle et al. (1979) seems more likely.

Taylorfjellet unit

The Taylorfjellet unit (Hjelle et al. 1999) (Fig. 2) is characterized by a carbonate facies with clastic influence and high contents of graphite. The unit comprises a succession of dark dolomite schists, quartz-dolomite schists, graphitic schists and some marbles. The boundary between the Glenbegdalen and Taylorfjellet units is indicated by a basal, clast-supported conglomerate with a grey dolomitic and pelitic matrix and subangular, 1–2 cm-size quartzite pebbles.

The dark-grey, grey-green weathering dolomite schists contain quartz pebbles and black chert concretions of up to 5 cm (Knoll & Ohta 1988; Knoll 1992). The fine-grained and fine-laminated quartz-dolomite schists are light- to dark-grey and contain different amounts of graphite and grains of clastic quartz, feldspar, and muscovite.

In the southeastern part of the study area, intensely tectonized greenish, dark-grey and pink chloritoid schists are exposed (Fig. 1). Based on mapping and observations by Manby (1986) and Post (1990), they probably belong to the Taylorfjellet unit (Fig. 2).

The thickness of the Taylorfjellet unit is estimated to be in the range between 550 and 750 m (Hjelle et al. 1979) and 1000 m (Harland et al. 1979).

Age of the Glenbegdalen and Taylorfjellet units

Harland et al. (1979) suggested a Late Vendian–Ediacaran age of the Taylorfjellet unit. Filaments of Cyanobacteria and remnants of acritarchs within chert concretions of this unit indicate an Early Vendian age (Knoll & Ohta 1988; Knoll 1992).

The age of the Glenbegdalen unit is uncertain. Graded bedding and cross-bedding in the Glenbegdalen unit indicate a normal position of the metasediments (Knoll

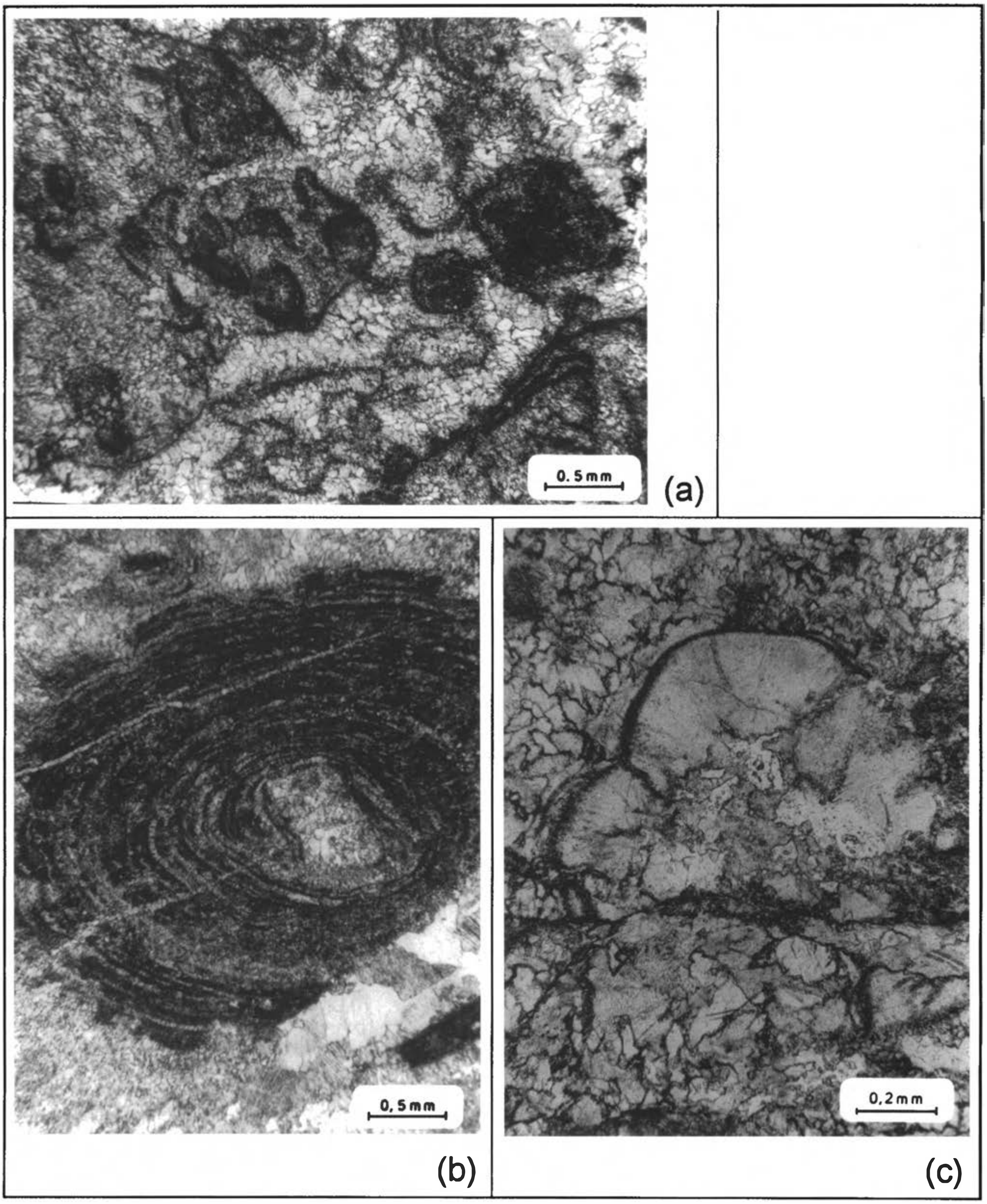

Fig. 3. Remnants of organic structures in dolomite pebbles of the conglomerate with clasts of quartzite and dolomite (lower Macnairrabbane unit) (Mersmann 1990). (a) ?*Renalcis*; (b) Oncoids; (c) ?Bryozoa.

& Ohta 1988; Klee 1990). In addition, the basal conglomerates of the Taylorfjellet unit contain pebbles derived from the Glenbegdalen unit (Knoll & Ohta 1988). These observations suggest that the whole succession is in upright position and that the Glenbegdalen unit is older than the Taylorfjellet unit (Fig. 2).

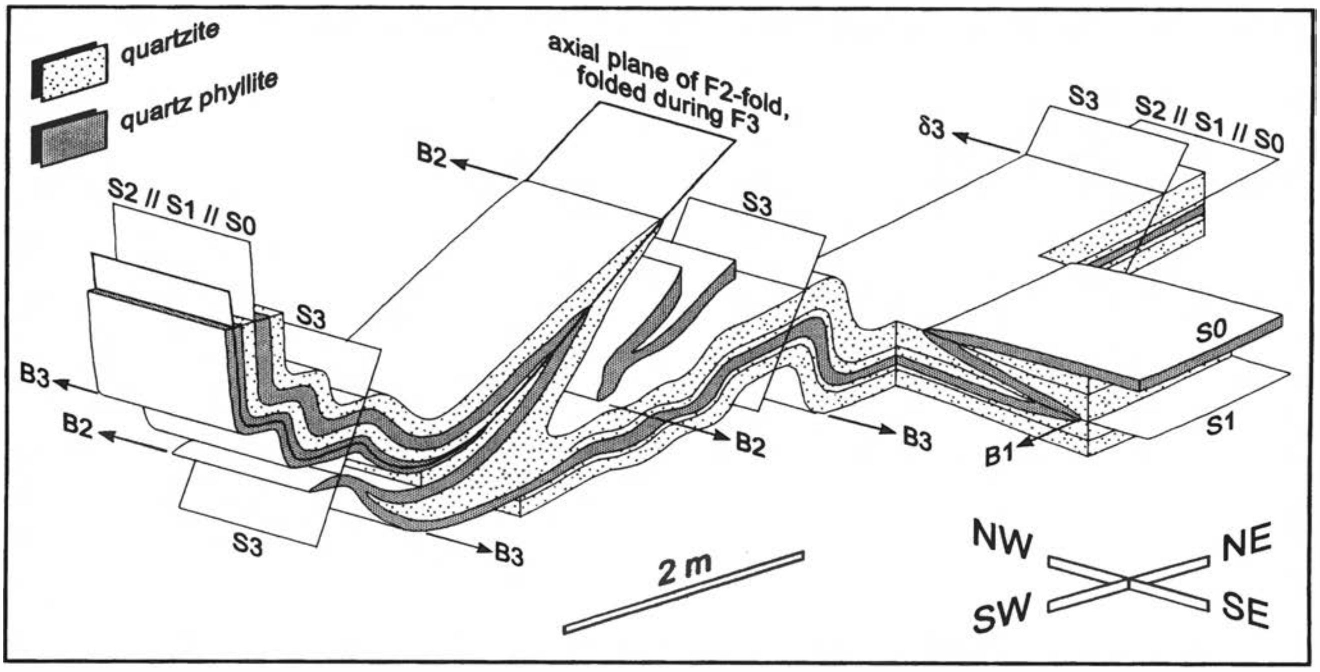

Fig. 4. Schematic sketch illustrating the relationships of D1-, D2- and D3-structures in the syncline of a F3-fold. B2- and B3-fold axes are co-axial and strike NW–SE. The NE–SW-trending isoclinal F1-folding was followed by a NW–SE-striking isoclinal F2-folding which affected bedding S0 and S1-cleavage planes. After D2, bedding S0, cleavage planes S1 and S2 as well as F2-fold axial planes were refolded by large-scale, NE-vergent F3-folds.

Macnairrabbane unit

In the Macnairrabbane area between Leefjellet and Brodden, a succession of alternating quartz-carbonate schists, phyllites, quartzites and quartzite-dolomite conglomerates in the lower part and green phyllites in the upper part is exposed (Fig. 1). The quartzite–dolomite conglomerates and the characteristic intense orange weathering of the dolomitic rocks set this unit apart from other rock units in this area. Therefore we propose to introduce the neutral term Macnairrabbane unit (equivalent to the PPV unit of Knoll & Ohta (1988), or to the Calc-argillo-volcanic Formation of Hjelle et al. (1979)) as a preliminary name (Fig. 2). The base of this unit is not exposed, whereas the upper boundary is represented by a thrust fault (Fig. 1).

The lower part of the Macnairrabbane unit is dominated by alternating blue-grey but orange-weathering quartz-carbonate schists and green-weathering phyllites. The quartz-carbonate schists comprise quartz, carbonate (mostly dolomite), sericite and feldspar. They contain up to 1.5 mm-large grains of detrital quartz and subordinate feldspar, sericite, chlorite and turmaline in a dolomitic matrix. The green phyllites are dominated by sericite and chlorite and are characterized by a millimetre- to centimetre-thin lamination and by isoclinal folds.

The quartz–carbonate schists and phyllites are interbedded by numerous characteristic, dm- to 5 m-thick, predominantly matrix-supported light-grey to dark-grey conglomerates. They are characterized by an intense orange-coloured, up to 5 mm thick weathering-crust.

The conglomerates contain pebbles of light-grey and white quartzites, dark-grey dolomites and some feldspar–quartz schists. The size of the subangular to rounded clasts varies between 1 cm and 5 cm.

The lower part of the heterogeneous Macnairrabbane unit is at least 350 m thick. To the top, the number of conglomerate beds decreases, while the quartzites and quartz–carbonate schists increase in relative abundance.

The upper part of the Macnairrabbane unit is at least 150 m thick and is dominated by monotonous, fine-grained phyllites. The fine-laminated succession consists of light-green (20–30% chlorite), white (rich in quartz and feldspar) and light-brown (rich in carbonate) weathering layers in a millimetre- to centimetre scale. Dm-thick, massive, light-grey to light-brown quartzite lenses and quartz–carbonate schists are intercalated.

Some phyllites contain numerous idiomorphic feldspars in the quartz- and feldspar-rich layers and are interpreted as volcanic tuffs by Mersmann (1990).

Age of the Macnairrabbane unit

Many dolomite pebbles in the Macnairrabbane conglomerates contain organic structures and remnants of badly preserved fossils (Klee 1990; Mersmann 1990):

1. Rather frequent are up to 0.3 mm-scale, round, tubular structures or aggregates which are bounded by fine micritic layers (Fig. 3a). According to A. May (pers. comm.), they are similar to shapes that are described as the calc-algae *Renalcis* by Roux (1985). This algae is a world-wide, common and important member of the Paleozoic reefs (Wray 1977). Its stratigraphic range is

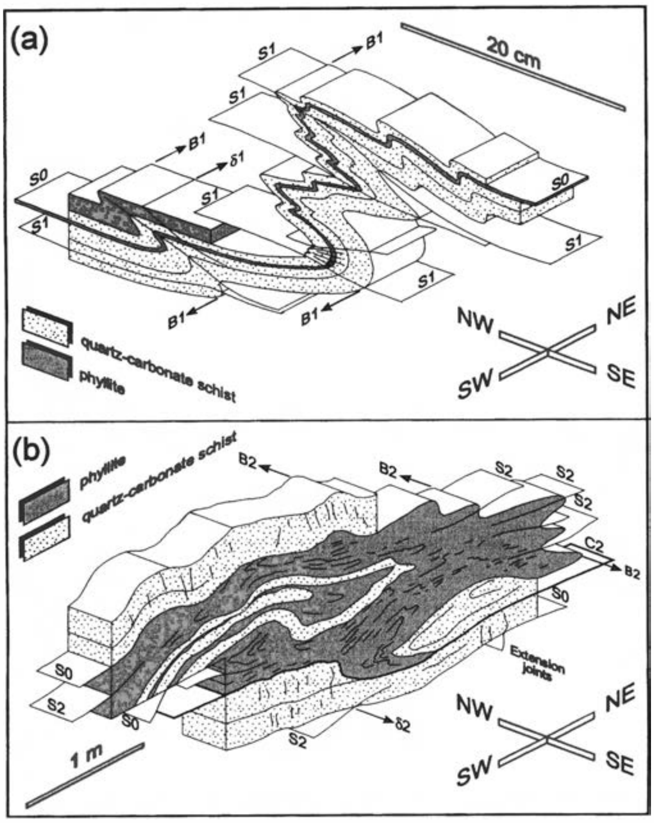

Fig. 5. (a) Schematic sketch illustrating the isoclinal folding Fl with NE–SW-trending B1-fold axes within fine-laminated phyllites and quartz–carbonate schists of the lower part of the Macnairrabbane unit. (b) Isoclinal F2-folding with NW–SE trending B2-fold axes in quartz–carbonate schists and phyllites of the lower Macnairrabbane unit (redrawn from Mersmann 1990).

between the Cambrian and Carboniferous (Chuvashov & Riding 1984), but it is less wide-spread in Ordovician and Silurian rocks (Wray 1977).

2. Shapes of red algae, rhodoids and stromatoliths occur in the dolomite pebbles.
3. Less common are up to 4 mm-large oval, concentric structures which consist of 2–5 µm-scale light, microsparitic and dark, micritic layers (Fig. 3b). These are interpreted as oncoids, but an age determination is not possible.
4. Semicircular to circular, up to 0.7 mm-scale structures are radiated in the central part and bounded by a dark, micritic rim (Fig. 3c). A very careful determination could assign these structures to bryozoa (A. May, pers. comm.).
5. Some dolomite pebbles contain polygonal structures with septae between double walls. These structures could probably represent remnants of juvenile archaeocyathids.
6. One remnant of a shell could possibly be assigned to pelecypods. Although it is very difficult to determine the fossil structures as archaeocyathids, bryozoa or pelecypods, they are evidence for multicellular organisms and argue against a Precambrian age of the dolomite pebbles within the Macnairrabbane unit. The fossil assemblage of probably archaeocyathids, stromatoliths, *Renalcis* sp. and red algae is similar to Cambrian fossil assemblages investigated by Brasier (1976). Although the Macnairrabbane unit must be younger than the reworked dolomite pebbles in the conglomerate, an Early Paleozoic age is most probable because the Macnairrabbane unit is involved in the ductile Caledonian orogeny (see below).

Sutorfjella conglomerate

The Sutorfjella conglomerate represents a unique rock unit in western Spitsbergen and is only exposed at the two Sutorfjella at the west coast of Prins Karls Forland near Kapp Sietoe (Fig. 1). It consists of approximately 200 m thick coarse-grained, mostly grey and green conglomerates with intercalated layers and lenses of sand-, silt- and mudstones. Klee (1990) and Mersmann (1990) described several types of clastic sediments within the Sutorfjella succession:

- Several metres-thick, clast-supported conglomerate beds are characterized by an intensely green-coloured, chlorite-rich matrix. They contain cm- to some dm-scale, subangular to rounded, light-grey quartzite pebbles.
- Some green and red quartzitic sandstones form up to 3 m-thick, massive and medium- to coarse-grained beds.
- Grey mudstones and siltstones occur within the entire sequence of the Sutorfjella conglomerate, forming cm- to 30 cm-thick intercalations which sometimes contain mm- to cm-scale quartzite pebbles. These fine-grained sediments are affected by a slaty to spaced cleavage.
- The dominant matrix-supported conglomerates are unsorted and characterized by metres-thick, massive beds. The blue-grey and green, fine-grained matrix contains detrital grains of quartz, chlorite and sericite and is also affected by a slaty to spaced cleavage.

The composition of clasts within the matrix-supported conglomerates is dominated by cm- to 1m-scale, angular to rounded yellow, green, brown and characteristic red quartzite pebbles. The latter are coated with an intense red weathering crust. In addition, there are three subordinate types of clasts which are important concerning the age of the Sutorfjella conglomerate:

1. Fine-grained quartzite clasts of a 5–15 cm-scale are affected by an intense cleavage which cannot be traced into the matrix of the Sutorfjella conglomerate.
2. Rounded to well-rounded, up to 5 cm-scale pebbles of grey and green phyllites are affected by two cleavages. They are very similar to the phyllites of the Glenbegdalen unit east of Sutorfjella (Klee 1990; Mersmann 1990).
3. Dm-large clasts of conglomerates are identical to the conglomerates in the Early Paleozoic Macnairrabbane unit in the eastern part of the study area. The dolomite

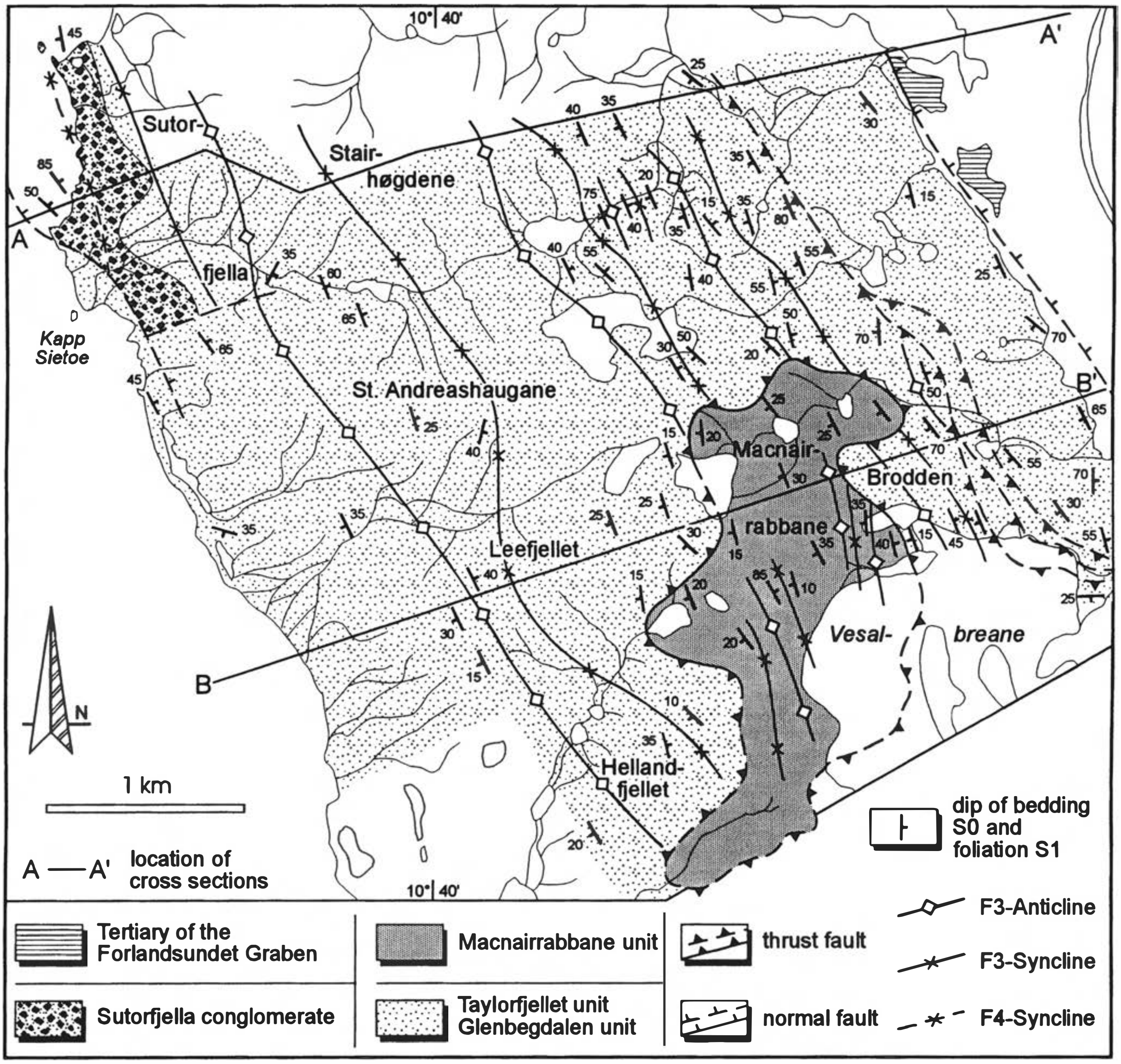

Fig. 6. Structural sketch map of the study area between Sutorfjella and Richardlaguna in northern Prins Karls Forland, compiled after Klee (1990), Mersmann (1990) and Post (1990).

pebbles in these resedimented conglomerate clasts contain the same organic structures that can be found in the dolomite clasts of the Macnairrabbane conglomerate (Klee 1990).

Structure of the study area

Previous works on the structure of northern Prins Karls Forland have been carried out by Tyrrell (1924), Atkinson (1956, 1960), Harland et al. (1979), Hjelle et al. (1979), Manby (1986) and Lepvrier (1990). Below, we present new interpretations of the structural evolution of the basement rocks and the Sutorfjella conglomerate, which is characterized by three stages of folding (D1–D3) and one later phase of thrust faulting (D4). The first three stages of deformation are summarized in a schematic sketch in Fig. 4.

The first observable deformation (D1) is characterized by dm- to metre-scale isoclinal folds in the phyllites and quartzites of the Glenbegdalen, Taylorfjellet and Macnairrabbane units (Figs. 4, 5a). The F1-folds are abundant in fine-laminated intercalations within the conglomerate beds of the Macnairrabbane unit. The B1-fold axes and $\delta 1$-lineations strike E–W to NE–SW. The S1-axial plane cleavage is developed as a pressure solution cleavage in quartz-rich metasediments and as a slaty cleavage in

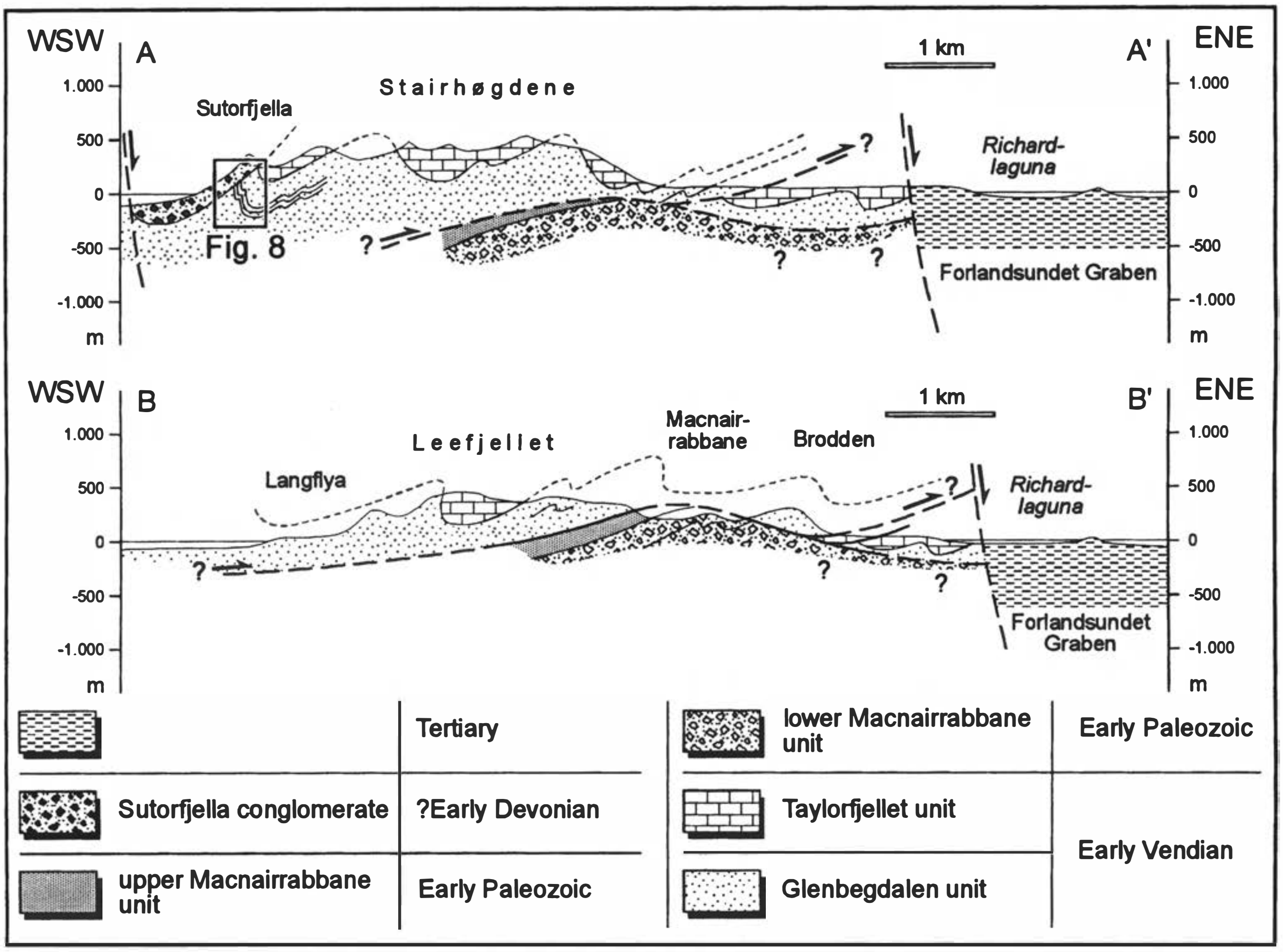

Fig. 7. WSW–ENE cross-sections through the study area between Sutorfjella and Richardlaguna. For locations, see Fig. 6.

phyllites. It is mostly oriented parallel to the bedding planes S0. Only in F1-fold hinges, S0 is truncated by S1-cleavage planes (Figs. 4, 5a). The general vergency of D1 is unclear, because the exposed fold-structures most probably represent second- or third-order folds.

The metasediments are affected by a low-grade metamorphism (Manby 1986). Sedimentary structures like graded bedding, cross-bedding and bedding S0 are often preserved. The new growth of solely sericite and chlorite and the consistent absence of biotite is evidence for low-grade greenschist facies, which probably was associated with the deformation D1 (Klee 1990; Mersmann 1990; Post 1990).

The second deformation (D2) is characterized by isoclinal folds on a dm- to several metres-scale (Figs. 4, 5b). The orientations of B2-fold axes and δ2-lineations are NW–SE to NNW–SSE and subperpendicular to the trend of the D1-structures. The slaty and pressure solution cleavage S1 is folded by isoclinal F2-folds (Mersmann 1990). F2 is accompanied by an axial-plane crenulation cleavage (S2) which crenulates the pre-existing slaty and pressure solution cleavage (S1). Sometimes, C2-shear zones and small-scale thrust faults are developed between the competent quartzites and the incompetent phyllites (Fig. 5b). D2-structures are more widespread than the first isoclinal F1-folds and affect also the Glenbegdalen, Taylorfjellet and Macnairrabbane units.

The third deformation (D3) is represented by hundreds-of-metres-scale, NW–SE trending and NE-vergent F3-anticlines and synclines (Figs. 6, 7) which affect the Glenbegdalen, Taylorfjellet and Macnairrabbane units. This deformation is co-axial to D2 and refolds S0, S1, S2 and F2-fold axial planes (Fig. 4). Fig. 8 shows the steeply inclined western short limb and the moderately SW-dipping eastern long limb of a NE-vergent F3-syncline, just below the Sutorfjella conglomerate. The short and the long limbs are accompanied by parasitic second-order folds. The associated S3-cleavage mostly dips to the SW and is often developed as a pencil cleavage, especially in the short limbs of F3-folds (Fig. 8). The pencil cleavage indicates brittle conditions during D3 and is common in more competent rocks like the Glenbegdalen quartzites.

The fourth deformation (D4) is dominated by gently SW- and NE-dipping, flat-lying brittle thrust faults which cut through the F3-fold structures (Figs. 6, 7). In the eastern part of the study area, Glenbegdalen quartzites are carried over calcareous schists of the Taylorfjellet unit. In

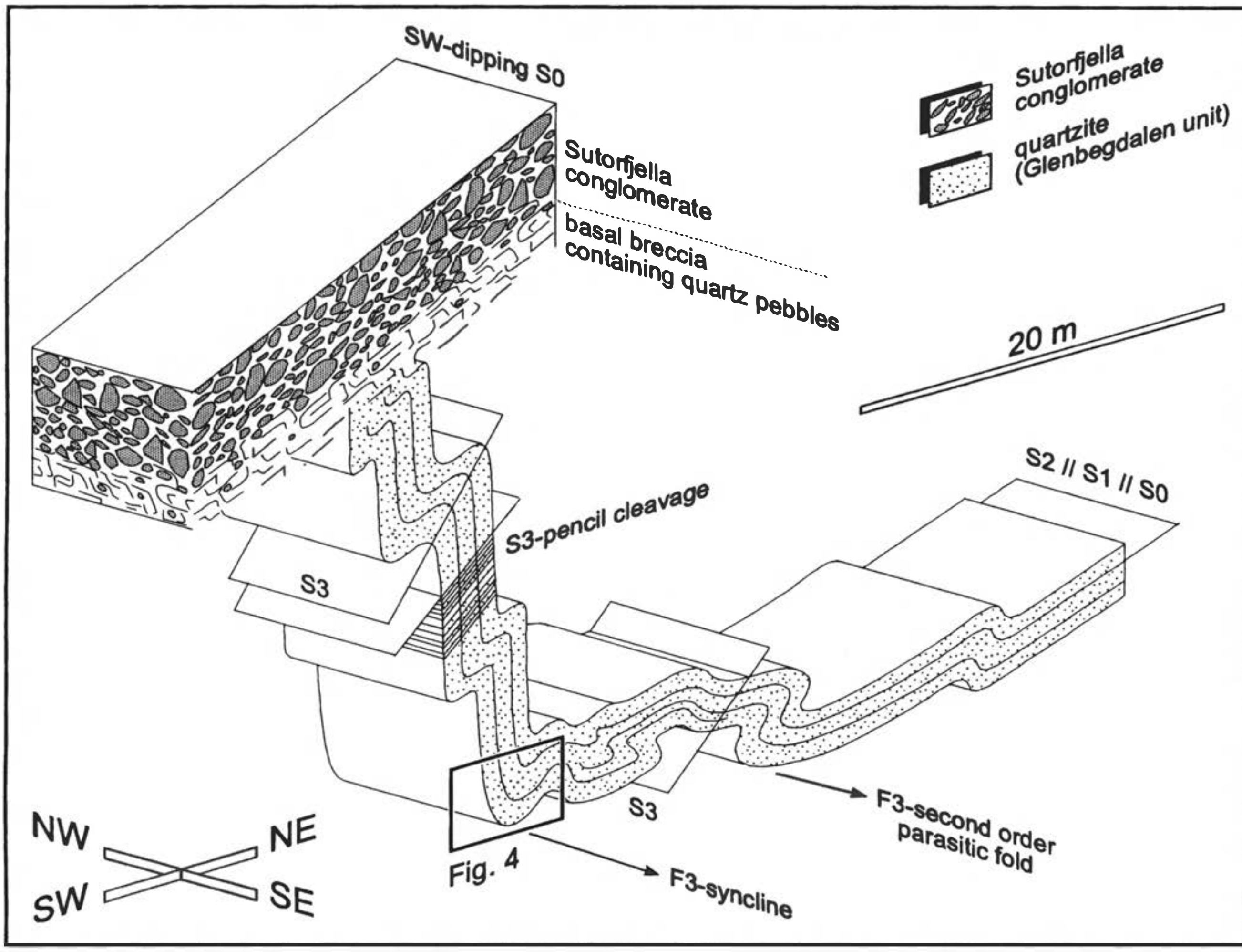

Fig. 8. Schematic sketch illustrating an open, NE-vergent F3-fold, associated S3-pencil cleavage and C3-shear planes in quartzites and quartz phyllites of the Glenbegdalen unit at northern Sutorfjellet. The short limb of the F3-fold is unconformably overlain by a basal breccia and conglomerates of the Sutorfjella conglomerate (for location, see Fig. 7).

the southern part of the thrust zone, chloritoid schists of the ?Taylorfjellet unit are imbricated between the Glenbegdalen unit (Fig. 1).

Besides the thrust-faults, several imbricate structures in the scale of some tens-of-metres are exposed at Brodden (Post 1990) and at Laurantzonfjellet south of the study area (Y. Ohta, pers. comm.).

The most prominent structure of D4 is located in the Macnairrabbane area. Here, Glenbegdalen quartzites are thrust over the Macnairrabbane unit, the latter being exposed in a tectonic window (Figs. 1, 6, 7). The D3-structures of the surrounding Glenbegdalen and Taylorfjellet units do not continue into the underlying Macnairrabbane unit. Vice versa, the NW–SE striking and SW–dipping, massive conglomerate beds and D3-structures within the Macnairrabbane unit cannot be traced into the surrounding Glenbegdalen quartzites (Fig. 6). The rapid decrease in thickness of the Glenbegdalen unit towards the exposed Macnairrabbane unit is also an indication for a thrust-faulted contact between both units (Fig. 7).

Although the thrust-faults cut through the F3-folds, they could be related to the F3-folding and thus could represent a late stage of the D3-deformation. But some observations indicate that the phase of thrust faulting represents a separate stage (D4) that took place after D3:

- No splay-faults could be detected in the cores of the NE-vergent F3-anticlines (see Fig. 7), which would be expected if thrusting was related to folding.
- If the thrusting is related to the NE-vergent F3-folding, the thrusts are expected to indicate transport to the NE. However, the main thrust carries Glenbegdalen quartzites that are not inverted over the Macnairrabbane unit cutting-down sequence (Fig. 7). This is not possible during a continuous process of thrust-related folding, and can only be explained by tilting of the Macnairrabbane unit after the F3-folding and prior to the thrust faulting (D4).
- South of the study area, two thrust sheets are exposed which form tectonic klippen along the mountain ridges of Laurantzonfjellet and Ulsfjordtoppen (Hjelle et al. 1999). The almost horizontal thrust faults cut through

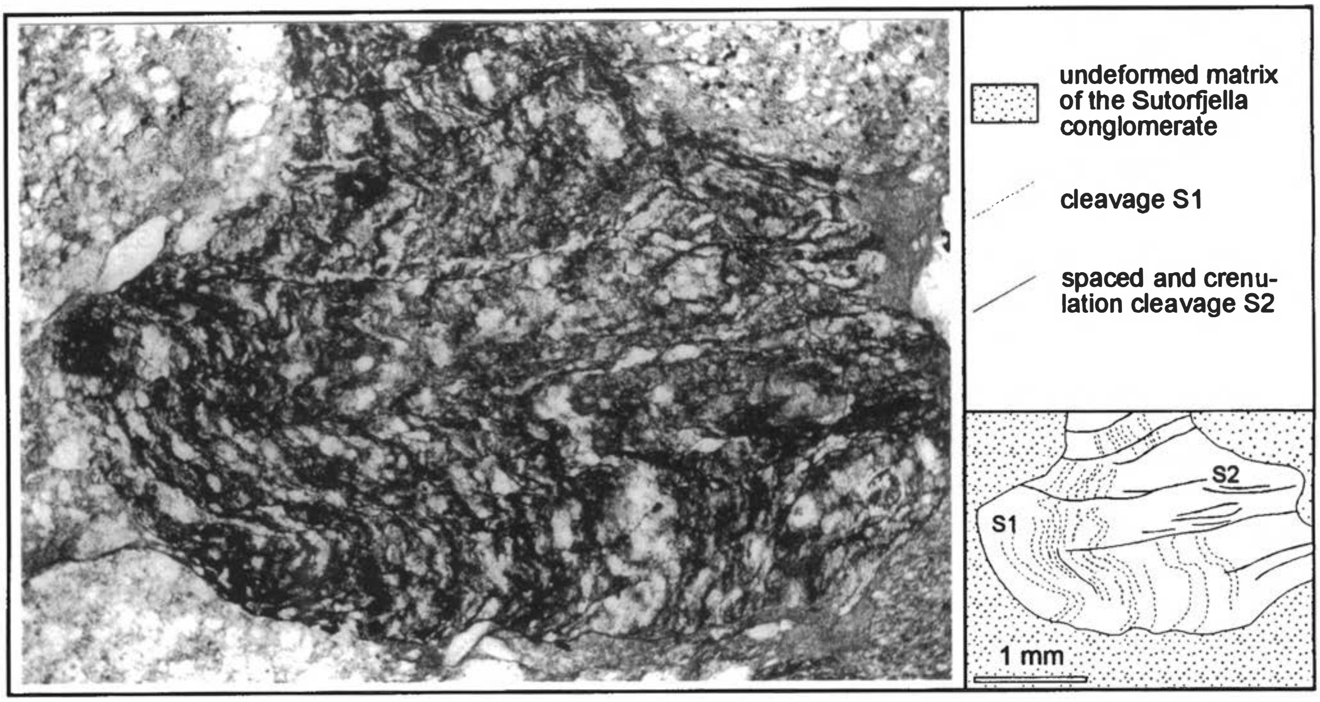

Fig. 9. Green phyllite clast of the Glenbegdalen unit in the Sutorfjella conglomerate, affected by a bedding-parallel foliation S1 and a S2-crenulation cleavage. The matrix of the conglomerate was not affected by S1 and S2, indicating the post-deformational deposition of the Sutorfjella conglomerate (Klee 1990).

the folded Glenbegdalen and Taylorfjellet units indicating that the emplacement of these thrust sheets took place after D3. Together with the thrust fault at Macnairrabbane, they form a stack of at least three thrust sheets.

Moreover, distinguishable D4-structures can be found in the Sutorfjella conglomerate. The matrix of the conglomerates and the interbedded mudstones and siltstones are affected by a spaced fracture cleavage S4, which is different from the slaty and pressure solution cleavage S1 and crenulation cleavage S2 in the Taylorfjellet, Glenbegdalen and Macnairrabbane units. It is probably related to the D4-thrust faulting. Furthermore, the Sutorfjella conglomerate is folded into a NNW–SSE trending syncline on the coastal area to the west of Sutorfjella (Figs. 6, 7). This syncline represents a F4-fold with an eastern limb overlying an older F3-syncline in the east (Fig. 7).

Discussion

The isolated position of the Sutorfjella conglomerate causes problems concerning the age of these coarse-clastic sediments. The composition of clasts as well as structural comparisons between matrix, embedded clasts and the Taylorfjellet, Glenbegdalen and Macnairrabbane units may permit a more reliable age determination:

1. Clasts of green phyllites of the Glenbegdalen unit which are just slightly older than the overlying Taylorfjellet unit indicate a post-Early Vendian deposition of the Sutorfjella conglomerate.
2. Pebbles of conglomerates of the Macnairrabbane unit indicate that the Sutorfjella conglomerate is younger than Early Paleozoic.
3. The basement rocks east of Sutorfjella were affected by a slaty and pressure solution cleavage S1 and a crenulation cleavage S2, which do not penetrate into the Sutorfjella conglomerate. In addition, a number of clasts within the Sutorfjella conglomerate were affected by deformations which can not be detected in the matrix. In particular, the green phyllite pebbles, derived from the Glenbegdalen unit, are characterized by an F1-isoclinal folding, a related bedding-parallel foliation S1, and a S2-crenulation cleavage – none of which affected the matrix of the Sutorfjella conglomerate (Fig. 9). This observation indicates that the deposition of the Sutorfjella conglomerate took place after the ductile deformations D1 and D2.
4. Craig (1916) inferred a marked discordance between the Sutorfjella conglomerate and the basement rocks. Although the contact is not well exposed, our own observations indicate that the conglomerates unconformably overlie the short limb of a NE-vergent F3-syncline consisting of Glenbegdalen and Taylorfjellet units (Figs. 7, 8):

- The contact between the basement and the conglomerates is undulated and seems to represent an erosional surface.
- The solid vertical Glenbegdalen quartzites pass over into an irregular breccia in approach to the contact. Near

Deformation		Sedimentation and tectonic events	Probable age
		Formation of mostly NNW-SSE trending normal faults; formation of the Forlandsundet Graben	Tertiary
D4	brittle	Development of thrust faults; formation of the tectonic window at Macnairrabbane; formation of a nappe stack; development of spaced fracture cleavage S4 and F4-syncline in the Sutorfjella conglomerate	Tertiary (?West Spitsbergen Fold-and-Thrust Belt)
Not detectable on Prins Karls Forland			Early Carboniferous (Svalbardian deformation)
		Deposition of the Sutorfjella conglomerate: clasts are derived from the deformed Glenbegdalen and Macnairrabbane units and are affected at least by the Caledonian deformations D1 and D2; conglomerates unconformably overlie the vertical short limb of a F3-fold	?Early Devonian
D3	brittle - ductile	Development of NE-vergent F3-synclines and anticlines with NW-SE trending axes; partly S3-pencil cleavage	Middle to Late Silurian (?Late Caledonian orogeny)
Deposition of the Bullbreen Group (St.Jonsfjorden)			Late Ordovician to Early Silurian
D2	ductile	2. isoclinal folding on a dm- to m-scale; NNW-SSE to NW-SE trending fold axes; crenulation cleavage (S2)	Middle Ordovician (?Early Caledonian orogeny)
D1	ductile	1. isoclinal folding on a dm- to m-scale; E-W to NE-SW trending fold axes; slaty cleavage (S1)	
		Erosion of the source rocks of the dolomite pebbles and (re-) deposition of (in) the Macnairrabbane unit	Early Paleozoic
		Deposition of the source rocks of the dolomite pebbles in the Macnairrabbane quartzite-dolomite conglomerate	
		Deposition of the calcareous sediments of the Taylorfjellet unit	Early Vendian
		Deposition of the clastic sediments of the Glenbegdalen unit	

Fig. 10. Succession of depositional and tectonic events in the study area on northern Prins Karls Forland.

the contact, the breccia contains subangular quartzite pebbles (Fig. 8).

- No shear planes or faults could be found parallel to the base of the conglomerate, either in the underlying basement or in the overlying conglomerate.

These observations indicate that the folded Glenbegdalen unit is unconformably overlain by the Sutorfjella conglomerate along an old erosional surface after the deformation D3.

Two separate stages of Caledonian events have been identified in Middle Ordovician (Early Caledonian) and Middle to Late Silurian times (Late Caledonian) by Ohta et al. (1983) and Ohta (1992). In St. Jonsfjorden, 50 km SE of the study area, both events are separated by the deposition of the Late Ordovician to Early Silurian Bullbreen Group (Scrutton et al. 1976; Harland et al. 1979; Armstrong et al. 1986; Ohta 1992). The age of the Sutorfjella conglomerate depends on the age of the youngest pre-Sutorfjella deformation D3 on Prins Karls Forland: if D3 is related to the Early Caledonian event, the Sutorfjella conglomerate could be correlated with the Bulltinden conglomerate of the Bullbreen Group. If D3 is Late Caledonian in age, the Sutorfjella conglomerate represents a post-Late Silurian sediment unit.

Detailed structural studies in carbonates, shales, sandstones and conglomerates of the Bullbreen Group by Morris (1988), Litjes (1994) and Sanders (1994) show that the fine-grained sediments of the sequence are intensely deformed during the Late Caledonian event: a first stage is dominated by mylonitization, intrafolial folding and a first bedding-parallel slaty cleavage (Sanders 1994). A second stage is characterized by large-scale NE-vergent folding with parasitic second-order folds and a second associated axial-plane cleavage (Litjes 1994; Sanders 1994).

This intense deformation differs from the deformation of the Sutorfjella conglomerate, which is only affected by the formation of a large-scale syncline (F4) and a spaced fracture cleavage (S4). In addition, the structures of the second deformation of the Bullbreen Group are very similar to the NE-vergent folding (F3) on northern Prins Karls Forland. In this case, the metamorphism and ductile deformations (D1, D2) on Prins Karls Forland could be related to the Early Caledonian event, whereas the ductile to brittle folding (F3) could be correlated with the Late Caledonian deformation, which suggests a post-Late Caledonian deposition of the Sutorfjella conglomerate.

Compared with the post-Caledonian evolution on the mainland of NW Spitsbergen, the Sutorfjella conglomerate could be related to the Late Silurian Siktefjellet Group (Gee & Moody-Stuart 1966) or to the Early Devonian Red Bay Group (Friend 1961). Remnants of red beds in the Sutorfjella conglomerate and the characteristic red weathered quartzite clasts in the matrix-supported conglomerates indicate that the Sutorfjella conglomerate could be correlated with the red- and green-coloured Red Bay Group, as suggested by Hoel (1912) and Craig (1916).

The deformation (D4) represents the youngest compressive event on northern Prins Karls Forland and affects both the Caledonian basement rocks and the ?Early Devonian Sutorfjella conglomerate. In NW Spitsbergen two post-Caledonian convergent deformations are known: the Svalbardian deformation (Vogt 1928), which took place in the Earliest Carboniferous (Piepjohn et al. subm.), and the Tertiary West Spitsbergen Fold-and-Thrust Belt (e.g. Dallmann et al. 1993). Although it is difficult to distinguish between these events, the structural architecture is similar to the nappe stack on Brøggerhalvøya: as in the Macnairrabbane area, comparable structures are exposed which are characterized by flat-lying, NE-directed thrust faults cutting down sequence of the footwall (Saalmann 1999). In addition, the formation of at least three thrust sheets within and south of the study area is similar to the lower part of the nappe stack of the West Spitsbergen Fold-and-Thrust Belt on Brøggerhalvøya described by Saalmann (1999) and Piepjohn et al. (in press). Although transport directions could not be determined, the similarity of the nappe stacks on both sides of the Forlandsundet Graben suggests that the D4-thrust faults in northern Prins Karls Forland represent the westernmost observable structures of the Tertiary West Spitsbergen Fold-and-Thrust Belt.

Conclusions

The observations described above can be summarized in the following evolution of the study area (compare Fig. 10):

1. Deposition of the sediments of the Glenbegdalen and Taylorfjellet units in the Early Vendian.
2. Deposition of the Early Paleozoic source rocks of the dolomite pebbles in the Macnairrabbane conglomerates.
3. Uplift, erosion and transport of the Early Paleozoic dolomite source rocks and redeposition in the conglomerates of the Macnairrabbane unit later in the Early Paleozoic. This unit represents the youngest basement unit in northern Prins Karls Forland.
4. After deposition of the Macnairrabbane unit, the Glenbegdalen, Taylorfjellet and Macnairrabbane units were affected by a lower greenschist facies metamorphism and three stages of deformation (D1, D2 and D3) which could possibly be related to the Middle Ordovician Early Caledonian event (D1, D2) and to the Middle to Late Silurian Late Caledonian event (D3).
5. After the Caledonian orogeny, the deposition of the Sutorfjella conglomerate took place during ?Early Devonian.
6. The final contractional event is represented by D4-thrust faulting, which carried the Glenbegdalen and Taylorfjellet units over the Macnairrabbane unit. Additionally, the Sutorfjella conglomerate was affected by a spaced fracture cleavage S4 and the formation of a F4-syncline.
7. The youngest observable tectonic event is represented by NNW–SSE trending normal faults (Figs. 1, 6) which cut through the Caledonian as well as the post-Caledonian structures. At least the fault to the west of Richardlaguna, which separates Tertiary sandstones in the east and the basement of Prins Karls Forland in the west, is related to the formation of the Forlandsundet Graben.

Acknowledgements. – We extend our thanks to the German Research Foundation (DFG) for financial support (Projects Th 127/17-3, Th 127/26-1) and the Alfred Wegener Institute for Polar and Marine Research (AWI) for material and logistic support. We gratefully acknowledge G. M. Manby's help and discussions in the field and we also thank K. Saalmann and W. von Gosen for many useful discussions. Finally, we express our thanks to H. Fossen and Y. Ohta for remarks and suggestions that improved the manuscript.

Manuscript received May 1999

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