RESEARCH/REVIEW ARTICLE

Stratigraphy of the uppermost Old Red Sandstone of Svalbard (Mimerdalen Subgroup)

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Abstract

Between the fjords Dicksonfjorden and Billefjorden in central Spitsbergen, Svalbard's youngest deposits (Early Givetian to Famennian in age) of the Old Red Sandstone—the Mimerdalen Subgroup—are exposed. They form a narrow outcrop area parallel to the Billefjorden Fault Zone and overlie unconformably the multicoloured sandstones of the Lower Devonian Wood Bay Formation. Stratigraphic rank and subdivision of the succession were changed repeatedly since its first mention in 1910. Based on student work in 1996, as well as regional mapping by the authors in 1993 and 2003, the present work formalizes the stratigraphic framework of the succession. This framework has already been applied in recent geological maps. At the same time it is a continuation of the lithostratigraphic standardization carried out by the Committee on the Stratigraphy of Svalbard (1999), where only post-Devonian rocks were considered. Except for some small-pebble conglomerate layers in the Wood Bay Formation, the upper part of the Mimerdalen Subgroup contains the first coarse-grained deposits in Svalbard's Old Red since the lowermost Devonian Red Bay Group. Faulting between its formations as well as conglomerate pebbles derived from the Lower Devonian Wood Bay Formation indicate the onset of the Svalbardian Event after the tectonic stability during the deposition of the Wood Bay Formation. The Mimerdalen Subgroup is probably the detrital fill of a small foreland basin derived from erosion during the uplift of the Ny-Friesland Block to the east of the Billefjorden Fault Zone. It was later affected by compressional tectonic movements during the Svalbardian Event.

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The Old Red Sandstone (ORS) represents the oldest sedimentary unit of post-Caledonian cover rocks on Svalbard. In north-west Spitsbergen, it was first described by Holtedahl (1914), who divided it into the Red Bay, Wood Bay, Grey Hoek and Wijde Bay Series. This division was later completed by the Mimervalley Series (Vogt 1938) at the top and the Siktefjellet Group (Gee & Moody-Stuart 1966) at the base of the ORS. Additional subdivision of the units was established by Kiær (1916), Føyn & Heintz (1943), Friend (1961) and Murašov & Mokin (1979).

The red, green and grey conglomerates, sandstones, siltstones and mudstones of the ORS in Spitsbergen are ?Late Silurian to Latest Devonian in age (e.g., Holtedahl 1914; Vogt 1938; Føyn & Heintz 1943; Friend 1961; Murašov & Mokin 1979; Piepjohn et al. 2000). They are concentrated within a NNW–SSE trending basin, 80 km across and 160 km long, in north-west Spitsbergen (Fig. 1a), which is bounded by Caledonian and older basement rocks along the Billefjorden Fault Zone in the east (Harland et al. 1974) and the Raudfjorden Fault in the west (Frebold 1935). Southwards, the ORS plunges beneath

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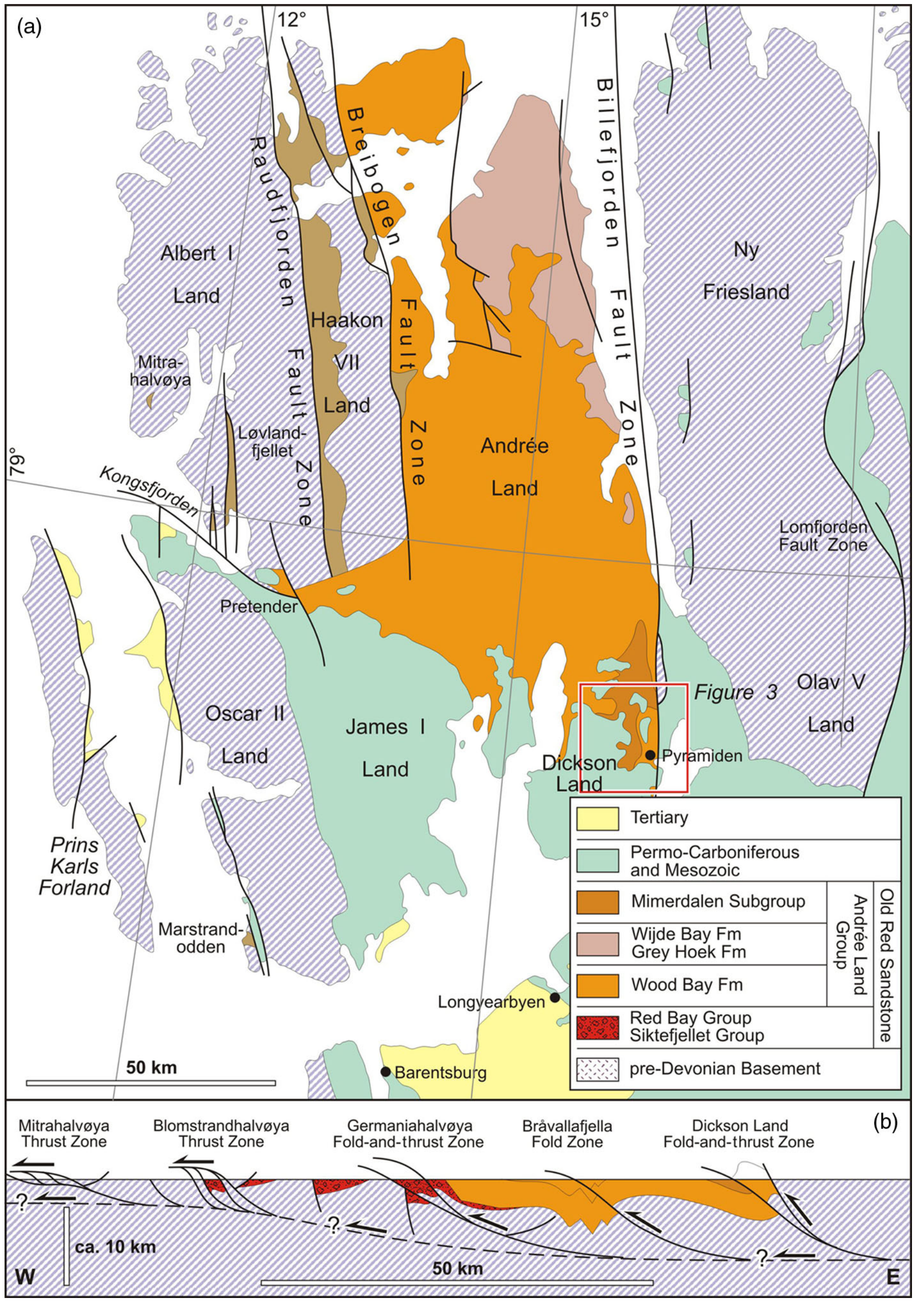

Fig. 1 (a) Geological overview map of north-western Svalbard showing the distribution of Old Red (Devonian) strata (e.g., Friend 1961). (b) Schematic east–west cross-section through the five fold-and-thrust zones of the Svalbardian fold–thrust belt between the Billefjorden Fault Zone in the east and the coast of north-west Spitsbergen in the west (Piepjohn 2000).

post-Devonian deposits of the Carboniferous and younger sedimentary basin of central Spitsbergen. The ORS Basin in north-west Spitsbergen is separated in the narrow Raudfjorden Trough in the west and the Andrée Land Basin (Harland 1997) in the east by basement rocks of the NNW–SSE trending Biskayarfonna–Holtedahlfonna High (changed from Biskayarfonna–Holtedahlfonna Horst; Gjelsvik 1979; Harland 1997).

The ORS in Spitsbergen can be divided into two major successions (Manby & Lyberis 1992; Piepjohn 2000). The lower one consists of Upper Silurian to Lower Devonian conglomerates and sandstones of the Siktefjellet and Red Bay groups (Fig. 2). They are concentrated in the Raudfjorden Trough, north and south of Liefdefjorden and along a narrow strip along the western margin of the Andrée Land Basin directly to the east of

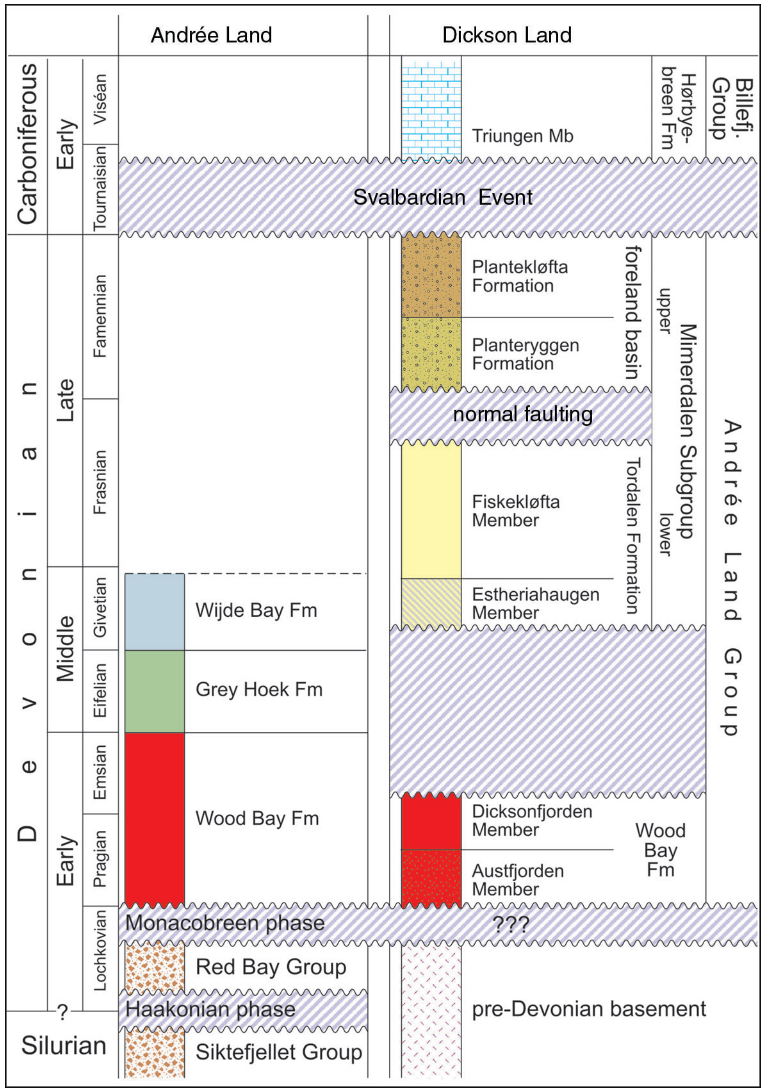

Fig. 2 Stratigraphic scheme of the Devonian Old Red Sandstone in north-western Spitsbergen, after Holtedahl (1914), Vogt (1941), Føyn & Heintz (1943), Friend (1961), Friend & Moody-Stuart (1972), Murašov & Mokin (1979), Piepjohn, Brinkmann et al. (1997), McCann (2000) and Piepjohn et al. (2000).

the Biskayarfonna–Holtedahlfonna High (Fig. 1a). In addition, red beds of the Red Bay Group also occur in small outcrops on Mitrahalvøya (Thielemann 1996; Piepjohn, Greving et al. 1997; Thielemann & Thiedig 1997), at Løvlandfjellet (Hjelle 1979; Piepjohn 1994; Lange & Hellebrandt 1997), on Blomstrandhalvøya and Lovénøyane in Kongsfjorden (Gjelsvik 1974; Kempe 1989; Niehoff 1989; Thiedig & Manby 1992; Kempe et al. 1997), at Haraldfjellet in northern Oscar II Land (Hjelle & Lauritzen 1982; Ohta et al. 2000) and probably at Marstrandodden (Piepjohn 1994; Tessensohn, Gosen et al. 2001) (Fig. 1a).

The upper ORS succession is represented by Lower to Upper Devonian fine clastic sediments of the Andrée Land Group (Harland et al. 1974) (Fig. 2), which represent the major infill of the entire Andrée Land Basin between the Billefjorden Fault Zone in the east and the Breibogen Fault in the west (Fig. 1a). To the south-west, the red beds of the Andrée Land Group extend towards the Kongsfjorden area (Pretender, Colletthøgda) (Orvin 1940; Friend & Moody-Stuart 1972; Piepjohn 1994; Tessensohn, Piepjohn et al. 2001) (Fig. 1a). In southern Spitsbergen, Devonian red beds are exposed in a narrow, 30 km long, isolated basin north and south of Hornsund (De Geer 1910a, b; Nathorst 1910; Hoel 1922; Heintz 1929; Orvin 1940). They were grouped in the Marietoppen Series (Birkenmajer 1964) or Marietoppen Formation (Friend et al. 1966), respectively, and are tentatively correlated with the Wood Bay Formation of the Andrée Land Basin (e.g., Dallmann et al. 1993).

Structural development of the ORS in north-west Spitsbergen

Development of the ORS Basin started with the deposition of coarse conglomerates and sandstones of the ?Upper Silurian/Lower Devonian Siktefjellet Group on Biskayarhalvøya (Gee & Moody-Stuart 1966). The development of this small and isolated basin was terminated by the Haakonian Phase (Gee 1972) which was probably related to Early Devonian sinistral displacements (McCann 2000). The Haakonian Phase was followed by the deposition of conglomerate and sandstone units at least 3.5 km in thickness (McCann 2000) of the Red Bay Group before renewed strike–slip faulting: the Monacobreen Phase at the end of the Lochkovian (McCann 2000) was dominated again by sinistral displacements which resulted in the formation of large rotated fault blocks, which were party tilted by up to 45° between the Raudfjorden Fault in the west and the Biskayarfonna–Holtedahlfonna High in the east (McCann 2000).

After the Monacobreen Phase, deposition of the Andrée Land Group took place under stable tectonic conditions with fine-grained mudstone, siltstone and sandstone successions (e.g., Friend 1961; Friend et al. 1966). Deposits of the Wood Bay Formation (Holtedahl 1914; Føyn & Heintz 1943), which is at least 3 km thick, are exposed across the entire Andrée Land Basin, but the overlying Grey Hoek and Wijde Bay formations are restricted to the northern part of the basin (e.g., Friend 1961) (Fig. 1a). In Dickson Land in the extreme south-east of the Andrée Land Basin, the deposits of the Wood Bay Formation are unconformably overlain by the Mimerdalen Subgroup. During the deposition of this subgroup, tectonic activities increased before the onset of the Svalbardian Event: in the time segment between the Tordalen and Planteryggen formations, a phase of normal faulting took place (Dißmann & Grewing 1997; Piepjohn 2000). In Hugindalen, deposits of the Fiskekløfta Member are offset by normal faults and afterwards overlain by the Planteryggen Formation (Fig. 3). This phase of block-faulting is possibly already related to uplift of the areas east of the Billefjorden Fault Zone. The conglomerates of the Plantekløfta Formation already contain sandstone pebbles of the Lower Devonian Austfjorden Member (Wood Bay Formation) which indicates that the Devonian cover east of the Billefjorden Fault Zone was already eroded, removed and partly resedimented during the deposition of the Mimerdalen Subgroup (Vogt 1938; Friend 1961; Piepjohn et al. 2000). Following the formation of the small foreland basin of the Mimerdalen Subgroup, the development of the Andrée Land Basin was terminated by the Svalbardian Event (Vogt 1928) in Early Tournaisian time (Piepjohn et al. 2000) which affected the ORS and the underlying Caledonian basement by thrusting and folding and the formation of five fold-and-thrust zones (Piepjohn et al. 2000) (Fig. 1b).

History of stratigraphic subdivisions and nomenclature of the Mimerdalen Subgroup

The youngest successions of the ORS in Svalbard are exposed in the extreme southeast of the Devonian Andrée Land Basin (Figs. 1a, 3). The clastic sediments and fossils of the post-Wood Bay deposits in Dickson Land were described during the first decades of the last century (Nathorst 1910; Stensiö 1918; Vogt 1938; Nilsson 1941; Høeg 1942). They were collectively called the Mimerdalen Series or Mimer Valley Series by Vogt (1938, 1941) and Friend (1961) who subdivided it—from bottom to top—into the Estheriahaugen Formation, Fiskekløfta Formation, Planteryggen sandstone and Plantekløfta conglomerate (Fig. 4). Harland et al. (1974) downgraded the Mimerdalen Series to formation rank and defined the Mimer Valley Formation as being the youngest formation of the Devonian Andrée Land Group. Murašov & Mokin (1979) and Lauritzen et al. (1989) upgraded the Mimer Valley Formation to the Mimerdalen Group, with the Estheriahaugen, Fiskekløfta, Planteryggen and Plantekløfta formations. Later, Pčelina et al. (1986) described cores from six boreholes drilled by the Russian coal mining company Trust Arktikugol in the Mimerdalen area. They subdivided the Mimerdalen succession into the sections II to V. Finally, Brinkmann (1997) divided the uppermost part of the Andrée Land Group into the Tordalen Formation (with Estheriahaugen and Fiskekløfta members), the Planteryggen and Plantekløfta formations (Figs. 4, 5). The latter stratigraphic subdivision and nomenclature have been applied on the Norwegian Polar Institute's 1:100 000 geological maps of Dicksonfjorden (Dallmann, Ohta et al. 2004) and Billefjorden (Dallmann et al. 2009), as well as its 1:50 000 map of Billefjorden (Dallmann, Piepjohn et al. 2004), and since then in other work (Bergh et al. 2012).

Lithostratigraphy of the Mimerdalen Subgroup

Because of the relatively small outcrop area of the Mimerdalen Subgroup, the intense tectonic deformation both by the Svalbardian compression and post-Svalbardian extension and the poor outcrop situation, it is difficult to find continuous sections of the stratigraphic units of the Upper Devonian ORS in Dickson Land. Therefore, the

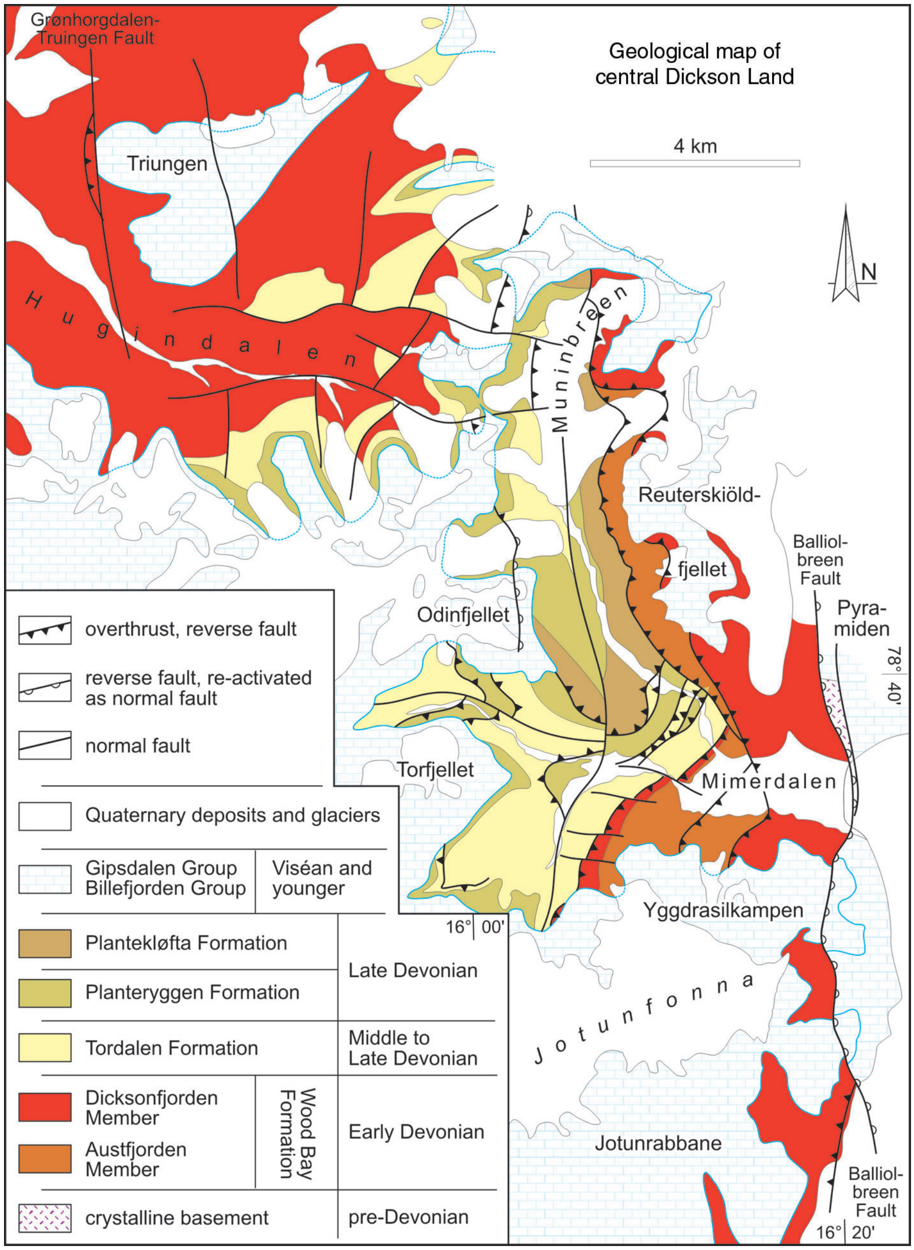

Fig. 3 Geological map of the south-easternmost part of the Andrée Land Basin in central Dickson Land west of Billefjorden, showing the distribution of the Mimerdalen Subgroup and its formations. From Dallmann, Ohta et al. (2004) and Dallmann, Piepjohn et al. (2004) and Dallmann (2009), partly based on Brinkmann (1997), Dißmann (1997), Grewing (1997), Piepjohn, Brinkmann et al. (1997) and Michaelsen (1998). For position see red frame in Fig. 1.

definition of type sections remains difficult. The only apparently continuous sections have been found in the six boreholes drilled by the Soviet coal mining company Trust Arktikugol, described by Pčelina et al. (1986).

As the drill cores of these boreholes are not publicly accessible, these cannot be formal type sections. We still regard the lithostratigraphic units of the Mimerdalen Subgroup as traditional formations, which were defined and used as such prior to the *Rules and recommendations for naming geological units in Norway* (Nystuen 1986, 1989). Although the name "Tordalen Formation"—uniting the former Estheriahaugen and Fiskekløfta formations—is not very old (1997), it was introduced to satisfy the demand that formations need to be easily distinguished, which was not the case with the former units. In this respect we regard also the Tordalen Formation—and the revised member rank of the contained units—as a traditional unit, in spite of this later adjustment.

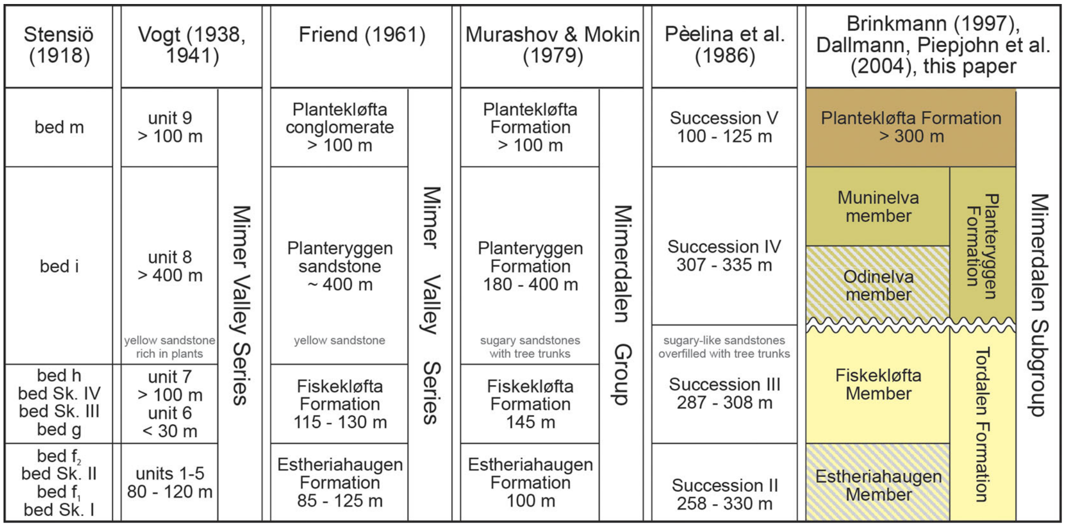

Fig. 4 Previous and present stratigraphic schemes of the Mimerdalen Subgroup and thickness of the stratigraphic units.

Another problem is the determination of the age of the units of the Mimerdalen Subgroup. At least one important stage of normal faulting took place within the Mimerdalen Subgroup (Piepjohn, Brinkmann et al. 1997; Piepjohn 2000). Due to the related uplift and erosion, one should take into account that rocks, fossils and spores have been resedimented partly massively in these units and sometimes may pretend older palynological ages than the actual depositional ages. Therefore, the youngest fossils found in the units were used to date the members and formations.

The structure of the stratigraphic descriptions below follows the one applied in the *Lithostratigraphic lexicon of Svalbard* (Dallmann 1999).

Mimerdalen Subgroup (Norwegian: Mimerdalsundergruppen)

Geographical distribution. The Mimerdalen Subgroup is exposed in a small, narrow area (12 × 25 km) directly west of the Balliolbreen Fault strand of the Billefjorden Fault Zone (Harland et al. 1974) in the eastern part of Dickson Land (Figs. 1, 3). It can be found in the valleys of Tordalen, Odindalen, Mimerdalen, Munindalen and Hugindalen below the angular unconformity of the post-Svalbardian Carboniferous sedimentary units. Northernmost occurrences of the Mimerdalen Subgroup are exposed at Sentinelfjellet south of Ålandsdalen.

Status of unit. Formal.

First use of name. Vogt (1938, 1941).

Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).

Synonym(s) and reference(s). Mimerdalen Series (Vogt 1938); Mimer Valley Series (Friend 1961); Mimer Valley Formation (Harland et al. 1974); Mimerdalen Group (Murašov & Mokin 1979).

Rank and revision of nomenclature. Brinkmann (1997), Piepjohn, Brinkmann et al. (1997) and Michaelsen (1998) reported that the sediments of the former Estheriahaugen and Fiskekløfta "formations" are so similar that differentiation in the field is difficult. Therefore, Brinkmann (1997) introduced the Tordalen Formation which includes the Estheriahaugen Member in the lower part and the Fiskekløfta Member in the upper part. The Planteryggen and Plantekløfta formations overlying the Tordalen Formation are very easy to recognize in the field, so we suggest keeping the formation rank for both units as proposed by Murašov & Mokin (1979). Concerning the question as to whether the Mimerdalen succession should form an individual lithostratigraphic group as suggested by Murašov & Mokin (1979) or should be considered part of the superior Andrée Land Group as previously proposed by Harland et al. (1974), we suggest to follow Harland. This is motivated by the fact that the entire, mainly clastic sedimentary succession of the tectonic Andrée Land Block should be one lithostratigraphic group, similar to the older Red Bay Group forming the sedimentary succession of the Raudfjorden Block. In this case, the Mimerdalen succession must have a subgroup rank.

Origin of name. Mimerdalen (Mimer Valley): About 6 km long valley extending from Mimerbukta in Billefjorden, to Tordalen in the eastern part of Dickson Land, named after the Swedish ship *Mimer* (1872). Mimer or Mimir is an Old Norse mythological figure.

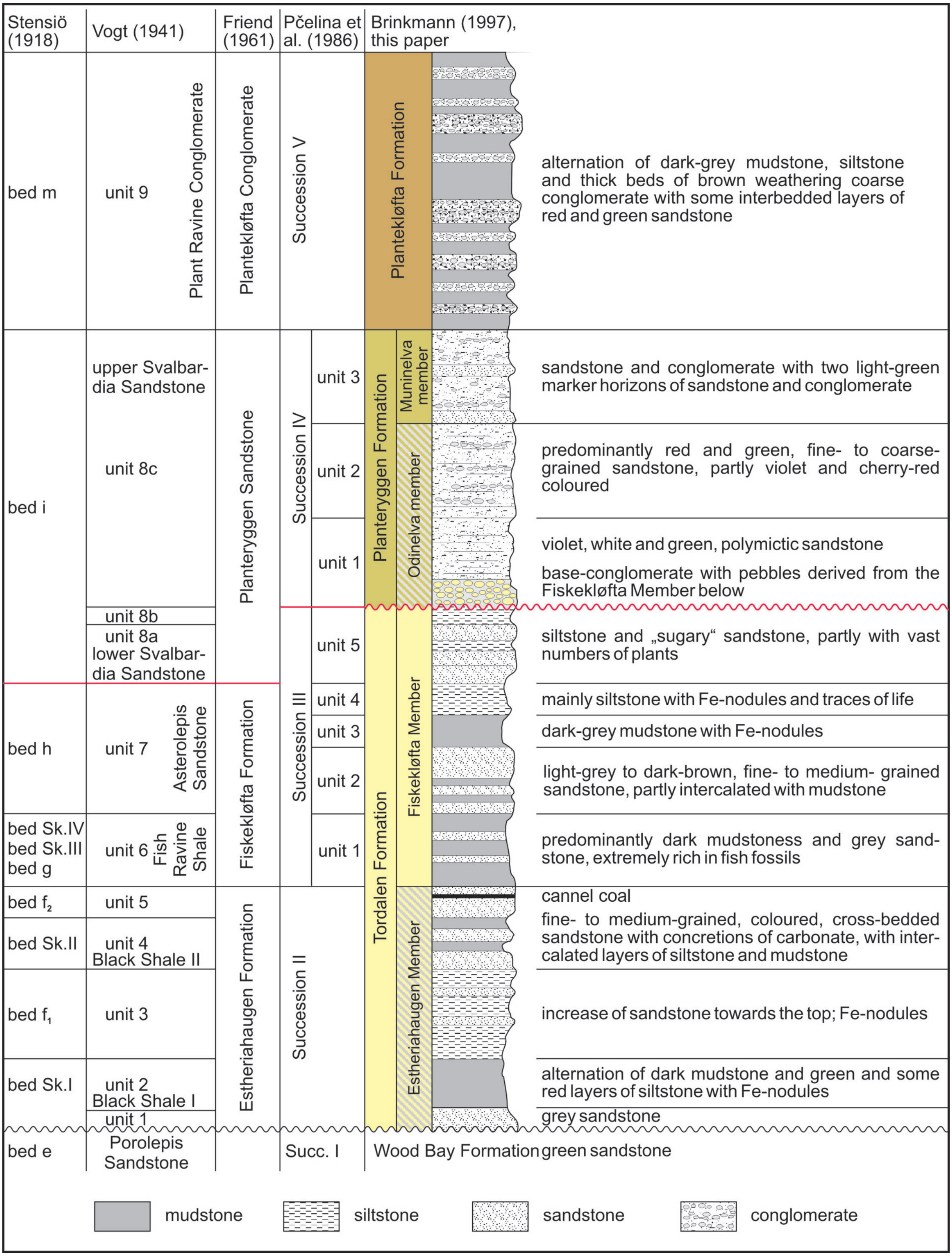

Fig. 5 Schematic stratigraphy and lithology (not to scale) of the Mimerdalen Subgroup, modified from Pčelina et al. (1986) and Piepjohn, Brinkmann et al. (1997).

These names, first appearing on a map published by Nathorst in 1884, were probably the initiation of naming many geographical features in the area from Old Norse mythology.

Reference section. The entire Mimerdalen Subgroup was found in borehole no. 64 by Trust Arktikugol (Pčelina et al. 1986) (Fig. 6).

Age. The age of the Mimerdalen Subgroup, especially the Plantekløfta Formation, has been a matter of debate for a long time. However, the age of the uppermost ORS in Svalbard and the overlying Billefjorden Group is essential for the timing of the Svalbardian (or its Greenlandic–Canadian counterpart, the Ellesmerian) Event. Based on ostracods, plant remains and palynomorphs, the estimations of the uppermost ORS ranged from Late Emsian through Eifelian and Givetian (Harland et al. 1974) to Late Givetian/Frasnian through Early Famennian (Heintz 1937; Nilsson 1941; Høeg 1942; Westoll 1951; Tarlo 1961; Vigran 1964; Allen 1965 1973) to Late Famennian (Schweitzer 1999) or even Early Carboniferous (Murašov & Mokin 1979) (Fig. 7). According to Pčelina et al. (1986), the deposition of the Mimerdalen Subgroup took place from the Middle Givetian to the Devonian/Carboniferous boundary which is similar to the lower Middle Givetian to Late Famennian age reported by Brinkmann (1997) and Piepjohn, Brinkmann et al. (2000) (Fig. 7).

Overlying unit(s). Billefjorden Group, Gipsdalen Group.

Underlying unit(s). Wood Bay Formation.

Superior unit. Andrée Land Group.

Thickness. In the boreholes of Trust Arktikugol, Pčelina et al. (1986) measured a thickness between 952 and 1098 m (Fig. 4). Because the Plantekløfta Formation is much thicker in Munindalen than in the boreholes in Mimerdalen, the uppermost part was probably already eroded before the Svalbardian deformation event. The entire Mimerdalen Subgroup is or was originally at least about 1300 m thick (Brinkmann 1997; Michaelsen 1998).

Main lithologies. Siltstone, sandstone, conglomerate.

Lower boundary definition. The base of the Mimerdalen Subgroup has been described as an erosional surface (Friend & Moody-Stuart 1972; Murašov & Mokin 1979), because the Middle Devonian Grey Hoek and Wijde Bay formations, which are widely distributed farther north in Andrée Land (Holtedahl 1914; Føyn & Heintz 1943; Murašov & Mokin 1979) thin southward and are missing in central Dickson Land. There, the Mimerdalen Subgroup unconformably overlies sandstones and siltstones of the Lower Devonian Wood Bay Formation (Vogt 1938, 1941). There is therefore probably a hiatus between the Late Emsian and the Early Givetian in the south-eastern part of the Andrée Land Basin.

Description. The Mimerdalen Subgroup consists of a lower silt- and sandstone unit, the Tordalen Formation, a middle sandstone and conglomerate unit, the Planteryggen Formation, and an upper siltstone and conglomerate unit, the Plantekløfta Formation (Figs. 4, 5). The Tordalen Formation (with Estheriahaugen and Fiskekløfta members) is dominated by intercalated dark grey mudstones and siltstones and brown, greenish and white sandstones. The Planteryggen Formation (with Muninelva and Odinelva members) is characterized by coloured, fine- to coarse-grained sandstones and conglomerates. The uppermost exposed unit of the ORS in Svalbard, the Plantekløfta Formation, consists of an alternation of black silt- and mudstones with coarse, dark brown conglomerates. The conglomerates of the Planteryggen and Plantekløfta formations are the first appreciable coarse clastic deposits in the Devonian Basin since deposition of the conglomerates of the Red Bay Group in Lochkovian times.

All units of the Mimerdalen Subgroup wedge out towards the west, whereupon the conglomerate-bearing units (Planteryggen and Plantekløfta formations) are restricted to the eastern distribution area in Munindalen and western Mimerdalen (Michaelsen 1998). Apparently, a narrow, north–south trending sedimentary foreland basin developed during sedimentation to the west and uplift to the east of the Billefjorden Fault Zone (Vogt 1938; Friend 1961; Piepjohn, Brinkmann et al. 1997). The size of the depositional area was consistently reduced during the sedimentation of the Mimerdalen Subgroup.

Tordalen Formation (Norwegian: Tordalsformasjonen)

Geographical distribution. The Tordalen Formation is widely exposed in central Dickson Land between the Balliolbreen Fault in the east, Tordalen in the south, Hugindalen in the west and Sentinelfjellet in the north. Outcrops of the Tordalen Formation are widespread in the gorges of Tordalen, in Odindalen and in Munindalen (Fig. 3).

Status of unit. Formal (on grounds of traditional usage).

First use of name. Brinkmann (1997).

Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).

Synonym(s) and reference(s). None.

Origin of name. Tordalen (Tor's Valley): Tributary valley to Mimerdalen between Torfjellet and Jotunfonna in the central part of Dickson Land. After Tor, a god of Old Norse mythology.

Reference section. The Tordalen Formation is most completely exposed in the gorges in the southern part of Tordalen. The only continuous section of the Tordalen

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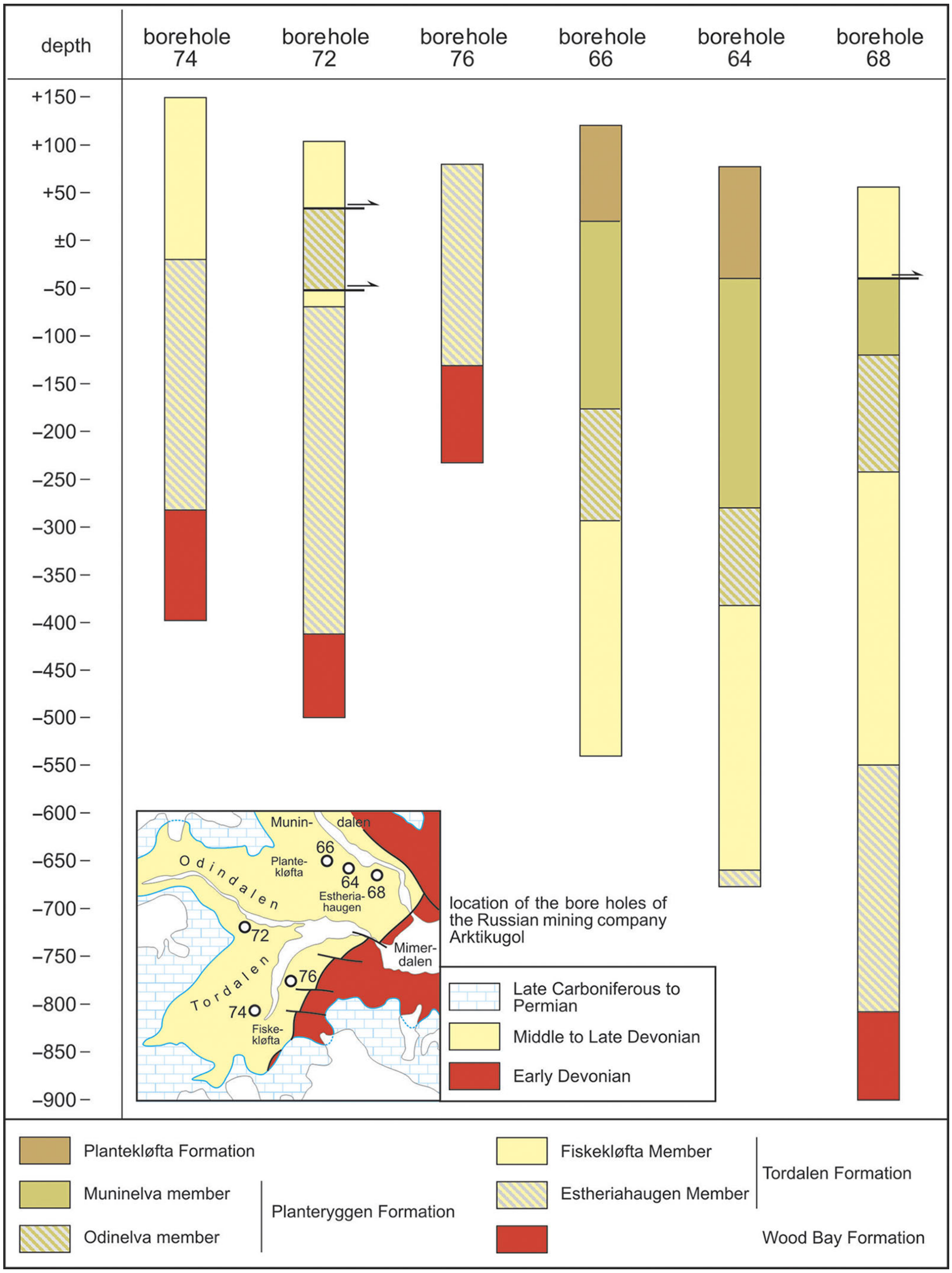

Fig. 6 Profiles of the six boreholes of the Russian mining company Trust Arktikugol in Munindalen, Odindalen and Tordalen (redrawn from Pčelina et al. 1986).

Formation was described in Trust Arktikugol's borehole no. 68 (Pčelina et al. 1986) (see Fig. 6).

Age. Late Givetian (Heintz 1937, Nilsson 1941, Westoll 1951, Tarlo 1961, Schweitzer 1999); Late Givetian to Frasnian (Murašov & Mokin 1979, Pčelina et al. 1986); early Middle Givetian to ?Early Frasnian (Brinkmann 1997) (Fig. 7), mostly based on palynology.

Overlying unit(s). Planteryggen Formation, Billefjorden Group, Gipsdalen Group.

Underlying unit(s). Wood Bay Formation.

Lateral equivalents. Føyn & Heintz (1943) and Pčelina et al. (1986) regarded the Tordalen Formation as a time equivalent of the Wijde Bay Formation in the northern part of the Andrée Land Basin, while Schweitzer (1999) opposed this.

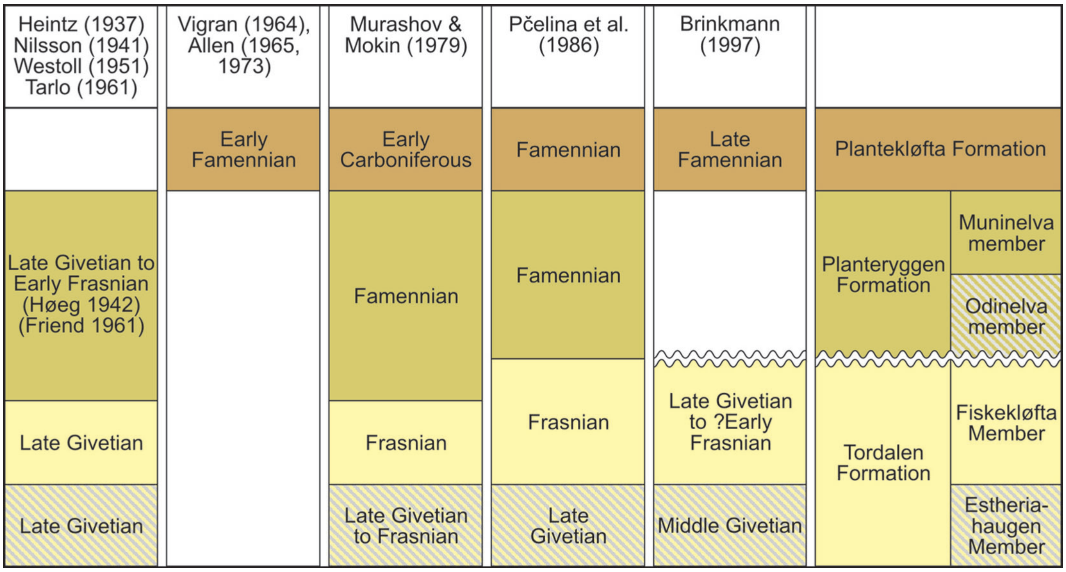

Fig. 7 Age of the Mimerdalen Subgroup, compiled from previous work.

Superior unit. Mimerdalen Subgroup.

Thickness. 545–638 m (Pčelina et al. 1986) (Fig. 4).

Main lithologies. Grey and green siltstone and sandstone.

Lower boundary definition. The lower boundary of the Tordalen Formation represents a low-angular unconformity, which, however, can only be verified by regional mapping (see above, Mimerdalen Subgroup). The boundary is drawn at the change from red and brown colours of the Dicksonfjorden Member (Wood Bay Formation) into grey and green siltstones of the Tordalen Formation (Vogt 1938; Pčelina et al. 1986). It marks a hiatus between Pragian to Emsian of the underlying Wood Bay Formation (Nathorst 1910; Føyn & Heintz 1943; Friend 1961; Ørvig 1969) and the early Middle Givetian base of the Tordalen Formation (Brinkmann 1997).

Description. The Tordalen Formation (Brinkmann 1997) is divided into the Estheriahaugen and Fiskekløfta members (Fig. 4) and consists of a monotonous succession of green and grey–green sandstones and siltstones which contain frequently coalified remnants of plants, clay galls and trace fossils (Brinkmann 1997; Michaelsen 1998). In contrast to the overlying Planteryggen and Plantekløfta formations, the Tordalen Formation is characterized by the absence of conglomerates (Murašov & Mokin 1979; Pčelina et al. 1986).

Estheriahaugen Member (Norwegian: Estheriahaugleddet)

Geographical distribution. The Estheriahaugen Member is restricted to the innermost part of Odindalen and to a narrow strip in Mimerdalen between Jotunfonna in the south-west and Muninelva in the north-east. A small number of outcrops occur in innermost Odindalen, in Fiskekløfta and around Estheriahaugen.

Status of unit. Formal (on grounds of traditional usage).

First use of name. Friend (1961).

Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).

Synonym(s) and reference(s). Estheriahaugen Formation (Friend 1961).

Origin of name. Estheriahaugen (Estheria Hill): Small hill in Mimerdalen in front of the entrance to Munindalen, in the central part of Dickson Land, named after an genus of fossil crustaceans (*Estheria nathorsti* R. Jones) that occur in these rocks.

Reference section. Good exposures of the Estheriahaugen Member can be found along the eastern part of Tordalen and in innermost Odindalen. The most continuous section through the Estheriahaugen Member was found in borehole no. 72 by Trust Arktikugol (Pčelina et al. 1986) (Fig. 6).

Age. Late Givetian (Heintz 1937; Nilsson 1941; Westoll 1951; Tarlo 1961; Pčelina et al. 1986; Schweitzer 1999), Late Givetian to Frasnian (Murašov & Mokin 1979), Middle Givetian (Brinkmann 1997) (Fig. 7).

Overlying unit(s). Fiskekløfta Member, locally probably also Billefjorden Group and Gipsdalen Group.

Underlying unit(s). Wood Bay Formation.

Superior unit. Tordalen Formation.

Thickness. 85–125 m (Friend 1961); 100 m (Murašov & Mokin 1979); 258–330 m (Pčelina et al. 1986) (Fig. 4).

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Main lithologies. Grey and greenish siltstone and sandstone.

Lower boundary definition. The lower boundary of the Estheriahaugen Member is characterized by the onset of grey and green siltstones overlying red beds of the Dicksonfjorden Member (Wood Bay Formation) (Pčelina et al. 1986). This disconformity is not exposed above ground but has been found in Trust Arktikugol's boreholes nos. 68, 72, 74 and 76 (Fig. 6) (Pčelina et al. 1986).

Description. The Estheriahaugen Member corresponds to the beds "Sk. I," "f_1," "Sk. II" and "f_2" of Stensiö (1918), to the units "1–5" of Vogt (1938, 1941) and to "Succession II" of Pčelina et al. (1986) (Fig. 4). It is dominated by an intercalation of dark grey, light grey and green, sometimes reddish mudstones, siltstones and sandstones.

The sandstones of the Estheriahaugen Member are light grey to light green, sometimes reddish, well-sorted and fine- to medium-grained. They are characterized by pronounced horizontal bedded layers 5 cm to several decimetres in thickness with flaser-bedding, large sets of cross-bedding, oscillation ripple marks, load marks and channel fillings (Supplementary Fig. S1) (Brinkmann 1997; Michaelsen 1998). The sandstones contain iron concretions, layers of clasts and oval clay lenses. In the upper part of the member, the sandstones are composed mainly of quartz grains and numerous rounded pyrite nodules which show rusty patches when oxidized. They contain mostly quartz grains and subordinate feldspars (5%), muscovite (3%) and some bioclasts, ore minerals and biotite. The matrix of the sandstones is often calcareous.

The mudstone and calcareous siltstone layers are thinner than the sandstones. They are well-bedded and contain pyrite nodules and numerous calcareous Fe-concretions (Friend 1961; Pčelina et al. 1986) which are characteristic for the entire Tordalen Formation. In the lower part, fragmentary mudstones dominate, with less common bands and lenses of light grey polymict quartzitic sandstones (Murašov & Mokin 1979). A large number of rounded argillaceous nodules and thin bands of coals and coaly rocks occur in the mudstones. Thick mudstone layers in the lower part (unit 2) and in the upper part (unit 4) represent the Black Shale I and II of Vogt (1941).

Fossils are not very frequent in the Estheriahaugen Member. Plants are sometimes concentrated on flood plains (Brinkmann 1997) and are represented by *Platiphyllum*, *Pseudoporochnus*, *Svalbardia* and *Protocephallopteris* according to Murašov & Mokin (1979). Spores are frequently preserved, whereas trace fossils are rare (Brinkmann 1997; Michaelsen 1998). In addition, fish fragments of crossopterygii, acanthodii, psammosteids (Friend 1961), *Asterolepis scabra* (Vogt 1941), *Wijdeaspis* (?), *Porolepis* sp. and *Arthrodira* gen. indet. (Pčelina et al. 1986) are common. In the siltstones, shells of pelecypods and ostracods as *Estheria nathorsti* R. Jones occur in great quantity in a relatively thin shale layer (Horn 1941; Vogt 1941).

Fiskekløfta Member (Norwegian: Fiskekløftleddet)

Geographical distribution. The Fiskekløfta Member is the most widespread unit of the Mimerdalen Subgroup and is exposed between the Balliolbreen Fault in the east, Tordalen in the south, Hugindalen in the west and Sentinelfjellet in the north.

Status of unit. Formal (on grounds of traditional usage).

First use of name. Friend (1961).

Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).

Synonym(s) and reference(s). Schiefer der Fischschlucht (Stensiö 1918); Black Shale III or Fish Ravine Shale (Vogt 1938, 1941); Fiskekløfta Formation (Friend 1961).

Origin of name. Fiskekløfta (Fish Ravine): Ravine in the lower part of Tordalen in the central part of Dickson Land. Rich finds of fossil fish were made here.

Reference section. Good exposures can be found in the gorges of Tordalen and in the entrance of Odindalen. However, continuous sections are not exposed, except for the red weathering upper sandstone units in the gorges of Tordalen. The most continuous section has been described in Trust Arktikugol's borehole no. 68 by Pčelina et al. (1986) (Fig. 6).

Age. The age of the Fiskekløfta Member has been estimated, mainly based on spores, to be late Middle Devonian (Heintz 1937; Føyn & Heintz 1943; Schweitzer 1999); Late Devonian (Nathorst 1910; Stensiö 1918); Late Givetian (Westoll 1951; Tarlo 1961); Late Givetian to ?Early Frasnian (Brinkmann 1997); Frasnian (Murašov & Mokin 1979; Pčelina et al. 1986) (Fig. 7). The Fiskekløfta Member contains *Chelinspora concinna* (Brinkmann 1997) which appears in the upper Middle Givetian (Streel & Loboziak 1996) or Late Givetian (Streel et al. 1987). The assemblage of *Samarisporites triangulates* with *Ancyrospora ancyrea* (Brinkmann 1997) is evidence for a Late Givetian age (Streel et al. 1987) of the lower Fiskekløfta Member.

Overlying unit(s). Odinelva member (Planteryggen Formation), Billefjorden Group, Gipsdalen Group.

Underlying unit(s). Estheriahaugen Member, Wood Bay Formation.

Superior unit. Tordalen Formation.

Thickness. 80–120 m (Vogt 1941); 145 m (Murašov & Mokin 1979); 287–308 m (Pčelina et al. 1986) (Fig. 4).

Main lithologies. Dark grey and green mudstone and siltstone and light grey sandstone.

Lower boundary definition. The lower boundary of the Fiskekløfta Member is characterized by the onset of predominantly dark mudstones with intercalated grey sandstones (Murašov & Mokin 1979; Pčelina et al. 1986; Michaelsen 1998). The mudstones are extremely rich in fish fossils (Nathorst 1884). The lower boundary represents an unconformity: in Tordalen and Odindalen, the Fiskekløfta Member disconformably overlies coloured sandstones of the Estheriahaugen Member (Murašov & Mokin 1979; Pčelina et al. 1986; Michaelsen 1998), but in the Hugindalen area, it unconformably overlies the Lower Devonian Dicksonfjorden Member (Dißmann 1997; Grewing 1997; Piepjohn, Brinkmann et al. 1997): the Estheriahaugen Member is missing north of Odindalen.

Description. The sediments of the Fiskekløfta Member correspond to the beds "Sk. III," "SK. IV," "h" and the lowermost part of "i" ("Schiefer der Fischschlucht") of Stensiö (1918), to the units "6" (Fish Ravine Shale), "7" (*Asterolepis* Sandstone), "8a" (lower *Svalbardia* Sandstone) and "8b" of Vogt (1941) and to "Succession III" of Pčelina et al. (1986) (Fig. 4). The Fiskekløfta Member is dominated by greenish and grey siltstones and dark grey mudstones with intercalated grey and green, medium-grained and quartz-rich sandstones in the Hugindalen area (Dißmann 1997; Grewing 1997) and by dark grey to black bituminous mudstones up to 15 m in thickness, olive-green and grey siltstones and light brown and yellow sandstones in the Mimerdalen area (Pčelina et al. 1986; Brinkmann 1997; Michaelsen 1998). Especially the siltstones contain numerous calcareous Fe-concretions, up to 5 cm in scale, similar to the Estheriahaugen Member. In contrast to the Esteriahaugen Member, calcareous siltstones and reddish deposits are missing (Pčelina et al. 1986). Although the Fiskekløfta Member does not contain red beds, the grey and green sandstone units are characterized by intense, reddish weathering colours especially north of Odinelva and in the gorges of Tordalen (Supplementary Fig. S2). Besides the horizontal bedding, the sediments of the Fiskekløfta Member contain sets of cross-bedding, load marks, groove marks, oscillation and current ripple marks and subordinate mud-cracks.

The Fiskekløfta Member can be divided into five units (Fig. 5) which have been defined by Pčelina et al. (1986) in the boreholes and which can be also recognized above ground (Michaelsen 1998):

Unit 1 is 29–49 m thick and is dominated by thin-skinned (<1 mm), intensely cleaved black mudstones which contain coalified plant remains. The thickness of the mudstones varies between several decimetres and 3 m. Intercalated are light grey siltstones with Fe nodules, dark grey sandstones with ankerite/siderite concretions and beds of quartzitic, fine-grained grey sandstones maximally 1 m in thickness. Characteristic are numerous load casts on the surface of stratum of the sandstone beds (Pčelina et al. 1986; Michaelsen 1998). Unit 1 corresponds to the Fish Ravine Shale of Vogt (1941).

Unit 2 consists of light grey to dark brown, fine-grained sandstones with intercalated dark mudstones which often contain pyrite nodules. The thickness varies between 50 and 79 m (Pčelina et al. 1986; Michaelsen 1998).

Unit 3 is dominated by dark grey mudstones which pass upwards into siltstones. Characteristic of unit 3, which is 15–25 m thick, is the content of calcareous Fe nodules and the conchiform cleavage in the lower part (Pčelina et al. 1986; Michaelsen 1998).

Unit 4 represents a marker horizon in the Mimerdalen and Munindalen areas. It is characterized by grey–green, light brown and dark grey, sandy siltstones and fine- to medium-grained sandstones. The bedding planes are often enriched in muscovite. The deposits contain quartz (up to 60%), plagioclase (up to 10%), microcline and muscovite. The matrix is formed by chlorite, hematite and granular opaque matter (Michaelsen 1998). The mudstones are affected by an intense cleavage. Characteristic are large quantities of Fe-rich clay galls and uneven bedding surfaces which are caused by life activity (Chondrites) (Supplementary Fig. S3). Unit 4 is 84–104 m thick (Pčelina et al. 1986; Michaelsen 1998). The units 2–4 can be correlated with the Asterolepis Sandstone of Vogt (1941).

Unit 5 is 55–85 m thick and consists of remarkable light grey to white, "sugar-like" quartzose sandstones several metres in thickness (Pčelina et al. 1986) in the lower part which form a marker horizon. They are monomict, medium- to coarse-grained and contain about 90% of quartz with a very small amount of matrix. Accessory, biotite, ore minerals and fragments of argillaceous sandstones occur. Massive, thick-bedded sandstones of this unit contain muscovite grains up to 1 cm in size. In the upper parts of unit 5, grey to green, silty, fine-grained sandstones occur, which are interbedded by some grey siltstones and mudstones. The sandstones are characterized by numerous trace fossils and fish fragments of placoderms and crossopterygii (Fig. 8). Typically, the bedding planes exhibit partly large quantities of alluvial, up to 3 m long, branches and trunks of trees (Supplementary Fig. S4) (Pčelina et al. 1986; Michaelsen 1998).

Unit 5 corresponds to the lower bed "i" of Stensiö (1918) and to the lower Svalbardia Sandstone (unit "8a") and the green shales of unit "8b" of Vogt (1941). Friend (1961) has correlated those beds with the lowermost part of the Planteryggen Sandstone, whereas Pčelina et al. (1986) have assigned them to unit 5 in the upper part of Succession III (Fig. 5). We would like to follow the

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Fig. 8 Remnants of placoderms in grey sandstones in unit 5 of the Fiskekløfta Member (Tordalen Formation) within a tectonic slice at the northern cliff of Muninelva (Munin River). (Photo by B. Michaelsen.)

latter stratification with the lower bed "i" (Stensiö 1918) and units "8a and b" (Vogt 1941) representing the upper part of the Fiskekløfta Member/Tordalen Formation because the upper boundary of the sugary sandstones and siltstones with vast numbers of trunks of trees is represented by an unconformity and an interruption of the sedimentation by a phase of normal faulting before the onset of deposition of the Planteryggen Formation (Dißmann 1997; Piepjohn, Brinkmann et al. 1997; Piepjohn 2000) (Fig. 5).

In contrast to the Estheriahaugen Member, the Fiskekløfta Member is characterized by numerous trace fossils as *Nereïtes*(?) (Dißmann 1997) and coalified plant remains as well as intense bioturbation (Brinkmann 1997; Grewing 1997; Michaelsen 1998). The most frequent fossils are lepidophytes and placoderms such as *Asterolepis scabra*, *Psammolepis undulata* and *Dictyonosteus arcticus* (Vogt 1941).

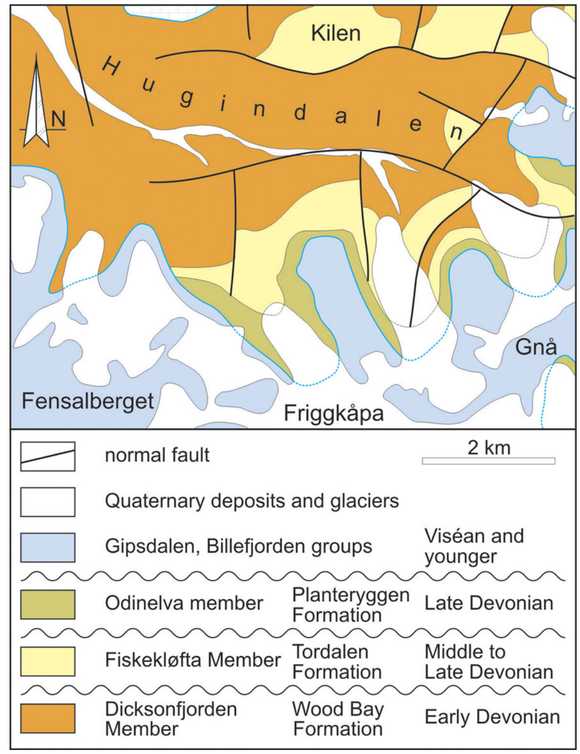

Fig. 9 Geological map of the Hugindalen area. The lowermost unit of the Mimerdalen Subgroup (Estheriahaugen Member) is not exposed. The Fiskekløfta Member unconformably overlies the Early Devonian Wood Bay Formation. The Odinelva member unconformably overlies the faulted Fiskekløfta Member and Wood Bay Formation. The Munindalen Member and the Plantekløfta Formation are not exposed.

Planteryggen Formation (Norwegian: Planteryggformasjonen)

Geographical distribution. The deposits of the Planteryggen Formation are exposed on the western slope of Munindalen between Estheriahaugen and Planteryggen in the south and Kilen in the north. Two more narrow occurrences can be found south of Hugindalen, north of Fensalberget and Gnå (Figs. 3, 9).

Status of unit. Formal (on grounds of traditional usage).

First use of name. Friend (1961).

Current definition. Murašov & Mokin (1979).

Synonym(s) and reference(s). Planteryggen Sandstone (Friend 1961); Planteryggen Sandstone Member (Harland 1997).

Origin of name. Planteryggen (Plant Ridge): About 2 km long, south-eastern part of Odinfjellet in the central part of Dickson Land. Due to the Devonian plant fossils found here.

Reference section. The Planteryggen Formation is exposed at Planteryggen (Plant Ridge) between Odinelva and Plantekløfta and at the west slope of Munindalen east of Odinfjellet. Good exposures are rare, and the most complete section was described by Pčelina et al. (1986) in Trust Arktikugol's borehole no. 64 (see Fig. 6).

Age. Late Givetian to Early Frasnian (Høeg 1942; Berry 2005); Frasnian to possibly Famennian (Schweitzer 1999); Famennian (Murašov & Mokin 1979; Pčelina et al. 1986) (Fig. 7).

Overlying unit(s). Plantekløfta Formation, Billefjorden Group, Gipsdalen Group.

Underlying unit(s). Fiskekløfta Member (Tordalen Formation).

Superior unit. Mimerdalen Subgroup.
Thickness. Ca. 400 m (Vogt 1941); 180–400 m (Murašov & Mokin 1979); 307– 335 m (Pčelina et al. 1986) (Fig. 4).
Main lithologies. Multicoloured sandstone, siltstone, conglomerate.
Lower boundary definition. The base of the Planteryggen Formation is characterized by an unconformity above the Fiskekløfta Member (Brinkmann 1997; Dißmann 1997; Grewing 1997; Michaelsen 1998; Schweitzer 1999). The unconformity represents a phase of normal faulting between the deposition of the Tordalen and Planteryggen formations (Grewing 1997; Piepjohn, Brinkmann et al. 1997; Piepjohn 2000). This unconformity is probably responsible for the problem of dating the sedimentary units of the Mimerdalen Subgroup. The occurrence of pebbles of the Fiskekløfta Member in the Planteryggen Formation or Lower Devonian sandstone pebbles of the Austfjorden Member in the Plantekløfta Formation indicates that uplift and fault tectonics caused erosion and redeposition of the clasts. This also applies to plant fossils and spores which can be eroded for example from the Upper Givetian to ?Lower Frasnian Fiskekløfta Member and being resedimented in the younger Planteryggen Formation.

The lower boundary of the Planteryggen Formation is marked by white to light grey quartzitic sandstones which laterally pass into a basal green conglomerate containing pebbles derived from the underlying Fiskekløfta Member (Pčelina et al. 1986).
Description. The Planteryggen Formation corresponds to the major upper part of bed "i" of Stensiö (1918), the unit "8c" of Vogt (1941) and to "Succession IV" of Pčelina et al. 1986 (Fig. 4). It consists of a crimson succession of red, grey, red–violet, white and green medium- to coarse-grained sandstones with shaly siltstones (Pčelina et al. 1986; Brinkmann 1997; Dißmann 1997; Michaelsen 1998). They are intercalated by massive conglomerates. The red colouration is a characteristic feature of the Planteryggen Formation which can be divided into two distinct and mapable units, the Odinelva and Muninelva members.

Odinelva member (Norwegian: Odinelvleddet)

Geographical distribution. The deposits of the Odinelva member are exposed on the western slope of Munindalen between Estheriahaugen and Planteryggen in the south and Kilen in the north. Two more narrow occurrences can be found south of Hugindalen, north of Fensalberget and Gnå.
Status of unit. Informal.
First use of name. *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).
Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).
Synonym(s) and reference(s). Unteres Planteryggen Member (Michaelsen 1998).
Origin of name. Odinelva (Odin River): river running in the valley Odindalen with the 60 m high waterfall Sjursethfossen, towards the river Mimerelva in the central part of Dickson Land. After Odin, god in Old Norse mythology.
Reference section. The Odinelva member is exposed in the inner part of Odindalen, at Planteryggen, at the east slope of Odinfjellet and south of Hugindalen. The most complete sequence of this unit has been described by Pčelina et al. (1986) in Trust Arktikugol's borehole no. 64 (Fig. 6).
Age. No diagnostic fossil record; see superior Planteryggen Formation; delimitation of members by fossil record not possible.
Overlying unit(s). Muninelva member, Billefjorden Group, Gipsdalen Group.
Underlying unit(s). Fiskekløfta Member (Tordalen Formation).
Superior unit. Planteryggen Formation.
Thickness. 106–125 m (Pčelina et al. 1986).
Main lithologies. Multicoloured sandstone and conglomerate.
Lower boundary definition. The base of the Odinelva member is marked by white to light grey quartzitic sandstones and a local basal green conglomerate containing pebbles derived from the underlying Fiskekløfta Member (Pčelina et al. 1986).
Description. The Odinelva member corresponds to member 1 (4–14 m thick) and member 2 (102–111 m thick) of "Succession IV" of Pčelina et al. (1986) (Fig. 5). It is composed of red, green, light green and violet coarse-grained sandstones and thick conglomerates with a calcareous matrix. Interbedded are grey mudstones and siltstones. The red colour is caused by hematite.

The conglomerates at the base of the Odinelva member contain pebbles from the underlying Fiskekløfta Member (Pčelina et al. 1986) indicating a phase of tectonic movements, which occurred between the deposition of the Fiskekløfta and Odinelva members. At the south slope of Hugindalen east of the mountain Gnå, the Odinelva member (Planteryggen Formation) unconformably overlies the faulted Fiskekløfta Member (Figs. 3, 9) (Dißmann 1997; Grewing 1997; Piepjohn, Brinkmann et al. 1997; Piepjohn 2000).

The lower parts of the Odinelva member (Planteryggen Formation) are characterized by coarse-grained, polymictic, quartzitic sandstones, gritstones and light grey conglomerates several metres in thickness. In the higher parts of the Odinelva member, layers of conglomerate up to 2 m in thickness are interbedded. They are massive, light grey, yellow and black and are poorly sorted, matrix-supported and poorly stratified. The pebbles are represented by black clay gulls (up to 10 cm), green, dark grey subangular siltstones (up to 10 cm), fragments of metamorphic quartzitic rocks and white and rounded quartzites up to 1.5 cm in scale (Brinkmann 1997; Dißmann 1997). Furthermore, metre-thick beds of yellow quartz-chip sandstones occur with well-rounded quartz-pebbles, up to 4 cm in scale, as well as coal lenses through the entire member.

Fossils are rare in the Odinelva member. Besides fish remains, some plant remains occur as imprints, coalified or silicified, up to 5 cm in size (Michaelsen 1998).

Muninelva member (Norwegian: Muninelvleddet)

Geographical distribution. The Muninelva member is restricted to Munindalen, Estheriahaugen and the south slope of Planteryggen in central Dickson Land.
Status of unit. Informal.
First use of name. Dallmann, Piepjohn et al. (2004).
Current definition. This paper. See also the legend of the *Geological map of Billefjorden* (Dallmann, Piepjohn et al. 2004).
Synonym(s) and reference(s). Oberes Planteryggen Member (Michaelsen 1998).
Origin of name. Muninelva (Munin River): river running in the valley Munindalen towards the river Mimerelva in the central part of Dickson Land. Named after Munin, one of the god Odin's ravens in Old Norse mythology.
Reference section. Exposures of the Muninelva member can be found along the erosional cliffs of Muninelva and on Estheriahaugen. A continuous section was described in borehole no. 64 (Pčelina et al. 1986) (Fig. 6).
Age. See superior Planteryggen Formation; delimitation of members by fossil record not possible.
Overlying unit(s). Plantekløfta Formation.
Underlying unit(s). Odinelva member.
Superior unit. Planteryggen Formation.
Thickness. 197–223 m (Pčelina et al. 1986) (Fig. 4).
Main lithologies. Sandstone and conglomerate.
Lower boundary definition. The base of the Muninelva member is marked by the lower of two light green sandstone and conglomerate layers (Pčelina et al. 1986) which is exposed at erosional cliffs of the west shore of Muninelva south of the moraine of Muninbreen.
Description. The Muninelva member corresponds to the upper Svalbardia Sandstone of Vogt (1941) and to the member 3 of "Succession IV" of Pčelina et al. (1986) (Fig. 5). It consists of thick beds of mostly grey and sometimes intensely green, medium-grained sandstones and gritstones which often contain angular to rounded clasts of quartzites up to 4 cm in scale. Intercalated are massive, metre-thick beds of grey conglomerate horizons.

Pčelina et al. (1986) describe two marker horizons, 9–36 m thick, in the Muninelva member which consist of green to light green, mica-bearing sandstones with intercalated coarse-grained gritstones and fine-grained conglomerates with quartz and quartzite clasts. The lower one represents the base of the member. Partly, the sandstones pass over in conglomerates with quartzite clasts. The top of the Muninelva member is characterized by a 40 m thick succession of red conglomerate and sandstones with centimetre-size pebbles of red and white quartzites, and mudstones (Murašov & Mokin 1979).

Plantekløfta Formation (Norwegian: Plantekløftformasjonen)

Geographical distribution. The Plantekløfta Formation is restricted to a small area mostly within Munindalen between Estheriahaugen and Plantekløfta in the south and the ridge between Caiusbreen and Stensiöbreen in the north (Fig. 3). The eastern boundary is formed by the lower Munindalen Thrust, which placed the Lower Devonian Austfjorden Member westwards over the Plantekløfta Formation (Fig. 10) (Brinkmann 1997; Michaelsen 1998).
Status of unit. Formal (on grounds of traditional usage).
First use of name. Friend (1961).
Current definition. Murašov & Mokin (1979).
Synonym(s) and reference(s). Plant Ravine Conglomerate (Vogt 1938); Plantekløfta Conglomerate (Friend 1961); Plantekløfta Conglomerate Member (Harland 1997).
Origin of name. Plantekløfta (Plant Ravine): ravine north-east of Planteryggen in the central part of Dickson Land. Named for the Devonian plants found here.
Type area/locality. The Plantekløfta Formation is restricted to a very small area in central Dickson Land. The best exposures are located in the Plantekløfta (Plant Ravine), at the steep cliffs east and west of Muninelva and at the east slope of Munindalen (Fig. 3). There, the highest and youngest parts, respectively, of the Devonian ORS are exposed below the lower Munindalen Thrust (Michaelsen et al. 1997; Piepjohn et al. 2000). In addition, Pčelina et al. (1986) described continuous sections of the lower parts of the Plantekløfta Formation in boreholes nos. 64 and 66 (see Fig. 6).
Age. Late Devonian (Vogt 1941); Early Famennian (Vigran 1964; Allen 1965, 1973); Famennian (Pčelina et al. 1986); Famennian, including latest Famennian (Schweitzer 1999); Late Famennian (Brinkmann 1997;

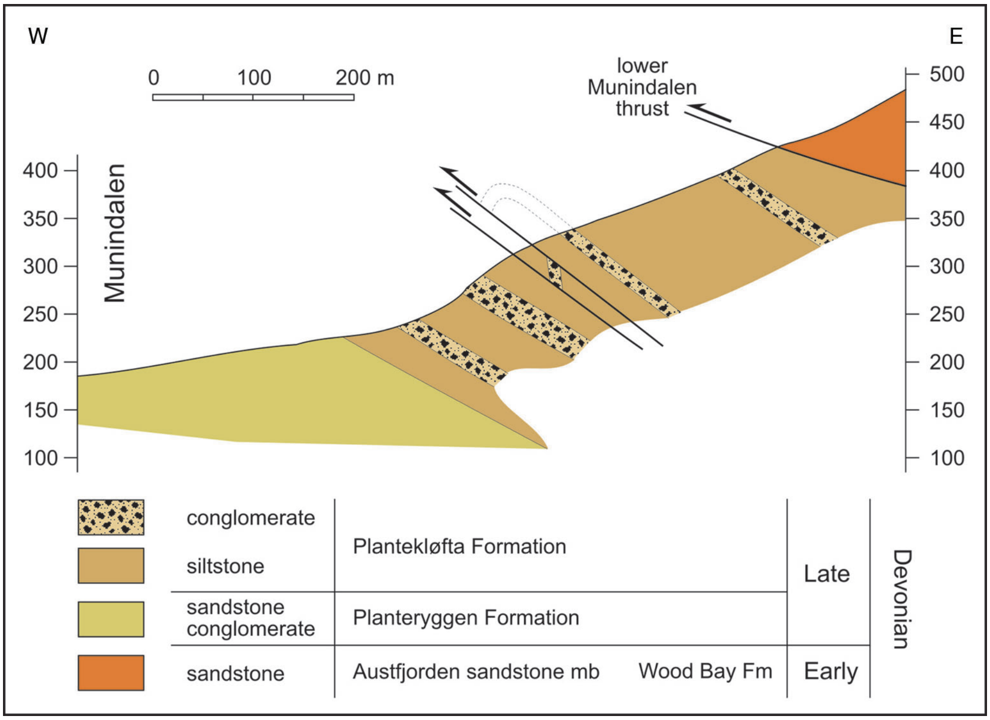

Fig. 10 Outcrop situation along the western slope of Reuterskiöldfjellet. The top of the Plantekløfta Formation is not exposed but is cut off by the west-directed lower Munindalen Thrust carrying the Early Devonian Austfjorden Sandstone Member (Wood Bay Formation) over the Plantekløfta Formation (Piepjohn, Brinkmann et al. 1997). The samples for palynological investigations were taken from siltstones of the uppermost Plantekløfta Formation directly below the lower Munindalen Thrust (Brinkmann 1997).

Piepjohn et al. 2000); Early Carboniferous (Murašov & Mokin 1979) (Fig. 7). The preservation of the spores in the Plantekløfta Formation is very poor due to erosion and resedimentation of the spores from older Devonian sedimentary units. This observation also explains that the Plantekløfta Formation contains mixed spores from different Devonian units below the Plantekløfta Formation. However, investigations of spores from the uppermost part of the Plantekløfta Formation just below the lower Munindalen Thrust at the eastern slope of Munindalen (Fig. 10) and the occurrence of a small number of *Retispora lepidophyta* indicate a Fammenian age of the uppermost exposed parts of the Plantekløfta Formation on Svalbard (Brinkmann 1997). Following Streel & Loboziak (1996), *R. lepidophytus* is characterized by a very short stratigraphic range between Late Famennian and the boundary between Devonian and Carboniferous. The Late Famennian age is supported by the assemblage of *Archaeozonotriletes variabilis* and *Lophozonotriletes* sp. as described by Kedo (1962).

Overlying unit(s). Gipsdalen Group.

Underlying unit(s). Muninelva member (Planteryggen Formation).

Superior unit. Mimerdalen Subgroup.

Thickness. More than 100 m (Vogt 1941; Murašov & Mokin 1979); 100–125 m (Pčelina et al. 1986); minimum 300 m (Brinkmann 1997; Michaelsen 1998) (Fig. 7).

Main lithologies. Alternation of dark grey mudstone, sandstone and dark grey conglomerate with boulders up to 40 cm in diameter.

Lower boundary definition. The lower boundary of the Plantekløfta Formation is marked by the first almost black siltstones of a thick siltstone/conglomerate sequence overlying the greenish sandstones and conglomerates of the Muninelva member (Pčelina et al. 1986).

Description. The Plantekløfta Formation conformably overlies the Planteryggen Formation and corresponds to the bed "m" of Stensiö (1918), the unit "9" of Vogt (1941) and "Succession V" of Pčelina et al. (1986) (Fig. 4). It represents the youngest unit of the ORS in Spitsbergen (Friend 1961) and is characterized by an intercalation of metre-thick, fine- to coarse-pebble conglomerates, dark brown to black mudstones and dark grey to green siltstones with interbedded yellow and red sandstone lenses (Murašov & Mokin 1979).

The green, grey to dark grey siltstones and mudstones constitute most of the Plantekløfta Formation (Supplementary Fig. S5). They contain single clasts of dark grey to black intraformational silt- and mudstones and are interbedded by red and green layers, maximally 10 cm in thickness, and lenses of sandstones. Characteristically, the mudstones and siltstones are affected by an intense pencil cleavage related to the Svalbardian Event (Michaelsen et al. 1997). Interbedded, polymict dark grey and dark green sandstones contain more than 50% of fragments of rocks, mostly flat mud drapes, but also sandstone and quartzite clasts.

Characteristic deposits of the Plantekløfta Formation are up to 15 m thick, unstratified and very coarse-grained, dark grey and dark brown conglomerates (Supplementary Fig. S6) which are interbedded in the mud- and siltstones (Brinkmann 1997; Dißmann 1997; Michaelsen 1998). The matrix of the poorly sorted and clast- and matrix-supported conglomerates consists of dark grey to black siltstones and mudstones. They contain lenses of sandstone and mudstone with ironstone concretions. Within the conglomerates and at the base of the conglomerate beds cross-bedded channels—often metres wide and decimetres deep—indicate a turbulent, fluvial environment of alluvial fan deposits (Friend 1961).

The intensely weathered conglomerates contain rounded to well-rounded pebbles, up to 40 cm in scale, which are typically coated by reddish brown to black Fe–Mn crusts (Brinkmann 1997; Michaelsen 1998). Ninety-five percent of the clasts consist of greenish grey and subordinate violet sandstones and 5% of white and yellow quartzites and dark grey to black siltstones (Murašov & Mokin 1979; Brinkmann 1997; Dißmann 1997; Michaelsen 1998). Gritstones cementing the pebbles contain 60% quartzite and 40% sandstone and siltstone.

The assemblage of clasts indicates that a part of the Devonian ORS sequence was already affected by erosion during the deposition of the Plantekløfta conglomerates. Pebbles of violet sandstones may have been derived from the underlying Planteryggen Formation or the Early Devonian Dicksonfjorden Member and the dark grey to black siltstone clasts from the Fiskekløfta Member. The green sandstone pebbles are most likely derived from the Early Devonian Austfjorden Member of the Wood Bay Formation. This is suggested because of the content of pink orthoclase crystals within the pebbles which are characteristic for the Austfjorden Member (Vogt 1941; Friend 1961; Brinkmann 1997; Dißmann 1997).

The siltstones of the Plantekløfta Formation especially at the steep cliffs on both sides of Muninelva locally contain a very rich flora of tree trunks, branches and leaves (Supplementary Fig. S7; see below). Vogt (1941) and Pčelina et al. (1986) observed a thickness of the Plantekløfta Formation which varies between 100 and 125 m. The geological situation on the eastern slope of Munindalen suggests that the Plantekløfta Formation below the lower Munindalen Thrust is at least 200 to 300 m thick (Brinkmann 1997; Michaelsen 1998) (see Figs. 4, 10). The top of the Plantekløfta Formation is not preserved, because its uppermost parts are overthrust westwards by the Early Devonian Austfjorden Member (Wood Bay Formation) along the lower Munindalen Thrust at the western slope of Reuterskiöldfjellet (Fig. 10).

Facies of the Mimerdalen Subgroup

The sediments of the uppermost ORS consist predominantly of terrestrial, fluvial and alluvial fan deposits (Michaelsen 1998).

The fine-grained deposits of the Tordalen Formation are relatively equigranular and consist of well-sorted sand- and siltstones which have been deposited in a terrestrial–fluvial environment. Dark, fine-grained deposits indicate euxinic conditions from time to time, probably in lakes with periodic prograding deltaic sediments as suggested by Friend (1961). Flaser bedding and marine ostracods indicate that the Tordalen depositional area was at least temporarily affected by marine ingressions (Grewing 1997). The good sorting of the silt- and sandstones as well as the absence of conglomerates indicate that the source area of the Tordalen Formation was far from the depositional area. There is no indication for any uplift east of the Billefjorden Fault Zone during that time (Michaelsen 1998).

The deposition of the Planteryggen and Plantekløfta formations took place under terrestrial conditions. The coarse sandstones and conglomerates indicate high stream power and relief intensity and a turbulent fluvial environment. The grain size in the Planteryggen Formation decreases immediately from the east towards the west: the Planteryggen conglomerates in Munindalen, Odindalen and Tordalen are replaced by fine-grained sandstones in the Hugindalen area (Dißmann 1997; Michaelsen 1998). The clasts in the conglomerates of the lower Planteryggen Formation indicate a reworking of the underlying Fiskekløfta Member, and the content of basement clasts is evidence for the onset of uplift and erosion in the basement areas in Ny-Friesland east of the Billefjorden Fault Zone.

The Plantekløfta Formation contains in parts a very rich flora with tree trunks, branches and leaves of a presumed Late Devonian forest. Along the eastern and south-western cliffs of the river Muninelva, several impressive outcrops in dark grey siltstones of the Plantekløfta Formation exhibit in situ tree trunks of lycopsid trees (genus *Archaeosigillaria* according to Piepjohn et al.

1997; reinterpreted as *Bergeria/Protolepidodendropsis* by Berry et al. 2012) almost in life position (Fig. 11, Supplementary Fig. S7) (Brinkmann 1997; Michaelsen 1998) which are up to 40 cm long and maximally 10 cm in diameter. Sometimes, up to 15 trunks can be seen grouped side by side in a single outcrop with about 20 cm interspaces indicating up to 25 trees per square metre.

Although the bedding planes along Muninelva dip 30° towards the east, most of the tree trunks are in a vertical position with the exception of some collapsed specimens (Fig. 11). They must have been inclined towards the west before the tilting of the Plantekløfta deposits. This suggests that the Late Devonian forests in the Munindalen area have been covered and disturbed by sudden events like mud flows, sheet floods or fanglomerates (Piepjohn, Brinkmann et al. 1997; Piepjohn 2000). The westwards tilting of the trees indicates transport directions from the east of the Billefjorden Fault Zone (Piepjohn 2000), which is consistent with the fact that the pebbles in the Planteryggen as well as in the Plantekløfta conglomerates were derived from the east (Brinkmann 1997; Dißmann 1997; Michaelsen 1998). These observations are also

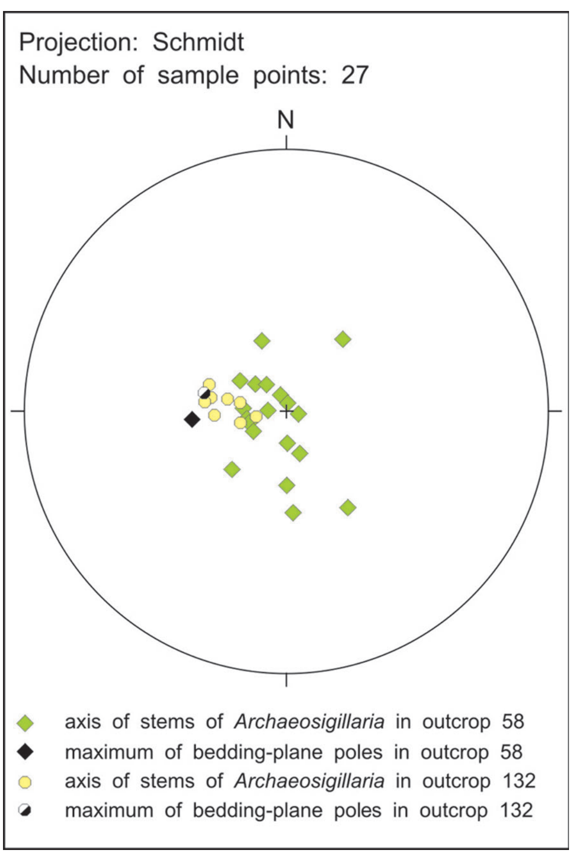

Fig. 11 Stereographic projection of the axis of the trunks of lycopsids in outcrops 58 and 132 along Muninelva (Munin River).

supported by Vogt (1938) and Friend (1961), who suggested that the conglomerates in the Planteryggen and Plantekløfta formations were the result of an uplift in the east, which led to the erosion of a thin Devonian cover (green sandstone pebbles of the Austfjorden Member) and the crystalline basement east of the Billefjorden Fault Zone during an initial stage of the Svalbardian Event (Piepjohn, Brinkmann et al. 1997; Piepjohn 2000).

The fast sedimentation of mud-flow-like deposits and conglomerates along a narrow, elongated north–south trending basin parallel to the Billefjorden Fault Zone suggests that the Planteryggen and Plantekløfta formations were deposited in a narrow foreland basin directly west of the Billefjorden Fault Zone (Vogt 1938; Friend 1961; Piepjohn, Brinkmann et al. 1997). The deposition of the ORS was terminated by the Svalbardian deformation event (Vogt 1928, 1930), which, according to palynological data from Brinkmann (1997) and Grewing (1997), most probably took place in Tournaisian times (Piepjohn 2000; Piepjohn et al. 2000). Constraining age determinations are the Late Famennian age (Brinkmann 1997) of the Plantekløfta Formation below, and the Triungen Member (Hørbyebreen Formation of the Billefjorden Group) above, which was determined to start at the Tournaisian–Viséan boundary (Grewing 1997; Piepjohn et al. 2000). We are aware of several determinations of Famennian spores and bone beds found in the Triungen Member (e.g., Lindemann et al. 2013), but due to the occurrence of Late Famennian spores in the uppermost Plantekløfta Formation we are inclined to consider the Famennian specimens as reworked.

In general, the deposits of the upper Frasnian to upper Famennian Planteryggen and Plantekløfta formations are characterized by a distinct increase of coarse clastic deposits and shrinking of the depositional area. They contain the first appreciable conglomerates in the Andrée Land Basin since the deposition of the Lower Devonian Red Bay Group, which indicates an important transition of the depositional regime from the widespread molasse facies of the Andrée Land Basin (Friend 1961) to the onset of the compressional Svalbardian Event in narrow tectonic zones (Fig. 1b) (Piepjohn 2000; Piepjohn et al. 2000).

Discussion of a previously proposed correlation with southern Spitsbergen

Based on a possible Late Devonian age of the Adriabukta Formation (Birkenmajer & Turnau 1962; Dallmann 1999) of the Hornsund–Sørkapp area in southern Spitsbergen proposed by one of the present authors (cited as W. Dallmann, pers. comm. 2009 in Bergh et al. 2012), Bergh et al. tentatively correlated the Mimerdalen Subgroup with the Adriabukta Formation. As the Mimerdalen Subgroup, the Adriabukta Formation likewise overlies unconformably a Lower to Middle Devonian red bed succession (Marietoppen Formation), which has been proposed to be a stratigraphic equivalent of the Wood Bay Formation of northern Spitsbergen (Birkenmajer 1964; Dallmann et al. 1993).

The Adriabukta Formation was subjected to folding and thrusting once prior to the Middle Carboniferous. Its originally suggested Viséan depositional age (Birkenmajer & Turnau 1962) was based on very few poorly defined palynomorphs and has been questioned, because a post-Viséan compressional tectonic event is unknown elsewhere in Svalbard. A Late Devonian age of the formation would certainly fit better into the structural framework and explain its folding as part of the Svalbardian Event.

Although a Late Devonian age of the Adriabukta Formation would open for the possibility that it is a time equivalent of the Mimerdalen Subgroup, both its structural setting and its stratigraphic record do not suggest a lithostratigraphic correlation. While the Mimerdalen Subgroup was deposited adjacent to the emerging Ny-Friesland High, the Adriabukta Formation's sediment source might have been related to an early predecessor of the Sørkapp–Hornsund High—a prevailing structural element mainly during the later part of the Carboniferous and the Permian (Steel & Worsley 1984; Dallmann 1992).

Lithostratigraphically the Adriabukta Formation is quite different from the Mimerdalen Subgroup. Starting with coarse conglomerates 450 m in thickness, the Adriabukta Formation shows a general fining-upward trend passing through 700 m of mainly grey sandstones with only thin conglomerate layers into dark bituminous shales with few quite thin pebble conglomerates (Dallmann et al. 1993; Dallmann 1999). This differs distinctly from the predominantly fine-grained lower part of the Mimerdalen Subgroup and the upward increasing presence of conglomerates in the two upper formations.

As a conclusion, the Mimerdalen Subgroup shows a locally limited, unique Late Devonian stratigraphic development close to the Billefjorden Fault Zone and has no correlatives—though possible time equivalents—in Svalbard.

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