Hirnantian (latest Ordovician) glaciations and their consequences for the Oslo Region, Norway, with a revised lithostratigraphy for the Langøyene Formation in the inner Oslofjorden area

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During the Hirnantian Age (Late Ordovician) the Oslo Region was located in a subtropical setting with siliciclastic input and carbonate production. At that time the sea level fluctuated in the Oslo Region during three regressive-transgressive episodes, some of which involved subaerial exposure and coastal valley erosion. The last major sea-level drop resulted in the formation of a conspicuous network of incised valleys that were subsequently filled with sediment during the transgression in the latest part of the Hirnantian. The continuing transgressive event rapidly flooded the exposed land areas in the central Oslo–Asker district. The areas towards the west in mainland Asker and Sylling in the adjacent Modum district were first transgressed in the late Rhuddanian (Early Silurian). Primarily eustatic processes affected the area, but synsedimentary faulting may also have been in play. There are two distinct palaeovalley trends: one at Hovedøya in Oslo more or less NW–SE, with narrow valley sides, the other at Kalvøya and surrounding areas trending approximately NE–SW, with one valley more than 10 km long. There may have been more than one filling phase. Sediment fill of the last-formed incised valleys were mapped and correlated across a large area of the Oslo–Asker district.

Electronically Supplement: Lithostratigraphy

Introduction

During the Hirnantian Age in the Late Ordovician Period glaciations on the palaeocontinent of Gondwana affected sea level on a global basis. Recently there have been a multitude of articles documenting the numbers and effects of these glaciations in terms of


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sea-level fluctuations on many continents at different palaeolatitudinal positions (Kaljo et al., 2001; Bergström et al., 2006; Brenchley et al., 2006; Storch, 2006; Johnson & Baarli, 2007; Davies et al., 2009; Ghienne et al., 2014; Demski et al., 2015; Kröger et al., 2015). The Oslo Region was situated in a subtropical position during the Ordovician (Torsvik & Cocks, 2013), and the effects of sea-level changes are also recorded there. Due to repeated glacial phases (Ghienne et al., 2014), one would expect a complex succession of regressive and transgressive system tracts during the Hirnantian, including subaerial exposures in certain areas. Kiær (1902) is the only worker to have suggested subaerial exposure in the study area while others have mentioned gradual shallowing into shore-face conditions during the Late Ordovician (Bruton et al., 2010).

The Cambro–Silurian sequence in the Oslo–Asker district is part of the frontal decollement unit of the Osen–Røa Nappe Complex (Nystuen, 1981; Bockelie & Nystuen, 1985; Morley, 1986; Bruton et al., 2010) and, thus, allochthonous and influenced by folding and thrusting that occurred during the Caledonian orogeny. Even so, sufficient exposures exist to obtain an overall picture of Hirnantian geological history. The district appears to be the key for unlocking the local history of this time interval in the Oslo Region.

The purpose of this study is to update and document effects of both the glaciations and possible tectonic movements that resulted in very complex lateral and stratigraphic facies changes. Emphasis is on the last phase of erosion and transgression. The Hirnantian succession was earlier divided into two formations in the central Oslo Region. This study introduces a refined lithostratigraphic scheme in which four new members for the Langøyene Formation and a bed at the top of the Ordovician are added.

### History of Hirnantian research in the Oslo–Asker district

Kjerulf (1857) divided marine deposits in the Oslo Region into 'Etage' 1 to 8, of which the upper Ordovician belonged to 'Etage' 5. He and Brøgger (1887) recognised calcareous sandstones as the uppermost part of the Ordovician succession in the Oslo area, particularly on the fjord islands in Oslo, Asker and Bærum. Kiær (1902) described in detail the uppermost Ordovician (Etage 5a and 5b) in Asker, both on some of the islands and on the mainland showing rapid changes in the strata, in what he defined as Etage 5b (most of Hirnantian). Kiær (1902) concluded that facies successions and changes indicating a shallowing of the deposits up to the base of the Silurian were related to the Taconic phase of the Caledonian deformation. Facies belts identified by him as parallel to the Caledonian deformation front were interpreted as original palaeo-bottom topographical features. He

![Figure 1. Map of Hirnantian strata in the Oslo–Asker district shown as red lines. Localities and numbers are those referred to in the text.](image-url)
recognised a range of facies belts from deeper-water brachiopod facies \textit{(Holorhynchus)} to shallow-water beach deposits with conglomerates.

Spjeldnæs (1957) described a deep channel cutting through Upper Ordovician deposits on the island of Hovedøya in Oslo (Fig. 1). He suggested that it represented a tidal channel positioned across the Ordovician–Silurian boundary and established a new chronostratigraphic unit, which he called Etage 5c. Furthermore, Spjeldnæs (1957) regarded the Etage 5c beds to post-date a folding phase and suggested that the sediments within the channel were unconformable or disconformable on the underlying sediments.

Seilacher & Meischner (1964), studying the Hovedøya outcrops and other sections, repeated Spjeldnæs' suggestions that the Etage 5c strata were erosional products deposited in longitudinal basins filled during successive phases. At Malmøya, they noted three phases of sediment fill. They also made a rough sketch of the channel at Hovedøya (without scale) and one sketch of a large (6 m long and more than 1 m wide) overturned block at Alnabru. It may have weighed more than 12 tons! The exposure at Alnabru has since been destroyed due to road building.

In his unpublished thesis, Lervik (1969) indicated that channels of similar age as those described by Spjeldnæs were common in Bærum. He considered them tidal in origin, formed during a general shallowing of the basin. He (Lervik, 1969, p. 91) pointed out that there is no clear angular unconformity between the Ordovician and the Silurian sedimentary rocks in Bærum west of Oslo.

Brenchley & Newall (1975) defined new lihostratigraphic units in the Upper Ordovician of the Oslo–Asker district for an interval now interpreted to start in the upper Katian. These included the Husbergøya, Langåra and Langøyene formations. They accepted the channel at Hovedøya as a tidal channel, following Spjeldnæs, but they rejected Spjeldnæs' stratigraphic unit 'Etage 5c'. Brenchley & Newall (1975) looked upon Stage 5a and 5b as local chronostratigraphic stages with the boundary between them the basis of the Hirnantian Stage.

Stanistreet (1978) argued for future reinstalment of Spjeldnæs' concept of 'Etage' 5c as a chronostratigraphic unit. He correlated the 'channel' fill across into Asker and Bærum. His view on the 'tidal' channel at Hovedøya was that it related to a drop in sea level and subsequent transgressive fill during the later part of the Ordovician. He also documented that this event had regional significance.

Brenchley & Newall (1980) suggested that the successions found in the Oslo Region reflect a record of glacio-eustatic changes. They suggested a sea level lowering of about 150 m during the Katian–Hirnantian interval, but did not mention subaerial exposure except for the northern areas of the Oslo Region. They recognised a large number of exposures with channels and channel fill at different stratigraphic intervals and interpreted them as tidal in origin. They also documented a complex of facies relationships and inferred these to be related to basement faults controlling uplift.

Working in the Hadeland district to the north, Braithwaite et al. (1997) presented a model of both bioclastic and siliciclastic sediments brought in from the east during the Late Ordovician and Early Silurian. This was in contrast to Brenchley & Newall (1975), who suggested input from either erosion off the nappes from the northwest or from the 'Telemark Land' to the west. Furthermore, Braithwaite et al. (1995) suggested that several faults were active during the Late Ordovician and into the Silurian. This is in agreement with Stanistreet (1983) regarding his Nesøya, Brennøya and Bønesfjorden fault lines. They also suggested that the millet-seed quartz grains in Hadeland were derived from a mature landmass on the eastern side of the Oslo Region. They reported a lack of lithic grains, but the presence of some unweathered feldspars in eastern Hadeland that suggested a granitic igneous or metamorphic complex as source area. They also suggested that crystalline basement uplift may have been activated, which infers a Precambrian basement source of clastics for the Oslo Region. Working in the Oslo–Asker district, Tonstad (1983) observed no feldspars in the clastic rocks, only quartz at Hoyerholmens. Braithwaite et al. (1995) rejected the interpretation of tidal channels set forth by Brenchley & Newall (1975) and proposed their creation by catastrophic events. They argued against tidal channels, pointing out that there were no peritidal sediments amongst the lithoclasts within the channels, and there was little correlation between the channel fill and the surrounding sediment. They also found three superimposed channel systems on the island of Langøyene.

Brenchley et al. (1997) performed $\delta^{13}$C analyses to establish the age of the brachiopod \textit{Holorhynchus giganteus} in the Oslo area and concluded that the brachiopod was of Katian age. This was supported by data from chitinozoa. They claimed there was a 'cryptic' unconformity between the Ordovician and Silurian strata. Therefore, they ascertained that Etage 5b is largely missing in the northwest Asker area. Brenchley & Marshall (1999) studied the sections at Hovedøya and Rambergøya looking to link extinction with isotope analyses. They claimed that the second phase of extinction happened during the mid–Hirnantian and that changes in $\delta^{13}$C values predate both the extinction and changes in sea level.

Kaljo et al. (2004) indicated a gap below the base of the Solvik Formation based on isotope studies. They found a less complete $\delta^{13}$C record at Kalvøya and Semsvannet
than at Konglunge, all between channels, concluding that there was a difference in length of time with nondeposition between the three areas.

Testing chemostratigraphy in the Oslo Region, Bergström et al. (2006) accepted Brenchley & Newall’s stratigraphy (with the Hovedøya tidal channel). Based on the δ^{13}C curve, they proposed that the upper parts of the Husbergøya Formation ought to be placed within the Hirnantian. The conodont *Ozarkodina oldhamensis* and the δ^{13}C excursion in the oolites at the top of the Langøyene Formation in the section at Hovedøya suggested correlation to highstands as observed in the North American Leemon Formation of the midcontinent, the Saldus Formation in Estonia, and the Loka Formation in Sweden. All these formations were deposited in the upper part of Hirnantian (*M. persculptus* graptolite Biozone). Since these oolitic beds were cut by channels indicating a lowstand in sea level, they correlated the channel fill with the American midcontinent and the beginning of the postglacial melting in Gondwana during the latest part of Hirnantian. They also inferred a possible time gap between the Langøyene and Solvik formations.

Brenchley & Cocks (1982) conducted extensive faunal studies on ecological associations confirming the presence of Hirnantian brachiopods and trilobites. Brenchley & Cullen (1982) worked further on the bathymetrical position of the different Hirnantian associations. A few other taxonomic studies based on material from these rocks are published (Neuman, 1969, 1975 on corals; Bockelie, 1984 on echinoderms; Cocks, 1982 on brachiopods, among others).

**Methods**

Asymmetrical folding, thrusting and faulting of the Cambro–Silurian rocks in the Oslo Region due to Caledonian and subsequent Permian deformation make inter-regional interpretations challenging. Detailed geological mapping in Asker and Bærum, as well as parts of Oslo, on the scale of 1:5000 has proven necessary to obtain a sufficiently detailed picture of the tectonic deformation of the strata to form a basis for more detailed analysis. Compilations are published at a scale of 1:50,000 (Naterstad et al., 1990) and recently at a scale of 1:10,000 for a restricted area (Bockelie & Rui, 2015). In order to study the details of the uppermost Katian and the Hirnantian, the 1:5000 maps may not be sufficiently detailed. In certain areas 1:2000 or 1:1000 maps have been used to follow the distribution of the Katian–Hirnantian formations and members.

Along strike, Upper Ordovician strata can generally be followed from one island to the next for several kilometres (Fig. 1). Detailed measured sections at every 5 m along strike have been attempted wherever possible, and locally every 1 m was measured along strike. These measured sections (up to 300 m in length) were drawn as continuous profiles wherever possible. Measuring sections in such detail reveals facies successions within the different stratigraphic units as well as facies changes along strike. Thus, it has been possible to establish fairly accurate stratigraphic, structural and geographical relationships among the measured sections along strike in certain areas. Locality numbers have been standardised, using numbers from Brenchley & Newall (1975) and subsequent additions by the present authors (Fig. 1).

At Hovedøya, the entire southern part was mapped at a scale of 1:1000 from its western tip towards the east over a distance of about 300–400 m. The actual incision was measured at a metre scale in order to build a continuous section.

By applying this level of detailed study to all the sections exposed along strike, it is possible to form a basis for correlations between strike sections. More than 20 strike sections have been mapped, many of which cannot be followed for more than 3–4 km. Kiær (1902) was the first to apply this type of analysis in order to define a series of facies maps. He suggested that to unfold the

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**Figure 2.** Lateral development of the Langåra Formation at Olledalen, Asker (Loc. 36; Fig. 1). The brachiopod *Holorhynchus giganteus* is present in the nodular limestone of the lower parts that show a normal development for the formation. The thick, more homogeneous, limestone bed near the top is common only in the westernmost parts of the formation.
they showed that the uppermost Ordovician consists of silty shale (the Husbergøya Formation) succeeded on the outer islands by a sandstone unit (Langøyene Formation) that in its upper part is an oolitic limestone with millet-seed quartz grains. Towards Asker in the west, a calcareous shale (Langåra Formation) is lateral to parts of the two formations. The Solvik Formation overlies the Langøyene Formation as a synchronous deposit in their model (Brenchly & Newall, 1975). However, this model is overly simplistic.

In some areas to the west (Konglungen), there are two separate and distinct sandy deposits within the Langåra Formation. These sandstones are wedges of the Langøyene Formation. Farther west (onshore in Asker), the Langøyene Formation is replaced by bioclastic limestones. These are generally considered as belonging to the Langåra Formation, but are not genetically connected.

**Results**

The current Upper Ordovician stratigraphic scheme for the Oslo–Asker district (Brenchley & Newall, 1975, fig. 3, p. 245) is based on a relatively simple geological model founded on observations from the islands near Oslo and the outer islands in Bærum and Asker. For these areas,
At Olledalen in Asker there is a section that traditionally has been described as the Langåra Formation (Fig. 2), but this section is dominated by calcareous sediments different from the more shale-rich sediments normally ascribed and seen farther east. At present, they are described as a lateral facies development of the Langåra Formation. Further investigation may warrant the erection of a separate stratigraphic unit.

The division of the former ‘Etage’ 5a and 5b into three formations by Brenchley & Newall (1975) is inadequate to describe the present understanding of the depositional history for the Upper Ordovician. Several successions with important breaks between them have been lumped together without recognising their complexity. Brenchley, himself, acknowledged this (Brenchley et al., 1997) and wrote that the stratigraphy that he and Newall had established in 1975 was in need of revision.

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**Figure 4.** Skaueren Member and part of the overlying Høyreholmen Member at Skogæholmen West, Asker (Loc. 13; Fig. 1). The key provides sedimentary symbols used in all the following stratigraphic sections.
Stratigraphy

Some necessary additions to the lithostratigraphic intervals are described in the Electronic Supplement. The principal evaluation is made from a section at Hovedøya comprising the transition from the Langøyene Formation into the base of the Solvik Formation. Studies from Asker and Bærum also are important elements, as described below.

The map in Fig. 1 shows the spatial distribution of the upper Katian and the Hirnantian in Oslo, Asker and Bærum. It differs somewhat from the distribution shown by Brenchley & Newall (1975, fig. 1). The revised lithostratigraphic scheme is given in Fig. 3 where the Langøyene Formation is divided into four new units to facilitate the descriptions and interpretations below. These units are in succeeding order the Skaueren, Høyerholmen and Pilodden members with type sections shown in Figs. 4 & 5. The new Kalvøya Member contains strata of the incised valley fill (Fig. 6). A new bed, the Brønnøya Bed (Fig. 7), is defined at the base of the overlying Solvik Formation.

Incised valleys in the Oslo–Asker district

The Late Ordovician glaciations are well accepted and already Brenchley & Newall (1980) acknowledged their influence in the Oslo Region, estimating a eustatic drop of about 150 metres. Similar trough-shaped surfaces as those found in the Oslo Region are also found in the Upper Ordovician in Iowa (Johnson & Baarli, 2007). In those regions, such surfaces are interpreted as incised valleys. The trough-shaped erosion surfaces are found on...
Hovedøya, Kalvøya, western Nesøya, Holmen and many other areas in the Oslo–Asker district (the base of the Kalvøya Member of the Langøyene Formation; Fig. 3; Electronic Supplement). Brenchley and Newall described them as tidal channels in their various publications and the same interpretation is found in Stanistreet’s papers. Stanistreet (1989) showed incisions in several figures and in the composition of the ‘channel fill’ and the ‘final transgressive sequence’, but explained the fill of the channels as due to storm events during the later part of the transgressive sequence, whilst marine fossils appear slightly above the conglomerates.

Both Stanistreet (1983) and Braithwaite et al. (1995) presented various models for potential fault patterns through the Oslo Region during the Late Ordovician. The glacio-eustatic or combined tectonic and glacio-eustatic events would lower the sea-level by several tens of metres. If an area were located in a shore-face setting, as is the case with the oolitic limestone of the Pilodden Member in the Langøyene Formation (Fig. 3), the result would be a palaeotopography in which the earlier seabed would lie ‘high and dry’ until the polar ice in the south melted and the sea transgressed over the Oslo–Asker district again. Meanwhile, there would have been considerable erosion and scouring of the landscape resulting in a complex of incised valleys caused by erosion by streams and rivers. How long such erosion lasted is not discernible at present, but it may conceivably have lasted for thousands or tens of thousands of years.

The locations and fill of the incised valley complex at selected localities are given below. Mapping has shown that some of the incised areas are connected. Lack of exposures and insufficient systematic searches made in certain areas limit a full understanding of the distribution of these valleys.

The valley at Hovedøya

The southern part of Hovedøya is the classical locality to demonstrate the latest Ordovician and transition into the Silurian (Kiær, 1908). The locality chosen by Brenchley & Newall (1975) is important because it exposes the full Hirnantian succession preserved, both the normal one between channels and a section with an incised valley. These sections sit more or less on the same line of strike. Fig. 8 shows a section from east to west where the Pilodden Member of the Langøyene Formation rapidly disappears and is replaced farther west by a well-exposed valley incision. Bockelie (2013) described it as a palaeovalley, but provided no documentation. Below are more detailed measurements of the fill strata.
In order to better document this incision and to study the amount of erosion, the extent of the incision and its relationship to the fill and its lateral facies, the deepest point of the incision is used as the reference point, and measurements were recorded west and east of it (Fig. 9). From this deepest part of the incision, 56 metres were measured towards the west, and 79 metres to the east up to the fault with a dyke, which forms a pronounced feature in the terrain (Fig. 9).

The incision can be seen to cut down more than 10 m in the deepest part. Detailed mapping reveals that it is terraced, and at least two terrace levels can be identified, 11 m to the east and 34 m to the east, as well as 20 m and 40 m to the west of the deepest part of the incision (Fig. 9). This shape is typical of an incised valley with periods of stand-still during the transgressive systems tract. The nature of the fill reveals a practically N–S-trending palaeovalley through which the sea entered during the transgressive system tract in the later part of the Hirnantian.

The incised valley can be followed until it reaches a NNW–SSE-trending Permian (?) fault containing a dyke 79 m east of its reference point. Following the strata farther east, considerable complexities can be demonstrated, most likely due to an overturned fold structure and the presence of a strike-slip fault in the upper part of the succession, which rapidly changes its angle and cuts below the valley fill. Detailed geological mapping has revealed that the massive limestone farther to the east is faulted against the shale of the Solvik Formation. The fault trace may cut into the uppermost part of the incised valley. This is more or less in the same area as where the thick-bedded limestones of the Pilodden Member increase in thickness to about 4–5 m. It is possible that the southwestern edge of the Pilodden Member formed an escarpment that may have been deformed during the Caledonian orogeny in this area, due to differences in competence resulting in both the overturning of the strata as well as some transpressional movements along the fold axis at the edge of the incised valley. The fault is mapped well below the palaeovalley fill and ends at the top of the Husbergøya Formation on the southwestern side of the island.

The different strata along the cross-section of the palaeovalley are given unit numbers, characterising smaller intervals of the fill that can be traced from cross-sections A through D (Figs. 8 & 9A, B). Unit 1 is the deepest sediment package found in the incised valley, whereas the shales of the Solvik Formation above the Brønnøya Bed define the completed drowning of the palaeovalley.
At about 20 m west of the deepest part, there is a 2 m-high overhang with stacked conglomerate. It cannot be established whether or not the conglomerate was river transported and subsequently reworked by the marine transgression.

In the easternmost part (79 m east of the deepest part of the valley), the conglomerate (60 cm thick) shows imbricated pebbles dipping SW into the palaeovalley. The pebbles consist of eroded Høyerholmen Member sandy limestone and large, weathered, redeposited quartz grains may occur as matrix. The imbricated pebbles may be very close to the line of the palaeoshore. The conglomeratic horizon thins to 30 cm over a distance of 4 m towards the west. The conglomerate shows variation in composition and thickness along strike. In the interval between 36 and 60 m east of the reference point (deepest part of incised valley), the conglomerate may be almost 1.8 m thick, whereas in a few places it was not deposited due to the presence of overhangs or the steep palaeovalley sides.

In the deepest part of the valley, erosion reached to a depth of about 16.4 m below the top of the Brønnøya Bed (nodular limestone unit 9) of the Solvik Formation. Conglomeratic blocks are large (up to one cubic metre or more) and the conglomeratic horizon with variable thickness lines the palaeovalley (Figs. 8 & 9A, B). About 5 m to the east of the deepest part (section D; Fig. 8), a large block is present; it is sharp-sided and shows no sign of long transport. Most likely it has fallen in as the cliff was undercut during the process of valley incision. The cliff gradually diminished due to erosion and its height became lower as the valley was filled in by sediment. Coarse millet-seed sand, presumably eroded from the Pilodden Member, is redeposited as matrix within the conglomeratic unit and close to the palaeoshore. This may be the reason why Brenchley & Newall (1975) regarded the fill as tidal deposits, believing the coarse sand was time-equivalent to the upper part of the Høyerholmen Member (Fig. 3).

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The topography was gradually levelled by a silty and sandy sediment that was deposited around the conglomerate and in several cases seems to be draping around and over the large conglomeratic blocks (Fig. 9). Therefore, this unit is only present in the deepest part of the valley. The sediments are brown, mostly silty and

**Unit 1.** The basal fill of the incised valley generally consists of a conglomerate with blocks of variable sizes eroded from the Pilodden and Høyerholmen members of the Langøyene Formation. These conglomerate blocks were not deposited all at the same time. Detailed studies of the relationship of the conglomerates to the overlying sediments indicate that the conglomerates were filled in by undercutting of overhangs, or as storm-generated fill deposits that tumbled down slope. The conglomerate blocks are in places imbricated, but also missing in some areas, thus recording a complex and long-term story as the palaeovalley was filled in.
sandy with a somewhat irregular-bedded configuration, indicating rapid sedimentation. Millet-seed sands eroded from the Pilodden Member are present as distinct rapidly deposited beds. The sand is derived from the east side of the palaeovalley. Fossils are scarce, but a brachiopod was detected about mid-way in unit 1. It may have been reworked. Consequently, it is unclear if these deposits are marine or nonmarine. Unit 1 can be studied along a distance of 15 m across the valley (section D; Figs. 8 & 9).

**Unit 2** extends 18–20 m to the east and about 14 m to the west. It reaches a maximum of 3 m in thickness and thins both to the east and to the west. It consists of laminated, fine to medium sand interbedded with calcareous sandstone beds containing large quartz grains reworked from the Langøyene Formation. Fossil brachiopods are commonly found in the lime-rich beds. Sediments show derivation from the east side of the palaeovalley. Synsedimentary faulting can be seen about 10 m west of the deepest part of the valley.

**Unit 3** varies in thickness (maximum 1.5 m thick). It extends 26.5 m to the west and 32 m to the east reaching the valley walls (a later conglomerate cut into the unit in the west). At its base is a brown siltstone with scattered millimetre-size quartz grains. Some small brachiopods are present within thin limestone beds in its lower part. The uppermost part of unit 3 consists of interbedded quartz sandstone and calcareous sandstone (usually grey in colour), in contrast to the brownish colour of quartz-rich sediments. The upper part of the unit shows cross-bedding with directions from both sides of the palaeovalley towards the valley centre. No clear axial direction of transport has been observed. The top of unit 3 shows distinct evidence of erosion (Fig. 8).

**Unit 4** continues to about 41 m east of the deepest part of the palaeovalley. It seems to continue all the way towards the west, dipping into the sea. It may be 6 m or more in thickness about 10 m west of the deepest centre of erosion. The trough-shaped erosion surface can be traced over a distance of 15 m within the valley. The base of the unit consists of a 20 cm-thick bed with small slumps, possibly seismically triggered. The succeeding sediment generally consists of a medium sandstone interbedded with thin light-grey calcarenites, thickening towards the deepest part. A few escape burrows occur in the lower part of the unit. About 1.2 m above the base of unit 4 there is a laminated fine-sand interval with large brachiopods. This interval is succeeded by 8–10 cm of thick calcareous sandstone, with large 1–2 mm quartz grains. The base is sharp, and the sandy bed is a storm-sand directed axially in the palaeovalley. Some 10–20 cm higher up is a 20–30 cm-thick laminated fine-to-medium sand bed. This is succeeded by a 70 cm-thick sand bed. Towards the east, almost where it dies out, there are finer-grained, 0.5 m-thick bioclastic beds in a shaly matrix that contain a Solenopora-like algae, small rugose corals and various brachiopods.

**Unit 5** is a greyish-green silty shale or mudstone, partly calcareous, showing a dramatic decrease in grain size from unit 4 to unit 5. It is about 1.5 m thick in the deepest exposed part and can be traced as an onlap event towards the east where it reaches as far as 70 m west of the deepest part of the valley. It is a good marker bed. In the more easterly part it fills in crevices in the conglomeratic boulders and can be very fossiliferous, containing a varied fauna of smaller fossils (ostacods? and other arthropods). Brachiopods and rugose corals are more common in the upper part.

**Unit 6** is present only in the eastern part of the palaeovalley. The lithology changes quickly along its 70 metres of continuous exposure (Fig. 8). At its base is a 6 cm-thick bioclastic bed, succeeded upwards by 80 cm of interbedded dark siltstone with starred ripples, in which Chondrites burrows increase in density and frequency eastwards. The interval contains common *Hindella* and rhyonchellid brachiopods and rugose corals. Above this is a 12 cm-thick storm sand with sharp base and rippled top followed by two 5 cm-thick, fine-sandstone beds with a thin shale layer in between. A few, very thin, sandstone beds occur with coarse sand, probably reworked from the Langøyene Formation. They are not extensive and terminate before they reach much farther west into the deeper part. However, a distinct storm sand continues into the deeper part of the valley deposits where it may be 25–30 cm thick. Above this sandy unit follows an interbedded dark siltstone with starred ripples and frequent *Chondrites* burrows. Sporadic *Heliocrinites* occur in this interval and gastropods may be locally quite common as are small stick bryozoa (*Hallopora* sp.?). Above this occurs a one metre-interval with storm sands, each 1–6 cm thick, with very nicely weathered *Chondrites* and many other trace fossils. The uppermost part of unit 6 contains several bioclastic beds with rugose corals, crinoid ossicles, brachiopods, bryozoa and *Cornulites*.

In the easternmost part (79 m east of the deepest part of the valley), unit 6 lies directly on the conglomerate. Here (section B; Fig. 8), a 40 cm-thick bioclastic unit with variable thickness gradually grades into or downlaps westward onto the greenish-grey calcareous shale (upper part of unit 5) after about 8–9 m (Figs. 8 & 9). Bioclastic fragments comprise brachiopods, crinoid ossicles, bryozoa, rugose corals, trilobite fragments and possibly ostracods. Unit 6 is capped by a 40 cm-thick storm sand of mostly bioclastic material that is very distinctive from about 40 to 79 m east of the deepest point in the palaeovalley.

**Unit 7** is about 3.5 m thick, starting with a fine silty mudstone about 75 cm thick, succeeded by interbeds of storm sands and fine silty mudstones. A small *Heliocrinites* cystoid (1.5 cm diameter) occurs in
the lower part of this unit. Within the unit, there are common rugose corals, gastropods, crinoids ossicles and brachiopods. *Chondrites* is present locally in clusters forming burrows about 10 cm in diameter. In the eastern part of the profile (section B; Fig. 8), Unit 7 is approximately 2 m thick as a calcareous mudstone with some interbedded storm sands and some ripple-drift lamination. Thin clasts of coarse sand beds eroded from the lower parts of the Langøyene Formation are redeposited at various horizons within this unit. The amount of sand decreases gradually westwards into the deeper part of the drowned valley after 30–35 m, but some of the sand beds can be traced laterally for more than 35 m. Unit 7 is highly fossiliferous and contains calymenid trilobites, rugose corals, stick bryozoa, crinoid ossicles and small brachiopods (*Hindella cassidea*, *Thebesia scopulosa*) and frequent trace fossils (*Chondrites, Diplocraterion*), particularly in the upper 2 m of the unit.

**Unit 8** amounts to 60–80 cm, increasing in thickness westwards. It consists of a brown, weathered siltstone (dolomitic?) with 2–3 discontinuous limestone beds each approximately 10 cm thick. In the deeper part of the incised valley there appears to be a slightly higher frequency of nodular limestone layers within this unit, thus making the boundary between units 8 and 9 less sharp in that direction. Locally, this unit contains brachiopods. It also is a very good marker horizon found throughout the Oslo–Asker district.

**Unit 9** consists of the Brønnøya Bed. The nodules are frequently somewhat irregular and 15–20 cm thick limestone beds occur within the 65 cm unit. On the transgressed surfaces away from the main incised valley, this limestone is thin and usually poorly fossiliferous. It increases to a 65 cm-thick nodular limestone about 150 m east of the incised valley. The Brønnøya Bed contains fragments of *Eospirigerina* and other brachiopods, illaenid trilobites (Brenchley & Cocks, 1982) and some bryozoan and orthocones.

**Interpretation of valley fill**

Rivers may have been responsible for transport of reworked blocks of Langøyene Formation and older sediments in the palaeovalleys. Some pebbles and boulders found in the conglomerate may have been undercut from valley sides and fallen in without much transport. The larger, angular blocks are always in the deepest parts of the valleys, and may be located where they fell. In some of the river-cut valleys, pebbles may have been transported more than 4–5 km down the palaeovalleys.

During the succeeding late Hirnantian, the river deposits may have been reworked by marine onlap. Shaly intervals in valley sides may not have been consolidated and could easily be washed out by the rising sea. The lithified limestones are thus undercut, and could easily break up and fall into the incised valleys where they are found today. This is typical for the section on the island at the outlet of Neselven in Asker (Loc. 27; Figs. 1 & 10) where the mudstone between individual *Palaeoporella* limestone beds was washed out and the limestone layers were undercut and slid into the palaeovalley during the transgression. Most likely, this is also the case for the large blocks at Hovedøya and Alnabru, but they also could have been undercut by rivers.

Conglomeratic blocks of the Pilodden Member in the Langøyene Formation occur at the base of the incised valley and line the palaeovalley wall at different stratigraphic levels through the filling phases. Consequently, the conglomerate is a lateral facies to each of the units of the filling described below.

To the east in the uppermost parts, imbricated pebbles dip into the valley and indicate a position very close to a palaeshoreline present during the later stages of the valley fill. The top of unit 3 shows distinct evidence of erosion (Fig. 8). This could be due to a lowering of the sea level. The same pattern of erosion may occur at Holmen in Asker (see description below). The incised valley, therefore, appears to have been filled in two phases. In a recent thesis, Sandbakken (2014) suggests a nonmarine lower fill of the incised valley. If so, that would be only unit 1. Alternatively, units 2 and 3 were deposited close to the marine environment in order to explain the presence of brachiopods there, unless they are reworked.

The fill in the upper units (4–8 m thick) seems to be axial in orientation and transported from the south towards the north. The more massive limestone of the Pilodden Member was exposed above sea level and eroded. At the edges of the mapped incised valley, this exposed limestone was eroded during the transgression and shed a 4.5 m-thick succession of rubbly limestones interbedded with thin storm sands towards the end of the filling history of the Hovedøya incised valley. The rubbly limestone (unit 6) may be a beach deposit and is generally 30–60 cm thick and laid down in what may have been a moderate-energy shore-face setting. Entering the incised valley, the amount of limestone pebbles is reduced and their size decreases, grading into more siltstone and silty mudstones as part of a slightly deeper-water fill. They are succeeded in Unit 7 by storm sand deposits.

The brown siltstone of Unit 8 represents an onlap event onto what was land during deposition of units 1–7. Consequently, the sediment may contain dolomite eroded from an onshore location. Oolitic blocks of the Pilodden Member are found throughout the fill from the base, so the incision must correlate with the latest part of the maximum HICE towards the end of Hirnantian.
The asymmetrical profile of the whole palaeovalley on Hovedøya becomes obvious when the complete cross-section is shown (Fig. 9). Because the conglomerate is quite thin through the last 15 m of the profile and the projected top of the Pilodden Member is only 2.5 m higher than the conglomerate towards the west, the top of the Pilodden Member would have been close by. It is unknown if there was a continuous slope up to the limestone or if there was a sharp incision with a bank. However, the section ends at the sea next to an important N–S trending fault.

The incised valley at Kalvøya
(Sandvika; Loc. 28; Figs. 1 & 6)

A detailed description of the Kalvøya Member from the type section at Kalvøya is given under the definition of the formation (see Electronic Supplement; Fig. 6). Whereas the incised valley on Hovedøya SW is relatively narrow (about 150 m) and approximately 14 m deep, the valley exposed at Kalvøya is about 350 m wide and about 18.5 m deep (Fig. 11). The valley at Kalvøya appears to connect to that on Holmen in a complex pattern. If this is the case, the valley in this area is more than 4 km wide. The gradient at Kalvøya is about 80 cm over a distance of 100 m in the eastern side of the valley axis, whereas at Hovedøya it is about 14 m over a distance of 100 m.

Road section at E18, Vakås
(Asker; Loc. 31; Figs. 1 & 12)

The section is located on the northwestern side of Highway E18 at Vakås, just below Nye Vakåsvei. The present description is preliminary and based on the photomosaic shown in Fig. 12. The total valley fill at this locality is 21 m thick from the base of the conglomerate to the base of the Solvik Formation at road level. The units described refer to this section and should not be correlated directly with those of Hovedøya. The section comprises a 8–10 m-high exposure showing rapid facies changes along strike.

Unit 1

is the base of the Kalvøya Member of the Langøyene Formation, a poorly sorted conglomerate with limestone pebbles from the underlying Palaeoporella beds. The conglomerate varies in thickness from 60 to 90 cm and cuts down into the Palaeoporella beds of the Langåra Formation, a nodular shale unit (see the right side of Fig. 12). The incision is deeper towards the road (SE) where it may cut about 1.5–2 m deeper than in the upper part of the section.

Unit 2

is approximately 2 m of dark shale with nodules of variable size and some sandy beds in the lowermost part. The lower, silty and sandy part containing corals onlaps the conglomerate. The top of the unit comprises interbedded shale, nodular limestone layers and thin
Several smaller aggrading channels are present, with their axes more or less in the middle of the section wall. These channels appear to be controlled by synsedimentary faults within the palaeovalley and the overlying Solvik Formation is downwarped into it. The uppermost part of the fill succession features about 2 m of oolitic calcareous sandstone with small quartz grains, waning towards the top of the section. The upper metre of the section viewed from the road just below the Solvik Formation appears to be a mega ripple.

The top of the third unit fill shows erosion close to the road of about 1–2 m, and the overlying Solvik Formation onlaps the top. This may indicate that the deposits of the palaeovalley fill were exposed and eroded prior to deposition of the Solvik Formation. If so, the result of eustatic or isostatic processes cannot be differentiated. Ordovician brachiopods have been collected up to 21 m into the Solvik Formation, whereas at Spirodden they occur up to 40 m into the Solvik Formation (Baarli, 2014).

This section is one of the few areas with palaeovalley fill parallel to the regional strike trend. It also differs distal sandstones and siltstones. The total thickness of this unit varies from about 4 m by the road to about 2 m at the top of the section. The interval contains abundant brachiopods, particularly Brevilamnulella kjerulfi, and also halysitid and rugose corals through a gradual shallowing up section.

Unit 3 starts with a 30–40 cm downlap succession seen at road level, thinning rapidly towards the top of the section. There is a thin conglomeratic horizon here also with small pebbles derived from the Palaeoporella limestone facies. The remaining part of this section (close to 4 m) consists of light-grey, fine bioclastic and quartz sand in a darker siltstone.

Unit 4 starts with a channel cutting into the second unit fill. It is about 60 cm thick at road level and thins to about 20 cm at the top of the section, migrating in that direction. Immediately above are abundant brachiopods of different types. The remaining part of the unit fill is complex and comprises several channels in a cut-and-fill setting towards the top of the stratigraphic interval. Some intervals show ripple marks. There appears to have been a high-energy, very shallow-water environment in this cut-and-fill setting. Several smaller aggrading channels are present, with their axes more or less in the middle of the section wall. These channels appear to be controlled by synsedimentary faults within the palaeovalley and the overlying Solvik Formation is downwarped into it. The uppermost part of the fill succession features about 2 m of oolitic calcareous sandstone with small quartz grains, waning towards the top of the section. The upper metre of the section viewed from the road just below the Solvik Formation appears to be a mega ripple.

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Unit 2 lies directly above the conglomerate with an approximately 1 m-thick interval of medium sandstone (‘storm sand unit’) as seen on Kalvøya, typical of the lower part of the Kalvøya Member. The remaining 2–3 m of the section towards the south is covered. There may be a fault in this area. The unit continues from a concrete wall by a red shed for just over a metre. The individual beds are fine to medium sand, about 5–7 cm thick, separated by equal thicknesses of fine siltstone.

Unit 3 starts with a siltstone interbedded with 3–5 cm-thick limestone layers, usually micritic. A few thin siltstone beds 4–5 cm thick occur in places. Rugose corals are common in the lower part and brachiopods (sowerbyellids, orthids) increase in number and diversity upwards in the section. Small crinoid ossicles are present throughout the unit; some of them very distinctive. Trace fossils (*Planolites*) increase upwards, and at 2.7 m below the top of the member there are trace fossils consisting of calcite plates set in a vertical chevron shape. This is the same type of trace fossil found at Kalvøya.

The top of the Kalvøya Member consists of three distinct planar limestone beds; a 5 cm-thick micritic bed, followed by 21 cm of siltstone, then a 7 cm micrite bed, followed by 17 cm of siltstone and topped by 20 cm of micritic limestone (possibly two beds with very little silt in between). This is comparable to sections at both Kalvøya and Brønnøya.

Unit 4 consists of the Brønnøya Bed represented by a nodular limestone in a dark-grey mudstone, about 5 m of which can be followed before the section ends at the sea. The lower part consists of about 3 m of densely nodular limestone, dominated by trilobites (*Bumastus* sp.), *Chondrites* traces and orthid brachiopods, particularly in the lower part. Towards the upper part of the section the limestone nodules become more scattered in the mudstone and fossils become less common. *Eospirigerina* was found together with a small stick bryozoan and a cephalopod about 5 m above the base of the Member. *Chondrites* occurs throughout, but *Bumastus* becomes less common towards the top.

Holmen islet (Asker; Loc. 27; Figs. 1 & 10)

The section on the small island at the outlet of the river Neselven has cut deeply into the *Palaeoporella* beds of the Husbergøya or Langåra formations. This was one of the localities where Brenchley & Newall (1975) interpreted the section as two tidal channels, partly because of collapse of the channel sides into the channel. However, the current authors see this as an incised valley where the side of the valley slid into the bottom of the deposits due to clay that was washed out between the *Palaeoporella* limestone beds. The fill, which is about 2–3 m thick, consists of Langøyene-type facies and bioclastic material, possibly reworked lithologies from the Langøyene...
Langóra Formation mixed with abundant millet-seed quartz grains 1–2 mm in diameter, in places 2–3 mm. Quartz grains occur throughout the conglomerate. There is no clear sorting of the pebbles, which may vary in diameter from 2 to 5 cm. Redeposited rugose corals are common in the conglomerate.

**Unit 2** sits immediately above the conglomerate as a 2 m-thick interval with coarse to very coarse channelled sandstone beds with frequent millet-seed sand grains throughout. No fossils are found in this interval.

**Unit 3** includes a more than 7 m thickness of medium sand interbedded with 5–10 cm-thick bioclastic limestone layers with millet-seed quartz grains. The limestone layers are spaced approximately one bed in every half metre. The lowermost part of this interval consists of laminated, partly rippled, fine- to-medium sandstone beds. The laminae are on a millimetre scale, and a few intervals appear as ‘silty paper shale’. A 5 cm-thick cross-bedded limestone bed tops this lowermost unit. No fossils have been found in this interval. From 13 m above the base of the conglomerate the slope is covered by soil.

**Rognskjær (Asker; Loc. 30; Figs. 1 & 14)**

At this locality, an island exposure comprises a relatively thin Hirnantian section (about 12 m in thickness) since the valley incision has removed most of the underlying strata.

**Unit 1** at the base of the incision is formed by a conglomerate >1 m thick that has filled a widely eroded disconformity cut into the Hovedøya Member in the Skogerholmen Formation (Owen et al., 1990, p. 33–34). The succession is complex and appears in places to have been subaerially exposed.

**Unit 2** follows the conglomerate as laminated siltstone and sandstone, in part showing ripple-drift laminations, and channelled interbeds thickening from 80 cm in the northeast to 4 m thickness in the middle of the 105 m-long section. Thereafter, the section thins farther southwest to 2.5 m returning to laminated sandstone. The quartz sandstone is mostly coarse, but contains calcareous siltstone pebbles, well rounded in certain horizons. Locally, they may form a zone up to 20 cm in thickness. No fossils have been found in this unit.

**Unit 3** consists of a thin brownish-green silty shale within 70 to 180 cm-thick laminated sandstone beds without fossils but with common mud cracks that characterise this unit. In places there are ripples. The unit may represent a nonmarine sediment or lagoonal deposit, but no microfauna has been recovered. The top of this shale is eroded in some areas over the entire 105 m-long section. It is overlain by 0.5 m of conglomerate (Fig. 14).

**Figure 13. Section at Kloåsen, Hvalstad (Loc. 37; Fig. 1). The exposed and excavated section shows the lower and middle parts of the Kalvøya Member, Langøyene Formation.**
Unit 4 may be traced laterally for more than 20 m, but then grades into coarse sandstone. The sandstone above the shale is coarse to very coarse (sand grains up to 1–2 mm in diameter) and also contains calcareous pebbles throughout, but more commonly in the lower part. Some distinctive erosional surfaces are found in the northeastern part of this unit. Unit 4 is about 3 m thick in the northeast but thins to a thickness of one metre over a distance of 107 m farther to the southwest.

Unit 5 is a high-energy sandstone probably deposited in a shore-face setting. It lies above units 1–4 to comprise a section of 5 m in the west and 8 m in the east (Fig. 14). A marked erosional surface occurs at the base of unit 5 along the entire 107 m profile of the island. This erosional surface may represent a second lowering of the sea level, due either to eustasy or to uplift. The contact with the overlying Solvik Formation occurs below present sea level.

Bjerkøya SW (Asker; Loc. 41; Figs. 1 & 15)

The succession exposed in the southwestern part of Bjerkøya is similar to that of Rognskjær. At Bjerkøya, the incision also cuts down into the lower part of the Hovedøya Member of the Skogerholmen Formation. The palaeovalley was subsequently filled with coarse sediment.

Unit 1 is a 4 m-thick polymictic conglomerate containing pebbles of oolitic limestone (Pilodden Member, without millet-seed quartz), Palaeoporella limestone and cross-bedded medium sandstone (Høyerholmen Member). The matrix typically consists of coarse quartz grains (1–2 mm in diameter). Fossils are very common in the conglomerate and appear to be reworked from mostly Katian strata.

Unit 2 comprises approximately 6 m of medium-to-coarse sandstone, commonly with some conglomeratic horizons and cross-bedding from a shallow-marine, shore-face setting along the western line of strike on the island. Fossils are rare, but rugose corals occur about 6–10 m above the base of the conglomerate.

Unit 3 is complete at the section near the windmill (Loc. 41; Fig. 15) where there is a slightly fining-upward trend dominated by cross-bedded sandstones and planar beds.
of fine sand, 11 m thick. There is a sharp boundary with the overlying Solvik Formation. The Kalvøya Formation here is 21 m in total thickness. No Brønnøya Bed sediments were found at this locality.

In the northwestern part of Bjerkøya, the Høyerholmen Member of the Langøyene Formation is present below the Solvik Formation. Here, structural deformation is complex and there are rapid facies changes in some of the coarse sand units, thus making detailed correlation difficult.

Road section at Slemmestadveien, Vettre, (Asker; Loc. 42; Figs. 1 & 16)

A road section exposing an anticline along Slemmestadveien just north of Vettre shows the contact between the palaeovalley fill and the underlying Pilodden Member of the Langøyene Formation, where the member displays an atypical facies development at the top. No conglomerate occurs at the base of the Kalvøya Formation at this locality, but a distinct erosional cut within the top of the Langøyene Formation is accessible (Fig. 16). About 3 m of the Kalvøya Member is exposed above. At this locality there are at least three shallow-marine successions with medium-to-coarse sandstone showing parallel laminations and particularly in the upper part cross-bedding and some channelling. These are interpreted either as shore-face or supratidal, high-energy deposits. The overlying contact with the Solvik Formation is not exposed, but the Solvik Formation is present on the west side of the road on the down-thrown nose of the anticline. No exposures of the Brønnøya Bed have been found at this locality.

Other localities

In addition to these localities, there are several others with lesser exposures in Asker and Bærum. Some of the localities were described by Brenchley & Newall (1975), including Torbjørnsøy. There, shales of the Solvik Formation drape down into a partly unfilled incision. Many of these localities seem to be part of a complex system of interconnected smaller valleys, generally less than 100 m across. Mikael Calner studied samples from the fill of at least one incised valley on Brønnøya, and this coincides with a falling limb of the δ13C trend (M. Calner, pers. comm., Dec. 2014), e.g., a latest Hirnantian age.

The incised valleys usually start with an infill of conglomerates and with a variety of other sediments that fill up-section before being covered by shales belonging to the Solvik Formation. In the Bunnefjorden area south of Hovedøya, incised valleys have been found on Rambergsøya and Langøyene south (Sandbakken, 2014; Franck et al., 2015). Conglomerates and successive fill have also been found on Malmøya and may be present on other islands in the Bunnefjorden area, including Ormøya. In several of these areas, more than one conglomeratic horizon has been observed. Franck et al. (2015) proposed that the three main phases of erosion in the Bunnefjord area may be connected to glacio-eustatic sea-level changes during the Hirnantian. Stanistreet (1978) indicated that these conglomerates might be related to what he called the Bunnefjorden fault system (Stanistreet, 1983) and synsedimentary faulting. Lervik (1969) recorded several localities with conglomeratic horizons in the Bærum area.

There exists only a single conglomerate, the basal conglomerate facies, within the type section and also at the section at Hovedøya. The conglomerate lining the base at Hovedøya contains blocks of the Pilodden Member, and the incision and fill therefore postdates

Figure 16. Anticlinal road section at Slemmestadveien at Vettre (Loc. 42; Fig. 1). (A) Photomosaic of the section showing lateral development of the upper Langøyene Formation. (B) Drawing of the same where bed (a) of the Pilodden Member is the typical development of thick oolitic limestone followed by bed (b) of the same member (coloured and approximately 1 m thick) consisting of sandstones and mudstones. Following above with an erosive base are sandstones of the Kalvøya Member (c) that is quite thin at this locality. Note the lack of conglomerate at the bottom of the Kalvøya Member.
brown siltstone facies can be traced across the area and used as a chronostratigraphic marker. These siltstones occur in the middle of the Langåra Formation in Katian strata. They were developed as a hardground or firm ground at Holmenskjæret immediately above the Palaeoporella limestone in brown, silty shale beds with Holorhynchus giganteus. Mudcracks in the Langåra Formation in the same kind of facies are observed at Konglungveien 97. The same facies is exposed near the top of the Husbergøya Formation in early Hirnantian strata to the east on the islands (Fig. 3) and may also represent a period of nondeposition. Here, the silty shale beds are dominated by ‘Heliocrinites balticus’ and the tops are completely reworked by animals that churned the sediments. Clearly, the extent of the brown siltstone facies is not synchronous, but seems to denote a shallowing trend that followed a shoreline as it retreated eastward. Possibly the source area was temporarily cut off.

Later during the Hirnantian, obvious erosional gaps were commonly developed (Figs. 3 & 17). With repeated periods of emergence and erosion of incised valleys of varying depth, a pattern of strong topography and diachronous boundaries of lithostratigraphic units are to be expected.

Subaerial exposure in the central Oslo Region

Fig. 3 shows there is no obvious gap in strata from the upper Katian of the Oslo–Asker district, suggesting that the area was continually submerged by the sea. However, evidence for periods of nondeposition can be observed. According to Brenchley & Newall (1975), a deposition of that unit (e.g., dated as late Hirnantian). At Holmen to the west (Loc. 27; Figs. 1 & 10), the Kalvøya Formation occurs at two stratigraphic levels separated by strata of the Langåra Formation. The sections at Våkås, Bjerkøya and Rognskjær all contain more than one conglomeratic horizon and erosion surfaces within the Kalvøya Member. This may be a manifestation of the multiple incision levels found south of Hovedøya at Rambergøya and Langøyene (Franeck et al., 2015). In the first two cases, the last episode of valley incision eroded and obliterated the earlier valley incisions. Where fill from earlier episodes remains intact, fossils are lacking. Periods of incision would be likely where there are district-wide erosion surfaces as found at the base of the Høyergolmen Member and especially at the base of the Pilodden Member (Fig. 3).
Shore-face deposits of the Piloddmen Member are preserved on Spannsløkket, Asker (Isaksen, 1982, p. 116), on Skogerholmen and on Høyerholmen (Tonstad, 1983), and at Vettre, Kloåsen and Rognkjær (this contribution). The Piloddmen Member displays oolite bars, tidal flats and in some areas possibly supratidal deposits. Both below and above the Piloddmen Member, there appear to be major breaks in the depositional history (Fig. 3). The relative sea-level drop following the deposition of that member naturally would have resulted in subaerial exposure, either locally or regionally. Above this break there may be different lithologies filling incised valleys with sediments of the Kalvøya Member. In areas without incisions, the Solvik Formation lies directly on the Langøyene or Langårå formations (Fig. 3).

The extent of subaerial exposure in the central Oslo Region remains unknown, but studies in Oslo–Asker and Bærum demonstrate the preservation of several incised valleys. These became widened towards the northwest. In particular, the upper fill deposit in the Hovedøya palaeovalley was transported from the south towards the north. The Kalvøya strata through the Nesøy and Holmen sections appear to be connected as part of a larger palaeovalley fill more than 10 km long and possibly a few kilometres wide and trending approximately NE-SW. The overall relationships of all sections in this study may be summarised in a palaeogeographic reconstruction (Fig. 18), although with so few points that other interpretations are possible.

Relative sea-level changes

The Husbergøya Formation shows an abrupt change from nodular limestone layers of the Skogerholmen Formation to shales denoting a deepening. The formation was deposited in an outer shelf setting...
(Brenchley & Marshall, 1999). There is a gradual increase in thin calcareous siltstones up through the formation. Furthermore, there is a faunal change from a Tretaspis to an Onniella-Tretaspis association that Brenchley & Cocks (1982) interpreted as a slight shallowing (Cycle 1; Fig. 17). The change corresponds to a glaciation phase linked to a low stand in the subtropical regions just above the Katian–Hirnantian boundary (Bergstrøm et al., 2014; Ghienne et al., 2014; Harper et al., 2014).

The Skaueren Member of the Langoyene Formation represents a minor transgression as part of a sea-level rise. It is succeeded by a regression demonstrated by an erosion surface at the base of the Høyerholmen Member with a high sediment input in shallow water during deposition (Cycle 2; Fig. 17). At the close of deposition in the Høyerholmen Member, there appear to have been subaerial exposure of larger areas indicated by angular unconformities. This emergence is regarded as an expression of maximum HICE and a draw-down of sea level during the glaciation (Bergstrøm et al., 2006). There are several phases of channel fill, and an early phase of incised valley formation is likely at this time.

The Pilodden Member has been correlated with the late Hirnantian _M. persculptus_ graptolite Biozone recorded in the Leemon Formation in the Cape Girardeau area of Missouri, USA, the Sulds Formation in Estonia and the Skultorp Member of the Loka Formation in Västergötland, Sweden, respectively (Bergstrøm et al., 2006). These formations also reflect oolite deposition bounded by gaps similar to what is recognised in the Pilodden Member in the Oslo area. The Pilodden Member, thus, represents a slight high-stand or warming period between two drops in sea level during the end of the HICE interval and the channels were cut during the last low-stand after deposition of the Pilodden Member (Cycle 3; Figs. 3 & 17). How long the last sea-level drop lasted is not known, but it resulted in the formation of the last of a series of incised valleys in the Oslo, Asker and Bærum. The geographic extent of these valleys and the depth of bedrock into which they eroded are considerable.

The main phase of deposition of the Kalvøya Member (Late Hirnantian) represents a transgression resulting in the final fill of the palaeovalleys. Its full extent and composition are not mapped, but it is present at several places in Oslo, Asker and Bærum. At Hovedøya, blocks of the Pilodden Member line the bottom of the Kalvøya Member followed by strata devoid of fossils and an erosional contact with marine fossils above. This transition may signify the changeover from river deposits to eroded beach and marine deposits. The sea-level rise that resulted in the terminal fill of the incised valleys continued into the Silurian. In certain places with valley fill, as at Nesøya, no gap between the fill and the Solvik Formation is observable. The filling history there may be more complex due to possible active faulting, particularly in the Bunnesfjorden area (Stanistreet, 1983).

The incised valley-fill strata indicate that there was a complex succession of relative sea-level drops and associated erosion succeeded by sea-level rises and subsequent development of marine infill in the incised valleys. The details and complexity of these events are known in enough detail to outline a preliminary scheme and put together the succession of events as now understood (Fig. 17).

**Hirnantian topography across the Oslo–Asker district**

Kiær (1902) established the presence of facies belts across the Oslo Region parallel to the Caledonian front and most subsequent workers in the Oslo Region have recognised these. During the Ordovician, there existed a very gentle slope across the Oslo–Asker district with shallower areas to the west and deeper areas to the east and south. This was also the case at the transition between Katian and Hirnantian, as shown by the dark siltstone facies seen at Holmen to the west (belonging to the upper Katian) and at Hovedøya to the east (belonging to the lower Hirnantian) as a consequence of shoreline retreat towards the deeper parts in the east.

Sea level was lower during most of the Hirnantian and during times with minimum sea level valleys were incised and the intervening areas were eroded. The final, end-Hirnantian, sea-level rise was responsible for flooding and infill of the valleys. The initial flooding must have been caused by a very rapid sea-level rise. The age of the base of the Solvik Formation is latest Hirnantian both at Hovedøya and at Konglunge (Fig. 3). The areas in between exhibit basal Solvik strata of a seemingly coeval age even though fossil assemblages indicate varying depths. Higher in the Rhuddanian, the same gentle slope from west to east was again established (Baarli, 2014).

The situation on the mainland in Asker, west of the islands, is different. At Vettre (Loc. 42; Fig. 1), a sandy shoreline developed. Farther inland, the locality at Kloåsen (Loc. 37; Fig. 1) is limited, so it is difficult to say if there was an incised valley. It could just as well constitute a boulder shore, because the conglomerate is monomictic and derived from the underlying formation. Kaljo et al. (2004) investigated a section at Sem (Loc. 45; Fig. 1). They found the δ13C excursion was less complete here as compared with Konglunge (Loc. 16; Fig. 1), where we know the base of the Solvik Formation was deposited during the late Hirnantian. They suggested the existence of a larger gap at Sem. Even farther west in Oittedalen (Loc. 36; Fig. 1), the gap is substantial and the area was first flooded in the late Rhuddanian (Coronograptus cyphus graptolite Biozone, see Electronic Supplement). This is in agreement with what Baarli (1988) found for the base of the Solvik Formation at Toverud in Sylling, approximately 4 km north of Oittedalen. Topographically, this appears to have been a well exposed high that
gradually became flooded until it was fully submerged in the late Rhuddanian. The scenario may represent the earliest manifestation of a minor bulge that moved across the Oslo Region, parallel to the Caledonian facies belts throughout Llandovery time (Baarli, 1990; Worsley the Oslo Region, parallel to the Caledonian facies belts.

Warm- and cold-water Hirnantian faunas in the central Oslo Region

The Hirnantia association occurs at the very top of the Husb ergøy Formation and extends just a few metres into the Skaueren Member of the overlying Langøyene Formation. The Dalmanella association occurs above in the lower parts of the same formation (Brenchley & Cocks, 1982). The Holorhynchus, Dalmanella, and more commonly the Cliftonia-Hindella associations, occur in the Langåra Formation. The latter two faunas are typical of the cold-water Kosovo province (Harper & Hints, 2016). This is in agreement with the onset of glaciation and cool periods during the early and middle phases of the Hirnantian. The fauna found in the Pilodden Member is poor, but Brevilamnulella occurs in large numbers in a few localities (Cocks & Brenchley, 1982). This is a warm-water element only found elsewhere in Laurentia that together with the occurrence of oolite banks, indicates a warming period. It is a part of the Laurentian Edgewood fauna that Wang et al. (2016) showed to stratigraphically follow the typical Hirnantian fauna. Faunas in the overlying Kalvøya Member are more diverse. These show a mix of cold- and warm-water elements and the latter are closely related to the Laurentian continent (Harper & Hints, 2016). Mucronaspis occurs throughout Hirnantian strata in the Oslo Region including the Kalvøya Member. This trilobite is common in the lower parts of Hirnantian strata in the East Baltic and there does not extend into the upper Hirnantian (Hints et al., 2012). However, it is found in the Leemon Formation in Illinois as part of the Edgewood fauna. The fauna in the Bronnøya Bed and further into the lower parts of the Myren Member retains many Hirnantian elements, although the shallow-water rhynchonellids are missing and new Silurian faunal elements are present. These gradually replace the old elements during Rhuddanian 1 (Baarli & Harper, 1986; Baarli, 2014).

Comparison with other areas

Ghiennie et al. (2014), working in Morocco off the Ordovician polar cap and also in Anticosti, Canada, in a subtropical setting similar to that in the Oslo Region, found that the end-Ordovician glaciation mirrored the Pleistocene with repeated episodes of glaciations and interglacial warm periods. This resulted in a complex series of eustatic changes with three main glacial cycles. Many sections around the world are incomplete, as also found in the Oslo Region. However, the Oslo record shows repeated cycles of offlap and onlap. A result of such cycles may be emergence with karst features, incision of valleys and palaeovalley fills or erosion of rocky shorelines on land and erosion of submarine channels on the shelf. Kröger et al. (2015) linked deep karstic surfaces from the Boda limestone in Sweden to the Hirnantian glaciations. Karstic surfaces of Hirnantian age are also found in submarine channels in Meifod, central Wales (Brenchley et al., 2006). Incised valleys are described from the Upper Ordovician in Iowa (Johnson & Baarli, 2007). On Anticosti island, two erosional subaerial surfaces were later flooded during the end Hirnantian (Ghiennie et al., 2014). These must be drowned shorelines, whereas repeated erosion and channelling of the shelf due to glacio-eustatic changes are reported from the Czech Republic (Storch, 2006) and Meifod, central Wales (Brenchley et al., 2006). The well-studied incised channels found in the Oslo area were mainly river-cut valleys. However, more distal areas in the west may show more varied effects of the glaciation such as tidal channels or palaeoshorelines.

Conclusions

Field studies in Oslo, Asker and Bærum have revealed areas with variable relationships between the Langøyene and the Solvik formations and the filling of incised palaeovalleys. To facilitate the descriptions, four new members of the Langøyene Formation (Skaueren, Høyerholmen, Pilodden and the Kalvøya members) and a new bed within the Solvik Formation (the Bronnøya Bed) have been erected. The Kalvøya Member is defined for its extensive channel fill, whereas the newly described overlying Brønnøya Bed is found in the basal part of the overlying Solvik Formation.

Many incised valleys in areas with deep erosion through the Langøyene, sometimes through the Husb ergøy and into even older deposits, have been infilled with a basal conglomerate and other incised-valley deposits. There appears to have been a major NE–SW-trending valley from Holmen through Kalvøya and towards Bekkestua with minor valleys either perpendicular to it, or at a slight angle towards the south. The valley incisions deepened slightly from Holmen towards the southwest in the direction of Rognskjær.

Most areas were exposed above sea level at several times during the Hirnantian due to substantial eustatic drops in sea level, possibly combined with tectonic movements. Three cycles of sea-level change occurred during the Hirnantian followed by a major transgression starting at the end of the Hirnantian. The valleys were filled with sediment, some most likely from a fluvial source, but also were reflooded from the sea during the latest phase of the Hirnantian, while other areas to the far west were not flooded until well into the Early Silurian (Rhudddanian) at Olledalen in Asker.
On the mainland in Asker and Bærum, bioclastic limestone layers form the areas between eroded valleys and contain faunas that suggest an early and mid Hirnantian age, whereas those on the islands contain oolitic limestone infused with 'millet seed' sand. These oolites contain warm-water faunas indicating a late Hirnantian age. Therefore, it is possible that the contrasting facies distribution represents two different carbonate factories. These two carbonate areas may not have been connected and the oolitic limestones were of different ages.

Addendum

The junior authors (Baarli and Johnson) re-established contact with Fredrik Bockelie in June 2013 during the post-conference field trip related to the Third Annual Meeting for the International Geoscience Programme Project 591 held in Lund, Sweden. Conducted in joint sponsorship with the international subcommissions on Cambrian, Ordovician and Silurian stratigraphy, the meeting and field trip excursions ended in the Oslo region. Fredrik was one of the featured field trip leaders who led the group on visits to some of the islands in the Oslo fjord. Close contact was maintained during the following three years, including summer visits with Fredrik to see several more of the islands in the Oslo fjord under his active study. Baarli et al. (2015) presented preliminary results from this collaboration at the 5th International Symposium on the Silurian System and the 5th Annual Meeting of the IGCP 591 in Quebec City, July 8–11, 2015. During the last month before he passed away, Fredrik reached out to the two junior authors and they were able to finalise and submit the manuscript for review. The junior authors witnessed a steady change in Fredrik’s thinking on possible ramifications on chronostratigraphy as an outcome of the highly developed physical stratigraphy he had charted in the

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Figure 19. Physical and chronostratigraphy for the Upper Ordovician and Lower Silurian in the Oslo region with regional variations indicated on an E–W axis. Bockelie in 2016 favoured application of ‘Etage’ units, in this instance Etage 5a, b and c, for his envisioned chronozones. The boundaries between these units are shown in red and highlight the differences between the senior author’s usage and correlations by the junior authors. The amount of removed strata in channel incisions (marked by *) varies widely.
Oslo region for over three decades. This addendum summarises the status of Fredrik’s thinking at the time of his death in 2016, and compares it to the present outcome of the project (Fig. 19).

Acknowledgements. Several aspects of the observations were discussed with Brenchley and Newall while they were working in the Oslo area in the 1970s, and they inspired the senior author to search into the controversial aspects, including subaerial exposure. During the 1980s the senior author supervised students at the University of Bergen (Dag Isaksen, 1982 and K. Tonstad, 1983) on studies of the Ordovician–Silurian in Oslo–Asker. Prof. Ian Stanistreet has rendered important views on the incised valleys described above (pers. comm., 2012) as have discussions about the subject with Johan Petter Nystuen. In recent years, Johan Petter Nystuen, Snorre Olaussen, Bjørn Tore Larsen, Hans Arne Nakrem, Mikael Calner, and students supervised by the present authors at the Natural History Museum, Oslo (Martin Kjærsgaard and Martin Sandbakken) all contributed to obtain a better picture of the depositional system of the Ordovician–Silurian transition. David Bruten has always been available for constructive comments and discussions to improve the work. We are grateful for insightful reviews by Johan Petter Nystuen (University of Oslo) and Stig M. Bergström (Ohio State University) that helped to improve the final product.

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