Electronic Supplement – Lithostratigraphy

The Husbergøya Formation

The lowermost formation, the Husbergøya Formation, has a sharp base as defined on the island Husbergøya in Oslofjord and consists of a shale with upwards increasing interbeds of sandstone sitting on Skogerholmen nodular limestone. The Husbergøya becomes more calcareous towards the west (Asker and Bærum). Its contact with the overlying Langøyene Formation is usually very clear, but may be arbitrary locally.

Age

The Husbergøya Formation (defined by Brenchley & Newall, 1975) has generally been regarded as correlated with the late Katian. In Olledalen to the west, the brachiopod *Holorhynchus giganteus* and $\delta^{13}C$ excursions (M. Calner, pers. comm.) indicate a Katian age in the overlying Langåra Formation. The same is true in Sandvika where *Holorhynchus giganteus* and $\delta^{13}C$ excursions also indicate a Katian age high up in the overlying Langåra Formation (Brenchley et al., 1997). However, Bergström et al. (2006, fig. 14), working at Hovedøya, indicate that the top of the Husbergøya Formation may be part of the lower Hirnantian. This is in agreement with Owen et al. (1990) who mention that both the brachiopod *Hirnantia* and the trilobite *Mucronaspis mucronata* occur in the top of the Husbergøya Formation. The strata of the Husbergøya Formation are thus for the most part of Katian age, but the uppermost layers to the east were deposited slightly into the Hirnantian.

The Langåra Formation

The Langåra Formation, a sedimentary wedge between the Husbergøya and the Langøyene formations, was defined by Brenchley & Newall (1975) based on the succession on the island Langåra in Asker, with the base placed at the top of the last distinct sandstone bed of the Husbergøya Formation. However, this definition is not always workable. According to Stanistreet (1978) the type section is faulted. In the western section of Hovedøya in Oslo, sediments defined as the upper part of the Husbergøya Formation by Brenchley & Newall (1975) appear very similar to sediments defined as the Langåra Formation.

Age

At Holmen in Asker, the *Holorhynchus* shale overlies the *Palaeoporella* limestone (both within the Langåra Formation) on a small island (Presteskjær) and on the main road to Slemmestad just above Holmen. Brenchley et al. (1997) convincingly described *Holorhynchus* as being of Katian age at Holmen and at a section in Sandvika where *Holorhynchus* was found within a few metres of the overlying Solvik Formation (Brenchley et al., 1997). The lower part of the formation was deposited in the Katian. The *Cliftonia-Hindella* association is common in much of the Langåra Formation (Brenchley & Cocks, 1982). This is a typical fauna of the cold-water Kosov Province that occurs in the lower parts of the Hirnantian Stage. The Langåra Formation is thus a lateral facies development to the upper parts of the Husbergøya Formation. It is also lateral to parts of the Langøyene Formation with which it interfingers in places (Fig. 3). The degree of erosional gap with the overlying Solvik Formation varies considerably (see below).

The Langøyene Formation

Brenchley & Newall (1975) defined the Langøyene Formation on the southeastern shore of Langøyene and put its base at the transition from buff massive sandstones of the Husbergøya Formation to shale with laminated sandstones and thin limestones. To distinguish the details of

the Langøyene Formation, four new members are established for Oslo and on the islands in Asker and Bærum and lateral facies described, but not separated at this point.

The Skaueren Member (new member)

Main lithology

Stacked micritic limestone beds followed by greenish siltstones and interbedded, thin, laminated sandstone beds with erosive bases. In Oslo and on many of the islands there are frequent slump horizons.

Basal stratotype

Oslo–Asker: Skogerholmen (Asker), (Loc. 13; Figs. 1 & 4; NM 862353).

Definition

The base of the member coincides with the base of the formation. It starts with micrite beds with very little shale in between followed by shale with thin sandstone beds immediately above a characteristic thick brown siltstone. This lowermost unit is about 0.5 m thick and stands out very clearly in the terrain. Interbedded calcareous mudstones and sand beds with erosive bases occur in the lower part. The calcareous mudstone is gradually replaced by more silty and sandy shale. Individual slump beds can be sandy in the lower part, followed by a nodular limestone in the upper unit in many areas. The limestone beds disappear about 10 m up through the type section at Skogerholmen and are replaced by sandstone beds, some of which are deformed through slumping.

Description

Unit 1

Rests immediately above the brown siltstone with cystoids 'Heliocrinites balticus' (Bockelie, 1984). The base of the member at Skogerholmen starts with five micrite beds, 0.5 m thick with

very little shale in between, that stick out in the terrain. They may be very fossiliferous and contain gastropods and bryozoa. The succession consists of interbedded calcareous mudstone and sand beds with erosive bases.

Unit 2

A number of slumped sandstone beds vary from about 0.5 to 1.5 m in thickness and are interbedded with calcareous mudstone and distal storm sands. The calcareous mudstone is gradually replaced by more silty and sandy shale. The individual slump beds can be sandy beds in the lower part, followed by nodular limestone in the upper part.

Unit 3

The limestone beds disappear about 10 m up through the section and are replaced by sandstone beds with erosive bases, some of which are deformed through slumping. The interval is not very fossiliferous, but rugose corals are present through the lower half of this member. The sandstones in the uppermost part of the member are usually laminated or cross-bedded. The total thickness of the member at Skogerholmen is 16.3 m.

Other areas with the Skaueren Member include Spannslokket where the sequence consists mainly of limestones and calcareous shales with sporadic distal sandstone beds, but lacking the slumped horizons. The sequence at Langåra is similar to that of Spannslokket, but the lower boundary is tectonised. At Hovedøya, the Skaueren Member is present on the southwestern shore of the island, but the top of the member is difficult to define and appears to grade into the overlying member. Also, there is a fault at the base. The full distribution of the Skaueren Member in the Oslo–Asker district has not yet been mapped.

Fauna and age

Fossils are present, particularly in the lower part where the *Dalmanella* and *Hirnantia* associations occur (Brenchley & Cocks, 1982). The brachiopod *Hirnantia* is found in the very basal layers both at Hovedøya and Langøyene, supporting a lower Hirnantian age for the topmost layers of Husbergøya and the base of the Langøyene Formation here. Both these associations belong to the cold-water Kosov faunal province that occurs in much of the Hirnantian. The fauna comprises rugose corals (Neuman, 1969) in the lower half of the member, some brachiopods and a few bryozoans as well as crinoid ossicles. At the very base of the member, stromatoporoids are found directly on top of the micritic beds. Gastropods are common, particularly in the lower part. The uppermost part is rich in *Cliftonia*, sporadic *Mucronaspis mucronata* and crinoid ossicles with square lumen and fulcra. This fauna belongs to the *Dalmanella* and *Hindella-Cliftonia* associations of Brenchley & Cocks (1982) typical of the Hirnantian cool-water Kosov Province. This kind of fauna does not occur in the uppermost parts of the Hirnantian (Wang et al., 2016) so the entire member was deposited in the lower parts of the Hirnantian.

The Høyerholmen Member (new member)

Main lithology

Homogenous medium-grained sandstone, laminated, cross-bedded and channellised.

Basal stratotype

Oslo–Asker: Spannslokket (Asker), (Loc. 18; Figs. 1 & 5; NM 855358).

Definition

The base of the Høyerholmen Member is set at a very sharp transition from the underlying member, possibly erosive, followed by medium to coarse, thick-bedded, laminated sandstone,

but in places a low-angle, cross-bedded, medium sandstone. The upper part at the type locality shows distinct cross-bedding and some channelling.

Description

Erosional contact at base and angular unconformity to the overlying oolitic limestone member. Five to six metres of laminated, in places low-angle, cross-bedded, medium sandstone. The upper part at the type locality shows distinct cross-bedding and some channelling in what appears to be a series of amalgamated graded sandstone beds. In some areas, notably at Konglungen, the Høyerholmen Member appears as two separate sandstone units within the Skaueren Member. In other areas, there is only one unit. At Høyerholmen, the member is much thicker than in other areas and appears as stacked sandstone deposits (33 m thick). At Langåra, the Høyerholmen Member has a sequence of migrating mega-ripples.

Fauna and age

No fossils have been found in this sandstone unit. Hirnantian fauna occurs in the Skaueren Member below. The top shows an erosional contact with the overlying Pilodden and Kalvøya members.

Comments

Other areas where the Høyerholmen Member is exposed include Hovedøya (5 m), Skogerholmen (6 m), Langåra (>2 m), Konglongø (2 units, 10 m and 12 m) and Ersvika.

The Pilodden Member (new member)

Main lithology

Oolitic limestone with millet-seed quartz grains.

Basal stratotype

Oslo–Asker: Spannslokket (Asker), (Locs. 17, 39; Figs. 1 & 5; NM 855358).

Definition

The base of the member is defined by an angular unconformity with the Høyerholmen Member seen in many places in the area, the rapid increase in quartz grain sizes and the presence of oolites. The member is usually rich in $CaCO_3$ (about 90–97%) and is a thick to very thick-bedded limestone.

Description

A sharp basal boundary (erosional) resting on variable lithologies of the underlying Høyerholmen Member. At many localities the boundary occurs above a 15–25° down-dip angular unconformity. The top is usually eroded. Thick to very thick oolitic carbonate beds with coarse millet-seed sand, oolitic limestone with low-angle cross-bedding, shallow channels, horizons with millet-seed sand as distinctive bedding or more evenly distributed. Quartz sand grains typically are 1–2 mm in diameter. The millet-seed sand varies in thickness throughout the Oslo–Asker district from just a few metres to about 8–10 m (Brønnøya). At Pilodden (Brønnøya), the top is not exposed, but the member is well exposed. A local development of the Pilodden Member is seen at Hvile, Asker (NM825334), where 110 cm of interbedded mudstones and sandstone beds overlie the oolitic beds (Fig. 16). This section thins from the southern part of the section to just a few centimetres 41 m towards the north. It starts with 6–10 cm-thick sandstone beds, but the amount of mudstone and micaceous, bedded siltstone increases in the upper part where it has a brown weathering colour and is possibly dolomitic. Fossils are uncommon, apart from horizontal and vertical trace fossils, usually filled with fine bioclastic material and silt-sized quartz. The Kalvøya Member lies disconformably above.

Fauna and age

Fossils are occasionally present although strongly eroded by wave action. They occur at different

intervals within the oolitic member. Crinoid ossicles are very common and diverse. In some geographical areas (Skogerholmen, Asker), bryozoans, brachiopods, corals and trace fossils are present. These fossils belong to the *Thebesia* association of Brenchley & Cocks (1982) that was defined as a warm-water Edgewood Fauna by Harper & Hints (2016). The Edgewood fauna has traditionally been ascribed to the entire Hirnantian, but Wang et al. (2016) showed that this fauna followed stratigraphically above the typical Hirnantian fauna in the late Hirnantian (*M. persculptus* graptolite zone). This fits with the correlation found by Bergstöm et al. (2006) from Hovedøya and with Kaljo et al. (2004) at Konglungen, Asker. They observed that the maximum HICE peak occurring in the upper parts of the Hirnantian around the world was fully developed here. Bergström et al. (2006, 2014) further correlated these oolitic limestones with the middle part of the Loka Formation in Västergötland which is of late Hirnantian age.

Other areas with the Pilodden Member include Hovedøya N. and E., Konglungen, Skogerholmen and Høyerholmen.

The Kalvøya Member (new member)

This interval was previously termed Stage 5c by Spjeldnæs (1957).

Main lithology

A trough-shaped erosive disconformity occurs at the base, eroding into a variety of lithologies. Conglomerate above the base is followed by sandstone and siltstone succeeded by mudstone and interbedded mudstone and sandstone with locally conglomeratic horizons.

Basal stratotype

Oslo–Asker: Kalvøya (Bærum), (Loc. 28; Figs. 1 & 6) at the eastern side of Bikkjebukta (NM 862399).

Definition

The base is an erosional, trough-shaped disconformity. The lowermost part consists of conglomerate of variable thickness, succeeded by sandstones. The remaining fill within the trough consists of fine siltstones, some erosive and graded sandstone beds and mudstones. The uppermost part is succeeded by the Brønnøya Bed (new) of the Solvik Formation.

Description

At Kalvøya the member reaches a maximum thickness of 17 m and is divided into six distinct units (Fig. 6). These are informal units not intended for correlation with other areas.

Unit 1

Conglomerate, 1.2 m at type section, thinning to 85 cm about 20 m to the west. It contains common millet-seed quartz sand (1–3 mm in diameter). There are some fragments of white oolites, 1–2 mm in diameter, rugose and tabulate corals, some of them partly silicified, fragments of micritic limestone and reworked calcareous sandstones from the underlying parts of the Langøyene Formation. The conglomerate at this locality contains both *Palaeoporella* and more sandy sediments from succeeding horizons, including locally large quartz grains (millet-seed quartz).

Unit 2

The conglomerate is succeeded by 1.7 m of siltstone and less common beds with bioclastic debris, ending with a 7 cm-thick brown-weathering sandstone with an erosive base. The siltstones contain common *Steptelasma*. This facies continues up to about 3 m above the base of the conglomerate where there are more calcareous silt beds weathering light grey, each about 3–5 cm thick and interbedded with 5–15 cm of silty shale with rare rugose corals.

Unit 3

The third unit is about 1 m thick and consists of thin indistinct limestone beds (micritic) interbedded with mudstone of similar thickness. In the lower part there are a few very thin (0.5–0.8 cm) siltstone beds. Rugose corals become more abundant up section as do stick bryozoa. A few small brachiopods, including *Sowerbyella* and *Brevilamnulella kjerulfi,* and small crinoid ossicles occur through the interval as well as gastropods and in places small rugose corals, particularly in the lower part of the unit (*Brevilamnulella* association of Brenchley & Cocks, 1982).

Unit 4

Light-grey, chiefly micritic, limestone beds about 10 cm thick interbedded with mudstone grading upwards into siltstone characterise the unit. The total thickness is about 4.5 m. The top of the unit consists of graded sandstone beds with erosive bases, each about 8–10 cm thick with sand and bioclastic material. This unit is fossiliferous with a varied fauna comprising *Brevilamnulella kjerulfi* and orthid brachiopods, large stick bryozoa and crinoid ossicles.

Unit 5

Unit 5 is 2.3 m thick with limestone beds in the lower part, grading into a nodular unit towards the top.

Unit 6

Unit 6 is 80 cm thick and consists of four, light-grey, planar, micritic limestone beds, each 10 cm thick, with interbedded mudstones to fine siltstones.

In Oslo, the erosion generally extends downward somewhere into the lower part of the Langøyene Formation. In Bærum and Asker, the erosion reaches the lower part of the Langåra

Formation (including the *Palaeoporella* beds) or the lower part of the Husbergøya Formation. In a few cases the erosion extends even into the Spannslokket Member of the Skogerholmen Formation below Rognskjær (Loc. 30; Fig. 1) and Kloåsen, Asker (Loc. 37; Fig. 1).

Fauna and age

The Kalvøya Member was deposited during successive episodes of valley erosion. Only the last phase of valley fill contains fossils. This incision generally eroded into and obliterated the preceding fill deposits. On Hovedøya, the brachiopods *Thebesia, Leptoskelidion, Hindella* among others (Brenchley & Cocks, 1982), trace fossils (Stanistreet, 1989) and rugose corals (Neuman, 1969, 1975) have been described. The fauna also includes echinoderms, bryozoa, tabulate corals (Hovedøya) and the trilobite *Mucronaspis mucronata.* It is therefore a mix of cold- and warm-water faunal elements in a similar fashion to what is seen in Östergötland at maximum HICE in the upper parts of Hirnantian strata (Harper & Hints, 2016). At Hvalsodden, the brachiopod *Brevilamnulella kerulfi* is very common high up in the member. This brachiopod also occurs at Osmundsberget in the Boda Limestone in the later parts of the *M. persculptus* graptolite Biozone (Kröger et al., 2015). The last phase of the member was, thus, both by superposition and its faunal elements, deposited during the late Hirnantian. Earlier phases of valley incisions may have corresponded to major breaks in deposition like those found at the base of the Høyerholmen Member and at the base of the Pilodden member.

Other important localities in Oslo–Asker: Hovedøya SW (NM 967406) where the unit is about 14 m in thickness, Nesøya W (NM 847373) ~5 m, at E18 near Vakås (Asker), Loc. 31, Fig. 1, it is 22 m.

The Brønnøya Bed of the Solvik Formation

Main lithology
Nodular limestone.

Basal stratotype
Oslo–Asker: Southeastern Brønnøya at Østre Brygge, (Loc. 40; Figs. 1 & 7A; NM 870371).

Definition
The base of the Brønnøya Bed coincides with the base of the Solvik Formation as defined on the south shore of Hovedøya (Worsley et al., 1983, p. 11), and is set at the transition from the planar limestones of the Kalvøya Formation to shales with a nodular limestone bed above. The nodular limestones in shale are relatively homogeneous with a limestone/shale ratio up to 80/20. The nodules are usually biomicritic and partly bioclastic with fragments of trilobites, brachiopods and bryozoa.

Description
The base of the Brønnøya Bed is distinctive with nodular limestone resting immediately above the last planar limestone bed of unit 6 in the Kalvøya Formation. The Brønnøya Bed is a nodular limestone with nodules up to 5 cm long and 2–3-cm thick.

The Brønnøya Bed is about 2.5 m thick at Brønnøya. At Hovedøya it is 85 cm. At W. Nesøya the thickness is about 5 m before the unit disappears into the sea. On Spannslokket in Asker, both the brown siltstone and the Brønnøya Bed are present, but only as a 15 cm-thick siltstone with about 10 cm of the Brønnøya facies above. At Øvre Nes Marina (BN845372), the upper part of the Kalvøya Member and no less than 3 m of the Brønnøya Bed are preserved. Here, there is a diverse brachiopod fauna in the member and a few specimens of *Mucronaspis mucronata* have been found.

The Brønnøya Bed is absent at many places at the base of the Solvik Formation. Where the Høyerholmen Member of the Langøyene Formation directly underlies shales of the Solvik Formation, there is usually a sharp lithological change between the two formations. Where the Kalvøya Bed below is present with the Brønnøya Bed above, the transition further into the Solvik Formation is gradual.

Fauna and age

The nodules are fossiliferous on Hovedøya and contain *Eospirigerina* (and other brachiopods), illaenid trilobites, some bryozoa and orthocones. Towards the west, in Asker, the Brønnøya Bed becomes both thicker and more fossiliferous. At the type locality on Brønnøya the nodular limestone contains a diverse fauna of brachiopods, small stick bryozoa, crinoid ossicles and fragments of *Bumastus*. In a road section at Vestre Vei, Nesøya, and its continuation at Vestre Vei 55B by the sea (Loc. 32; Figs. 1 & 7B), the nodular limestone is about 4–5 m thick and contains well preserved brachiopods, bryozoa and fragments of trilobites. *Bumastus* is common in the lower part of the member. Orthid brachiopods are also common as are trace fossils, including *Chondrites.*

Bergström et al. (2012) placed the Ordovician–Silurian boundary above the Brønnøya Bed in the Solvik Formation based on a $\delta^{13}C$ curve at Hovedøya. At Konglungø in Asker where the bed is missing, Alridge et al. (1993) placed the Ordovician–Silurian boundary at 8 m above the base of the Solvik Formation based on conodonts, while Howe (1982) described graptolites indicative of the lowest *acuminatus* graptolite Biozone at 11 m above the base at Ormøya in the east. The Brønnøya Bed is, thus, of latest Hirnantian age, because it overlies the upper Hirnantian Pilodden Member and falls below the O/S boundary.

The Olledalen facies development of the Langåra Formation

Brenchley & Newall (1975) did not map so far west in the Asker area. The development seen here occurs as a lateral lithology of the Langåra Formation where the nodular limestone of a typical Langåra facies is succeeded by bioclastic limestone. The best development is seen at the Olledalen shooting range, Asker (NM 774352; Loc. 36; Figs. 1 & 3).

At the base is a dyke followed by 2 m-thick nodular limestone with *Holorhynchus giganteus*. This is succeeded by a very dense nodular limestone (unit 1) about 1-m thick, and then massive carbonate (unit 2) about 3 m thick on top at the main locality. The interval is fossiliferous. The calcareous development may vary slightly in thickness and composition along its outcrops from Lier in the west to Østerås and the border to Oslo in the east.

Fauna and age

The rocks immediately below the Langåra Formation contain *Holorhynchus giganteus,* large *Leptaena,* atrypids, smaller orthids, rugose corals, *Palaeofavosites* and stick bryozoa. Recent $\delta^{13}C$ studies at Olledalen show that the *Holorhynchus* level is of Katian age at this locality (Calner et al., unpublished). In the more massive bioclastic part, there are rugose corals, brachiopods, crinoid debris, and favositid corals about 10 cm diameter, some possibly in growth position, gastropods and bryozoan fragments. In some of the more shaly intervals, there are trace fossils. Analysis of $\delta^{13}C$ (Calner et al., unpublished) indicates that this rock unit is of early Hirnantian age. The overlying Solvik Formation contains *Stricklandia lens lens* throughout up to about 7–8 m above the Olledalen Formation, indicating the *Coronograptus cyphus* graptolite Biozone, of late Rhuddanian age. There is a considerable gap between the Langåra and the Solvik formation at this locality.