DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/18

Completion report Billegrav-2 well (DGU 248.61) southern Bornholm

Part 4: Stratigraphy and sedimentological description of the cored Lower Silurian - Lower Cambrian strata

Arne Thorshøj Nielsen & Niels H. Schovsbo

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/18

Completion report Billegrav-2 well (DGU 248.61) southern Bornholm

Part 4: Stratigraphy and sedimentological description of the cored Lower Silurian - Lower Cambrian strata

Arne Thorshøj Nielsen & Niels H. Schovsbo

Released 31.03.2017

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

GEUS

Table of Contents

1. Introduction

The well ‘DGU 248.61’ (referred to as the Billegrav-2 well) was drilled as part of a scientific drilling campaign conducted by GEUS on southern Bornholm in August 2010 (Figure 1). The aim was to obtain fresh core material for stratigraphical and geochemical studies of the Lower Palaeozoic shales as well as documenting the thickness of the strata.

This report is part of a study program on the Billegrav-2 well. It summarizes the stratigraphy and sedimentology of the cored Lower Silurian to Lower Cambrian strata. Other reports in this series are: ‘Results of down hole logs and core scanning’ (Schovsbo 2011a), ‘Review of the Billegrav-1 and Skelbro-1 wells’ (Schovsbo 2011b), ‘Results of core plug analysis’ (Schovsbo 2012) and ‘Fracture description and mineralogical analysis’ (Jakobsen & Schovsbo 2012).

The data in this report includes: Stratigraphy, sedimentology, sea level changes and analysis of TOC, sulphur and carbonate content. All data are included on the attached CD.

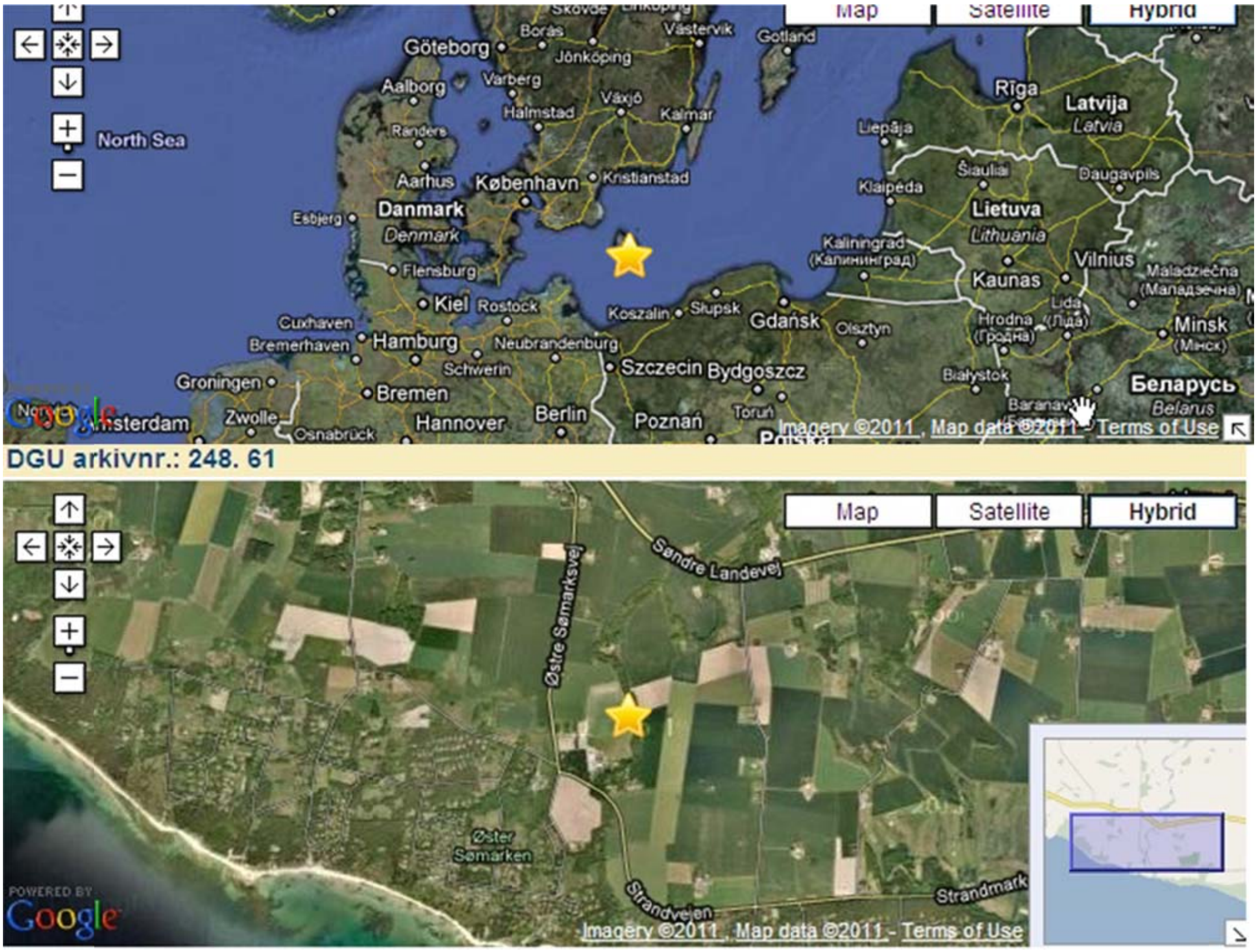


Figure 1. Location of the Billegrav-2 well, southern Bornholm, Denmark.

2. Lithostratigraphy

The Billegrav-2 well penetrated Lower Silurian to uppermost Lower Cambrian strata. The encountered lithostratigraphic units are shown in Figure 2. The Cambrian lithostratigraphy of Scandinavia has recently been reviewed and revised by Nielsen & Schovsbo (2006), and their terminology is adopted here. The naming of the younger lithostratigraphic units has been established over a long period of time and according to changing principles (for an older summary, see Poulsen 1966a) and a modern revision is needed. Below is outlined the current status.

Rastrites Shale (uppermost Ordovician to Lower Silurian): 2.7-c. 60.85 m (> 58 m)

Rastrites Shale is the traditional term – used for Bornholm since Johnstrup (1889) – for the grey to dark grey graptolitic Lower Silurian shales overlying the trilobitic Lindegård Mudstone. For a review of older designations, see Bjerreskov (1975). Limestone concretions and lenses are common at some levels. The basal part of the unit (c. 1 m in the Billegrav-2 core, interval 59.9-c. 60.85 m) is of latest Ordovician age according to modern standards (cf. Koren & Bjerreskov, 1997), but the main upper part of the unit is of Early Silurian age (Bjerreskov 1975; Koren & Bjerreskov 1997); for details, see the section on biostratigraphy. The base of the unit is, on a scale of 0.5 m (core interval 60.5-61.0 m), gradual, with lithology changing from light grey, bioturbated mudstone (Lindegård Fm) to darker grey graptolite bearing laminated shale (Rastrites Shale). The formational boundary is located somewhere between 60.80-60.95 m and is here defined at 60.85 m.

The name Kallholn Formation was coined for the Rastrites Shale of south central Sweden by Bergström & Bergström (1996) and this designation was extended to include the Rastrites Shale of Scania by Bergström et al. (1997). However, the delimitation from the overlying Cyrtograptus Shale is still based on palaeontological data and it is here preferred to maintain the old term Rastrites Shale for the time being, pending the introduction of a proper lithostratigraphy for the Silurian shales of Scania-Bornholm.

The total thickness of the Rastrites Shale on Bornholm (i.e. the shales below the *M. griestoniensis* Zone according to traditional usage) has been estimated at c. 80 m. This thickness is calculated based on levelling along the Øleå River (Bjerreskov 1975), combined with data from the Billegrav-1 drilling (Pedersen 1989; Koren & Bjerreskov 1997). The calculation is based on the assumption that no faults are present between the outcrops along Øleå (cf. Bjerreskov 1975). However, the Billegrav-2 drilling demonstrates that this is not the case (for details, see section on biostratigraphy) and at least c. 20 m should be added to Bjerreskov's calculation. Hence, the total formation thickness is minimum c. 100 m but additional unrecognized faults may be present along the Øleå downstream of the Billegrav-2 drill site.

The Rastrites Shale may be subdivided into at least four characteristic members, here informally referred to as R-I to R-IV. This provisional lithostratigraphical terminology should not be confused with the log-stratigraphic units (labelled F1-F5) introduced by Pedersen & Klitten (1990).

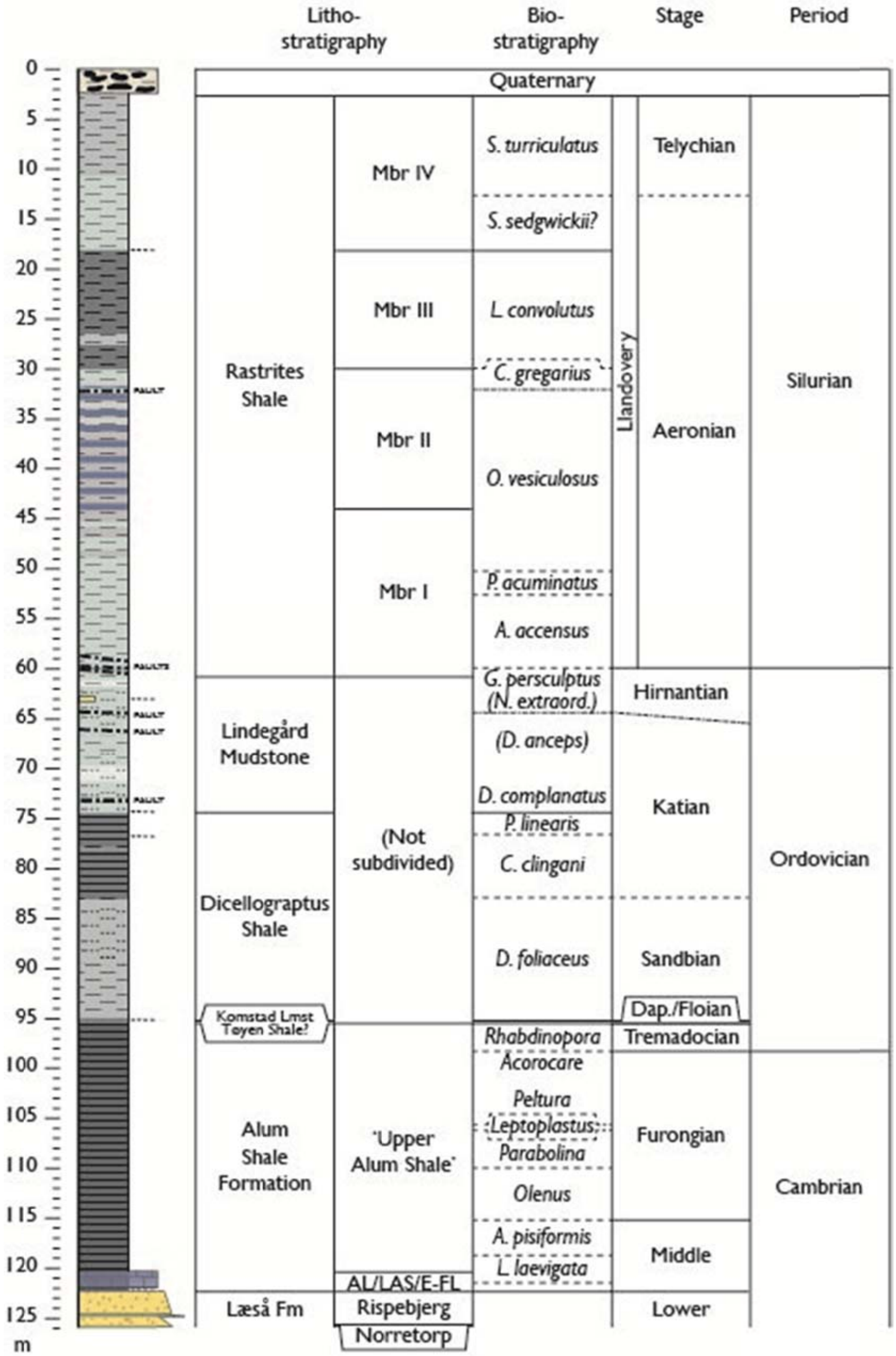


Figure 2. The encountered lithostratigraphic units in the Billegrav-2 well. A simplified log for the Billegrav-2 well is shown to the left.

Mbr I: c. 44.1-60.85 m. The core is transected by a couple of faults and the unit is probably slightly thicker. Predominantly grey to lighter grey laminated mudstone; a thin darker grey interval is present near the base. Thin silt laminae are common in some parts of the unit. This member broadly corresponds to log units F1 and F2 (see Schovsbo et al. 2011). The boundary between these units is marked by a thin interval (55.0-56.0 m) with numerous thin silt-streaks.

Mbr II: 29.99-44.1 m. Unit dominated by grey to darker grey, somewhat calcareous mudstone with numerous large limestone nodules and beds. The lower boundary is defined at the first occurrence of limestone. The uppermost part of the unit is lighter greyish in colour. This member corresponds to log unit F3 (cf. Schovsbo et al. 2011).

Mbr III: 18.12-29.99 m. Dominated by dark to blackish mudstone, laminated, mostly rather graptolitic. The lower boundary marks an abrupt change from grey to light grey limestone-bearing mudstone to dark grey mudstone. This member corresponds to the lower part of log unit F4 (cf. Schovsbo et al. 2011).

Mbr IV: 2.7–18.12 m. Mostly grey, in the lower part light grey to greenish mudstone. The lower boundary is sharp and associated with a thin conglomerate. This member corresponds to the upper part of log unit F4 (cf. Schovsbo et al. 2011). Mbr IV may encompass the entire upper part of the Rastrites Shale, but which is not penetrated by the Billegrav-2 drilling. The upper part of core is transected by a couple of faults and Mbr IV is at least 14 m thicker than drilled.

Lindegård Mudstone (Upper Ordovician): 60.85-74.3 m (13.5 m)

The term Lindegård Mudstone, introduced by Glimberg (1961), is here used instead of the older traditional names Tretaspis shale and Brachiopod beds and their more recent “topostratigraphical” synonyms Jerrestad and Tommarp mudstones (Jaanusson 1963; see also Poulsen 1966a and Bergström et al. 1997). Topostratigraphical units are defined based on a mix of lithological and palaeontological criteria (Jaanusson 1976). The Lindegård Mudstone rests unconformably on the Dicellograptus Shale and has a distinctive pyritic conglomerate at the base. The Lindegård mudstone is lighter coloured than the bounding units below and above and is dominated by poorly fissile, grey mudstone, somewhat calcareous and often mottled due to intense bioturbation. Thin sandy intercalations occur in the upper part. The Lindegård Mudstone is cut by a couple of faults in the core and the unit is somewhat thinner than in the nearby wells Billegrav-1 (16.5 m, see Pedersen 1989) and Sømarken-2 (21 m, see Pedersen & Klitten 1990) (for location, see Figure 4). Interpolation between these wells suggests that ca. 7 m of the Lindegård Mudstone is faulted out in the Billegrav-2 core (see section on biostratigraphy).

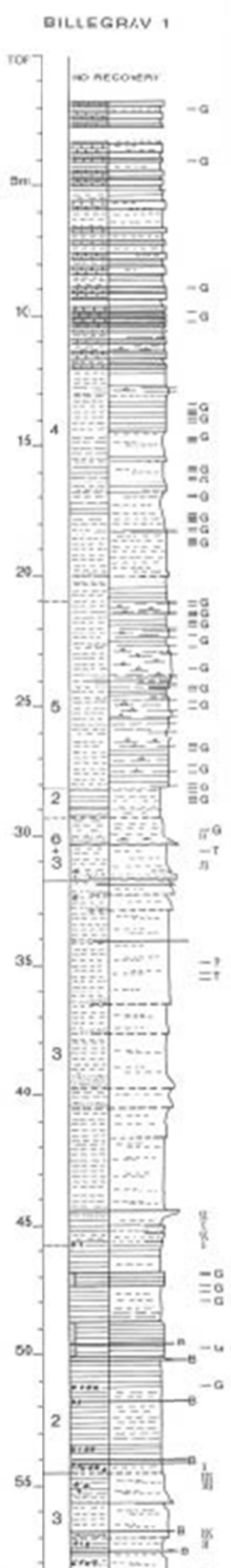


Figure 3. The Billegrav-1 core (Pedersen 1989).

Dicellograptus Shale (Upper Ordovician): 74.3-95.1 m (20.8 m)

The traditional designation Dicellograptus Shale is here maintained for the grey to blackish, in part bentonite-rich unit bounded by the Komstad Limestone below and the Lindegård Mudstone above. The Dicellograptus Shale of Scania has recently been assigned to the Sularp, Mossen and Fjäcka shales (Bergström et al. 1997). The Sularp Shale is characterized by numerous bentonite layers and corresponds to the interval 95.1-88.27 m in the Billegrav-2 core. The Mossen and Fjäcka shales were originally defined in central Sweden for two thin tongues of black shale that undoubtedly represent incursions of the Dicellograptus Shale onto the carbonate platform, associated with prominent sea level rises (see e.g. Wærn 1948). However, in Scania-Bornholm there is no lithologic difference between the amalgamated Mossen and Fjäcka Shales and distinction relies on palaeontological criteria. Hence we prefer to maintain the original designation Dicellograptus Shale since this is a proper lithostratigraphic unit despite the incorrect naming.

The Dicellograptus Shale is somewhat thicker in the Billegrav-2 core than in the classical section at Vasagård, Læså, where it is c. 12 m thick (Hadding 1915; Funkquist 1919; Bruvo 2005). There is a considerable hiatus between the Dicellograptus Shale and the underlying Komstad Limestone (Figure 2). There is no conglomerate at the base of the Dicellograptus Shale as seen elsewhere on Bornholm (e.g. Poulsen 1936); a thin bentonite is resting directly on the eroded top of the Komstad Limestone.

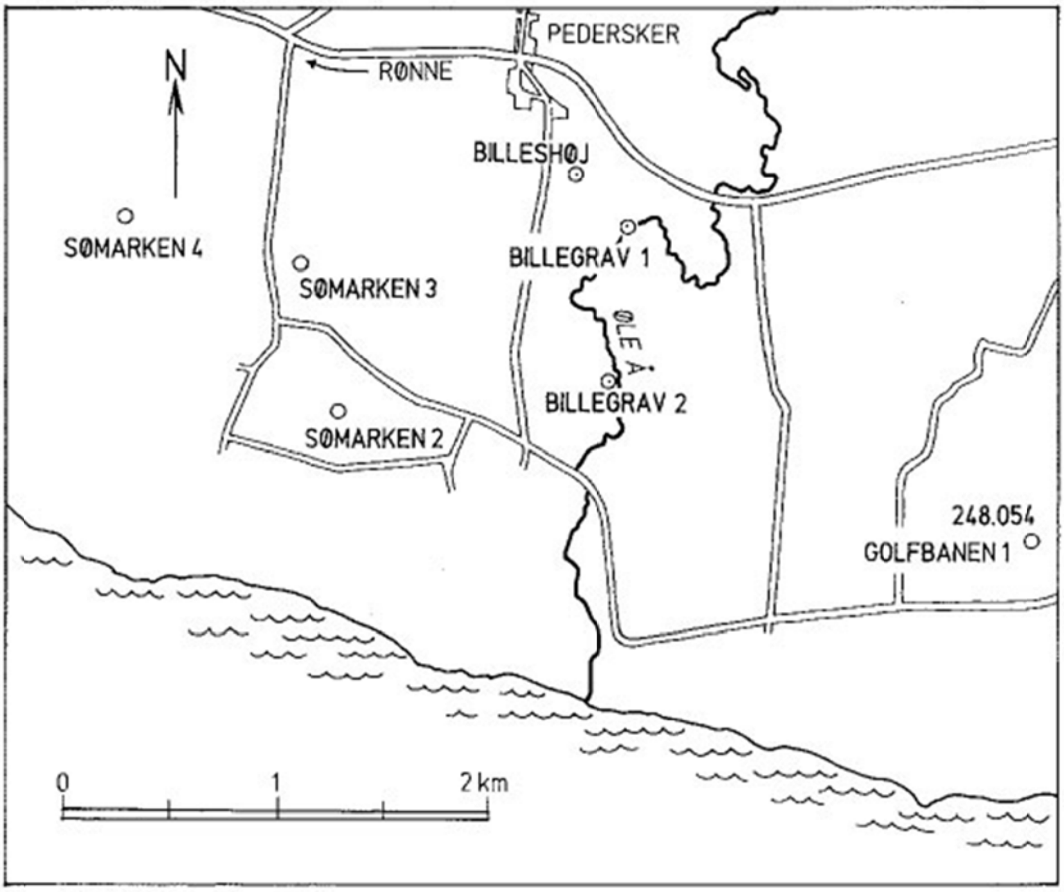


Figure 4. Location of shallow wells in the Øleå area (updated and modified from Pedersen & Klitten 1990).

Komstad Limestone Formation (Middle Ordovician): 95.1-95.17 m (0.07 m)

The Komstad Limestone is a characteristic greyish thin-bedded limestone unit of "Orthoceres limestone" type. It may be envisaged as a tongue of the shallower marine Ordovician limestone present on Öland and in south central Sweden. In the Læså area the Komstad Limestone is some 4-5 m thick of which the lowermost 0.5 m previously was separated as the Skelbro Limestone, but this designation is now abandoned (Nielsen 1995). The Komstad Limestone is thinner in the Øleå area with a reported thickness (estimated from gamma logs) of about 2-3 m in various water wells (Pedersen & Klitten 1990). In the Billegrav-2 core the Komstad Limestone is represented only by its basal conglomerate.

Tøyen Shale Formation? (Lower Ordovician): 95.17-95.39 m (0.22 m)

The Tøyen Shale Fm, in older literature referred to as Lower Didymograptus Shale, is well-known from Scania and the Oslo area, where is may be several tens of metres thick, even exceeding 100 m in NW Scania (Nielsen 1995, figure 41 and references therein), but the formation has never before been reported from Bornholm, where the Komstad Limestone in most places rests unconformably on the Alum Shale Fm (e.g. Poulsen 1966a; Nielsen 1995). The Tøyen Shale Fm of Scania-Oslo comprises a lower, generally greenish to light greyish part, often with some sandstone stringers (Oslo) or limestone beds or nodules (Scania), and an upper dark grey to blackish part. In the Oslo area these subunits are formally separated as distinct members (Owen et al. 1990), but which has not been done in Scania. The thin light grey to greenish shale in the Billegrav-2 core intercalated between the Komstad Limestone and the Alum Shale Fm may well represent an erosional remnant of the Tøyen Shale, which otherwise for the greater part has been eroded away in the Bornholm area. The upper boundary is clearly unconformable, whereas the lower boundary is obscure and tentatively placed at an erosive bedding plane just above a bed of amalgamated barite crystals. Tiny nodules of phosphorite suggest that the light coloured greenish mudstone cannot just represent bleached Alum Shale.

Alum Shale Formation (Middle Cambrian-Lower Ordovician): 95.39-122.17 m (26.78 m).

The Alum Shale Fm is a characteristic unit comprising black, organic rich mudstone, often distinctly laminated and pyrite-rich (for definition, see Nielsen & Schovsbo 2006). It rests unconformably on Lower Cambrian sandstone. On Bornholm the Alum Shale is mostly unconformably overlain by the Komstad Limestone, but in the Billegrav-2 core it is overlain with a sharp boundary by a light grey greenish mudstone, suggested to represent the Tøyen Shale (see above). The boundary must represent an unconformity; at this level is missing the Bjørkåsholmen Fm (= Ceratopyge Limestone of older literature) and the upper part of the Ordovician Alum Shale.

The Alum Shale Fm contains nearly no diagenetic limestone nodules (stinkstone/"anthraconite") in the Billegrav-2 core, which is unusual. In the lower part is seen the two characteristic marker beds Andrarum Limestone (120.41-121.33 m) and Exsulans Limestone (122.03-122.17 m). The latter is probably amalgamated with the Forsemölla Limestone Bed (the 'green' Exsulans Limestone sensu Hansen 1945, corresponding to 122.085-122.17 m in the Billegrav-2 core). The Alum Shale separating the Exsulans and Andrarum units, the so-called 'Lower Alum Shale', is thin in the Borggård core, but this is typical for the Øleå area, where maximum recorded thickness is 0.8 m (cf. Grönwall 1899, 1902; Hansen 1945). Overall the Middle Cambrian Alum Shale tends to be slightly thinner in the Øleå area compared with the Læså area (0.7 m in the Skelbro cores; Pedersen 1989; Schovsbo et al 2011; 1.4 m in the Læså near Kalby (Grönwall 1902)).

Læså Formation (Lower Cambrian): 122.17-125.9 m (>3.73 m)

The Billegrav-2 drilling terminated in the upper part of the Lower Cambrian Læså Fm (see Nielsen & Schovsbo 2006 for details). This unit comprises the c. 100 m thick silt-dominated Norretorp Mbr, of which only the very top part (probably 125.77-125.9 m) has been cored in Billegrav-2, and the sand-dominated Rispebjerg Mbr (125.77-122.17 m). However, it is even possible that the drilling has not yet reached the Norretorp Mbr.

3. Correlation

The Billegrav-2 drilling was spudded close to Øleå just east of locality 14b sensu Bjerreskov (1975) (Figure 6). This location was chosen in order to drill from within the lowermost part of the *S.* t*urriculatus* Zone and below that the entire *convolutus* Zone, the most TOC-enriched unit of the Silurian onshore Bornholm. This objective was accomplished. Depths refer to ground level at the drilling location. Merete Bjerreskov has kindly scanned the graptolites in the upper 18 m of the core, but no detailed taxonomic work has been undertaken. The lowermost Silurian – uppermost Ordovician are correlated using the Billegrav-1 core as template (for description, see Pedersen 1989; Koren & Bjerreskov 1997). The numerous graptolites present in the Ordovician Dicellograptus Shale have not been investigated and correlation relies on comparison with the exposure at Vasagård, Læså (Hadding 1915; Bjerreskov & Stouge 1985; Bruvo 2005).

Silurian

Core interval 2.7-18.13 m: Rastrites Shale

The uppermost part of the core represents the Lower Silurian *Spirograptus turriculatus* Zone (*s.l.*) like the shales in the nearby exposure 14b within the Øleå (Bjerreskov 1975). *S. turriculatus* itself, which is readily identified even by non-specialists, has been found at 2.7 m, 5.4 m, 5.49 m, 5.54 m, ?6.05 m, 6.85 m, ?7.85 m and 12.315 m. Correlation is further supported by findings of fragmentary *Rastrites* sp. at 7.73 m, 7.83 m, ?8.54 m and 10.72 m; this genus is characteristic of the lower part of the *S. turriculat*us Zone. Please note that subspecies of *S. turriculatus* are not distinguished in the present work; the lower part of the zone is characterized by *S. turriculatus minor* and this interval was separated as the *Spirograptus guerichi* Zone by Loydell et al. (1993). Here a broad definition of an undivided *S. turriculatus* Zone is upheld.

According to the thickness calculations presented by Bjerreskov (1975, here Figure 5), based on levelling along the Øleå, 3-4 m of shales representing the *S. turriculatus* Zone were anticipated present at the Billegrav-2 drill-site before reaching the top of the underlying *Lituigraptus convolutus* Zone. However, this zone was not reached before 18.13 m, the upper boundary being marked by a 1 cm thick conglomerate.

Within the Øleå the upper boundary of the *L. convolutus* Zone is exposed at Loc. 13 sensu Bjerreskov (1975); above follows c. 3.5 m of unfossiliferous shale in turn overlain by the *S. turriculatus* Zone (Bjerreskov 1975). A gap is present between the *L. convolutus* and *S. turriculatus* zones according to Bjerreskov (1975), comprising the *Stimulograptus sedgwickii* Zone, which forms the uppermost zone of the Aeronian Stage.

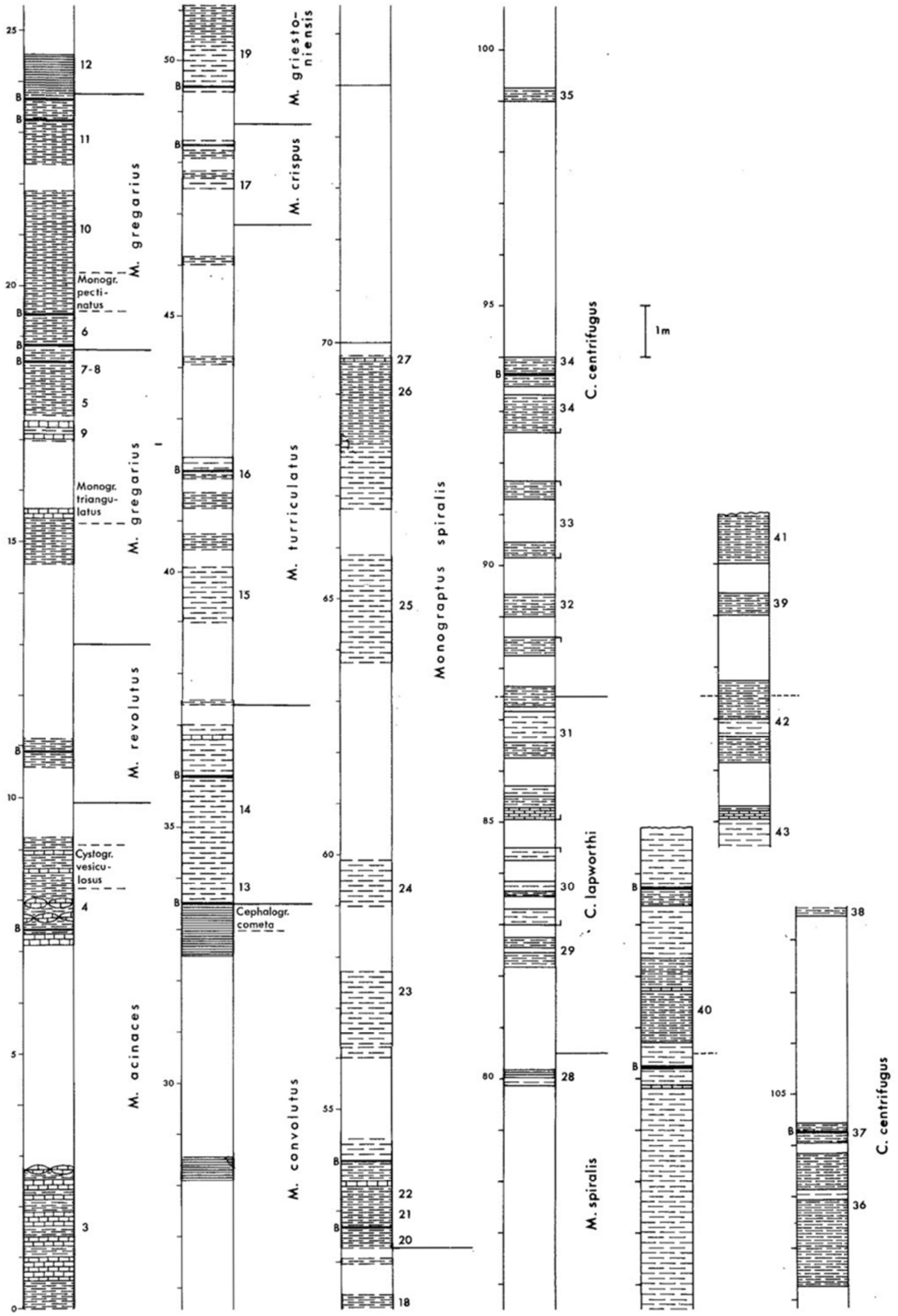


Figure 5. Thickness of the Silurian shales along the Øleå (from Bjerreskov 1975). Small numbers on the right hand side refer to locality (see Figure 6). The thickness is calculated based on levelling, assuming that no faults are present.

Graptolites occur abundantly from the top of the Billegrav-2 core and down to 11.76 m. Below that level graptolites have been found only at 12.03, 12.31, 15.15, 15.71, 16.08, 16.43 and 16.45 m. Light grey mudstone occurs between 17.49 m and the conglomerate at 18.12-18.13 m. Hence, there is only 1.7 m of non-graptolitic shales in the core just above the *L. convolutus* Zone, not 3.5 m as recorded within the Øleå by Bjerreskov (1975) – even without systematically splitting the core. The recorded fossils are those incidentally exposed on the bedding planes present. The core data thus do not fit with the observations made by Bjerreskov (1975). Besides, the strata are much thicker in the core, where there was 18 m to the top of the *L. convolutus* Zone at the drill-site and not 3-4 m as indicated by Bjerreskov (1975, here Figure 5). It thus appears that at least 12-14 m of shales are faulted out in the Øleå section and the fault must be located between locations 14 and 14b in the river (see Bjerreskov 1975, here Figure 6). However, it is strongly suspected that this fault also cuts the Billegrav-2 core at around level 32 m; the offset of that fault is calculated to be about 16-17 m (see below). The apparent difference in offset may at least partly reflect the elevation of the drill-site above the shales exposed at loc. 14b.

The graptolites found in the core between 12.3 and 16.45 m should be determined precisely in order to establish which biozone is present. Bjerreskov (pers. com. 2011) hold it possible that the *S. sedgwickii* Zone actually is developed. It is not possible to match the bentonite levels recorded in the core with those registered in the outcrops (Bjerreskov 1975, here Figure 5), partly because the river sections are incompletely exposed and partly because thin bentonites may have escaped recognition in the weathered and somewhat overgrown sections. The outcrops should be reinvestigated in order to secure consistent identification of thin bentonites. The one bentonite level recorded by Bjerreskov (1975, here Figure 5) at loc. 14 c. 2 m above the *L. convolutus* Zone likely corresponds to one of the thicker bentonites recorded at 9.12-9.145, 12.19-12.205 or 12.37-12.38 m in the Billegrav-2 core. If so, another fault must be crossing the Øleå between locations 13 and 14. It may correspond to the fault seen in the Billegrav-2 core between 64.3-65.4 m.

Core interval 18.13-c. 30.0 m: Rastrites Shale

The shales of the *L. convolutus* Zone between 18.13 to c. 30.0 m are darkish, almost black and strongly graptolitic and constitute a very characteristic marker level. The zone is thus a couple of metres thicker than calculated by Bjerreskov (1975, here Figure 5), based on scattered exposures along the Øleå. The lower boundary is likely located at c. 30 m, but the zone may start slightly lower, down to 30.4 m in the Billegrav-2 core. It is possible that the thickness calculated by Bjerreskov (1975) is too low due to the presence of a minor fault in the river or calculation error; only 1/3 of the zone is exposed in the river.

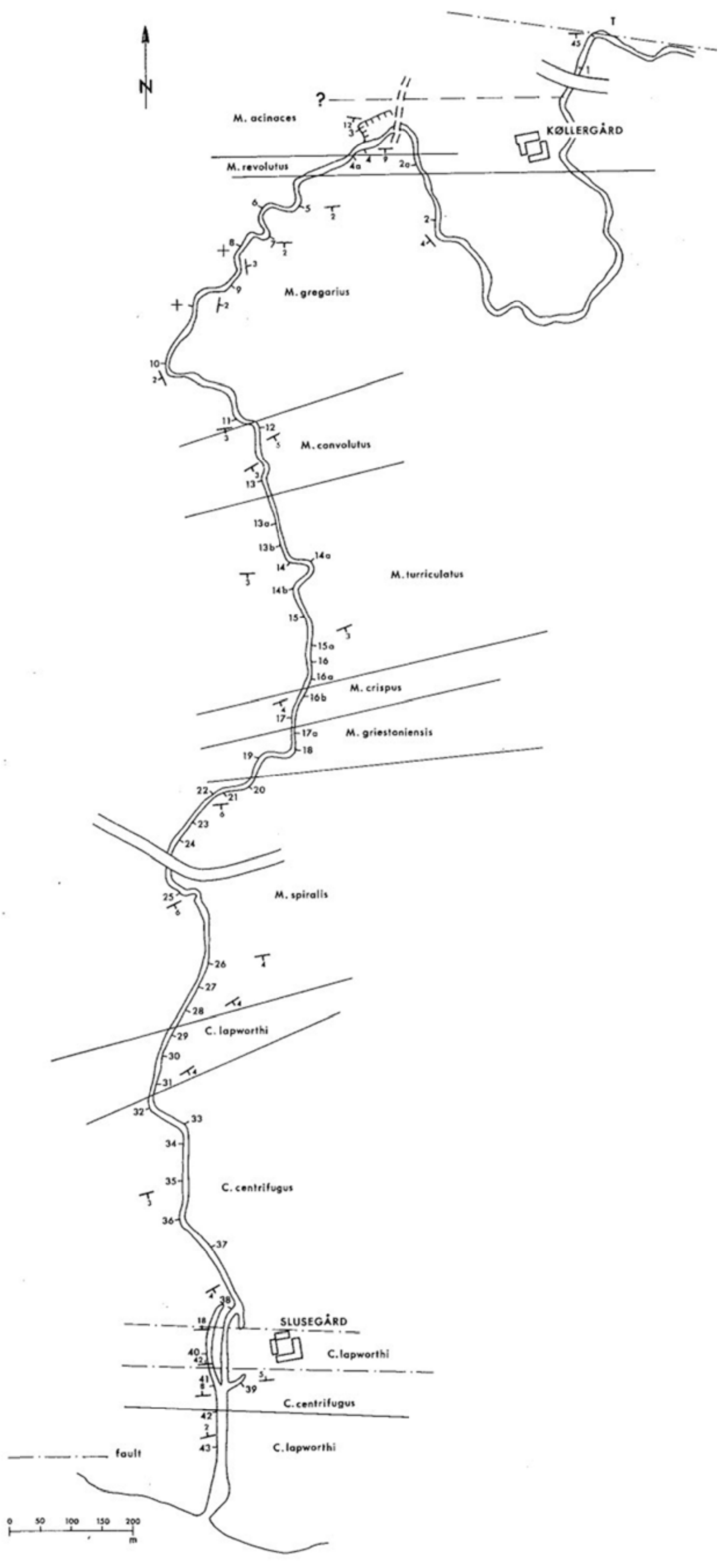


Figure 6. Locality map of Bjerreskov (1975) showing Silurian exposures along the Øleå.

Core interval c.30.0-c. 50.1 m: Rastrites Shale

The dark shales of the *L. convolutus* Zone are underlain by lighter coloured shales assigned to the *Monograptus* [now *Coronograptus*] *gregarius* and *Monograptus* [now *Pernerograptus*] *revolutus* zones by Bjerreskov (1975); distinction of these zones requires identification of graptolites. The two zones are altogether c. 14 m thick in the Øleå river according to Bjerreskov (1975, here Figure 5), provided that no faults are present. The underlying *Orthograptus vesiculosus* Zone (referred to as the *Monograptus acinaces* Zone by Bjerreskov 1975) has a characteristic lithology with numerous limestone intercalations and is readily identified. Note, however, that scattered limestone bands are present also within the *C. gregarius* Zone as seen at loc. 9 in the Øleå river (Figure 5). The *O. vesiculosus* Zone probably starts below the fault at 32.1-32.2 m in the Billegrav-2 core. If so, only the upper part of the *C. gregarius* Zone is present in the Billegrav-2 core (c. 30.2 to 32.1 m) and the lower part of that zone as well as the *P. revolutus* Zone are faulted out. The very top of the *O. vesiculosus* Zone is probably also missing. The offset of the fault is at least 12 m and it is highly likely that it is the same fault that cuts out the lower part of the *S. turriculatus* Zone and maybe also the *S. sedgwickii* Zone in the Øleå river between locations 14 and 14a of Bjerreskov (1985); see discussion of core interval 2.7-18.13 m above.

The Billegrav-1 drilling was spudded adjacent to loc. 4 sensu Bjerreskov (1975) in the Øleå and penetrated an unfaulted lower part of the Silurian (Pedersen 1989; Koren & Bjerreskov 1997) which can be used as template for correlation of the Billegrav-2 core. The uppermost c. 5 m of the *O. vesiculosus* Zone is above the level penetrated by the Billegrav-1 core, hence this zone is c. 24 m thick at Øleå (cf. Koren & Bjerreskov 1997).

The lime-rich shales representing the upper part of the *O. vesiculosus* Zone extends to 44.1 m in the Billegrav-2 core; this level corresponds to 12 m in the Billegrav-1 core (= 17 m below top of the *vesiculosus* Zone). Hence 4 to 5 m of the lime-rich *O. vesiculosus* Zone seems to be faulted out in the Billegrav-2 core, suggesting that offset of the fault at 32.1-32.2 m in the core is 16-17 m. It is strange, however, that the characteristic log-unit F3 is only 17 m in the nearby Sømarke-2 well (Pedersen & Klitten 1990), leaving no room for the *C. gregarius* and *P. revolutus* zones (combined thickness calculated at c. 14 m by Bjerreskov 1975). This suggests that a fault likely is present in the Sømarke-2 well between log units F3 and f4.

The *O. vesiculosus* Zone extends to 19 m in the Billegrav-1 core (Koren & Bjerreskov 1997) i.e. 7 m below the lime-rich succession (compare Pedersen 1989, fig. 3). The zonal boundary is not associated with readily identified lithological changes but from 2 m lower in the Billegrav-1 core and 7 m downwards to about level 28 m abundant silt laminae occur in the mudstone. This silt-rich level probably corresponds to the interval 52.3-59.2 m in the Billegrav-2 core. If so, the boundary between the *O. vesiculosus/Parakidograptus acuminatus* zones may be located at around 50.1-50.30 m in the Billegrav-2 core.

Core interval c. 50.1-62.24 m: Mainly Rastrites Shale (incl. uppermost part of the Ordovician)

Within the Billegrav-1 core the *O. vesiculosus* Zone is underlain by the *P. acuminatus* and *Akidograptus ascensus* zones (2.6 m and 4.8 m thick, respectively), in turn underlain by the Ordovician *Normalograptus persculptus* Zone (c. 2 m thick) (Koren & Bjerreskov 1997). A lower non-graptolitic part of the *N. persculptus* Zone is likely corresponding to the top part of the underlying Lindegård Mudstone. The graptolitic *N. persculptus* Zone (uppermost

Ordovician) forms the basal part of the Rastrites Shale and the very top of the Lindegård Mudstone.

The graptolite zonal boundaries are not associated with distinct lithological changes, so there are few tie points for correlation between the Billegrav-1 and -2 cores. However, the upper part of the *N. persculptus* Zone is in part a dark coloured pyritic shale c. 28.1-29.2 m in the Billegrav-1 core, likely corresponding to c. 60-61 m in the Billegrav-2 core. Two metres below the *O. vesiculosus* Zone and 7 m downwards is seen a high silt content in the Billegrav-1 core (below level 21 m in that core, see Pedersen 1989, fig 3); this level may correspond to c. 52.3-59.2 m in the Billegrav-2 core although the downwards incoming of silt here is heralded by thin laminae at around 51.7 m. Hence, the thicknesses of the Lower Silurian shale seem to be approximately the same between the two cores, so the *P. acuminatus*/*A. ascensus* zonal boundary is probably located at around 52.7 m in the Billegrav-2 core. The fault located at 59.7-59.9 m possibly forms the *A. ascensus*/*N. persculptus* zonal boundary. However, the offset of the three faults seen between 58.7 and 60.4 m in the Billegrav-2 core must be minimal since the thickness of the shale between the limestone-rich upper part of the *O. vesiculosus* Zone and the Lindegård Mudstone is almost the same as encountered in the Billegrav-1 core.

The graptolites recorded in the Billegrav-2 core have not been identified and it is emphasized that the indicated zonation is based solely on comparison with the lithology of the Billegrav-1 core. The lowermost graptolites recorded were found at 62.24 m in the Billegrav-2 core.

Ordovician

Core interval 62.24-74.3 m: Lindegård Mudstone

The very top of the Lindegård Mudstone contains a few graptolites, likely representing the *N. persculptus* Zone; this interval (60.85-62.24 m) has been treated above. The main lower part of the Lindegård Mudstone is non-graptolitic in the core. A few trilobite fragments have been found near the top of the formation, including *Mucronaspis* sp. (?*mucronata*) at 62.82 m, and the upper interval is likely of Hirnantian age. Numerous ostracods have also been found, but which have no biostratigraphical value as long as they are not determined.

The Lindegård Mudstone straddles the *Dicellograptus complanatus*, *Dicellograptus anceps*, *Normalograptus extraordinarius* and likely also the lower part of the *N. persculptus* graptolite zones, but of which only the *D. complanatus* Zone has been proven present by actual findings of graptolites 3-3.5 m above the base of the formation at Læså (= *Dicellograptus anceps* var. *bornholmiensis* reported by Poulsen 1936). The intraformational location of the *D. complanatus*/*D. anceps* zonal boundary is unknown but may be positioned at about 69-69.6 m where the grey mudstone overlies a light grey interval with numerous ostracods. The lithological change possibly marks a minor depth increase, i.e. a sea level rise. The *D. anceps* and *N. extraordinarius* zones are developed in shelly facies all over Scandinavia and no graptolites diagnostic of these zones have been recorded so far.

The fault located at 64.3-65.5 m in the Billegrav-2 core presumably forms the boundary between the Katian and Hirnantian. The Lindegård Mudstone is 3 m thinner in the Billegrav-2 core in comparison with the Billegrav-1 core, 5 m thinner than in Sømarke-3 and 8 m thinner than in the Sømarke-2 water well, judging from the gamma-log motif of those wells (Pedersen

& Klitten 1990). Hence the fault between 64.3-65.5 m likely has an offset of 3-8 m, probably c. 7 m (based on preliminary isopach mapping of the Lindegård Mudstone in the area).

The sandy sharp-based bed 63.19-62.99 m in the Billegrav-2 core probably signals peak lowstand of the Hirnantian, but whether this was an intra-*persculptus* event or forms the base of the *N. persculptus* zone remains uncertain.

It is tentatively suggested that the core correlates as follows:

60-62.24 m: *N. persculptus* Zone (with graptolites)
62.24-63.19: Probably *N. persculptus* Zone but without graptolites
63.19-64.3: Possibly *N. extraordinarius* Zone without graptolites (lower part faulted out)
64.3-65.5: Fault, offset c. 7 m?
65.5- c. 69.6: Possibly *D. anceps* Zone (no graptolites)
c. 69.8-74.31: *D. complanatus* Zone (no graptolites in the upper part; graptolites in lower 3.5 m the Læså area)

Core interval 74.3-95.1 m: Dicellograptus Shale

The upper part of the Dicellograptus Shale is very rich in graptolites, but none in the core have been determined. The corresponding strata at Læså have recently been investigated in great detail with regard to graptolite stratigraphy (Bruvo 2005) and these results are used as template for correlation of the Billegrav-2 core. However, the Dicellograptus Shale is almost twice as thick in the core as at Læså (20.8 m vs 10.8 m).

The thin conglomerate at 76.7 m in the core likely marks the boundary between the *Pleurograptus linearis*/*Dicranograptus clingani* zones; an inconspicuous conglomerate is also present at this level in the Læså section. The *P. linearis* Zone is 3.5 m thick at the Læså (Bruvo 2005) and apparently only 2.4 m in the Billegrav-2 core.

The *D. clingani*/*Diplograptus foliaceus* [formerly *D. multidens*] zonal boundary is also marked by a phosphorite conglomerate at Læså, but no corresponding unconformity has been recorded in the Billegrav-2 core. The sea level became very low in the latest part of the *D. foliaceus* Zone (Frognerkilen Lowstand Event of Nielsen 2004) and it is logical to assume that the bioturbated light grey mudstone 83-85 m broadly speaking marks this event. Hence it is assumed that the base of the *D. clingani* Zone is located at c. 83 m in the core and if so, the zone is about 5.3 m thick (vs 4.4 m at Læså).

The lower part of the Dicellograptus Shale contains numerous bentonite beds and was correlated with the *D. multidens* [now *foliaceus*] Zone by Bergström & Nilsson (1974). This unit is much thicker in the Billegrav-2 core (c. 12 m) than at Læså (2.9 m, cf. Funkquist 1919). It is apparently about 1 m thinner in the Sømarken-2 well (see Pedersen & Klitten 1990 fig. 5). Please note that bentonites are particularly abundant in the lowermost 8 m of the Dicellograptus Shale (= Sularp Shale according to the terminology proposed by Lindström 1953; Bergström et al. 1997); this level corresponds to log unit D1 of Pedersen & Klitten (1990).

Core interval 95.1-95.39 m: Komstad Limestone and ?Tøyen Shale

The Komstad Limestone, representing four earliest Mid Ordovician trilobite zones (Dapingian-Darriwillian, cf. Nielsen 1995) is 4-5 m thick in the Læså area. It has also been inferred present in the Øleå area, where it is c. 2-2.5 m in the uncored Sømarke-2 and Billeshøj wells according to log interpretation (Pedersen & Klitten 1990). In other water wells in the area it is thinner. Only the basal conglomerate of this unit, likely representing the basal most part of the *Megistaspis polyphemus* trilobite Zone, is present in the Billegrav-2 core (95.1-95.17 m); no fossils have been encountered.

The limestone is underlain by greenish light grey shale with sporadic phosphorite pebbles; this lithology strongly resembles the lower part of the Tøyen Shale in Scania (Lower Ordovician: Hunneberg regional Stage). This unit has so far been regarded absent on Bornholm (e.g. Poulsen 1966a). No fossils have been encountered. The unit rests unconformably on the Alum Shale Formation; no Bjørkåsholmen Fm [previously Ceratopyge Limestone] is developed.

Core interval 95.39-c. 98.10 m: Ordovician Alum Shale Fm

The Alum Shale Fm is slightly thinner in the Billegrav-2 core, 26.8 m (total thickness), than in the Læså area, where the unit is 33.5 m thick in the Skelbro-1 and Skelbro-2 cores (Pedersen 1989, Schovsbo et al. 2011). A thickness of c. 38.5 m was calculated along the Læså based on levelling between outcrops (ATN unpublished). The formation is strongly condensed compared with Scania (cf. Westergård 1922, 1942, 1944).

Within the Billegrav-2 core the Ordovician interval of the Alum Shale Fm comprises blackish, pyritic, laminated shale with abundant barite pseudomorphs, in particular in the lower part. Graptolites (*Rhabdinopora* spp.) are common in the upper part (Appendix A); lowermost occurrence is at 98.105 m, but since no systematic splitting of the core has been undertaken the Ordovician section of the Alum Shale (previously referred to as the Dictyonema Shale) may be slightly thicker. The Ordovician Alum Shale is 4 m thick at Limensgade, Læså (von Jansson 1979). *Rhabdinopora* ranges to the very top of the Alum Shale Fm in the Billegrav-2 core, indicating that the *Adelograptus tenellus* Zone and the *Bryograptus kjerulfi* Zone recorded in the Læså area (von Jansson 1979), are not preserved in the Billegrav-2 core. These zones measure 0.34 m and 0.13 m at Læså, respectively (von Jansson 1979).

Cambrian

Core interval c. 98.10-120.40 m: Furongian and upper Middle Cambrian Alum Shale Fm

This core interval comprises the Furongian (upper Cambrian) part of the Alum Shale Fm. It contains surprisingly few stinkstone concretions and the registered fossil content is low. The biozonation of the Furongian was treated by Poulsen (1923), but the precise thicknesses of the individual zones are only partly known. Terfelt et al. (2010) recently proposed to abandon the traditional trilobite zonation and instead elevate the former subzones to zonal rank. However, here the traditional zones are treated as superzones.

The core interval 107.36-109.18 m contains abundant articulate brachiopods (*Orusia lenticularis*) and undoubtedly represents the *Parabolina* Superzone. The interval 112.89-114.67 contains *Olenus* spp. and a few *Homagnostus obesus* and represents the lowermost part of the *Olenus* Superzone. Base Furongian is usually marked by a stinkstone band, likely the stinkstone between 114.97-115.16 m. Hence, base Furongian is likely located at about

115.2 m and the interval 120.4-115.2 m represents the upper part of the Middle Cambrian *Lejopyge laevigata* Zone and the *Agnostus pisiformis* Zones. This Middle Cambrian interval is 6.2 to 6.5 m thick in the Skelbro-1 core (cf. Pedersen 1989). The *Olenus* Superzone is max. 6 m thick in the Billegrav-2 core vs max 8.8 m in the Skelbro-1 core.

The Alum Shale above the *Orusia* shell beds (incl. the Ordovician) is 12 m thick in the Billegrav-2 core vs 16.4 m in the Skelbro-1 core. The *Leptoplastus* Superzone is very thin in the Læså river (0.5 m, Poulsen 1923); it is located around 106.0 m in the Billegrav-2 core as suggested by finding an isolated *Leptoplastus* cranidium at this level. This suggests in turn that the *Parabolina* Superzone extends above the *Orusia* shell bed, which is also the case at Læså (cf. C. Poulsen 1923). A cranidium of *Peltura* found at 102.41 show that this level likely is somewhere within the *Peltura* superzones. The *Acerocare* Superzone is thus maximum 4.3 m thick, probably less.

Core interval 120.40-122.17 m: Lower Middle Cambrian Alum Shale Fm

This thin Middle Cambrian interval includes from above the Andrarum Limestone Bed, a thin 'Lower Alum Shale' and the amalgamated Exsulans and Forsemölla Limestone beds, resting unconformably on the Lower Cambrian Læså Fm. No fossils have been encountered, but there is little doubt that the Andrarum Limestone represents the *L. laevigata* Zone (see Axheimer *et al*. 2006; previously it was assigned to the *Solenopleura brachymetopa* Zone). The thin 'Lower Alum Shale' below may represent the *Ptychagnostus punctuosus* or *Hypagnostus parvifrons* zones (Grönwall 1902; Weidner & Nielsen in press) and the Exsulans-Forsemölla limestones represent the *Triplagnostus gibbus* Zone (Nielsen & Schovsbo 2006). The corresponding strata are thicker in the Læså area, notably the 'Lower Alum Shale', which there is up to 1.4 m thick (Grönwall 1902). It is only 0.7 m in the Skelbro-1 core (Pedersen 1989). A very major stratigraphic gap, encompassing the upper Lower Cambrian and the lower Middle Cambrian, separates the Læså and Alum Shale formations (cf. Nielsen & Schovsbo 2006). The hiatus is ascribed to the Hawke Bay regressive Event.

Core interval 122.17-125.9 m: Lower Cambrian Læså Fm

No fossil have been found in the core – but macrofossils are also generally rare in this unit on Bornholm (Poulsen 1967). Acritarch dating of the Norretorp Mbr of the Læså Fm (for lithostratigraphic terminology, see Nielsen & Schovsbo 2006) suggests that the upper part, likely including the Rispebjerg Mbr, represents the 'Ljuboml' regional Stage (see Nielsen & Schovsbo 2011 for details and references).

4. Gamma log stratigraphy

Pedersen & Klitten (1990) published gamma logs from several water wells on southern Bornholm and proposed a log stratigraphy for the Middle Cambrian-Silurian for Bornholm that is also applicable in the Billegrav-2 well (Schovsbo et al., 2011). The log stratigraphy was originally calibrated using the Skelbro-1 and Billegrav-1 cores (Pedersen & Klitten 1990) and comparison with the thickness calculations of the overlying Silurian published by Bjerreskov (1975). However, the upper main part of the Silurian has never been cored and levels above the *S. turriculatus* Zone are poorly defined in terms of log stratigraphy, compare the well Golfbanen-1 in Pedersen & Klitten (1990, fig. 5). Billegrav-2 provides supplementary core data for comparison with log-units F3 to F5 of Pedersen & Klitten (1990) and shows that the tentative correlation indicated by Pedersen & Klitten (1990), based on comparison with Bjerreskov (1975), is inaccurate.

Log unit F

The log boundary F5/F4 at 10 m in the well apparently is not associated with lithological changes and corresponds to a level within Rastrites Shale Mbr IV. It may theoretically approximate the *S. turriculatus*/*S. sedgwickii* zonal boundary.

The very distinct lithological boundary between Rastrites Shale Mbrs III/IV at 18 m is associated with a readily recognizable log signal inside log unit F4. This spike can also be seen in the nearby Sømarke-2 well (Pedersen & Klitten 1990, fig. 5) and log unit F4 should be subdivided on this basis. The lower boundary of log-unit F4 closely approximates the lower boundary of Rastrites Shale Mbr III. The underlying log unit F3 has a very characteristic motif and is readily recognized, which has been ascribed to the mixed silt/limestone lithology of the *Orthograptus vesiculosus* graptolite Zone. It should be noted, however, that this zone is 17 m thick at the Billegrav-1 drill site (Koren & Bjerreskov 1997), i.e. as thick as log unit F3 in the Sømarke-2 well, the “type section” of the youngest Silurian log-stratigraphical units. But this leaves no room for the *C. gregarius* and *P. revolutus* graptolites zones, having a total thickness of some 14 m in the Øleå section according to calculations by Bjerreskov (1975). This strongly suggests that a fault is present in the Sømarke-2 well somewhere in the uppermost part of log-unit F3 or at the F3/F4 boundary. Unfortunately the *C. gregarius* and *P. revolutus* graptolites zones are also nearly faulted out in the Billegrav-2 well (fault at c. 32 m) so this well does not provide data to verify this conclusion. But we stress that it is possible that an as yet unrecognized log-unit or sub-unit is present between log-units F3/F4.

The lower boundary of log unit F3 in turn approximates the lower boundary of Rastrites Shale Mbr II, whereas the lower boundary of log-unit F2 at c. 55.8 m correlates with a silt-rich horizon in an otherwise fairly uniform grey shale succession (undoubtedly signalling a higher order sea level lowstand). The lower boundary of log unit F1 approximates the lower boundary of the Rastrites Shale.

Log unit E

Log unit E corresponds to the Lindegård Mudstone. The subdivisions E1-E3 do not correspond to obvious lithological changes. The E3/E2 boundary is located a little below the sand intercalation in the upper part of the Lindegård Mudstone in both Billegrav-2 and Billegrav-1. The E2/E1 boundary may theoretically approximate the *D. complanatus*/*D. anceps* zonal boundary.

Log unit D

Log unit D corresponds to the Dicellograptus Shale. It is subdivided into units D1-D3 of which the D3/D2 boundary approximates the *D. foliaceus*/*D. clingani* zonal boundary and the D2/D1 boundary approximates the top of the bentonite rich interval (Sularp shale in Swedish terminology).

Log unit C

The Komstad Limestone (log unit C) is too thin to be resolved in the log of the Billegrav-2 well and that also concerns the suspected Tøyen Shale. Hence log-unit D is directly underlain by log-unit B (Alum Shale) in the Billegrav-2 well.

Log unit B

The Alum Shale is subdivided into log units B1-B4. The log-boundary B4/B3 is for all practical purposes corresponding to the Cambro-Ordovician boundary, whereas the B3/B2 boundary approximates the Middle Cambrian/Furongian boundary (slightly above). The B2/B1 boundary approximates the top of the Middle Cambrian limestones.

Log unit A

Log unit A corresponds to the Læså Fm.

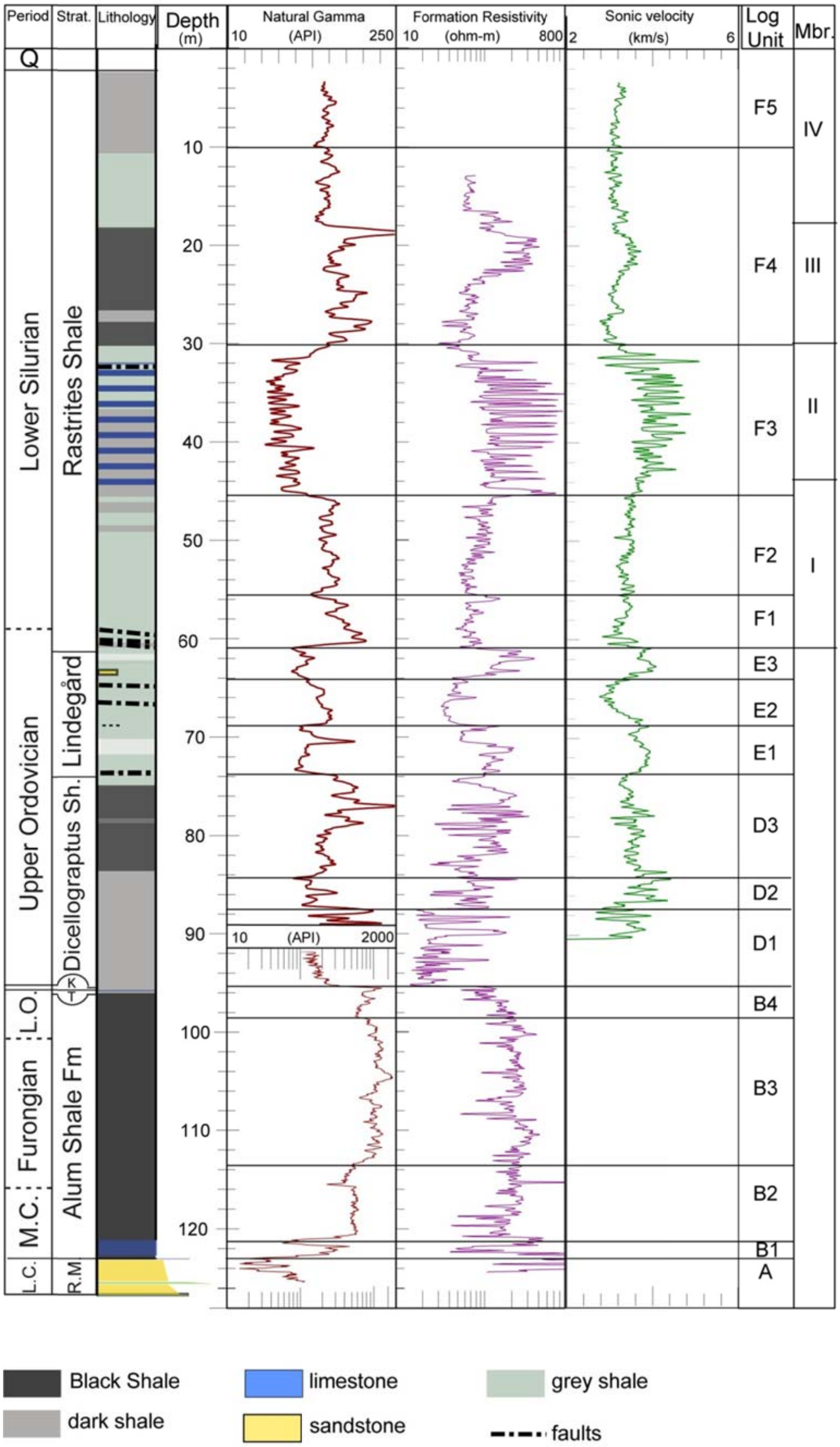


Figure 7. Gamma log, formation resistivity and sonic log measured in the bore hole. Modified from Schovsbo et al. (2011).

5. Cambro-Silurian stratigraphy of Bornholm: New insights

The Billegrav-2 well supplements the stratigraphical data provided by Billegrav-1 core, partly because it penetrates younger levels, partly because it bridges the gap between the shallow Billegrav-1 and Skelbro-1 wells.

The new well shows that the Silurian is at least c. 20 m thicker onshore Bornholm than calculated by Bjerreskov (1975) and Koren & Bjerreskov (1997). The *S. turriculatus* Zone (incl. the *S. guerichi* Zone of Loydell et al. 1993) is c. 10 m thicker and maybe a *S. sedgwickii* Zone, c. 6 m, is present. Alternatively this interval also represents the basal part of the *S. turriculatus* Zone. The *L. convolutus* Zone is 2 m thicker in the Billegrav-2 well and seemingly 4 m thicker in the Sømarke-2 well (see Pedersen & Klitten 1990) than calculated by Bjerreskov (1975). It is also possible that an as yet unrecognized log-unit or sub-unit is present between log-units F3/F4; this interval is faulted out in the Billegrav-2 and probably also in the nearby Sømarke-2 well.

It is proposed to subdivide log unit F4 into two, for the time being referred to as log units F4A and F4B (lower and upper, respectively). In the Billegrav-2 well the intra-unit boundary is located at 18 m, precisely corresponding to the upper boundary of the *L. convolutus* Zone (black shales). Log-unit F4B for all practical purposes corresponds to the *L. convolutus* Zone and the unit is very useful for regional correlation.

The Billegrav-2 well also shows that the Dicellograptus Shale is much thicker in the Øleå area than at the Læså, notably due to a thicker bentonite-rich interval. The Dicellograptus Shale is thus 20.8 m thick in the Billegrav-2 core vs. only 11 m in the section at Vasagård, Læså (Bruvo 2005).

The Komstad Limestone is virtually absent in the Billegrav-2 well, suggesting a rather strong thickness variation of this unit on Bornholm from 4-5 m in the Læså-Skelbro area (Nielsen 1995) to 0.1-2.5 m in the Øleå area (compare Pedersen & Klitten 1990).

The Komstad Limestone seems to be underlain be a thin erosional remnant of the Tøyen Shale in the Billegrav-2 core. It strongly resembles the Hunnebergian (i.e. Floian) lower part of the unit as seen in Scania. The Tøyen Shale has hitherto been regarded entirely absent on Bornholm (e.g. Poulsen 1966a).

The Alum Shale Fm is thinner in the Øleå area than in the Læså-Skelbro area, 26-27 m vs 33.5 m (see Pedersen & Klitten 1990). The unit contains very few stinkstone concretions in the Billegrav-2 core.

6. Sedimentological description

The sedimentology of the Billegrav-1 and Skelbro-1 cores was described by Pedersen (1989). Billegrav-2 largely covers the same stratigraphic interval below the fault zone at 32.1-32.2 m and there is little need for repeating the comprehensive description provided by Pedersen (1989). The present notes are intended as supplementary to that description. To facilitate later fossil collection the core was kept as intact as possible and it was not cut prior to description. In order to remove scratches on the core surface made by the drill-bit selected core pieces were polished. The stated colours are in dry state. When wet, the general hue is slightly darker compared to dry state. The core was studied both dry and wet. For photography the core surface was made wet if not otherwise stated (see appendix D).

Rastrites Shale

Core interval 2.7-18.13 m: Rastrites Shale

The interval is dominated by grey to slightly darker grey silty shale albeit some parts are greenish grey, i.e. lighter coloured. The shale appears laminated but the scratched core surface makes it difficult to verify this impression. The shale generally exhibits a colour banding where greenish grey (lighter coloured) shale, mostly 1-2 mm but up to 10 mm thick, are interbedded with grey shale, 15-30 mm thick. In the intervals marked as greenish grey shale in Appendix A the greenish lighter coloured laminae/bands dominate relative to the greyish shale. A few silt-laminae (0.5-1 mm) occur but they are scarce. A few very thin limestones (beds or nodules; the limestone at 9.78-9.79 m surely represents a nodule) occur between 9.45-13.40 m; they vary in thickness between 1-2.5 cm. Pyrite laminae and small nodules are seen here and there but are not abundant. Sporadic bioturbation is noted, but is also uncommon. The lithology broadly corresponds to the lower part of facies 4 sensu Pedersen (1989), although it is the impression that the disseminated silt content is slightly lower.

The interval 4.04-5.67 m is dominated by greyish laminated shale largely without colour banding. Below 5.67 m the greenish laminae appears again in increasing abundance downwards; below 5.84 m the ratio of grey vs greenish colour bands is about fifty-fifty (in Appendix A can be seen which intervals are dominated by greenish or greyish bands).

Bentonite beds are fairly common and have been noted at: ?4.69 m (thin film, uncertain), 5.01 (thin film), 6.17 m (2-3 mm; crosses lamination maybe due to compaction), ?6.90 m (2-3 mm but may alternatively be horizontal crushing), ??7.41 (1-2 mm: most likely crushing/rock flour, but it cannot entirely be excluded that this is a thin bentonite), 9.12-9.145 m (25 mm), 9.71 mm (1 mm), 10.63 m (2 mm), 10.84 m (1 mm), 12.05-12.07 m (crushed interval but one bedding surface seems to contain a bentonite; it is probably 1-2 mm thick), 12.19-12.205 (crushed interval, bentonite 15-20 mm thick), 12.37-12.38 m (crushed, bentonite at least 10 mm), 13.65 m (film, less than 0.5 mm).

Core interval 18.13-29.99 m: Rastrites Shale

The upper boundary of this interval is marked by a thin conglomerate 18.12-18.13 m. The conglomerate is pyritic and contains small black clasts, 6-7 mm in diameter (?phosphorite). The interval is dominated by dark grey to blackish, distinctly laminated and highly pyritic shale. The pyrite occurs as very small nodules and non-through going thin laminae which are difficult to depict in the log.

There is almost no colour variation, i.e. no colour banding, but the shale is a little lighter coloured, but still grey and quite dark, between 26.39-27.6 m. The upper 6.5 cm are burrowed (?*Chondrites*). Thin laminae of whitish silt occur commonly below 21.90 m, and they are quite abundant between 24.00-28.10 m. The shale contains very abundant silt laminae between 27.35-27.60 m. Because of the colour contrast between the white silt and the dark host rock they are eye-catching. The presence of silt is associated with a decrease in pyrite content; macroscopic pyrite is uncommon below 25.8 m. Most of the interval and in particular the upper part is highly graptolitic. It is noted that the core is in excellent condition hence the core pieces are relatively intact with few surfaces to scan for graptolites and the graptolite abundance would undoubtedly be prominently higher if the core was further split.

The dark shales resemble the Ordovician Dicellograptus Shale, i.e. facies 2 of Pedersen (1989), but the common silt laminae in the lower part are not seen in the Dicellograptus Shale.

Bentonite beds have been noted at: ?19.72 m (film), 22.24-22.25 (8 mm), 27.99-28.01 (20 mm), and 29.795-29.805 (20 mm).

Core interval 29.99-32.1 m: Rastrites Shale

The lithology of this interval resembles core interval 2.7-18.13 m with colour-banded laminated shale. The grey bands/laminae dominate the interval 29.99-30.42 m, and that upper interval also contains fairly common pyrite (small nodules 1-10 mm, no laminae); below that level the lighter grey bands dominate (they are light greyish, not greenish-grey) and the interspersed dark bands/laminae are rather thin, mostly about 1 mm. No pyrite or silt-laminae were recorded. A large limestone nodule occurs between 31.71-31.92. The boundaries of the nodule are indistinct; the nodule itself is rather crystalline and there is no doubt that the limestone is diagenetic.

The lithology of the interval broadly corresponds to the lower part of facies 4 sensu Pedersen (1989).

The lower boundary of the interval is a fault.

A bentonite bed was been noted at c. 30.30-30.31 m (10 mm).

Core interval 32.2-44.11 m: Rastrites Shale

This interval corresponds to the upper 12 m of the Billegrav-1 core. That interval was included in facies 4 by Pedersen (1989) although the lithology is rather different from the underlying shale, also assigned to facies 4. We here refer to the limestone-rich facies as 4B. The entire interval is characterized by the regular presence of thick limestone intercalations, of which some likely are beds and other concretions. The shale itself also seems to contain disseminated lime throughout.

The shales are laminated/colour banded with grey bands interspersed by thin dark laminae so the rock appears striped. The core is of excellent quality and as a result there are not many surfaces available for the search of fossils, but graptolites appear overall to be rare. Only sporadic silt laminae occur in the main upper part of the interval and pyrite is also uncommon.

Downwards the shale becomes generally darker coloured and below 43.30 silt-laminae become common.

No bentonite beds recorded.

Core interval 44.11-52.62 m: Rastrites Shale

This interval corresponds to core interval 12-21 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 4. We refer to it as facies 4A. It contains no limestone unlike the upper part of facies 4 (facies 4B). The upper c. 1 m of the interval comprises darker grey mudstone with common silt-laminae. Some are so thin that they are not indicated in the log. A few graptolites have been found.

The shale does exhibit colour banding but because of the general comparatively dark hue the banding is not so distinct. It is the impression that the silt content below 46.7 m is lower than in the interval 32.2-44.11 m. Silt-laminae are not so common below 45.7 m. Here the general colour of the shale becomes a little lighter, but is still grey. The colour banding is easier to see in the intervals that are less dark. The silt-laminae indicated in the log in the lower part of the interval are very thin and inconspicuous.

Macroscopic pyrite is uncommon, but parts of the core has a white coating which looks like disintegrating pyrite, possibly suggesting a high content of disseminated pyrite (46.49-47.65 m; 48.14-48.35 m; 50.66-50.76 m; 51.17-51.23). Jarosite noted between 47.40-47.65 m.

Bentonite beds have been noted at: 46.405-c. 46.415 (c. 10 mm, uncertain), 47.505 m (2-3 mm); 48.62 (< 0.5 mm), 49.67 m (c. 3 mm); ?51.51 m (1-2 mm; uncertain but likely).

Core interval 52.62-c. 60 m: Rastrites Shale

This interval corresponds to core interval 21-28 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 5. The upper part of the interval is characterized by common presence of thin silt laminae. The shale itself is a grey laminated silty mudstone, slightly lighter coloured than in the interval above, but the presence of whitish silt-laminae of course also adds to the lighter colouration. Below 56.14 m the shale is slightly darker but still classified as grey. The core is in rather poor condition 58.80-60 m (crushed). Virtually no macroscopic pyrite observed. No bentonite beds seen.

Core interval c. 60-60.5 m: Rastrites Shale

This interval corresponds to core interval 28-29.3 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 2. The interval is cut by a fault in the Billegrav-2 core and maybe 0.7 m is faulted out. Laminated darker grey rather homogeneous shale rich in graptolites. The interval is clearly darker than the surrounding shales, but not nearly as dark as the Dicellograptus Shale, so it is not entirely clear why Pedersen (1989) considered this as the same facies.

Lindegård Mudstone

Core interval 60.5-74.3 m: Mainly Lindegård Mudstone

This interval corresponds to core interval 29.3-45.9 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 6+3 and 3. The interval is cut by a fault in the Billegrav-2 core and it is estimated that c. 7 m is faulted out (see section on biostratigraphy). The interval comprises lighter coloured mudstone, in part light grey or greenish grey, with sandy horizons in the upper part. It is the impression that the mudstone is calcareous throughout and quite bioturbated. Some sections are thoroughly bioturbated and individual burrows cannot be identified. At other levels *Chondrites* has been identified and the mudstone is indistinctly laminated. A highly pyritic conglomerate, 0.13 m thick, forms the basal part of the interval. No graptolites found, except in the uppermost part, and the fossil fauna is dominated by ostracods and sporadic trilobites. No bentonites.

Dicellograptus Shale

Core interval 74.3-83.01 m: Dicellograptus Shale

This interval corresponds to core interval 45.9-54.5 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 2. The interval is dominated by dark grey to blackish laminated shale rich in pyrite. Graptolites are frequent in the upper part of the interval, but fairly sparse below 81 m. Inarticulate brachiopods are frequent in the lower part of the interval but are also found scattered in the upper part. A thin conglomerate with small phosphorite nodules is present at 76.70-76.71 m. The shale is less distinctly laminated and slightly lighter coloured (albeit still dark grey) in the interval 77.33-77.9 m and here is also seen quite a few thin limestone laminae. The basal interval 82.43-83.01 m is also less distinctly laminated and forms a transitional interval from the grey shales below.

Bentonite beds have been noted at: 77.135 m (5 mm), 77.475-77.485 m, 77.73 m (max 4 mm), 78.05-78.055 m, 78.56 m (< 1mm), 78.56-78.695 m (maybe two amalgamated beds; dark 5 mm band of shale at 78.615 m), 79.117-79.119 m, 79.750-79.757 m, 80.268-80.275 m, 80.985-80.995 m, 82.57 m (very thin, not even completely through going lamina), 82.625-82.63 m (maybe few mm thicker), 82.68-82.70 m, 82.825-82.835 m, 82.87 (c. 1 mm), 82.935-82.937 m, 83.00 (c. 2 mm).

Core interval 83.01-87.27 m: Dicellograptus Shale

This interval corresponds to core interval 54.5-59.1 m in the Billegrav-1 core, which Pedersen (1989) assigned to facies 3. The dominant lithology is non- or indistinctly laminated grey to lighter grey shales, visibly burrowed for the greater part. Limestone beds or nodules occur moderately frequently. Graptolites and inarticulate brachiopods have only been found in the lower part of the unit. Pyrite is much less common than in the interval above.

Bentonite beds have been noted at: 85.815-85.88 m, 86.190-86.194 m, 86.395-86.405 m, 86.515-86.52 m, 86.77-86.785 m, 87.25 (< 1 mm).

Core interval 87.27-95.10 m: Dicellograptus Shale

This interval corresponds to the basal part of the Billegrav-1 core below 59.1 m, and which Pedersen (1989) assigned to facies 7. The most characteristic feature of this interval is the numerous bentonite beds accounting for about nearly half of the stratigraphic thickness and they are too numerous to state the level for each (the bentonites are altogether 3.3 m thick). The intervening shales are generally like those seen in core interval 83.01-87.27 m except that they generally are silicified. A few inarticulate brachiopods have been found, but no graptolites. Nearly no macroscopic pyrite observed.

Komstad Limestone

Core interval 95.10-95.17 m: Komstad Limestone

The Komstad Limestone was not separated as a numbered facies by Pedersen (1989). Only the basal conglomerate is preserved in the Billegrav-2 core.

Core interval 95.17-95.36 m: Tøyen Shale?

This facies was not recognized by Pedersen (1989) as the Billegrav-1 well stopped in the lower part of the Dicellograptus Shale. The interval consists of light coloured grey to green mudstone. It is likely that the greenish light grey colour is original and that the upper greyish zone (4 cm thick) is a bleaching phenomenon. The greenish mudstone appears homogenous but in wet condition lamination is revealed. No fossils found. The mudstone is separated from typical Alum Shale by a barite bed (95.36-95.43 m). It is uncertain which unit this bed belongs to.

Alum Shale

Core interval 95.36-122.17 m: Alum Shale

This interval corresponds to the Alum Shale penetrated by the Skelbro-1 drilling, and which Pedersen (1989) assigned to facies 1 [excl. the interspersed thin Middle Cambrian limestone beds, in the Billegrav-2 core present between 120.41-121.33 m (Andrarum Limestone Bed) and 122.03-122.17 m (Exsulans Limestone Bed)]. The Alum Shale is a blackish, mostly finely laminated shale with abundant pyrite. It usually contains frequent stinkstone lenses, but this is not the case in the Billegrav-2 core. Fossils are frequent in some intervals, including graptolites, trilobites and brachiopods. Barite or pseudomorphs after barite (calcite and pyrite, occasionally just empty voids) are also common in many intervals. The Andrarum and Exsulans limestone marker beds (the latter likely incl. a thin Forsemölla limestone in the basal part) comprises grey “fragment” limestone with numerous fossil fragments; none were determined. The rich fauna from these units have been described by Grönwall (1902). The Exsulans Limestone contains reworked phosphorite clasts of Rispebjerg sandstone. For description of these limestones, see also Hansen (1945).

Læså Fm

Core interval 122.17-125.77 m: Rispebjerg Mbr, Læså Fm

This facies was not described by Pedersen (1989). It is dominated by fine to medium grained grey quartz sandstone, in part x-bedded. There is a few greenish siltstone intercalations and phosphorite nodules as well as glaucony are also seen at a couple of levels.

Core interval 125.77-125.9 m: Norretorp Mbr, Læså Fm

This facies was not described by Pedersen (1989). It is dominated by sandy siltstone; only the very top of this unit was reached by the drilling. For general description of the unit, see Nielsen & Schovsbo (2006) and references therein.

7. Early Cambrian-Early Silurian sea level changes

The changing sea levels of the Early Cambrian are dealt with by Nielsen & Schovsbo (2011, in prep.); only the very top of the Lower Cambrian are reached by the Billegrav-2 drilling. The Rispebjerg Mbr records a very extensive forced regression, likely due to a glaciation. The area was flooded again in the late Early Cambrian with deposition of condensed strata corresponding to the Gislöv Fm of Scania (for references on this unit, see Nielsen & Schovsbo 2006), but the deposits were later eroded away. Reworked late Early Cambrian fossils have been found in the overlying Exsulans Limestone (C. Poulsen 1942; V. Poulsen 1965, 1966b).

Cambrian

The early Mid Cambrian is not represented in the sedimentary record on Bornholm, where the so-called Hawke Bay unconformity is more extensive than elsewhere in Scandinavia except for the Oslo area. Work is in progress on this event (Nielsen & Schovsbo, in prep); the extensive sedimentary gap was due to a prolonged uplift of the Scandinavian peninsular, presumably in response to plate tectonic changes (?onset of subduction in the Iapetus Ocean). It was during this episode that the late Early Cambrian Gislöv Fm was eroded (see above). Despite being uplifted most of Scandinavia incl. Bornholm was, however, inundated as evidenced by local deposition of condensed authigenous sediments (limestone, glaucony; for details, see Nielsen & Schovsbo in prep.). The uplift of Bornholm lasted well into the Mid Cambrian with clastic sedimentation resuming in the upper part of the *Acidusus atavus* Zone (Weidner & Nielsen, in press).

The Alum Shale records deposition under outer shelf conditions, but due to the monotonous lithology in the Billegrav-2 well it is not possible to unravel synsedimentary changes in sea level as in central Sweden. Overall the sea level remained fairly high until the late Tremadocian (Early Ordovician). Here another major gap is present in the sedimentary succession on Bornholm, likely due to another uplift (late Tremadocian-late Sandbian), only punctuated by deposition of the authigenous Komstad Limestone. However, Tøyen Shale (at least of early Floian age) was presumably originally deposited in the Bornholm area but later removed during the uplift. A thin veneer seems to have been preserved at the Billegrav-2 drill-site which is the first record of Tøyen Shale on Bornholm.

Late Ordovician

For discussion of Ordovician sea level changes in general, see Nielsen (2004) and with regard to the Komstad Limestone in particular, see Nielsen (1995). Despite being uplifted Bornholm was likely still inundated during most or all of the Ordovician.

From the late Sandbian (Late Ordovician) the sedimentary record is more continuous on Bornholm. The sea level was moderately high during the late Sandbian and light grey, partly bioturbated mudstones were deposited in the Bornholm area (lower part of the Dicellograptus Shale). Preservation of numerous, easily reworked bentonites and absence of storm layers suggests deposition on the outer shelf, presumably proximal outer shelf. A rapid and very significant sea level fall, presumably glacioeustatic, took place at the close of the Sandbian. This event was referred to as the Frognerkilen Lowstand by Nielsen (2004) and it likely corresponds to the bioturbated interval 83.0-85.3 m in the Billegrav-2 core. At this stage a benthic fauna invaded Scania and a widespread gap developed on the more proximal parts of the Baltic shelf (central Sweden-Estonia).

The Katian was initiated by a fairly marked sea level rise, on Bornholm signalled by the shift to dark grey Dicellograptus Shale above level 83.0 m in the Billegrav-2 core. However, the lower part of the *D. clingani* Zone was characterized by a moderately high sea level (/depositional depth) and it was first with a second drowning pulse in the late half of the *D. clingani* Zone that graptolite facies s.str. was introduced in the Bornholm area (c. 78.2-81.0 m in the Billegrav-2 core).

Another temporary sea level fall, named the Solvang Lowstand by Nielsen (2004), took place in the late part of the *D. clingani* Zone, likely corresponding to the non-graptolitic and, in part, less distinctly laminated interval 77.3-78.2 m in the Billegrav-2 core. The sea level rose again in the late *D. clingani* Zone (76.7-77.30 m in the Billegrav-2 core) with a major hike at the base of the *P. linearis* Zone, marked by a drowning surface in the Dicellograptus Shale (conglomerate at 76.7 m in the Billegrav-2 core). The sea level during the *P. linearis* Zone was very high albeit with oscillations (cf. Nielsen 2004), but these cannot be resolved in the outer shelf deposits on Bornholm (74.4-76.7 m in the Billegrav-2 core).

The sea level fell significantly at the *P. linearis*/*D. complanatus* zonal boundary and stayed comparatively low albeit the depositional environment still was below storm wave base most of the time during the remainder of the Ordovician (Lindegård Mudstone deposition, well ventilated, bioturbated, mostly non-graptolitic and with some shelly fossils). The non-laminated (presumably strongly bioturbated) light grey mudstone 69.70-71.30 m in the Billegrav-2 core likely reflects a transient sea level lowstand in the late Katian, presumably the one recorded by the upper part of the Skogerholmen Fm in the Oslo area (cf. Nielsen 2004).

Latest Ordovician and Silurian

The sandy strata between 62.7-63.4 m in the Billegrav-2 core are likely bioturbated sandy storm layers, which are taken to signal peak lowstand of the Hirnantian at which stage a forced regression affected the greater part of Scandinavia and at the same time distal inner shelf conditions prevailed in the Bornholm area. Thereafter renewed sea level rise in the latest Ordovician and into the Silurian was associated with renewed deepening of the depositional environment in the Bornholm area and the uppermost Ordovician may be interpreted as a graptolite-rich MFS, eventually resulting in deposition of grey offshore mudstones (60.05-60.45 m in the Billegrav-2 core). In detail the drowning may comprise a couple of pulses of sea level rise. After maximum flooding the sea level fell again. The strata are so thin that they cannot have affected the depositional depth and the sea level fall was likely eustatic. The numerous thin silt intercalations, most abundant between 57.4-58.2 m and 55.1-56.05 m, suggest deposition within reach of distal storm beds i.e. distal inner shelf. The silt laminae may have been deposited by currents associated with storms and maybe not storms waves per se; this requires further investigation.

Above 55 m in the Billegrav-2 core the silt laminae becomes less abundant and nearly disappear above 51.5 m although with return between 49.4-49.9 and 47.5-48.0 m, which may be 4th order shallowings or periods with increased storm activity. Above 48.8 m the mudstone also becomes a little darker coloured. However, it is the impression that the depositional environment never became very deep and abundant distal storm beds (silty) reappear between

43.3-45.7 m in the Billegrav-2 core. Above, the mudstone becomes a little darker, but it is the general impression is still rather silty and limestone is abundant and it is inferred that this lithology was deposited on the proximal outer shelf. Upwards the TOC content is again lower above 36.4 m and up to 30.4 m. Upwards, the shale becomes dark coloured and is dark grey to blackish above 30.0 m, suggesting a fairly abrupt deepening of the depositional environment, likely due to a rapid third order sea level rise. Still, numerous silt laminae, suggestive of storm activity, are present in the succession up to c. 22 m in the core, above which level they are essentially absent. This pattern is suggestive of gradual deepening with maximum flooding conditions equivalent to the upper part of the *convolutus* Zone. Although the dark shales of the *convolutus* Zone superficially resemble the Ordovician Dicellograptus Shale the depositional environment was likely shallower, at least early on, as indicated by the presence of distal storm beds. It is peculiar that the blackish graptolitic shale contains so many storm beds, suggesting that the low-oxygen conditions presumably was not only linked to a changing sea level. Associated with the upwards disappearance of silt laminae the pyrite content increases significantly and graptolites are very common between 18.25-16.65 m in the core, an interval which may be interpreted as a MFS (the ‘cometa band’ of Bjerreskov 1975). There is a discontinuity surface associated with a conglomerate above the *convolutus* Zone, suggestive of a marked, possibly rapid, sea level fall. The upper part of the core is dominated by greyish and greenish partly graptolite bearing shales, suggesting an upwards increase in depositional depth in the aftermath of the lowstand at the close of the *convolutes* Zone. The thin silt storm beds thus disappear, grey colours become dominating and graptolites become more common.

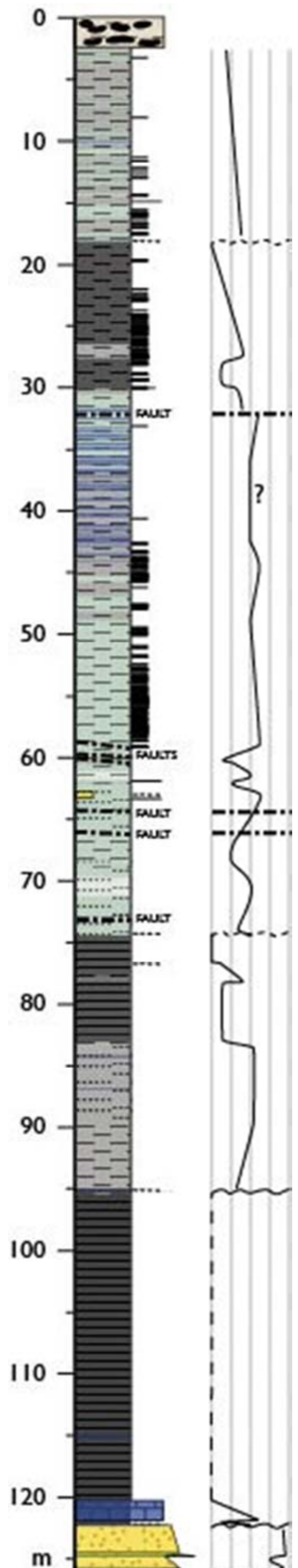


Figure 8. Simplified sea level curve for the Billegrav-2 well. Numbers (1-4) reefers to shallow (1-2) and deep water (3-4) conditions.

8. Geochemical measurements

212 samples were picked from the core. TOC, carbonate and total sulphur measurements analyses were performed on 167 samples, the mineralogical content was measured on 60 samples and 30 samples were characterised by Rock Eval measurements. The Rock Eval data was reported in the completion report part 3 (Schovsbo 2012). It was originally planned to perform Rock Eval on about 120 samples but pyrolysis yields of 0 mg HC/g rock and consistently high Tmax (about 600 ^{o}C) deemed this unnecessary. Instead a higher number of TOC analyses were made than the planned 1 pr. m with an increased sample density in intervals with a strong gamma ray signal.

TOC, carbonate and sulphur method

The total carbon (TC) and total sulphur (TS) contents were measured on a LECO CS-200 carbon/sulphur analyser. Approximately 0.05 g of dried rock powder was oxidised in an owen at 1300°C, the evolved gasses were measured by infrared absorption. The carbonate content was measured on sample splits by titration and the carbonate content (TCC) was used to correct the TC to TOC using the formula:

$$TOC\ (wt.\%) = TC\ (wt.\%) – TCC\ (wt.\%)$$

Total sulphur (TS) content was measured by combustion of the samples in a LECO-type oven. All measurements were made at the Institute of Geography and Geology, University of Copenhagen.

Variation in TOC content

The classical TOC rich Lower Palaeozoic units in Scandinavian (e.g. Schovsbo 2003) can be readily identified on the TOC screening profile (Figure 10); TOC content >1 wt% occur 1) in the Alum Shale, 2) the upper part of the Dicellograptus shale, 3) in the basal most part of the Rastrites shale (F1) and within the Rastrites shales (F4 unit). The high TOC levels occur within typical black shales apart for the F1 unit. Here the high TOC content occurs in a dark mudstone.

In the Alum Shale the highest TOC content is measured in the Furongian part (logunit B3). Within this unit the TOC defines 3 cycles of increasing-decreasing TOC content. A similar ‘step-wise’ increase was also observed in the Alum Shale in Scania (Schovsbo 2001). The TOC variation thus has regional significance. The local high TOC content in the basal part of the Furongian has informally been termed the *Olenus* maximum (Schovsbo 2002). The local maxima in TOC content at 100.5 m and at 103.7 m are informally referred to at the Lower *Peltura* and upper *Peltura* TOC maxima.

Variation in S content

The S content generally follows the TOC content and is thus very high in the Alum Shale, the D3 unit and in the F4 unit (Figure 9). The S content is, however, also high in the TOC lean F2 unit where up to 2 wt % TS is measured in large parts of the unit. The elevated S content may reflect intense sulphate reduction during deposition that could indicate oxygenation of high amount of organic carbon or, alternatively, the high S content could result from a high iron content possible reflecting a change in source area.

Variation in quartz content

The quartz content in the Alum Shale ranges between 9–54%. Highest quartz content occurs in the B4 unit with corresponds roughly to the Ordovician part of the formation.

The quartz content in the Dicellograptus Shale ranges between 32–60%. Highest concentrations are measured in the basal part of the shale (unit D1) where the shale is interbedded with bentonites and in the topmost part of the shale (unit D3).

The quartz content in the Rastrites shale ranges between 23–63%. Highest concentrations are measured in the F4 unit between 21-23.5 m.

Variation in carbonate content

The carbonate content in the Alum Shale ranges between 0.0–6.8%. Highest content is measured in the B3 unit.

The Dicellograptus Shale has low carbonate content that ranges between 2.1–6.4%. The carbonate content in the Lindegård Fm ranges between 3.7–31.6%. The highest value is measured in a sample from the E3 unit.

The carbonate content in the Rastrites shale ranges between 0.0–23.7%. Concentrations above 15% are measured in the F3 unit. This unit contains abundant carbonate cemented beds (Nielsen and Schovsbo 2012).

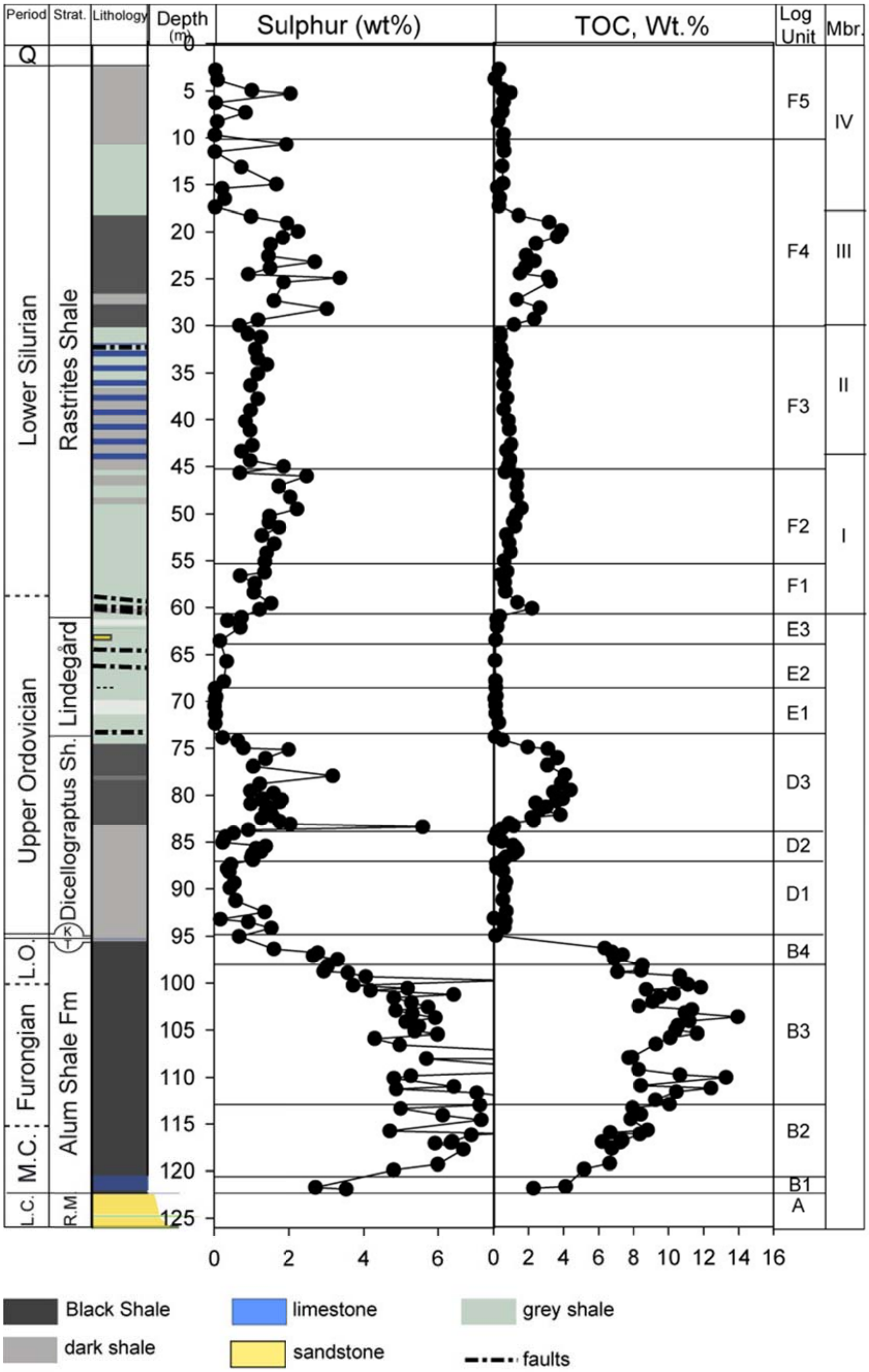


Figure 9. Variation in TOC and sulphur content in the Billegrav-2 well. The log units are adopted from Schovsbo et al. (2011).

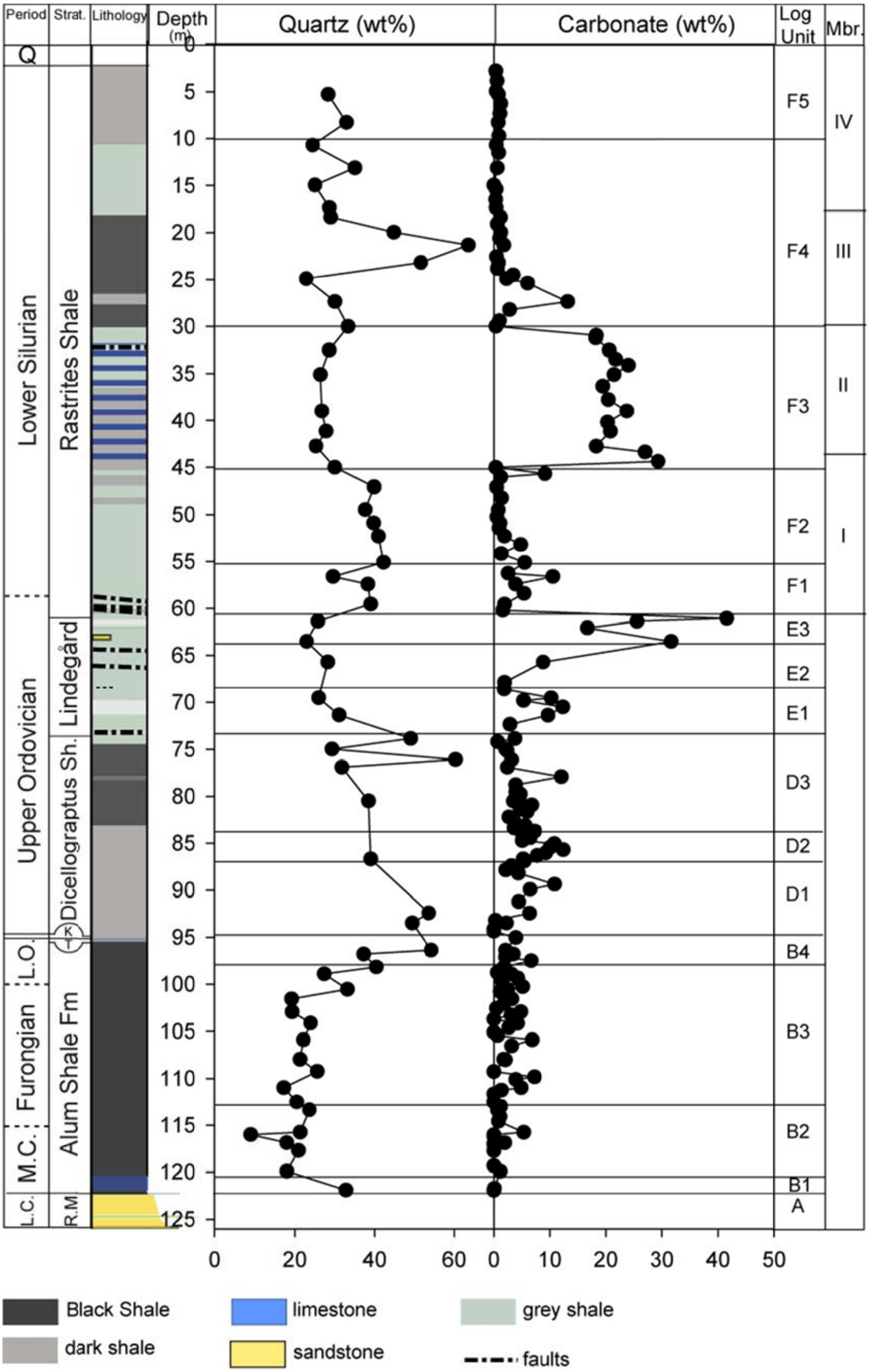


Figure 10. Variation in quartz and carbonate content in the Billegrav-2 well. The log units are adopted from Schovsbo et al. (2011).

9. References

Axheimer, N., Eriksson, M.E., Ahlberg, P., Bengtsson, A., 2006. The middle Cambrian cosmopolitan key species *Lejopyge laevigata* and its biozone: new data from Sweden. Geological Magazine 143, 447–455.

Bergström, S.M., Nilsson, R., 1974. Age and correlation of the Middle Ordovician bentonites on Bornholm. Bulletin of the Geological Society of Denmark 23, 27–48.

Bergström, S.M., Bergström, J., 1996. The Ordovician-Silurian boundary successions in Östergötland and Västergötland, S. Sweden. GFF 118, 25–42.

Bergström, S.M., Huff, W.D., Koren, T., Larsson, K., Ahlberg, P., Kolata, D.R., 1997. The 1997 core drilling through Ordovician and Silurian strata at Röstånga, S. Sweden: Preliminary stratigraphic assessment and regional comparison. GFF 121, 127–135.

Bjerreskov, M., 1975. Llandoverian and Wenlockian graptolites from Bornholm. Fossils and Strata 8, 1–94.

Bjerreskov, M., Stouge, S., 1985. Field Excursions Guide, Bornholm, Denmark. 3rd International Conference Graptolite working Group. International Palaeontological Association, Copenhagen 1985, 23 pp.

Bruvo, M., 2005. Graptolitzoneringen i Dicellograptus Skiferen (Øvre Ordovicium) på Bornholm, Danmark. Unpublished Master Thesis, University of Copenhagen, 1–97.

Funkquist, H.P.A., 1919. Asaphusregionens omfattning i sydöstra Skåne och på Bomholm. Lunds Univ. Ärsskr. N. F. Avd. 2, 16, 56 pp.

Glimberg, C.F., 1961. Middle and Upper Ordovician strata at Lindegård in the Fågelsång District, Scania, S. Sweden: Preliminary report. Geologiska Föreningens i Stockholm Förhandlingar 83, 79–85.

Grönwall, K.A., 1899. Bemærkninger om de sedimentære dannelser paa Bornholm og deres tektoniske Forhold. Danmarks geologiske Undersøgelse 2, 1-48.

Grönwall, K.A., 1902. Bornholms Paradoxideslag og deres fauna. Danmarks geologiske Undersøgelse 2, 1–250.

Hadding, A., 1915. Der Mittlere Dicellograptus–schifer auf Bornholm. Lunds Universitets Årsskrift, N. F. 2, 1–39.

Hansen, K., 1945. The Middle and Upper Cambrian sedimentary rocks of Bornholm. Danmarks Geologiske Undersøgelse 2. række 72, 1–81.

Jakobsen, P.R., Schovsbo, N.H., 2012. Completion report Billegrav-2 well (DGU 248.61) Part 5: Fracture descriptions and mineralogical analysis. Geological Survey of Denmark and Greenland Report 2012/26, 1–31.

Johnstrup, F., 1889. Abriss der Geologie von Bornholm als Führer zu der Excursion der Deutschen Geol. Gesellsch. Nach der Insel Bornholm 1889. IV Jahresber. Derr Geograph. Gesellsch. Zu Greifswald. 61 pp. Greifswald.

Jaanusson, V., 1963. Classification of the Harjuan (Upper Ordovician) rocks of the Mainland of Sweden. GFF 85, 110–144.

Jaanusson, V., 1976. Faunal dynamics in the Middle Ordovician (Viruan) of Baltoscandia. In: M.G. Bassett (Editor). The Ordovician System: proceedings of a Palaeontological Association Symposium. Univ. Cardiff Press, Cardiff, 301–326.

Koren, T., Bjerreskov, M., 1997. Early Llandovery monograptids from Bornholm and the southem Urals: taxonomy and evolution. Bulletin of the Geological Society of Denmark 44, 1–43.

Lindström, M., 1953. On the Lower Chasmops beds in the Fågelsång district (Scania). Geologiska Föreningens i Stockholm Förhandlingar 75, 125–148.

Loydell, D.K., Storch, P., Melchin, M.J., 1993. Taxonomy, evolution and biostratigraphical importance of the Llandovery graptolite Spirograptus. Palaeontology 36, 909–926.

Nielsen, A.T., 1995. Trilobite systematics, biostratigraphy and palaeoecology of the Lower Ordovician Komstad Limestone and Huk Formations, southern Scandinavia. Fossils and Strata 38, 1–374.

Nielsen, A.T., 2004. Sea-level Changes – a Baltoscandian Perspective. In: Webby, B., Droser, M, Paris, F. & Percival, I. (eds): "The Great Ordovician Biodiversification Event", Part II. Conspectus of the Ordovician World. Columbia University Press, 84–93.

Nielsen, A.T., Schovsbo, N.H., 2006. Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. Bulletin of the Geological Society of Denmark 53, 47–92.

Nielsen, A.T., Schovsbo, N.H., 2011. The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth-Science Reviews 107, 207–310.

Nilsson, R., 1977. Boring through Middle and Upper Ordovician strata at Koängen in western Scania, southern Sweden. Sveriges Geologiska Undersökning C 733, 1–58.

Owen, A.W., Bruton, D.L., Bockelie, J.F., Bockelie, T.G., 1990. The Ordovician successions of the Oslo Region, Norway. Norges Geologiske Undersøkelse Special Publication 4, 1–54.

Pedersen, G.K., 1989. The sedimentology of Lower Palaeozoic black shales from the shallow wells Skelbro-1 and Billegrav-1, Bornholm, Denmark. Bulletin of the Geological Society of Denmark 37, 151–173.

Pedersen, G.K., Klitten, K., 1990. Anvendelse af gamma-logs ved korrelation af marine skifre i vandforsyningsboringer på Bornholm. Dansk geologisk Forening, Årsskrift for 1987-89, 21–35.

Poulsen, C., 1923. Bornholms Olenuslag og deres Fauna. Danmarks geologiske Undersøgelse 2. række 40, 5–83.

Poulsen, C., 1936. Übersicht über das Ordovizium von Bornholm. Meddelelser fra Dansk Geologisk Forening 9, 43−66.

Poulsen, C., 1942. Nogle hidtil ukendte fossiler fra Bornholms Exsulanskalk. Meddelelser fra Dansk Geologisk Forening 10, 212–235.

Poulsen, C., 1967. Fossils from the Lower Cambrian of Bornholm. Det Kongelige Danske Videnskabernes Selskab Matematisk-fysiske Meddelelser 36, 1–48.

Poulsen, V., 1965. The Oldest Trilobite Remains from Denmark. Meddelelser fra Dansk Geologisk Forening 15, 559–560.

Poulsen, V., 1966a. Cambro-Silurian stratigraphy of Bornholm. Meddelelser fra Dansk geologisk Forening 16, 117–137.

Poulsen, V., 1966b. Early Cambrian Distacodontid conodonts from Bornholm. Biologiske Meddelelser udgivet af Det Kongelige Danske Videnskabernes Selskab 23(15), 1–10.

Schovsbo, N.H., 2011a. Completion report Billegrav-2 well (DGU 248.61) Part 1: Down hole logs, core scanning data and core photos. Geological Survey of Denmark and Greenland Report 2011/53, 1–18.

Schovsbo, N.H., 2011b. Completion report Billegrav-2 well (DGU 248.61) Part 2: Review of Skelbro-1 and Billegrav-1. Geological Survey of Denmark and Greenland Report 2011/79, 1–32.

Schovsbo, N.H., 2012. Completion report Billegrav-2 well (DGU 248.61) Part 3: Results of core plug analysis. Geological Survey of Denmark and Greenland Report 2012/16. 1–52.

Schovsbo, N.H., Nielsen, A.T., Klitten, K., Mathiesen, A., Rasmussen, P., 2011. Shale gas investigations in Denmark: Lower Palaeozoic shales on Bornholm. Geological Survey of Denmark and Greenland Bulletin 23, 9−12.

Terfelt, F., Ahlberg, P., Eriksson, M.E., 2011. Complete record of Furongian polymerid trilobites and agnostoids of Scandinavia – a biostratigraphical scheme. Lethaia, 44, 8–14.

von Jansson, C., 1979. Zur biostratigraphie des Tremadociums auf Bornholm, Dänemark. Unpublished Diploma Work. University of Hannover, 1–55.

Weidner, T., Nielsen, A.T., in press. A highly diverse trilobite fauna with Avalonian affinities from the Middle Cambrian *Acidusus atavus* Zone (Drumian Stage) of Bornholm, Denmark. Journal of Systematic Palaeontology.

Westergård, A.H., 1922. Sveriges olenidskiffer. Sveriges Geologiska Undersökning Ca 18, 1–205.

Westergård, A.H., 1942. Stratigraphic Results of the Borings Through the Alum Shales of Scania Made in 1941 – 1942. Meddelanden från Lunds Geologisk-Mineralogiska Institution 100, 1-20.

Westergård, A.H., 1944. Borrningar genom Skånes alunskiffer 1941–42. Sveriges Geologiska Undersökning C 459, 1–45.

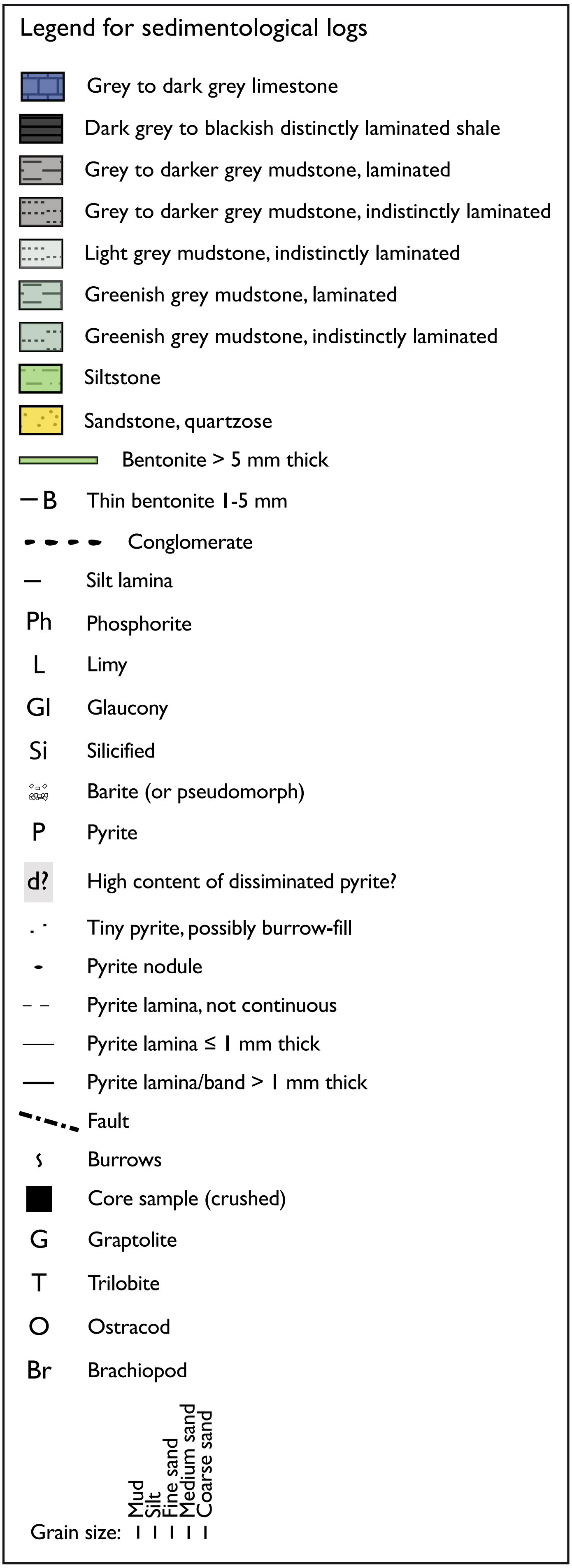
Wærn, B., 1948. The Silurian strata of the Kullatorp core. Bulletin of the Geological Institution of the University of Uppsala 32, 433–473.

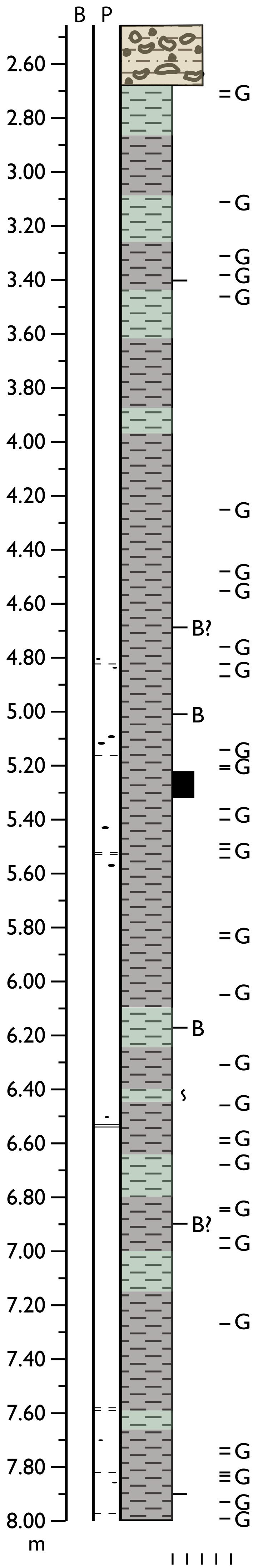
10. Data included on CD

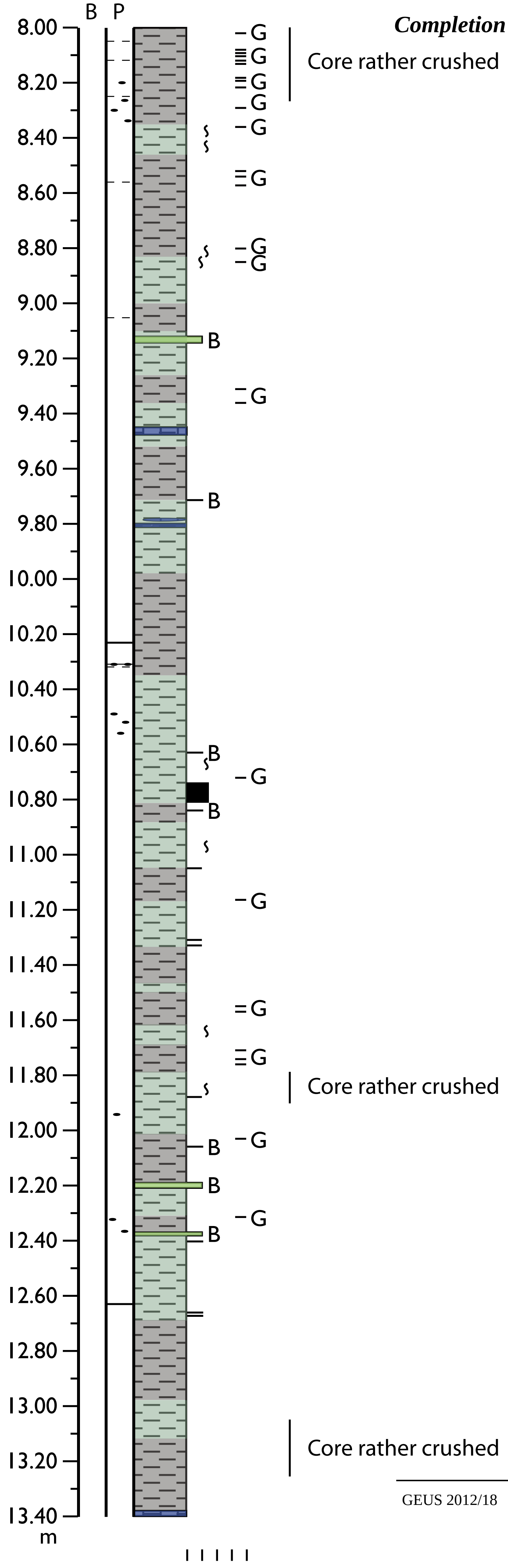
Attached to this report is a CD that contains the following documentation:

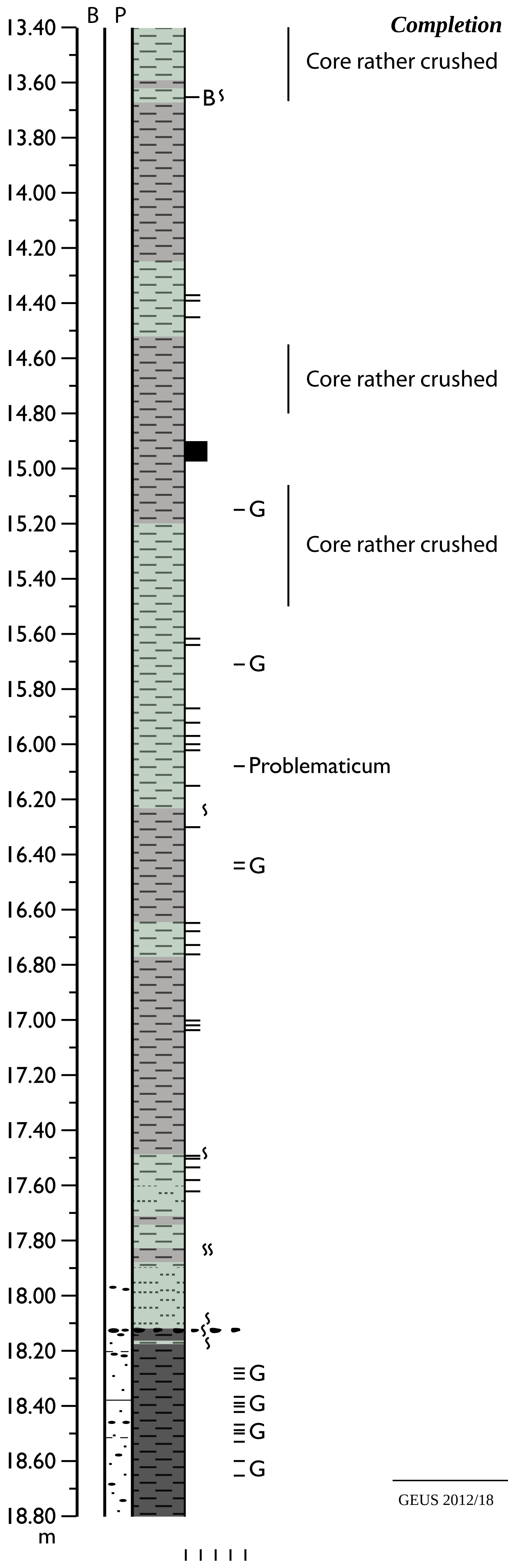
1. In folder *Appendix:*
    a. Pdf file of core description presented in Appendix A
    b. Pdf file of the simplified lithlogical log presented in Appendix B
    c. Excel version of the geochemical analysis presented in Appendix C
    d. Plates with core photos
2. A pdf of the report 'Completion report Billegrav-2 part 4.pdf'

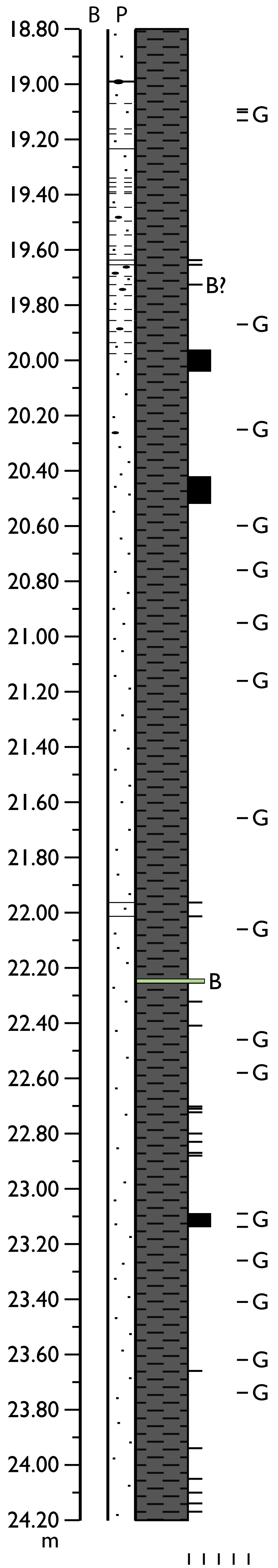
11. Appendix A: Log of the core in scale 1:20

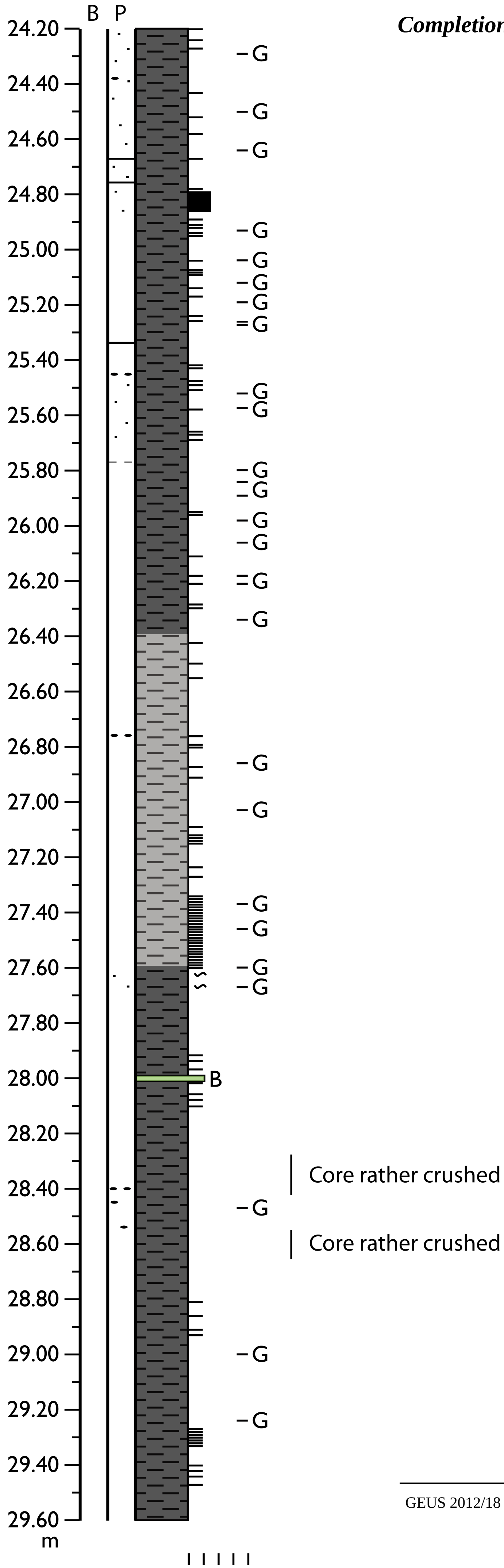

Legend for sedimentological logs
Grey to dark grey limestone
Dark grey to blackish distinctly laminated shale
Grey to darker grey mudstone, laminated
Grey to darker grey mudstone, indistinctly laminated
Light grey mudstone, indistinctly laminated
Greenish grey mudstone, laminated
Greenish grey mudstone, indistinctly laminated
Siltstone
Sandstone, quartzose
Bentonite > 5 mm thick
B Thin bentonite 1-5 mm
Conglomerate
Silt lamina
Ph Phosphorite
L Limy
Gl Glaucony
Si Silicified
Barite (or pseudomorph)
P Pyrite
d? High content of dissiminated pyrite?
Tiny pyrite, possibly burrow-fill
Pyrite nodule
Pyrite lamina, not continuous
Pyrite lamina ≤ 1 mm thick
Pyrite lamina/band > 1 mm thick
Fault
Burrows
Core sample (crushed)
G Graptolite
T Trilobite
O Ostracod
Br Brachiopod
Mud
Silt
Fine sand
Medium sand
Coarse sand
Grain size:

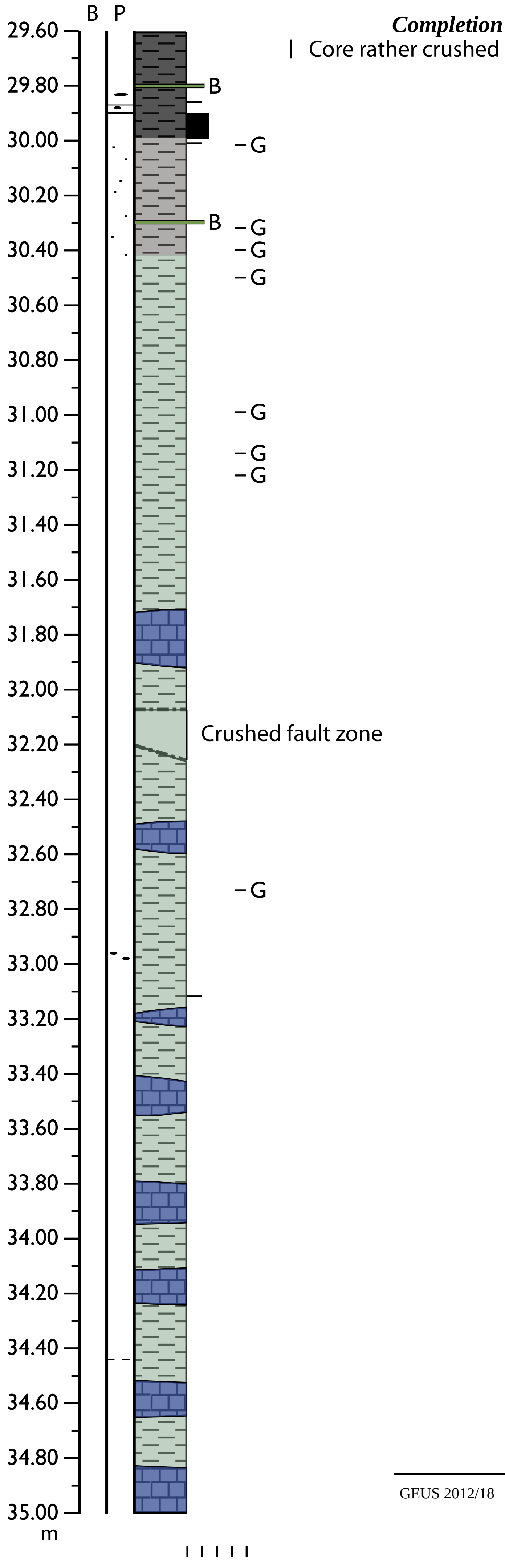

B
P
2.60
2.80
3.00
3.20
3.40
3.60
3.80
4.00
4.20
4.40
4.60
4.80
5.00
5.20
5.40
5.60
5.80
6.00
6.20
6.40
6.60
6.80
7.00
7.20
7.40
7.60
7.80
8.00
m
B?
B
B
B?
G


B P
8.00
8.20
8.40
8.60
8.80
9.00
9.20
9.40
9.60
9.80
10.00
10.20
10.40
10.60
10.80
11.00
11.20
11.40
11.60
11.80
12.00
12.20
12.40
12.60
12.80
13.00
13.20
13.40
m
Core rather crushed
Core rather crushed
Core rather crushed

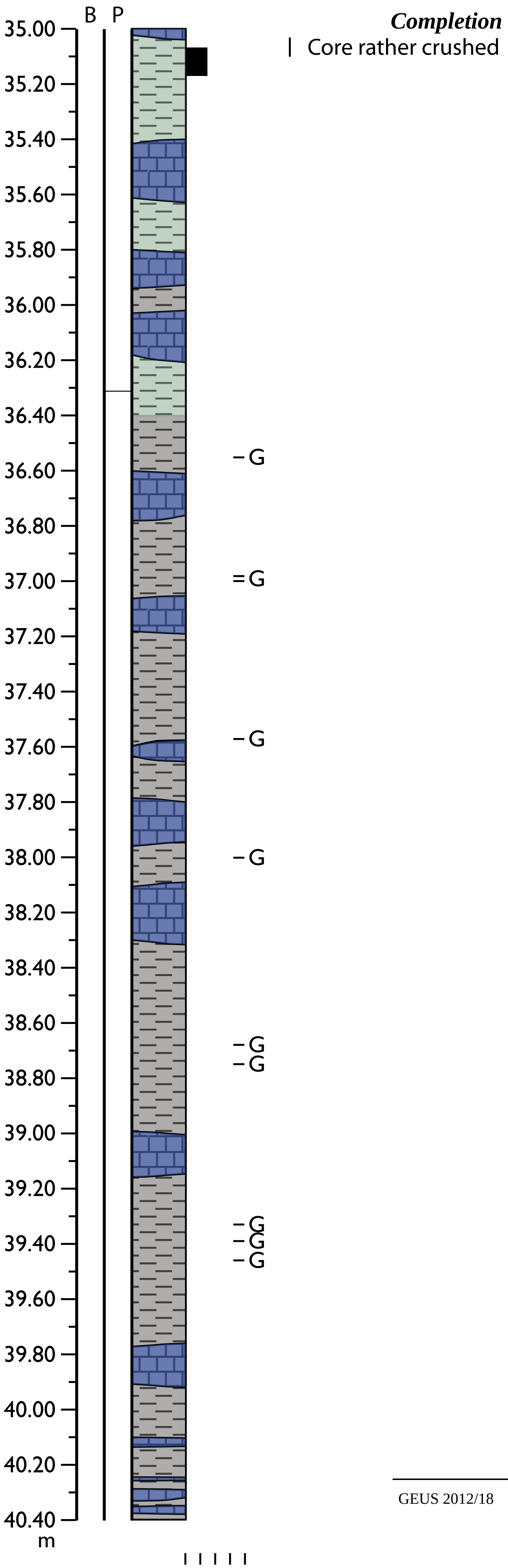

B
P
13.40
13.60
13.80
14.00
14.20
14.40
14.60
14.80
15.00
15.20
15.40
15.60
15.80
16.00
16.20
16.40
16.60
16.80
17.00
17.20
17.40
17.60
17.80
18.00
18.20
18.40
18.60
18.80
m
B
Core rather crushed
Core rather crushed
G
Core rather crushed
G
Problematicum
G
G
G
G
G

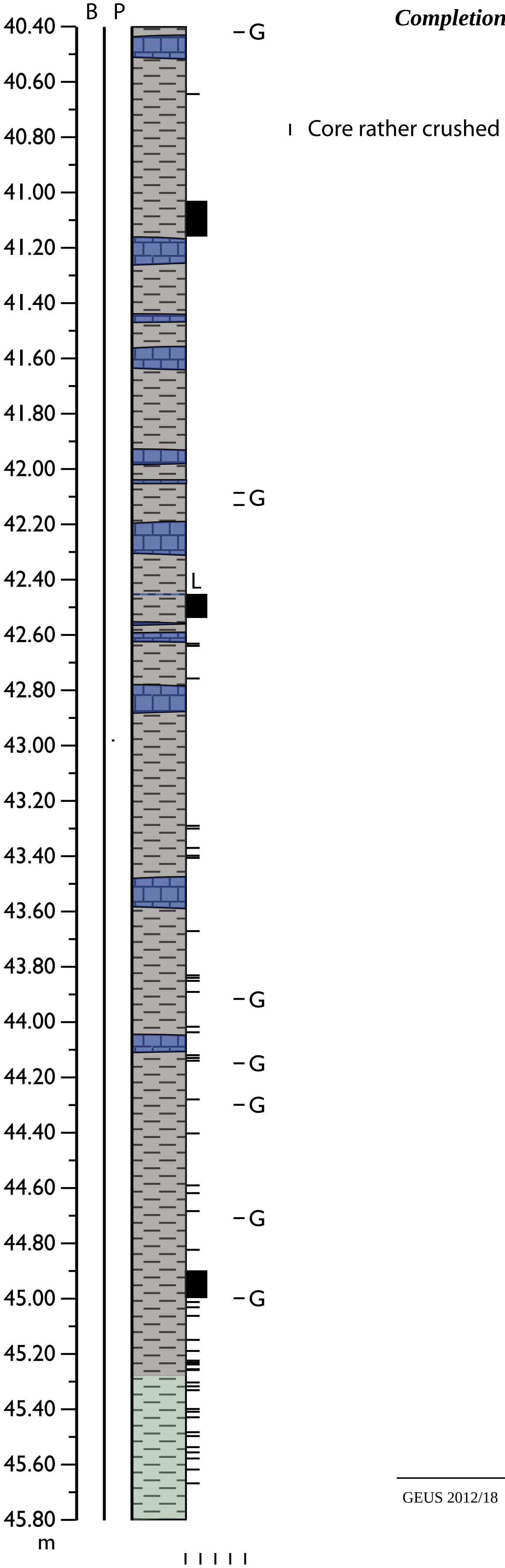

B
P
18.80
19.00
19.20
19.40
19.60
19.80
20.00
20.20
20.40
20.60
20.80
21.00
21.20
21.40
21.60
21.80
22.00
22.20
22.40
22.60
22.80
23.00
23.20
23.40
23.60
23.80
24.00
24.20
m
G
B?
B

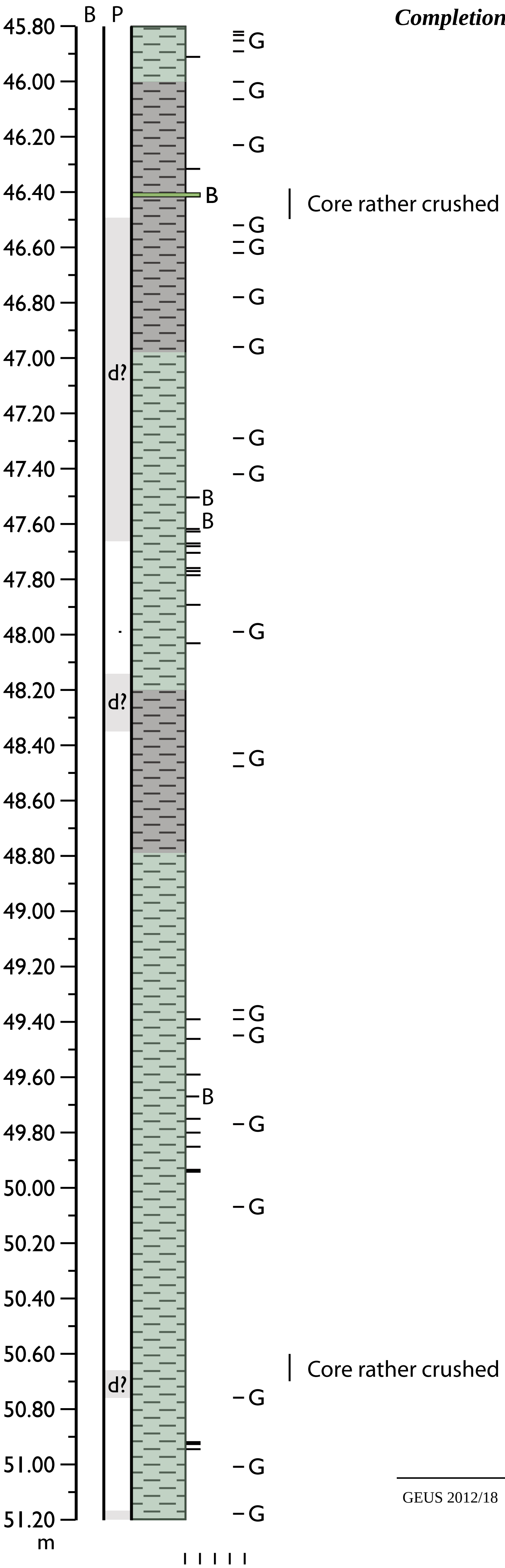

B
P
24.20
24.40
24.60
24.80
25.00
25.20
25.40
25.60
25.80
26.00
26.20
26.40
26.60
26.80
27.00
27.20
27.40
27.60
27.80
28.00
28.20
28.40
28.60
28.80
29.00
29.20
29.40
29.60
m
G
B
Core rather crushed
Core rather crushed

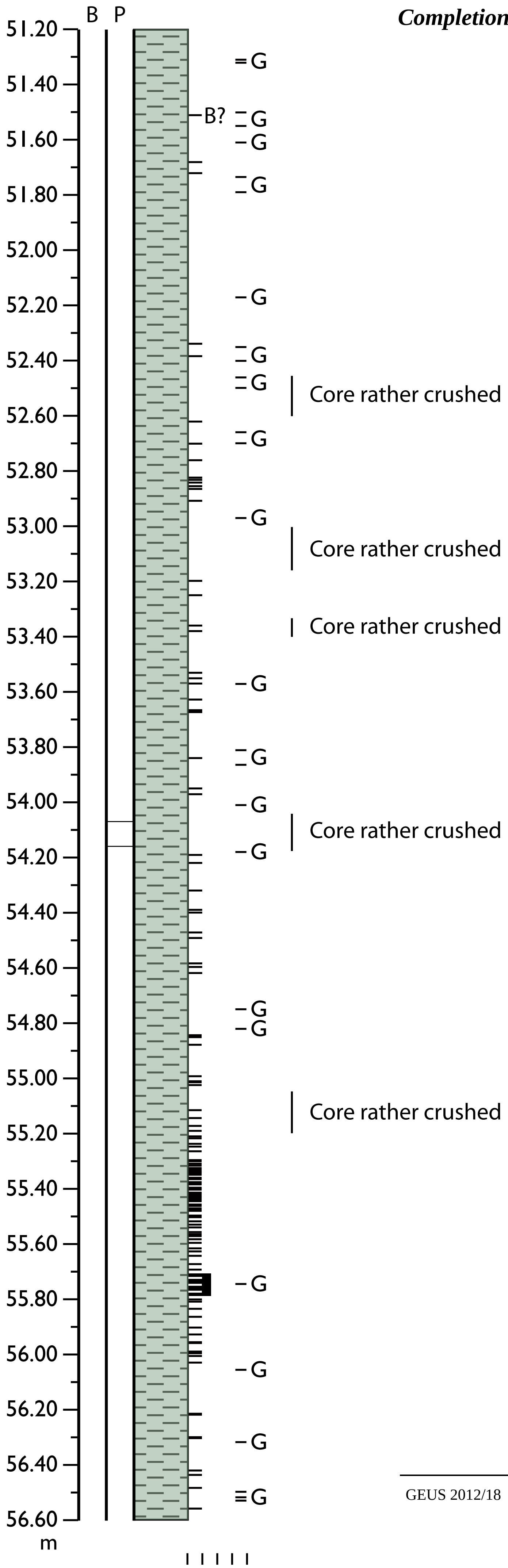


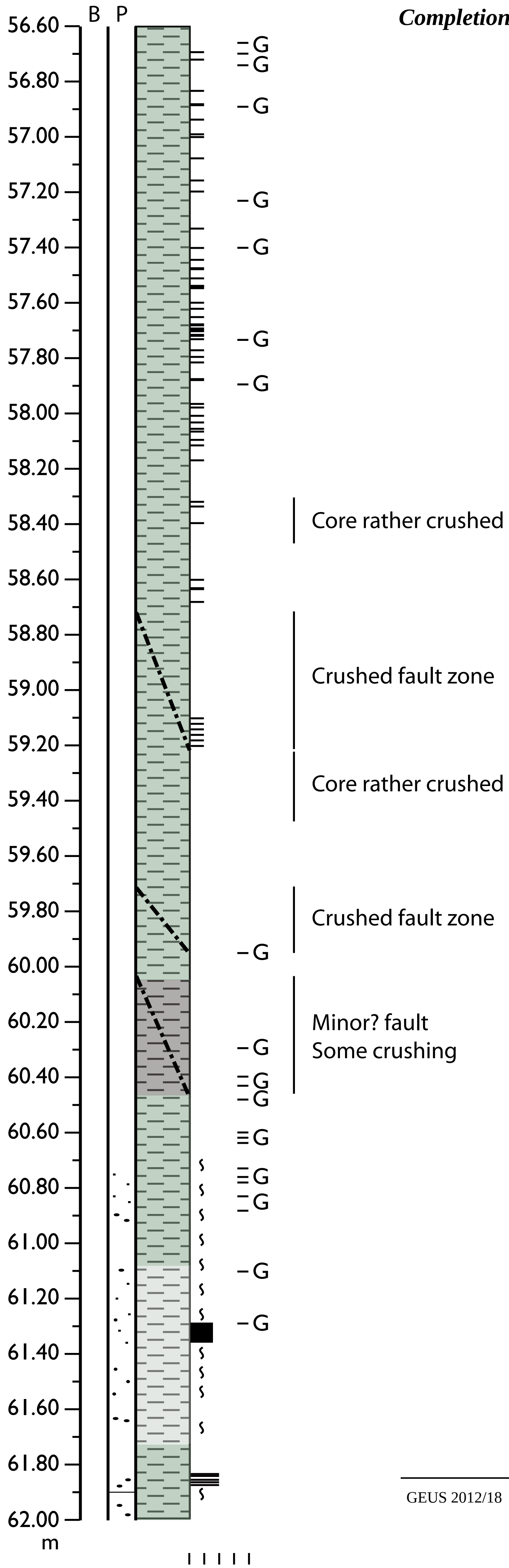
B
P
29.60
29.80
30.00
30.20
30.40
30.60
30.80
31.00
31.20
31.40
31.60
31.80
32.00
32.20
32.40
32.60
32.80
33.00
33.20
33.40
33.60
33.80
34.00
34.20
34.40
34.60
34.80
35.00
m
Core rather crushed
B
G
B
G
G
G
G
G
G
Crushed fault zone
G

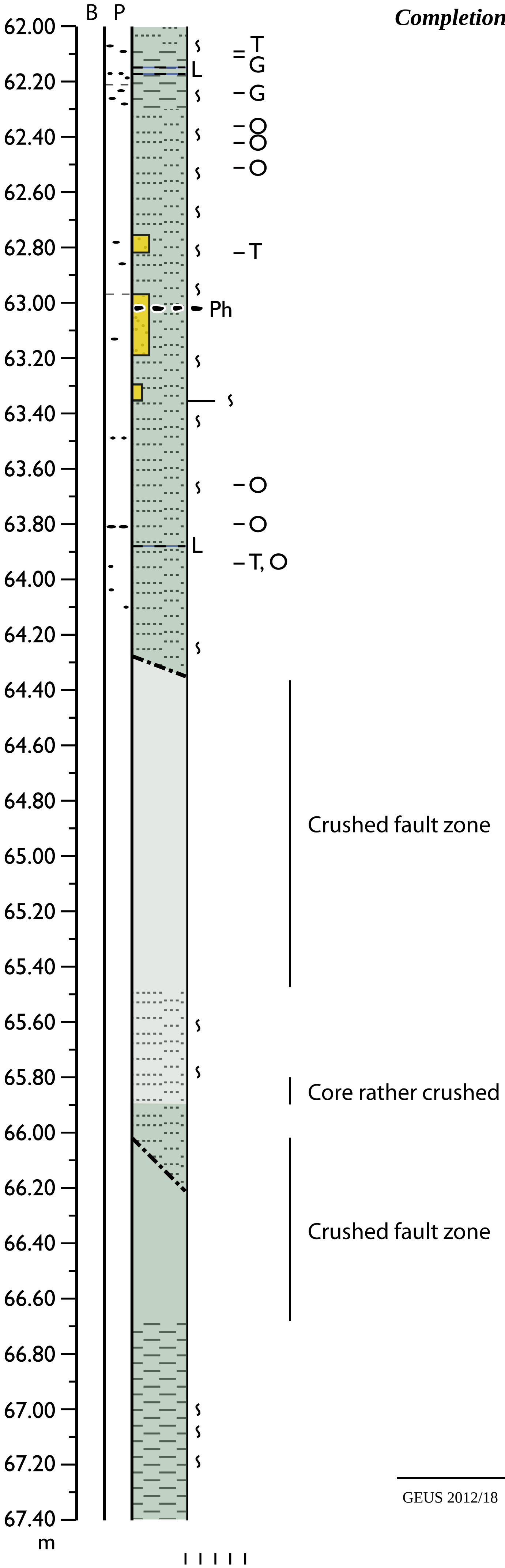

B
P
35.00
35.20
35.40
35.60
35.80
36.00
36.20
36.40
36.60
36.80
37.00
37.20
37.40
37.60
37.80
38.00
38.20
38.40
38.60
38.80
39.00
39.20
39.40
39.60
39.80
40.00
40.20
40.40
m
Core rather crushed
G
=G
G
G
G
G
G
G
G

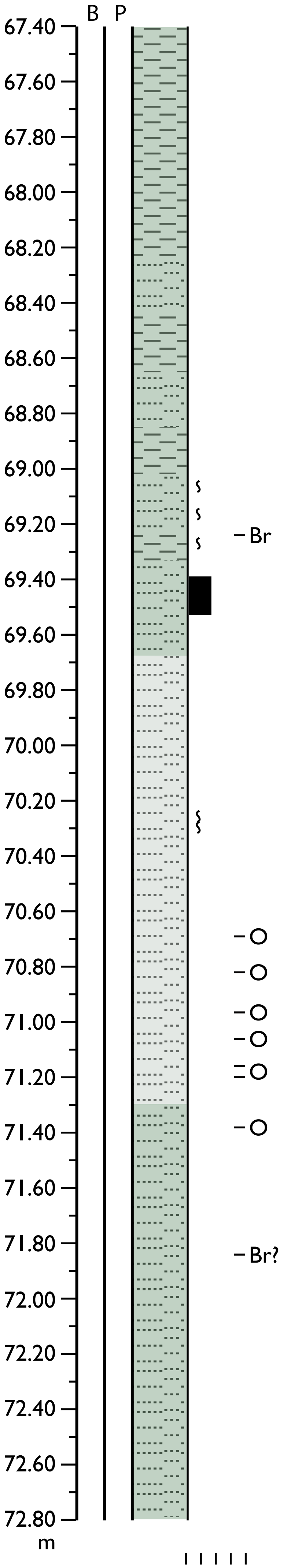

B
P
40.40
40.60
40.80
41.00
41.20
41.40
41.60
41.80
42.00
42.20
42.40
42.60
42.80
43.00
43.20
43.40
43.60
43.80
44.00
44.20
44.40
44.60
44.80
45.00
45.20
45.40
45.60
45.80
m
G
Core rather crushed
G
L
G
G
G
G
G

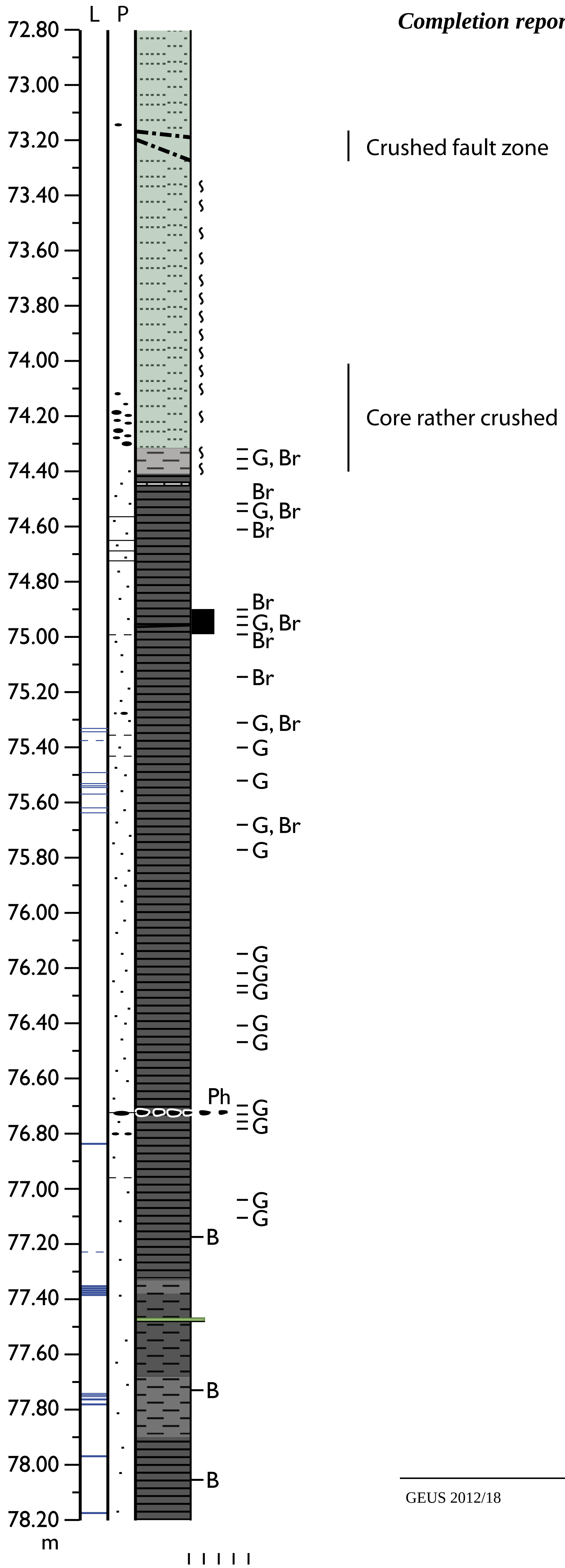

B P
45.80
46.00
46.20
46.40
46.60
46.80
47.00
47.20
47.40
47.60
47.80
48.00
48.20
48.40
48.60
48.80
49.00
49.20
49.40
49.60
49.80
50.00
50.20
50.40
50.60
50.80
51.00
51.20
m
d?
d?
d?
B
B
B
B
G
Core rather crushed
Core rather crushed

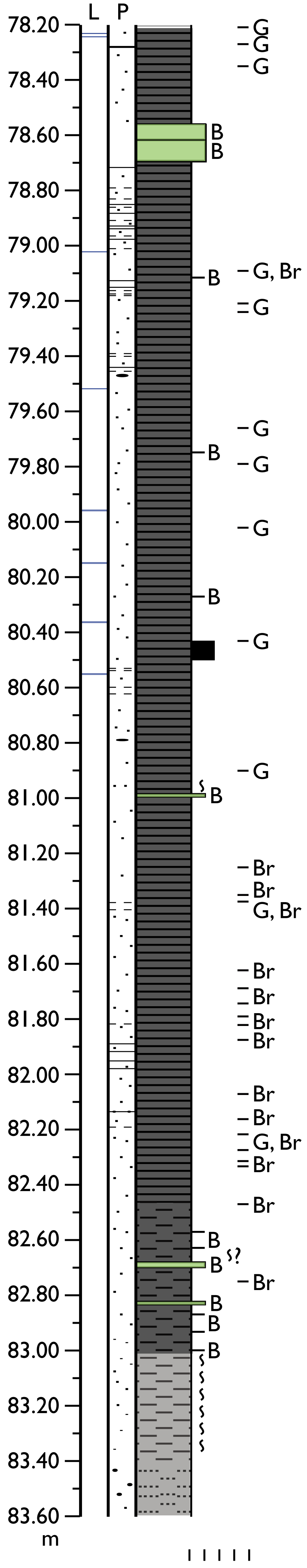

B
P
51.20
51.40
51.60
51.80
52.00
52.20
52.40
52.60
52.80
53.00
53.20
53.40
53.60
53.80
54.00
54.20
54.40
54.60
54.80
55.00
55.20
55.40
55.60
55.80
56.00
56.20
56.40
56.60
m
B?
G
Core rather crushed
Core rather crushed
Core rather crushed
Core rather crushed
Core rather crushed

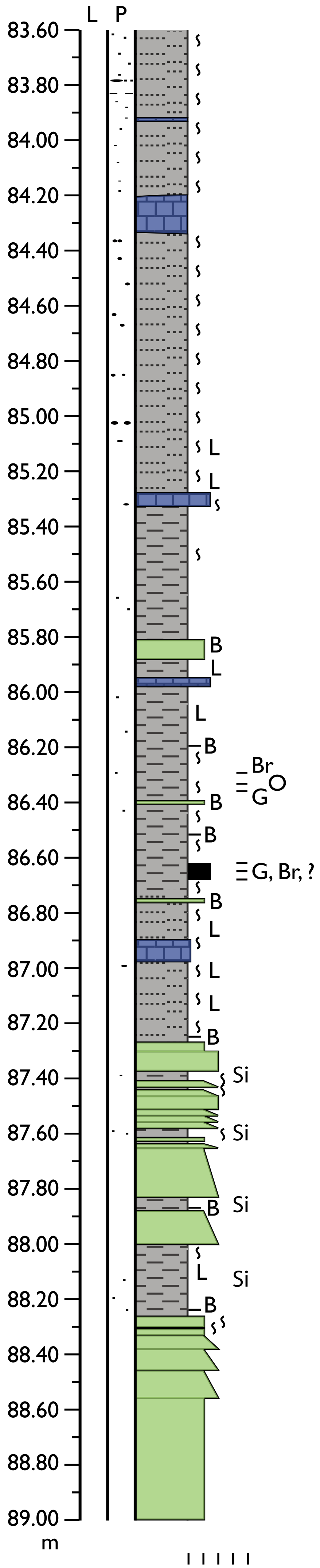

B
P
56.60
56.80
57.00
57.20
57.40
57.60
57.80
58.00
58.20
58.40
58.60
58.80
59.00
59.20
59.40
59.60
59.80
60.00
60.20
60.40
60.60
60.80
61.00
61.20
61.40
61.60
61.80
62.00
m
G
Core rather crushed
Crushed fault zone
Core rather crushed
Crushed fault zone
Minor? fault
Some crushing

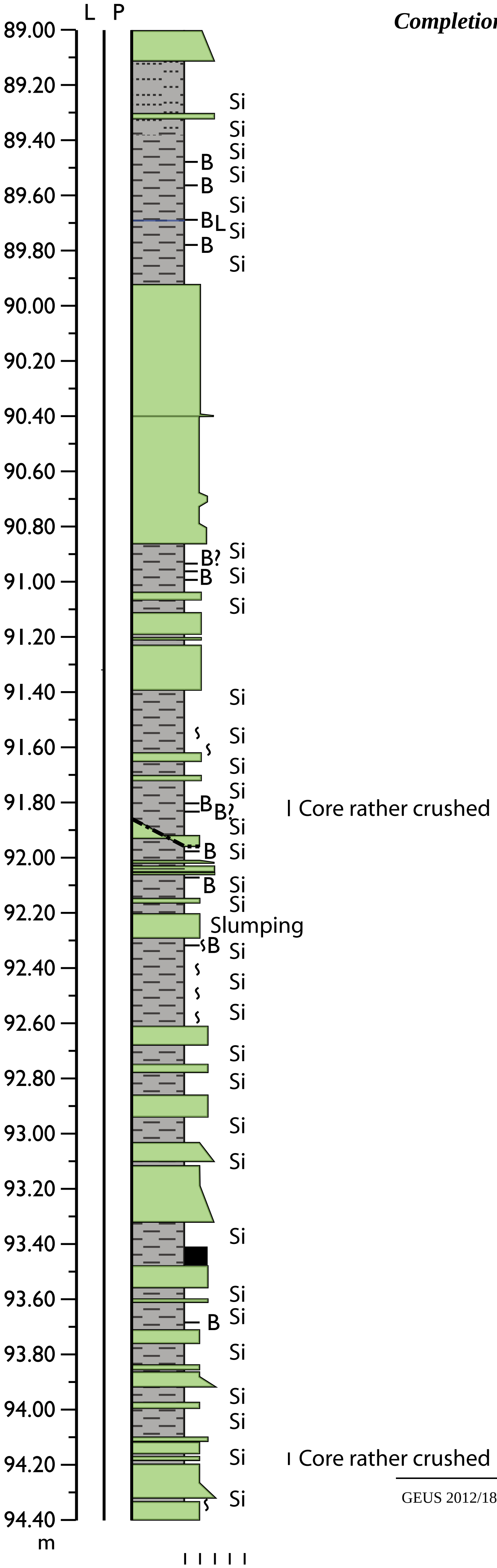

B
P
62.00
62.20
62.40
62.60
62.80
63.00
63.20
63.40
63.60
63.80
64.00
64.20
64.40
64.60
64.80
65.00
65.20
65.40
65.60
65.80
66.00
66.20
66.40
66.60
66.80
67.00
67.20
67.40
m
T
G
L
G
O
O
O
T
Ph
O
O
L
T, O
Crushed fault zone
Core rather crushed
Crushed fault zone

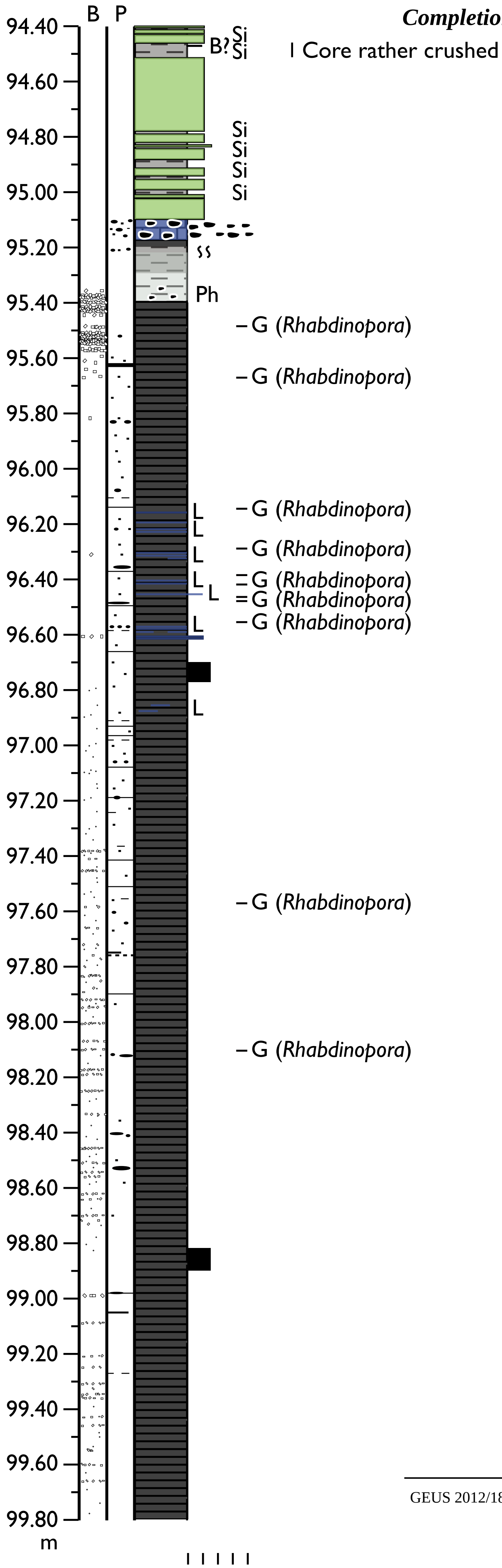

B
P
67.40
67.60
67.80
68.00
68.20
68.40
68.60
68.80
69.00
69.20
69.40
69.60
69.80
70.00
70.20
70.40
70.60
70.80
71.00
71.20
71.40
71.60
71.80
72.00
72.20
72.40
72.60
72.80
m
Br
Br?

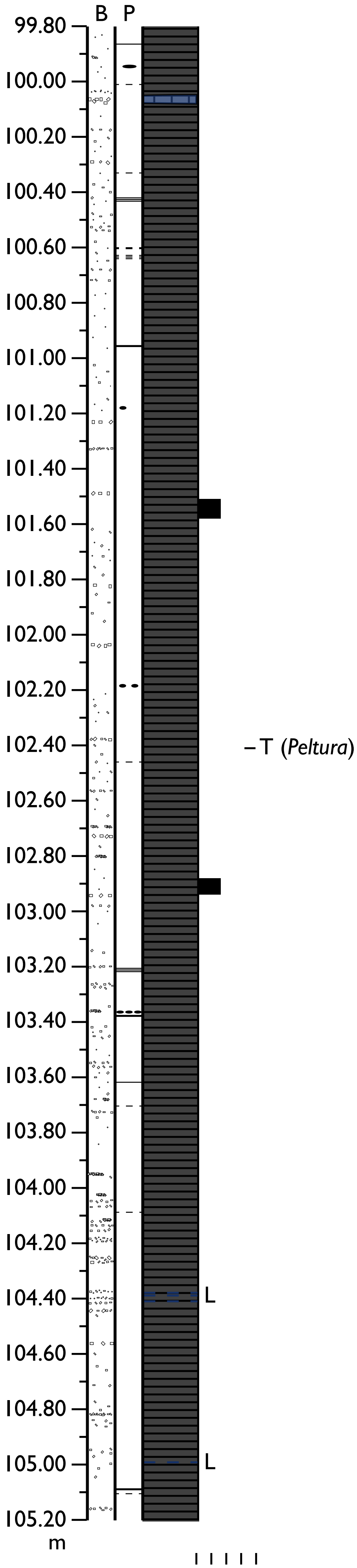

L
P
72.80
73.00
73.20
73.40
73.60
73.80
74.00
74.20
74.40
74.60
74.80
75.00
75.20
75.40
75.60
75.80
76.00
76.20
76.40
76.60
76.80
77.00
77.20
77.40
77.60
77.80
78.00
78.20
m
Crushed fault zone
Core rather crushed
G, Br
Br
G, Br
Br
Br
G, Br
Br
Br
G, Br
G
G
G, Br
G
G
G
G
G
G
Ph
G
G
G
G
B
B
B

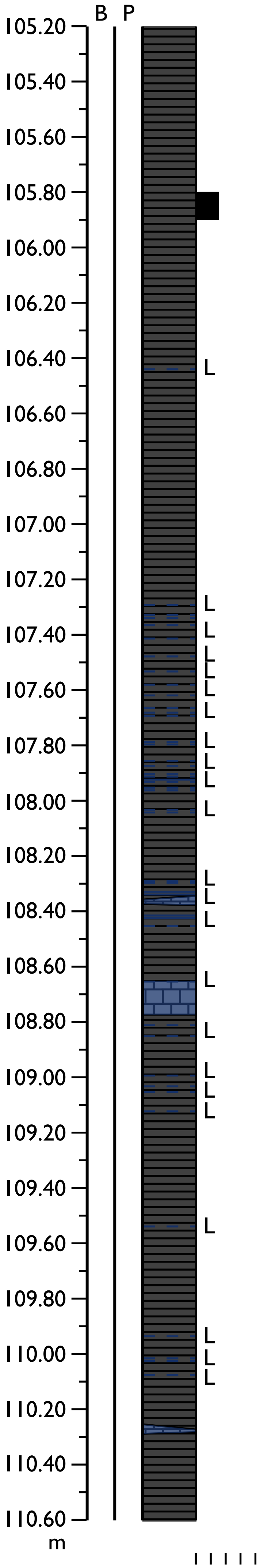

L
P
78.20
78.40
78.60
78.80
79.00
79.20
79.40
79.60
79.80
80.00
80.20
80.40
80.60
80.80
81.00
81.20
81.40
81.60
81.80
82.00
82.20
82.40
82.60
82.80
83.00
83.20
83.40
83.60
m
G
G, Br
Br
B

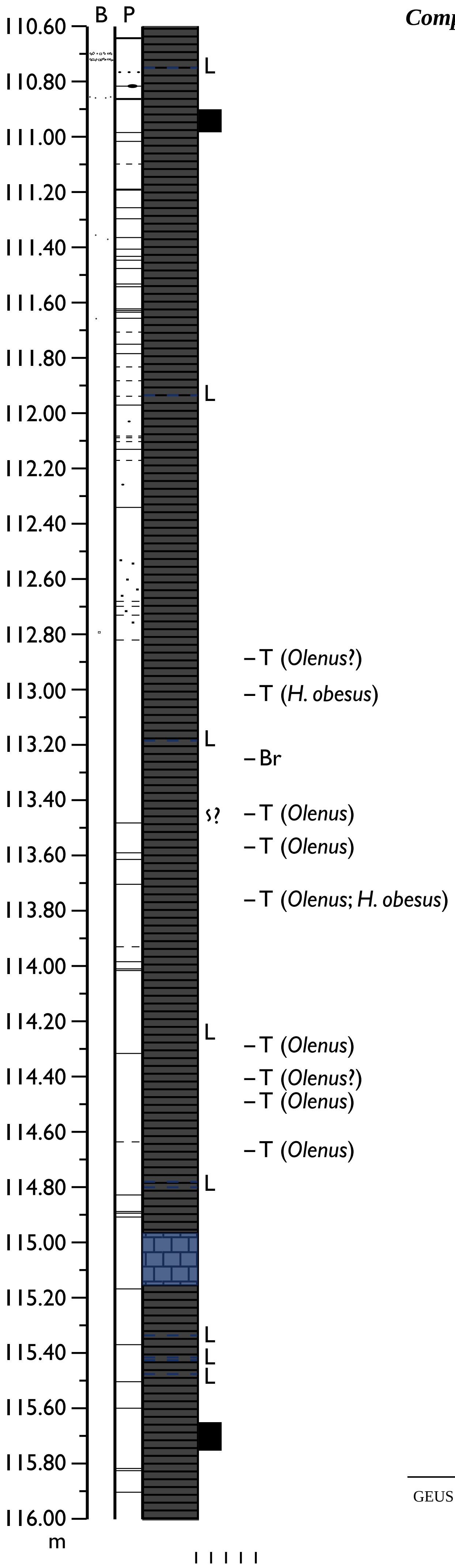

L
P
83.60
83.80
84.00
84.20
84.40
84.60
84.80
85.00
85.20
85.40
85.60
85.80
86.00
86.20
86.40
86.60
86.80
87.00
87.20
87.40
87.60
87.80
88.00
88.20
88.40
88.60
88.80
89.00
m
L
L
B
L
L
B
Br
O
G
B
B
G, Br, ?
B
L
L
L
B
Si
Si
B
Si
L
Si
B

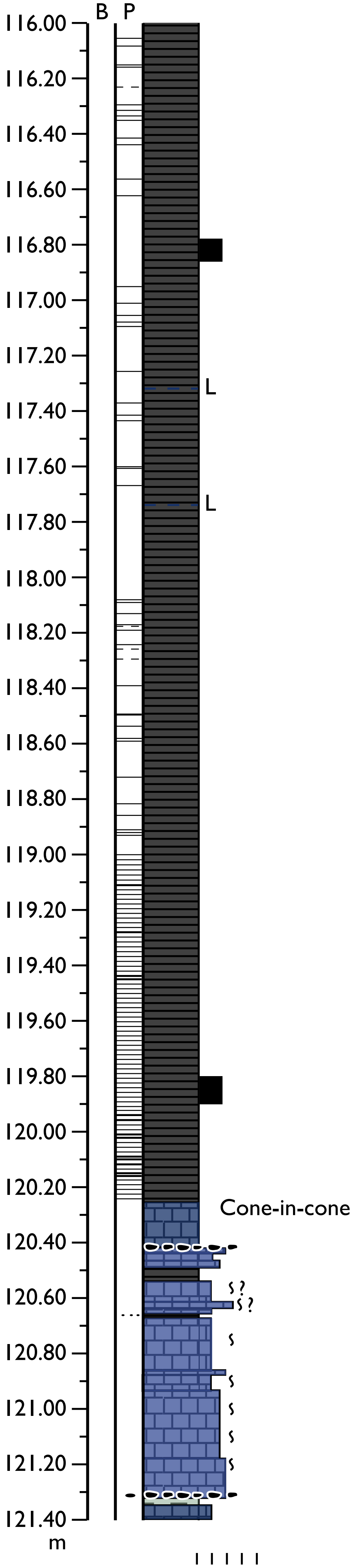

L
P
89.00
89.20
89.40
89.60
89.80
90.00
90.20
90.40
90.60
90.80
91.00
91.20
91.40
91.60
91.80
92.00
92.20
92.40
92.60
92.80
93.00
93.20
93.40
93.60
93.80
94.00
94.20
94.40
m
Si
B
BL
B?
Slumping
Core rather crushed
Core rather crushed


B
P
94.40
94.60
94.80
95.00
95.20
95.40
95.60
95.80
96.00
96.20
96.40
96.60
96.80
97.00
97.20
97.40
97.60
97.80
98.00
98.20
98.40
98.60
98.80
99.00
99.20
99.40
99.60
99.80
m
Si
B?
Si
Core rather crushed
Si
Si
Si
Si
Ph
– G (Rhabdinopora)
– G (Rhabdinopora)
L
– G (Rhabdinopora)
L
L
– G (Rhabdinopora)
L
= G (Rhabdinopora)
L
= G (Rhabdinopora)
L
– G (Rhabdinopora)
L
– G (Rhabdinopora)
– G (Rhabdinopora)

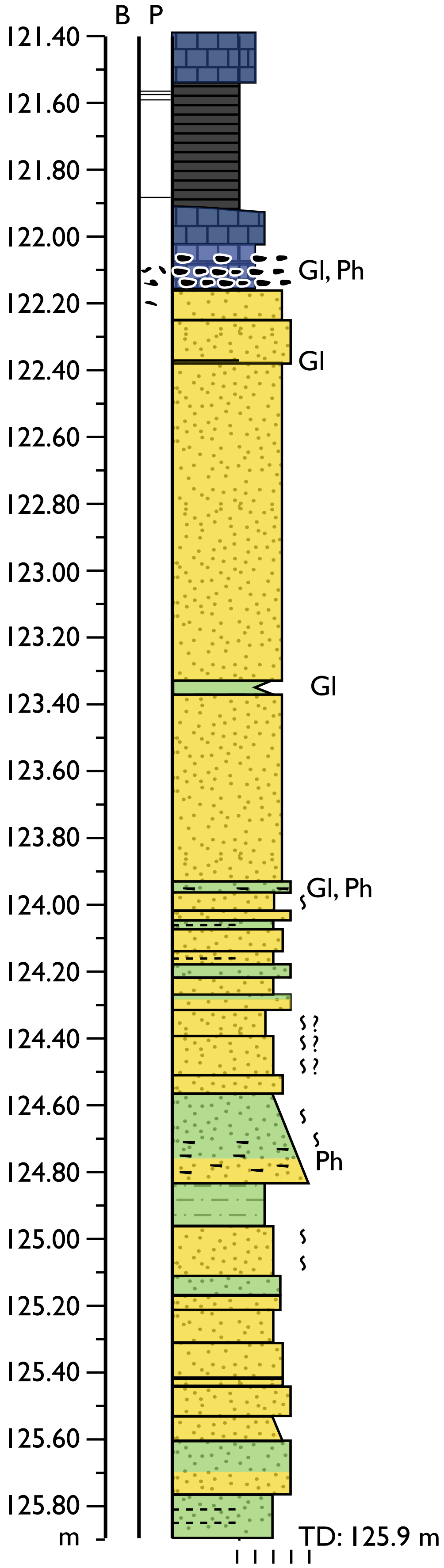

B
P
99.80
100.00
100.20
100.40
100.60
100.80
101.00
101.20
101.40
101.60
101.80
102.00
102.20
102.40
102.60
102.80
103.00
103.20
103.40
103.60
103.80
104.00
104.20
104.40
104.60
104.80
105.00
105.20
m
– T (*Peltura*)
L
L


B
P
105.20
105.40
105.60
105.80
106.00
106.20
106.40
106.60
106.80
107.00
107.20
107.40
107.60
107.80
108.00
108.20
108.40
108.60
108.80
109.00
109.20
109.40
109.60
109.80
110.00
110.20
110.40
110.60
m
L

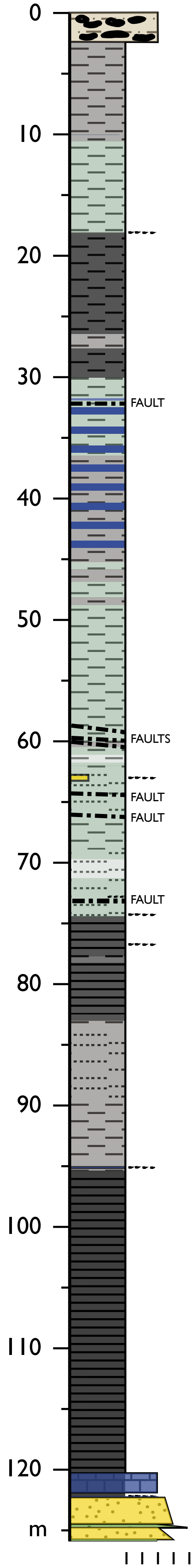

B
P
110.60
110.80
111.00
111.20
111.40
111.60
111.80
112.00
112.20
112.40
112.60
112.80
113.00
113.20
113.40
113.60
113.80
114.00
114.20
114.40
114.60
114.80
115.00
115.20
115.40
115.60
115.80
116.00
m
L
L
– T (Olenus?)
– T (H. obesus)
L
– Br
ʕ?
– T (Olenus)
– T (Olenus)
– T (Olenus; H. obesus)
L
– T (Olenus)
– T (Olenus?)
– T (Olenus)
– T (Olenus)
L
L
L
L



B
P
116.00
116.20
116.40
116.60
116.80
117.00
117.20
117.40
117.60
117.80
118.00
118.20
118.40
118.60
118.80
119.00
119.20
119.40
119.60
119.80
120.00
120.20
120.40
120.60
120.80
121.00
121.20
121.40
m
L
L
Cone-in-cone


B
P
121.40
121.60
121.80
122.00
122.20
122.40
122.60
122.80
123.00
123.20
123.40
123.60
123.80
124.00
124.20
124.40
124.60
124.80
125.00
125.20
125.40
125.60
125.80
m
Gl, Ph
Gl
Gl
Gl, Ph
Ph
TD: 125.9 m

12. Appendix B: Simplified sedimentological log


0
10
20
30
FAULT
40
50
60
FAULTS
FAULT
FAULT
70
FAULT
80
90
100
110
120
m

13. Appendix C: Total sample list and geochemical results

File: 'Appendix C geochemical analysis Billegrav-2.xlsx' in folder Appendix on the attached CD.

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
21197	1001	2.81	2.82	Rastrites	F5	0.3	0.3	0.0	0.4	0.1
21198	1002	3.81	3.83	Rastrites	F5	0.1	0.1	0.1	0.6	0.2
21199	1003	4.92	4.93	Rastrites	F5	0.5	0.5	1.0	0.4	1.9
20025	1	5.18	5.28	Rastrites	F5	1.0	1.1	2.0	0.8	3.8
21200	1004	6.24	6.25	Rastrites	F5	0.6	0.7	0.0	1.2	0.1
21201	1005	7.29	7.31	Rastrites	F5	0.5	0.6	0.8	1.1	1.6
	1006	7.80	7.81	Rastrites	F5	not analysed				
21202	1007	8.26	8.27	Rastrites	F5	0.3	0.4	0.1	0.8	0.1
21203	1008	9.69	9.7	Rastrites	F5	0.6	0.7	0.0	0.9	0.0
	1009	10.42	10.44	Rastrites	F5	not analysed				
20026	2	10.63	10.70	Rastrites	F4	0.5	0.6	1.9	0.4	3.6
21204	1010	11.51	11.52	Rastrites	F4	0.6	0.7	0.0	0.9	0.0
	1011	11.76	11.77	Rastrites	F4	not analysed				
21205	1012	13.11	13.13	Rastrites	F4	0.5	0.6	0.7	0.6	1.3
	1013	13.81	13.83	Rastrites	F4	not analysed				
	1014	14.20	14.21	Rastrites	F4	not analysed				
20027	3	14.90	14.97	Rastrites	F4	0.5	0.5	1.7	0.0	3.1
21206	1015	15.39	15.4	Rastrites	F4	0.2	0.3	0.2	0.4	0.4
21207	1016	16.49	16.5	Rastrites	F4	0.4	0.4	0.3	0.3	0.5
21208	1017	17.35	17.36	Rastrites	F4	0.3	0.4	0.0	0.4	0.0
	1018	18.03	18.04	Rastrites	F4	not analysed				
	1019	18.26	18.27	Rastrites	F4	not analysed				
21209	1020	18.36	18.37	Rastrites	F4	1.4	1.6	1.0	1.2	1.8
	1021	18.50	18.51	Rastrites	F4	not analysed				
	1021-1	18.58	18.59	Rastrites	F4	not analysed				
	1022	18.91	18.92	Rastrites	F4	not analysed				
21210	1023	19.07	19.08	Rastrites	F4	3.2	3.3	1.9	0.6	3.6
	1024	19.19	19.2	Rastrites	F4	not analysed				
	1025	19.29	19.3	Rastrites	F4	not analysed				
20028	4	19.87	19.95	Rastrites	F4	3.9	4.0	2.2	1.2	4.2

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
21211	1026	20.59	20.59	Rastrites	F4	3.6	3.8	1.8	1.0	3.4
21212	1027	21.30	21.31	Rastrites	F4	2.4	2.6	1.5	1.8	2.8
	1028	21.96	21.97	Rastrites	F4	not analysed				
21213	1029	22.54	22.57	Rastrites	F4	1.9	1.9	1.4	0.5	2.7
	1030	22.82	22.83	Rastrites	F4	not analysed				
20029	5	23.13	23.18	Rastrites	F4	2.3	2.4	2.7	0.8	5.0
21214	1031	23.80	23.82	Rastrites	F4	1.8	1.9	1.5	0.6	2.8
21215	1032	24.50	24.51	Rastrites	F4	1.5	1.9	0.9	3.4	1.7
20030	6	24.80	24.90	Rastrites	F4	3.1	3.4	3.4	2.3	6.3
21216	1033	25.37	25.38	Rastrites	F4	3.2	4.0	1.9	6.0	3.5
	1034	25.99	26.00	Rastrites	F4	not analysed				
21217	1035	27.34	27.35	Rastrites	F4	1.3	2.9	1.6	13.2	3.0
21218	1036	28.20	28.21	Rastrites	F4	2.7	3.0	3.0	2.8	5.6
	1037	28.68	28.69	Rastrites	F4	not analysed				
21219	1038	29.40	29.41	Rastrites	F4	2.3	2.4	1.2	1.0	2.2
20031	7	29.90	29.99	Rastrites	F4	1.2	1.2	0.7	0.4	1.3
21220	1039	30.92	30.93	Rastrites	F3	0.4	2.6	0.9	18.3	1.7
21221	1040	31.22	31.23	Rastrites	F3	0.4	2.6	1.2	18.2	2.3
21222	1041	32.51	32.52	Rastrites	F3	0.4	2.9	1.1	20.6	2.1
21223	1042	33.46	33.47	Rastrites	F3	0.5	3.1	1.2	21.8	2.2
21224	1043	34.10	34.11	Rastrites	F3	0.7	3.6	1.4	24.0	2.6
20032	8	35.00	35.10	Rastrites	F3	0.6	3.1	1.2	21.4	2.2
21225	1044	36.31	36.32	Rastrites	F3	0.6	2.9	1.0	19.4	1.8
21226	1045	37.75	37.76	Rastrites	F3	0.8	3.2	1.2	20.4	2.2
21227	1046	38.98	38.99	Rastrites	F3	0.6	3.4	1.0	23.7	1.8
21228	1047	40.18	40.19	Rastrites	F3	0.8	3.3	0.8	20.3	1.6
20033	9	41.02	41.15	Rastrites	F3	0.9	3.4	1.0	20.8	1.8
20034	10	42.65	42.74	Rastrites	F3	1.0	3.2	1.0	18.3	1.9
21229	1048	43.35	43.36	Rastrites	F3	0.7	4.0	0.7	27.0	1.4
21230	1049	44.35	44.36	Rastrites	F3	0.9	4.5	1.0	29.3	1.8
20035	11	44.90	45.00	Rastrites	F2	0.8	0.9	1.9	0.4	3.5
21231	1050	45.66	45.67	Rastrites	F2	0.6	1.7	0.7	9.1	1.3
21232	1051	46.02	46.03	Rastrites	F2	1.4	1.5	2.5	1.2	4.6
	1052	46.41	46.42	Rastrites	F2	not analysed				
21233	1053	47.06	47.07	Rastrites	F2	1.3	1.4	1.7	0.5	3.2
	1054	47.54	47.55	Rastrites	F2	not analysed				
21234	1055	48.19	48.20	Rastrites	F2	1.3	1.5	2.0	1.4	3.8
	1056	48.80	48.81	Rastrites	F2	not analysed				
21235	1057	49.47	49.48	Rastrites	F2	1.6	1.7	2.2	0.8	4.1
	1058	49.65	49.66	Rastrites	F2	not analysed				
21236	1059	50.23	50.24	Rastrites	F2	1.3	1.3	1.5	0.5	2.7

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
20036	12	50.82	50.90	Rastrites	F2	1.1	1.3	1.5	1.1	2.7
21237	1060	51.42	51.43	Rastrites	F2	1.2	1.3	1.7	0.9	3.2
	1061	51.90	51.91	Rastrites	F2	not analysed				
21238	1062	52.29	52.30	Rastrites	F2	0.7	1.0	1.3	1.9	2.4
21239	1063	53.17	53.18	Rastrites	F2	0.9	1.4	1.6	4.8	3.0
21240	1064	54.15	54.16	Rastrites	F2	1.0	1.1	1.4	1.3	2.6
	1065	54.37	54.38	Rastrites	F2	not analysed				
21241	1066	55.09	55.10	Rastrites	F1	0.6	1.3	1.3	5.5	2.5
21242	1067	56.24	56.25	Rastrites	F1	0.8	1.1	1.3	2.6	2.5
20037	13	56.52	56.60	Rastrites	F1	0.4	1.7	0.7	10.6	1.3
	1068	56.95	56.96	Rastrites	F1	not analysed				
21243	1069	57.41	57.42	Rastrites	F1	0.6	1.1	1.1	3.8	2.0
	1070	57.64	57.65	Rastrites	F1	not analysed				
	1071	57.92	57.93	Rastrites	F1	not analysed				
21244	1072	58.39	58.40	Rastrites	F1	0.7	1.3	1.1	5.4	2.0
	1074	59.47	59.48	Rastrites	F1	not analysed				
21245	1073	59.56	59.57	Rastrites	F1	1.4	1.6	1.5	1.9	2.8
	1075	59.63	59.64	Rastrites	F1	not analysed				
21246	1076	60.21	60.22	Rastrites	F1	2.2	2.4	1.2	1.6	2.3
21247	1077	61.04	61.05	Lindegård	E3	0.3	5.3	0.7	41.5	1.4
20038	14	61.30	61.37	Lindegård	E3	0.2	3.2	0.3	25.5	0.6
21248	1078	62.08	62.09	Lindegård	E3	0.2	2.2	0.7	16.7	1.3
21249	1079	63.51	63.52	Lindegård	E3	0.1	3.9	0.1	31.6	0.3
21250	1080	65.69	65.70	Lindegård	E3	0.1	1.1	0.3	8.8	0.6
21251	1081	67.85	67.86	Lindegård	E3	0.1	0.3	0.3	1.9	0.5
21252	1082	68.57	68.58	Lindegård	E3	0.1	0.3	0.0	1.8	0.0
20039	15	69.39	69.53	Lindegård	E2	0.2	1.4	0.0	10.2	0.1
21253	1083	69.80	69.81	Lindegård	E2	0.1	0.7	0.0	5.3	0.1
21254	1084	70.49	70.50	Lindegård	E2	0.1	1.6	0.0	12.3	0.0
21255	1085	71.37	71.38	Lindegård	E2	0.1	1.3	0.0	9.7	0.1
21256	1086	72.35	72.36	Lindegård	E1	0.3	0.6	0.0	2.9	0.0
21257	1087	73.86	73.87	Lindegård	E1	0.1	0.5	0.2	3.7	0.4
21258	1088	74.20	74.21	Lindegård	E1	0.5	0.6	0.6	0.7	1.2
	1089	74.48	74.49	Dicellograptus	D3	not analysed				
	1090	74.76	74.77	Dicellograptus	D3	not analysed				
20040	16	74.90	74.99	Dicellograptus	D3	2.0	2.2	0.8	2.1	1.4
21259	1091	75.15	75.16	Dicellograptus	D3	3.1	3.4	2.0	2.4	3.7
	1092	75.32	75.33	Dicellograptus	D3	not analysed				
	1093	75.50	75.51	Dicellograptus	D3	not analysed				

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
	1094	75.63	75.64	Dicellograptus	D3	not analysed				
	1095	75.78	75.79	Dicellograptus	D3	not analysed				
21260	1096	76.08	76.09	Dicellograptus	D3	3.7	4.0	1.4	3.2	2.5
	1097	76.29	76.30	Dicellograptus	D3	not analysed				
	1098	76.85	76.86	Dicellograptus	D3	not analysed				
20041	17	76.51	76.89	Dicellograptus	D3	3.1	3.4	1.0	2.4	1.9
	1099	77.35	77.36	Dicellograptus	D3	not analysed				
	1100	77.89	77.90	Dicellograptus	D3	4.6	5.1	3.2	5.9	12.1
	1101	78.75	78.76	Dicellograptus	D3	4.0	4.2	1.2	2.3	3.9
	1102	79.51	79.52	Dicellograptus	D3	4.6	4.7	1.0	1.8	3.9
	1103	79.75	79.76	Dicellograptus	D3	3.6	3.8	1.6	2.9	4.7
	1104	80.35	80.36	Dicellograptus	D3	3.9	4.1	1.3	2.4	4.5
20042	18	80.40	80.47	Dicellograptus	D3	3.9	4.4	1.8	3.5	3.4
	1105	80.71	80.72	Dicellograptus	D3	3.7	4.0	1.7	3.3	4.3
	1106	80.89	80.90	Dicellograptus	D3	2.8	3.0	1.0	1.8	6.8
	1107	81.33	81.34	Dicellograptus	D3	3.2	3.4	1.5	2.8	4.7
	1108	81.61	81.62	Dicellograptus	D3	2.9	3.1	1.4	2.6	5.9
	1109	82.16	82.17	Dicellograptus	D3	3.8	4.0	1.5	2.9	2.7
	1110	82.46	82.47	Dicellograptus	D3	2.3	2.5	1.3	2.4	3.5
	1111	82.78	82.79	Dicellograptus	D3	2.3	2.6	1.7	3.3	3.7
	1112	83.08	83.09	Dicellograptus	D2	1.0	1.4	2.0	3.8	5.6
	1113	83.36	83.37	Dicellograptus	D2	0.6	1.5	5.6	10.5	3.6
	1114	83.69	83.70	Dicellograptus	D2	0.9	1.1	0.9	1.7	7.3
	1115	84.04	84.05	Dicellograptus	D2	0.5	0.6	0.5	1.0	5.1
	1116	84.41	84.42	Dicellograptus	D2	0.7	0.7	0.3	0.6	6.4
	1117	84.71	84.72	Dicellograptus	D2	0.4	0.5	0.3	0.5	5.1
	1118	85.04	85.05	Dicellograptus	D2	1.3	1.4	0.2	0.4	10.8
	1119	85.43	85.44	Dicellograptus	D2	1.7	2.0	1.4	2.6	10.1
	1120	85.67	85.68	Dicellograptus	D2	2.1	2.3	1.1	2.1	12.4
	1121	86.03	86.04	Dicellograptus	D2	1.9	2.1	1.2	2.3	9.3
	1122	86.29	86.30	Dicellograptus	D2	1.7	1.8	1.0	1.9	7.7
20043	19	86.62	86.68	Dicellograptus	D2	0.7	1.3	1.0	5.2	1.9
	1123	86.89	86.90	Dicellograptus	D2	0.9	1.0	1.0	1.9	5.4
	1124	87.37	87.38	Dicellograptus	D2	0.3	0.4	0.4	0.8	3.1
	1125	87.82	87.83	Dicellograptus	D1	0.3	0.4	0.3	0.6	2.1
	1126	88.17	88.18	Dicellograptus	D1	0.8	0.9	0.4	0.7	4.4
	1127	89.35	89.36	Dicellograptus	D1	1.5	1.6	0.5	1.0	10.9
	1128	89.89	89.90	Dicellograptus	D1	1.1	1.2	0.4	0.8	6.5
	1129	91.19	91.20	Dicellograptus	D1	0.8	0.9	0.6	1.1	4.4
	1130	91.84	91.85	Dicellograptus	D1	not analysed				
21261	1131	92.41	92.42	Dicellograptus	D1	0.7	1.5	1.3	6.4	2.5
	1132	92.45	92.46	Dicellograptus	D1	not analysed				

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
	1133	92.82	92.83	Dicellograptus	D1	not analysed				
21262	1134	93.16	93.17	Dicellograptus	D1	0.0	0.1	0.2	0.3	0.3
20044	20	93.40	93.47	Dicellograptus	D1	0.7	0.9	0.9	2.2	1.7
21263	1135	94.11	94.12	Dicellograptus	D1	0.6	0.6	1.5	0.0	2.8
	1136	94.33	94.34	Dicellograptus	D1	not analysed			0.0	
21264	1137	95.00	95.01	Dicellograptus	D1	0.1	0.6	0.7	3.9	1.2
	1138	95.23	95.24	Dicellograptus	D1	not analysed				
	1139	95.71	95.72	Dicellograptus	D1	not analysed				
21265	1140	96.35	96.36	Alum Shale	B4	6.3	6.6	1.6	2.1	3.0
20045	21	96.69	96.76	Alum Shale	B4	6.7	7.2	2.8	3.5	5.2
21266	1141	97.08	97.09	Alum Shale	B4	7.4	7.6	2.6	2.1	4.9
21267	1142	97.46	97.47	Alum Shale	B4	6.9	7.7	3.3	6.6	6.2
21268	1143	98.17	98.18	Alum Shale	B4	8.5	8.7	3.0	1.8	5.7
21269	1144	98.75	98.76	Alum Shale	B4	8.4	8.5	2.9	0.6	5.5
20046	22	98.81	98.90	Alum Shale	B3	7.1	7.4	3.6	3.1	6.7
21270	1145	99.31	99.32	Alum Shale	B3	10.6	11.2	4.1	4.2	7.6
21271	1146	99.72	99.73	Alum Shale	B3	10.7	10.8	7.8	1.5	14.5
21272	1147	100.24	100.25	Alum Shale	B3	11.1	11.7	3.7	5.1	7.0
21273	1148	100.54	100.55	Alum Shale	B3	11.8	12.1	5.2	2.5	9.7
21274	1149	100.78	100.79	Alum Shale	B3	8.7	8.9	4.2	1.1	7.8
21275	1150	101.22	101.23	Alum Shale	B3	10.3	10.5	6.4	1.9	12.0
20047	23	101.50	101.57	Alum Shale	B3	9.5	9.9	4.8	3.2	9.0
21276	1151	102.07	102.08	Alum Shale	B3	9.1	9.3	5.3	1.8	9.9
21277	1152	102.55	102.56	Alum Shale	B3	8.3	8.4	5.7	0.5	10.7
20048	24	102.87	102.93	Alum Shale	B3	11.3	11.9	4.9	4.8	9.1
21278	1153	103.26	103.27	Alum Shale	B3	10.9	11.3	5.3	3.1	9.9
21279	1154	103.70	103.71	Alum Shale	B3	13.9	13.8	5.9	0.0	11.1
21280	1155	104.13	104.14	Alum Shale	B3	11.2	11.7	5.1	4.2	9.6
21281	1156	104.59	104.60	Alum Shale	B3	10.5	10.9	5.5	2.7	10.3
21282	1157	105.07	105.08	Alum Shale	B3	10.4	10.4	5.4	0.0	10.1
21283	1158	105.43	105.44	Alum Shale	B3	11.6	11.7	6.0	0.7	11.2
20049	25	105.80	105.90	Alum Shale	B3	10.1	10.9	4.3	6.8	8.0
21284	1159	106.55	106.56	Alum Shale	B3	9.3	9.7	5.0	3.2	9.3
21285	1160	107.96	107.97	Alum Shale	B3	7.9	8.1	12.2	1.8	22.8
21286	1161	108.00	108.01	Alum Shale	B3	7.7	8.0	5.7	2.1	10.6
21287	1162	109.25	109.26	Alum Shale	B3	8.3	8.3	9.6	0.0	17.9
21288	1163	109.83	109.84	Alum Shale	B3	10.7	11.5	5.3	7.2	9.9
21289	1164	110.10	110.11	Alum Shale	B3	13.3	13.7	4.8	3.9	9.0
20050	26	110.90	110.98	Alum Shale	B3	8.4	9.0	6.4	4.8	12.0
21290	1165	111.25	111.26	Alum Shale	B3	12.4	12.6	4.9	1.4	9.1
21291	1166	111.65	111.66	Alum Shale	B3	10.4	10.3	7.0	0.0	13.1
21292	1167	112.51	112.52	Alum Shale	B3	9.3	9.1	8.8	0.0	16.4
21293	1168	112.98	112.99	Alum Shale	B3	10.1	10.2	7.1	1.2	13.3
20051	27	113.30	113.35	Alum Shale	B2	7.9	8.0	5.0	0.6	9.3
21294	1169	114.07	114.08	Alum Shale	B2	8.4	8.6	6.1	1.1	11.4
21295	1170	114.56	114.57	Alum Shale	B2	7.8	7.9	7.1	0.8	13.4

GEUS Lab. no.	Sample	Depth top (m)	Depth bottom (m)	Formation	Log unit	TOC (%)	TC (%)	TS (%)	Carbonate (%)	Pyrite (%)
20052	28	115.65	115.75	Alum Shale	B2	8.8	9.4	4.7	5.3	8.8
21296	1171	116.01	116.02	Alum Shale	B2	6.6	6.6	7.6	0.0	14.3
21297	1172	116.16	116.17	Alum Shale	B2	8.4	8.3	6.9	0.0	12.9
20053	29	116.775	116.86	Alum Shale	B2	7.3	7.6	6.4	1.9	11.9
21298	1173	116.97	116.98	Alum Shale	B2	6.2	6.1	6.3	0.0	11.9
21299	1174	117.04	117.05	Alum Shale	B2	7.2	7.0	5.9	0.0	11.1
21300	1175	117.69	117.70	Alum Shale	B2	6.7	6.7	6.7	0.0	12.5
21301	1176	119.27	119.28	Alum Shale	B2	6.6	6.5	6.0	0.0	11.2
20054	30	119.80	119.90	Alum Shale	B2	5.2	5.3	4.8	1.1	9.0
21302	1177	121.70	121.71	Alum Shale	B1	4.1	4.1	2.7	0.1	5.1
21303	1178	121.88	121.89	Alum Shale	B1	2.3	2.2	3.5	0.0	6.6

14. Appendix D: Plates with core photos

Plate 1

A: 3.135-3.185 m.
Greenish grey mudstone, laminated. Because the core is photographed wet the lithology appears rather dark.

B: 5.82-5.87 m
Laminated grey mudstone with thin greenish bands.

C: 9.145-9.19 m
Predominantly lighter grey-greenish laminated mudstone with few darker bands; small limestone nodule.

D: 9.77-9.805 m
Grey greenish mudstone with thin darker bands. Sporadic small burrows (dark, right hand side). Small limestone nodule.

E: 9.805-9.885 m (some reflection)
Grey-greenish mudstone few thin dark bands. Thin limestone band near top of core piece.

F: 10.95-11.01 m
Banded grey greenish mudstone

G: 14.51-14.58 m
Banded grey mudstone with some greenish bands.

Plate 2

A: 15.84-15.90 m
Banded mudstone, predominantly greyish.

B: 15.99-16.11 m
Thin-banded grey-greenish mudstone with some silt streaks (white; a thick one is seen near top of core piece). OBS: the apparent difference in dip is artificial due to turning of upper core piece

C: 16.66-16.745 m
Greenish, relatively lighter coloured mudstone

D:17.49-17.59 m
Grey to lighter grey mudstone with thin irregular silt laminae. Note burrowed sharp upper boundary of greyish mudstone.

Plate 3

A: 18.045-18.215 m
Upper part light grey non-laminated burrowed mudstone. Conglomerate with pyrite and small phosphorite nodules marks lower boundary of light grey mudstone. This horizon at 18.12-18.13 m marks upper boundary of the *convolutus* Zone. The conglomerate is underlain by 6.5 cm of burrowed grey mudstone, below which the mudstone becomes dark grey.

B: 19.70-19.88 m
Laminated, rather pyritic dark grey mudstone.

C: 19.88-19.96 m
Dark grey laminated mudstone. Whitish streaks are pyrite.

Plate 4

A: 23.36-23.515 m
Dark grey laminated mudstone with pyrite. Very thin laminae of silt (whitish) are also seen, e.g. close to bottom of core piece.

B: 27.035-27.12 m
Dark grey laminated mudstone with numerous laminae of silt (whitish).

C: 27.495-27.60 m
Dark grey laminated mudstone with thin laminae of silt (whitish), no macroscopic pyrite.

D: 30.50-30.57 m
Banded grey mudstone.

Plate 5

A: 32.02-32.23 m
Fault; crushed mudstone.

B: 33.38-33.56 m
Limestone concretion in rather dark grey mudstone.

Plate 6

A: 37.28-37.37 m
Relatively dark mudstone, laminated.

B: 38.06-38.31 m
Large limestone concretion. Surrounding mudstone relatively dark, laminated.

Plate 7

A: 39.72-39.96 m
Limestone concretion with internal calcite-filled vertical crack.

B: 45.26-45.35 m
Grey laminated mudstone with silt laminae (whitish).

C: 49.055-49.17 m
Banded, relatively lighter coloured mudstone. The colour bands are 2-10 mm thick.

Plate 8

A: 53.615-53.705 m
Grey laminated mudstone with thin silt laminae. Lithology lighter coloured than in interval with large limestone concretions above.

B: 55.49-55.62 m
Laminated grey mudstone with many and relatively thick silt bands, up to 7 mm thick (whitish).

C: 57.23-57.34 m
Banded grey mudstone; nearly no silt laminae.

D: 57.99-58.14 m
Grey laminated mudstone with some silt laminae, up to 3 mm thick.

Plate 9

A: ca. 59.05-59.20 m
Brecciated fault zone.

B: 61.21-61.29 m
Light grey mudstone, bioturbated.

C: Surface 61.36 m
Chondrites burrow.

D: 61.44-61.55 m
Light grey mudstone, partly bioturbated.

Plate 10

A: 61.73-61.94 m
Grey, indistinctly laminated mudstone above, becoming sandy downwards with c. 1 cm of sand at the base. Underlain by light grey mudstone burrowed at the top. Below pyrite laminae follows bioturbated light grey to grey mudstone.

B: 61.655-61.72 m
Light grey mudstone, burrowed.

C: 62.135-62.21 m
Limy mudstone (white speckled), bioturbated.

D: 62.57-62.64 m
Burrowed lighter grey to grey mudstone. Note Chondrites ”tree” in upper right hand side; also shown on Pl. 11:A.

Plate 11

A: 62.57-62.61 m
Close up of Chondrites “tree” seen on Pl. 10:D

B: 62.95-63.19 m
Sandy mudstone. Note black phosphorite nodules not far below top.

C: 63.28-63.33 m
Light grey bioturbated (”mottled”) mudstone.

Plate 12

A: 64.11-64.39 m
Fault

B: 69.02-69.19 m
Upper part bioturbated, non-laminated light grey mudstone. Lower part bioturbated but colour banded.

C: 70.26-70.33 m
Bioturbated light grey mudstone with thin dark mudstone seams.

Plate 13

A: 72.1-72.24 m
Bioturbated, rather homogenous grey to darker grey mudstone (whitish stripes: scars made by drilling equipment)

B: 73.66-73.79 m
Strongly bioturbated mudstone, predominantly lighter grey-greenish.

Plate 14

A: 74.18-74.31 m

Pyrite conglomerate at the base of the Lindegård Mudstone. Matrix bioturbated light grey mudstone.

B: 75.53-75.68 m
Laminated black shale with scattered pyrite ”plebs” (?burrows). Whitish laminae react with acid and seemingly represents disseminated lime.

C: 75.68-75.77 m (dry core)
Laminated black shale with scattered pyrite ”plebs” (?burrows). Whitish laminae react with acid and seemingly represents disseminated lime.

Plate 15

A: 76.295-76.41 m
Laminated black shale with scattered pyrite ”plebs” (?burrows, ?microbial mats). Whitish laminae react with acid and seemingly represents disseminated lime.

B: 78.125-78.21 m
Slightly less dark mudstone, laminated. Lesser pyrite than above (?microbial mats). Whitish laminae seemingly represents disseminated lime.

C: 78.25-78.32 m
Laminated black shale with abundant pyrite (laminae, band). Pyrite laminae may represent microbial mats.

D: Surface 78.29 m
Bedding surface covered by pyrite – microbial mat?

Plate 16

A: 78.77-78.895 m
Laminated black shale with abundant pyrite (laminae, “plebs”). Pyrite laminae may represent microbial mats. Other type of pyrite is suspected representing filled burrows.

B: Surface 78.86 m
Bedding surface covered by pyrite – microbial mat?

C: Surface 78.895 m
Bedding surface covered by pyrite – microbial mat?

D: 79.87-79.99 m
Laminated black shale with abundant pyrite (laminae, “plebs”). Pyrite laminae may represent microbial mats. Other type of pyrite is suspected representing filled burrows. Whitish horizons limy.

E: Surface 80.515 m
Bedding surface covered by pyrite – microbial mat?

F: Surface 81.455 m
Bedding surface covered by pyrite – microbial mat?

Plate 17

A: 81.465-81.62 m (dry core)
Laminated black shale with abundant pyrite (“plebs”, streaks), which are suspected representing filled burrows.

B: 81.49-81.59 m
Laminated black shale with abundant pyrite (“plebs”, streaks), which are suspected representing filled burrows.

C: Surface 82.47 m
?Burrow filled with pyrite

D: 83.12-83.23 m
Strongly bioturbated grey mudstone. White speckles represent highly reflective pyrite.

Plate 18

A: 83.42-83.52 m
Bioturbated grey to darker grey mudstone. Whitish spots represents highly reflective pyrite.

B: 83.915-83.975 m
Thin limestone with pyrite underlain by bioturbated grey-greenish mudstone.

C: 84.94-85.135 m
Bioturbated grey to lighter grey mudstone. White bands in the middle and near base: limestone.

Plate 19

A: 86.68-86.75 m (some reflection)
Bioturbated grey mudstone.

B: 86.90-86.975 m
86.9-86.975
Diagenetic limestone.

C: 86.97-87.08 m
Bioturbated grey mudstone.

D: 87.435-87.51 m
Grey mudstone (top) underlain by bentonite bed (composite). Note gradation in upper greenish bentonite.

Plate 20

A: 88.24-88.44 m
Thick composite bentonite, note variable grain size

B: 89.10-89.24 m
Thick composite bentonite, note variable grain size

C: 89.24-89,32 m
Silicified mudstone overlying bentonite, boundary irregular, erosive

Plate 21

A: 91.52-91.62 m
Dark coloured bentonite

B: 92.205-92.29 m
Slumped bentonite

C: 93.61-93.71 m
Silicified mudstone with thin bentonite

Plate 22

A: 95.095-95.26 m
Upper part of core pyritic conglomerate at base of the Komstad Limestone. Lower part of core greenish grey mudstone, bioturbated (?Tøyen Shale).

B: Approx. 95.29-95.39 m
Tøyen Shale? Greenish mudstone with small phosphorite nodules.

C: 95.325-95.435 m
Transition Tøyen Shale? / Alum Shale Fm with abundant barite. Note black small phosphorite nodules.

Plate 23

A: 96.30-96.38 m
Alum Shale with large pyrite nodule.

B: Surface 96.485 m
Bedding surface covered with *Rhabdiniopora* (graptolite).

C: 96.565-96.65 m
Pyrite and lime in Alum Shale

D: Surface 98.105 m
Bedding surface covered with *Rhabdiniopora* (graptolite).

E: 98.475-98.56 m
Alum Shale with large pyrite nodule.

F: 99.335-99.425 m (dry core)
Baryte in Alum Shale

Plate 24

A: 100.115-100.20 m
Baryte in Alum Shale

B: 103.12-103.22 m
Baryte in Alum Shale. Laminae of pyrite near base of core piece.

C: 103.97-104.04 m
Baryte in Alum Shale. Note horizons with concentrated “lumps” near base

D: 105.92-106.00 m
Baryte in Alum Shale.

Plate 25

A: 105.09-105.14 m
Laminae of disseminated pyrite in Alum Shale

B: 106.13-106.225 m
Small byrite crystals in Alum Shale

C: 106.74-106.83 m (some reflection)
Laminae of disseminated pyrite in Alum Shale. Note also horizons with white “dust”, likely barite.

D: 107.40-107.41 m
Shell beds in Alum Shale (*Orusia* level)

E: 107.56-107.645 m
Shell beds in Alum Shale (*Orusia* level)

Plate 26

A: Surface at 108.10 m
Shell bed in Alum Shale (brachiopod: *Orusia*)

B: 108.65-108.78 m

Stinkstone concretion with unusual diagenetic phenomena

C: 109.94-110.015 m
Concentration of small barite crystals in Alum Shale; most of the barite is recrystallized to pyrite

D: 110.76-110.86 m (dry core)
Pyrite in Alum Shale. Note high concentration of disseminated pyrite in same level as concretion.

Plate 27

A: 113.46-113.545 m
Laminated Alum Shale

B: 120.39-120.52 m
Upper part of the Andrarum Limestone. Note thin intercalation of Alum Shale at the base of the core piece.

C: 122.07-122.19 m
Conglomeratic Exsulans Limestone

D: 123.33-123.45 m
Strongly glauconitic intercalation in Rispebjerg Sandstone.

Plate 28

A: 123.88-124.0 m
Bioturbation in Rispebjerg Sandstone, partially glauconitic

B: 123.95-124.06 m
Bioturbation in Rispebjerg Sandstone, partially glauconitic

C: 124.52-124.65 m
Rispebjerg Sandstone, partially glauconitic

D: 124.75-124.87 m
Small phosphorite nodules in Rispebjerg Sandstone

A: 3.13-3.18 m

B: 5.82-5.87 m

C: 9.145-9.19 m

D: 9.77-9.805 m

E: 9.805-9.885 m

F: 10.95-11.01 m

G: 14.51-14.58 m

Plate 1

A: 15.84-15.90

C: 16.66-16.745 m

B: 15.99-16.11 m

D: 17.49-17.59 m

A: 18.045-18.215 m

B: 19.70-19.88 m

C: 19.88-19.96 m

A: 23.36-23.515 m

B: 27.035-27.12 m

C: 27.495-27.60 m

D: 30.50-30.57 m

A: 32.02-32.23 m

B: 33.38-33.56 m

A: 37.28-37.37 m

B: 38.06-38.31 m

Plate 6

A: 39.72-39.96 m

B: 45.26-45.35 m

C: 49.055-49.17 m

A: 53.615-53.705 m

B: 55.49-55.62 m

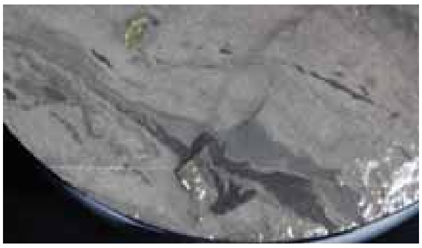
C: 57.23-57.34 m

D: 57.99-58.14 m

Plate 8

A: c. 59.05-59.20 m

B: 61.21-61.29 m

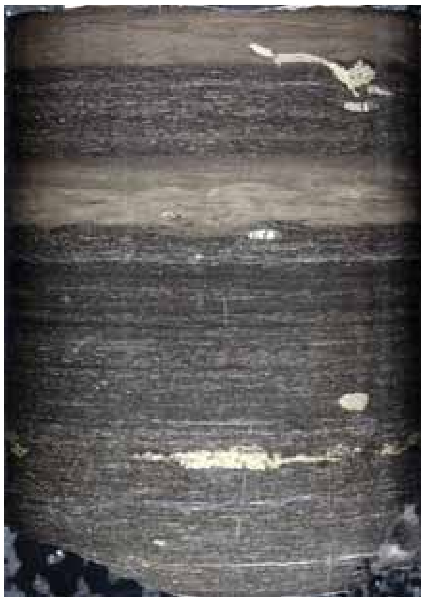


C: Surface 61.36 m

D: 61.44-61.55 m

A: 61.725-61.94 m

B: 61.655-61.72 m



C: 62.135-62.21 m

D: 62.57-62.64 m

Plate 10

A: 62.57-62.61 m

B: 62.95-63.19 m

C: 63.28-63.45 m

A: 64.11-64.39 m

B: 69.02-69.19 m

C: 70.26-70.33 m

A: 72.1-72.24 m

B: 73.66-73.79 m

A: 74.18-74.31 m

B: 75.53-75.68 m

C: 75.68-75.77 m

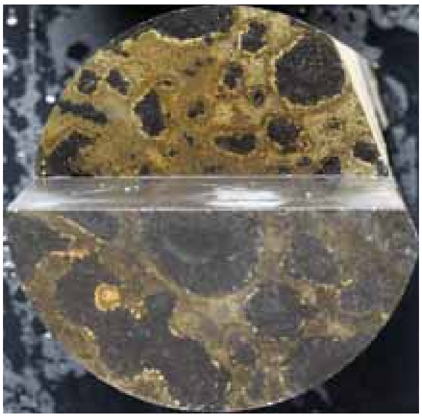
A: 76.295-76.41 m

B: 78.125-78.21 m

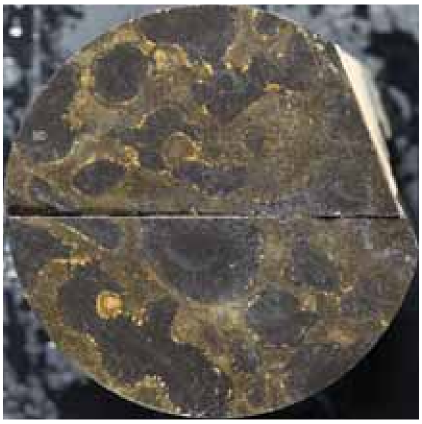
C: 78.25-78.32 m

D: Surface 78.29 m

A: 78.77-78.895 m

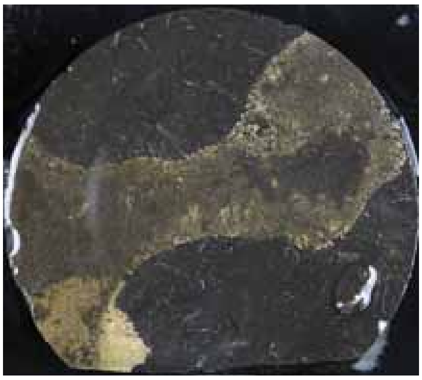


B: Surface 78.86 m

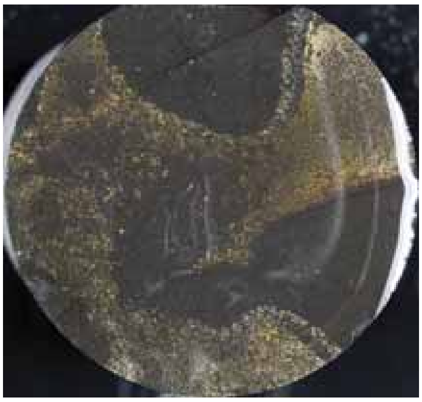


C: Surface 78.895 m

D: 79.87-79.99 m



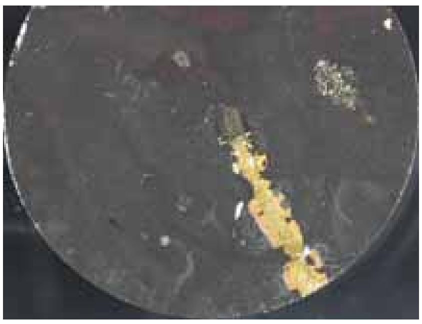
E: Surface 80.515 m



F: Surface 81.455 m

A: 81.465-81.62 m

B: 81.49-81.59 m



C: Surface 82.47 m

D: 83.12-83.23 m

A: 83.42-83.52 m

B: 83.915-83.975 m

C: 84.94-85.135 m

A: 86.68-86.75 m

B: 86.90-86.975 m

C: 86.97-87.08 m

D: 87.435-87.51 m

A: 88.24-88.44 m

B: 89.10-89.24 m

C: 89.24-89.32 m

A: 91.52-91.62 m

C: 93.61-93.71 m

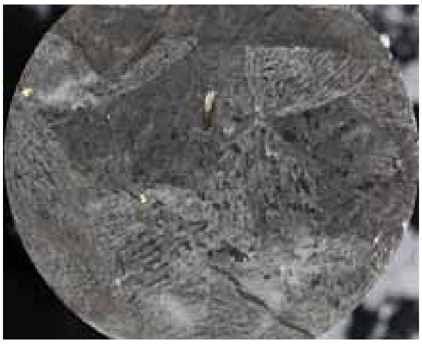
B: 92.205-92.29 m

A: 95.095-95.26 m

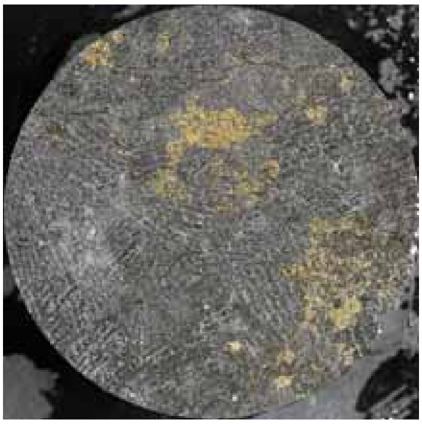
B: C. 95.29-95.39 m

C: 95.325-95.435 m

A: 96.30-96.38 m



D : Surface 98.105 m



B: Surface 96.485 m

E: 98.475-98.56 m

C: 96.565-96.65 m

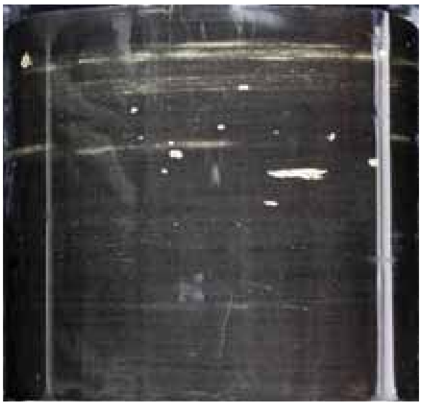
F: 99.335-99.425 m

A: 100.115-100.20 m

B: 103.12-103.22 m

C: 103.97-104.04 m

D: 105.92-106.00 m



A: 105.09-105.14 m

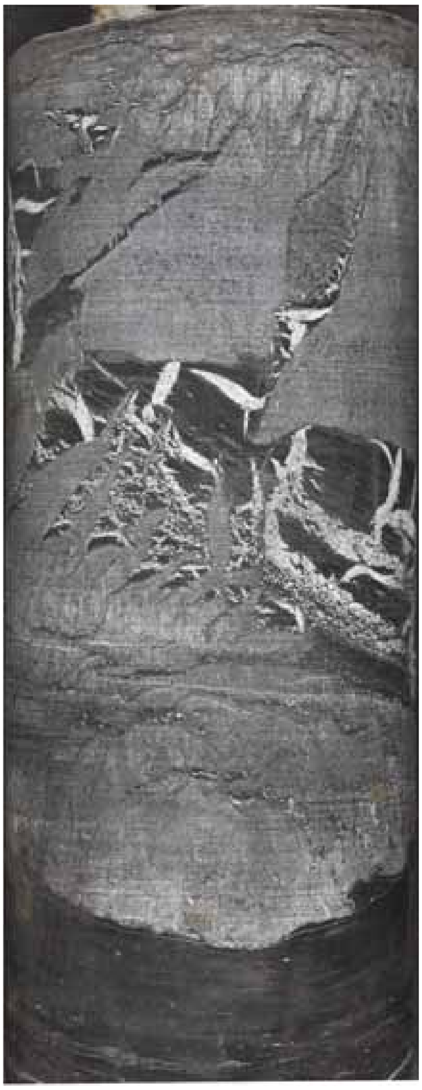
B: 106.13-106.225 m

C: 106.74-106.83 m

D: 107.385-107.425 m

E: 107.56-107.645 m

A: Surface 108.10 m



B: 108.65-108.78 m

C: 109.94-110.015 m

D: 110.76-110.86 m

A: 113.46-113.545 m

B: 120.39-120.52 m

C: 122.07-122.19 m

D: 123.33-123.45 m

A: 123.88-124.0 m

C: 124.52-124.65 m

B: 123.95-124.06 m

D: 124.75-124.87 m