The Cambro–Ordovician stratigraphic successions encountered in the Vasegård-1, Hjulmagergård-1 and Gravgærde-1 shallow boreholes on Bornholm, Denmark

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Geological Society of Denmark
https://2dgf.dk

Received 27 October 2025
Accepted in revised form 4 December 2025
Published online 18 December 2025

Nielsen, A.T. & Schovsbo, N.H. 2025. The Cambro–Ordovician stratigraphic successions encountered in the Vasegård-1, Hjulmagergård-1 and Gravgærde-1 shallow boreholes on Bornholm, Denmark. Bulletin of the Geological Society of Denmark, Vol. 74, pp. 267–277. ISSN 2245-7070. https://doi.org/10.37570/bgsd-2025-74-15

The Cambro–Ordovician successions penetrated by the fully cored shallow boreholes Gravgærde-1, Hjulmagergård-1 and Vasegård-1 are summarised; none has been described previously. All three boreholes are located south-west of Åkirkeby on Bornholm, Denmark. Gravgærde-1 drilled 4.1 m of the Alum Shale Formation and the upper 2.2 m of the Rispebjerg Member (Læså Formation). Hjulmagergård-1 drilled 7.65 m of the Dicellograptus Shale, 1.55 m of the Sularp Formation and 4.6 m of the Komstad Limestone before being terminated 3.7 m into the Alum Shale. The basal part of the Komstad Limestone is faulted and shows slight repetition, suggestive of reverse reactivation of the fault. The underlying Alum Shale is completely brecciated and clearly represents a fault zone. Vasegård-1 drilled the basal 2.0 m of the Dicellograptus Shale, the Sularp (1.65 m) and the Komstad Limestone (4.8 m) formations in their entirety, before being terminated 9.65 m into the Alum Shale.

The Alum Shale succession in Vasegård-1 was analysed using a handheld XRF analyser, allowing construction of a core gamma-ray curve that can be correlated with wireline-logged boreholes as well as with the Alum Shale exposed at Limensgade, where a detailed tie between the gamma-ray log pattern and the Tremadocian graptolite zonation has been established using a handheld gamma-ray logger. The correlation indicates that the upper part of the Alum Shale Formation in the Vasegård-1 core represents the Tremadocian (4.9 m) and the Furongian *Acerocarina* (1.5 m) plus the uppermost *Peltura* (3.2 m) superzones.

Gravgærde-1 confirms that the Alum Shale constitutes the bedrock in a belt extending from Soldatergård to north of Gravgærde. This belt is separated from the Ordovician strata to the east by a NW–SE striking fault with a vertical offset of around 40–50 m, which was intersected by the Hjulmagergård-1 borehole. A combination of data from Vasegård-1, Limensgade quarry and the nearby St. Bukkegård-1 borehole indicates that the Alum Shale Formation is at least 35.6 m thick in the Læså area but may reach 38 m. The maximum documented thicknesses on Bornholm of the Komstad Limestone (4.8 m) and the Ordovician Alum Shale (4.9 m) are recorded in the Vasegård-1 borehole.

Keywords: Bornholm, Cambrian, Ordovician, lithostratigraphy, Alum Shale Formation, Komstad Limestone, wireline log correlation.

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The Geological Survey of Greenland, now part of the Geological Survey of Denmark and Greenland (GEUS), developed a lightweight mobile drilling rig in the early 1980s for use in Greenland. To test the rig, two short boreholes (10.4 m and 19.6 m) were drilled on Bornholm in 1982: one in the garden at Gravgærde (then a field station of the Geological Institute, University of Copenhagen) and one in the meadow north-west of Vasegård in the Læså area, both south-west of Åkirkeby (Fig. 1). These boreholes are hereafter referred to as Gravgærde-1 and Vasegård-1. Both were fully cored; the core is 1 inch

(25 mm) in diameter. They have not previously been described, apart from a sketch log of the Sularp Formation in Vasegård-1 (Pedersen 1989, fig. 8). Given their usefulness for mapping, they are briefly documented here. Neither borehole was wireline logged, but the Vasegård-1 core has subsequently been analysed using a handheld XRF analyser, allowing construction of a gamma-ray log. All depths mentioned are drilled (isochore) depths below ground level.

The Hjulmagergård-1 borehole was drilled in 2012 using a larger rig operated by Faxe Kalk (see Schovsbo *et al.* 2015); the core diameter is 2 inches (55 mm). The borehole was planned to penetrate the Komstad Limestone Formation and the Alum Shale Formation in their entirety, and was therefore located a little WSW of the water-filled former Komstad Limestone Quarry in the field to the south-east of Hjulmagergård (*c.* 250 m ESE of Gravgærde-1; see Fig. 1). However,

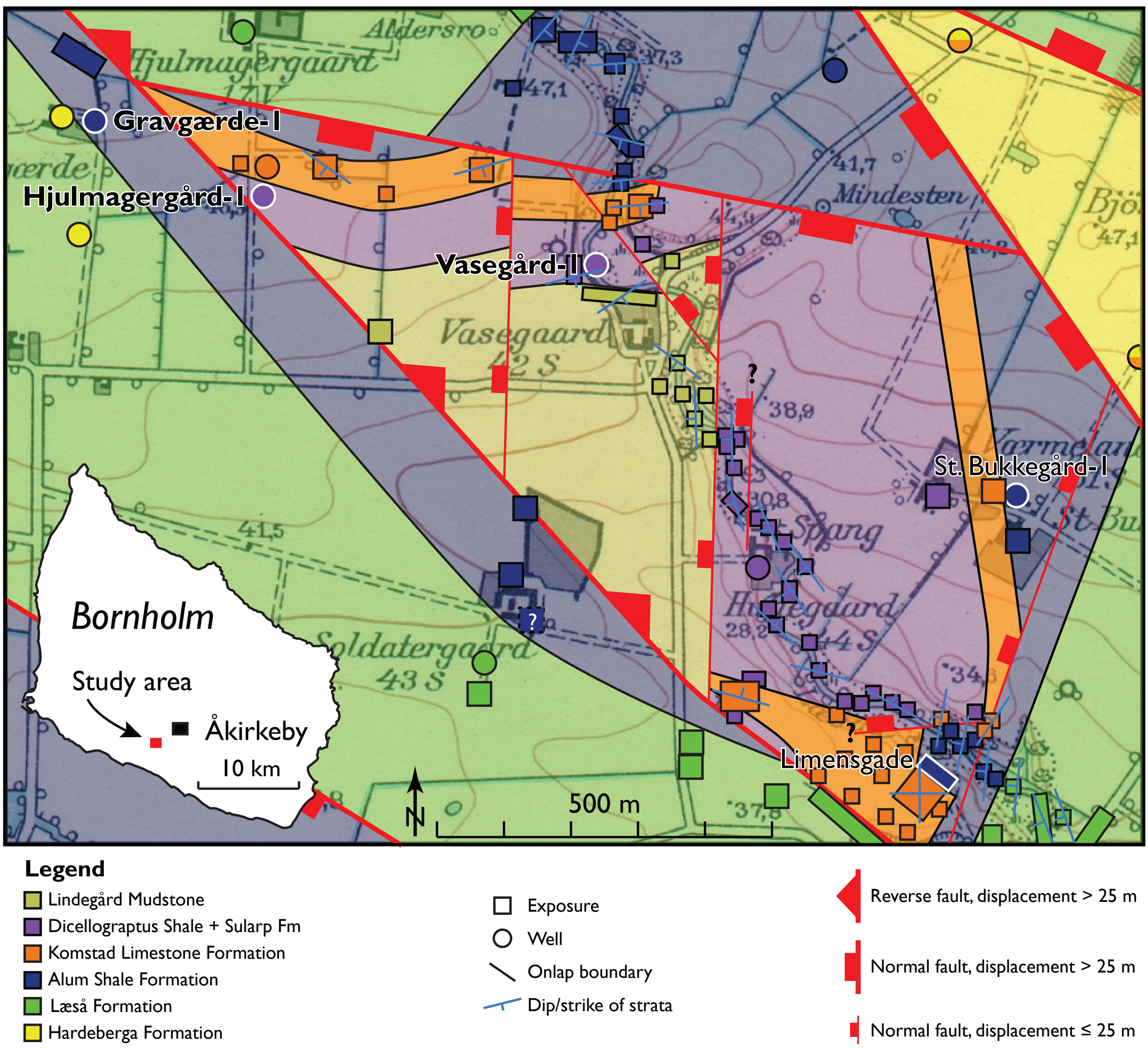

Fig. 1. Location of the discussed boreholes Gravgærde-1, Hjulmagergård-1, Vasegård-1 and St. Bukkegård-1 on southern Bornholm, plotted on a revised geological map of the area (ATN, unpublished). The abandoned shale–limestone quarry at Limensgade is also shown. The inset map of Bornholm in the lower left corner indicates the location of the mapped area (red square). The Rispebjerg sandstone (marked in yellow in wells) is mapped together with the Norretorp Member as the Læså Formation. Two wells within the north-eastern area mapped as the Hardeberga Formation are shown in two colours, indicating that it is not possible to determine whether these wells penetrate the Hardeberga or Langeskanse sandstone. The revised map will be discussed in greater detail in a forthcoming paper.

an unexpected major fault was encountered at the drill site, and drilling was abandoned at 20.5 m after penetrating only a short distance into the Alum Shale. The borehole collapsed after retrieving the drill string and no wireline logs were recorded.

All described cores are archived at GEUS. Synoptic logs of the three boreholes are presented in Fig. 2, and the lithostratigraphy is summarised in Table 1.

The Alum Shale on Bornholm straddles the Miaolingian ('Middle' Cambrian), Furongian ('Upper' Cambrian) and lower part of the Tremadocian (Lower Ordovician); the modern global series names are used hereafter.

The Gravgærde-1 borehole (DGU 246.912)

The core obtained is somewhat incomplete; the relatively low recovery for the Alum Shale as a whole (average 61%) reflects that this was the first borehole drilled with the then new equipment, and the operation – notably core take-up – was complicated by technical start-up issues. The approximate coordinates of the well site are N 55° 3′26.52″, E 14°52′27.11″ (garden east of the Gravgærde farmhouse, north of the small pond).

The core from the Quaternary till (0–4.05 m) was not preserved, except for a 0.2 m section from the interval 3.00–3.75 m. Alum Shale was encountered between 4.05 and 6.95 m, the basal 0.02 m of which consists of anthraconite (bituminous limestone). The recovered core totals 1.95 m and almost certainly represents the Miaolingian (cf. Nielsen *et al*. 2018, table 4).

Below follows grey, bedded limestone, presumably the Andrarum Limestone Bed, between 6.95 and 7.40 m; however, only 0.21 m of core was recovered from this section, so the true thickness is uncertain. The core from the interval 7.40–8.15 m consists predominantly of anthraconite with minor crumbling Alum Shale between 8.0–8.1 m. The recovered core from this 0.75 m thick interval is only 0.35 m. There is no Exsulans Limestone Bed in the core; whether this interval was lost during core recovery or whether the bed is genuinely absent at the drill site remains unknown. The total thickness of the Alum Shale in Gravgærde-1 is thus 4.1 m. Below follows the Rispebjerg Member of the Læså Formation (8.15–10.35 [TD] m). It consists mostly of grey, medium-grained, well-cemented sandstone. Between 8.98 and 9.11 m, common black nodules, up to 15 mm in diameter are present, presumably phosphorite. The basal interval (10.21–10.35 m) consists of fine-grained sandstone to siltstone containing some glauconite. A total of 2.03 m of core was recovered from the Rispebjerg Member, corresponding to a recovery of 92%.

The Hjulmagergård-1 borehole (DGU 246.838)

This borehole was drilled to a depth of 20.5 m in December 2012. The coordinates of the well site are N 55° 3′ 23.90″, E 14° 52′ 40.98″. Below 3.0 m of till, a strongly fractured section of the Dicellograptus Shale was encountered down to 10.65 m. For this reason, the stated depths are approximate, as the recovered core expanded in the boxes upon retrieval. Between 9.5 and 9.7 m, the core is finely crushed, and the interval presumably represents a minor fault. Thin bentonites were observed at 9.6 m (6–7 mm thick), 9.65 m (5 mm thick), 9.95 m (*c.* 5 mm thick), *c.* 10.5 m (a few mm thick) and possibly also at 9.9 m (a few mm thick), though the latter is uncertain owing to the fractured state of the core. Indistinct bioturbation (probably *Chondrites*) is seen from 9.65 m and continues down to *c.* 10.55 m. In this part the shale is dark grey and unlaminated. The bioturbation is recognised as a faint mottling and lack of lamination.

At 10.55 m, the colour of the shale changes to light grey. This shale contains dark burrows (probably *Chondrites*). At *c.* 10.72 m, a dark angular clast, 50 x 35 mm, is present together with several smaller black clasts in the light grey shale; this level evidently represents a sedimentary breccia. The bentonite-rich strata below this horizon are assigned to the Sularp Formation, traditionally regarded as the lower part of the Dicellograptus Shale on Bornholm.

Table 1. Thicknesses of the Cambro–Ordovician formations in the Gravgærde-1, Hjulmagergård-1 and Vasegård-1 boreholes

		Gravgærde-1	Hjulmagergård-1	Vasegård-1
Ordovician	Dicellograptus Shale		3.0–10.72 m (>7.72 m)	1.58–3.56 m (>1.98 m)
	Sularp Formation		10.72–12.20 m (1.48 m)	3.56–5.23 m (1.67 m)
	Komstad Limestone		12.20–16.80 m (~4.6 m)	5.23–10.01 m (4.78 m)
Cambrian	Alum Shale Formation	4.05–6.95 m (>2.9 m)	16.80–20.50 m (>3.7 m)	10.01–19.64 m (>9.63 m)
	Rispebjerg Member	6.95–10.35 m (>3.4 m)		

The Sularp Formation (proposed by Lindström 1953) has traditionally been regarded as the lower part of the Dicellograptus Shale on Bornholm.
The Rispebjerg Member forms the upper part of the Læså Formation (Nielsen & Schovsbo 2007).

Below 10.85 m the core was intact when recovered but has since disintegrated. The main part consists of a slightly more than 1-m-thick bentonite with a few thin shale interbeds (not logged in detail). A 0.1 m-thick conglomerate follows between 12.10 and 12.20 m, underlain by the Komstad Limestone Formation. The core of this grey, compact limestone is in good condition. Between 15.45 and 15.7 m, the limestone is crushed (later cemented, presumably with calcite), forming a fault breccia (Fig. 5A). Below this level,

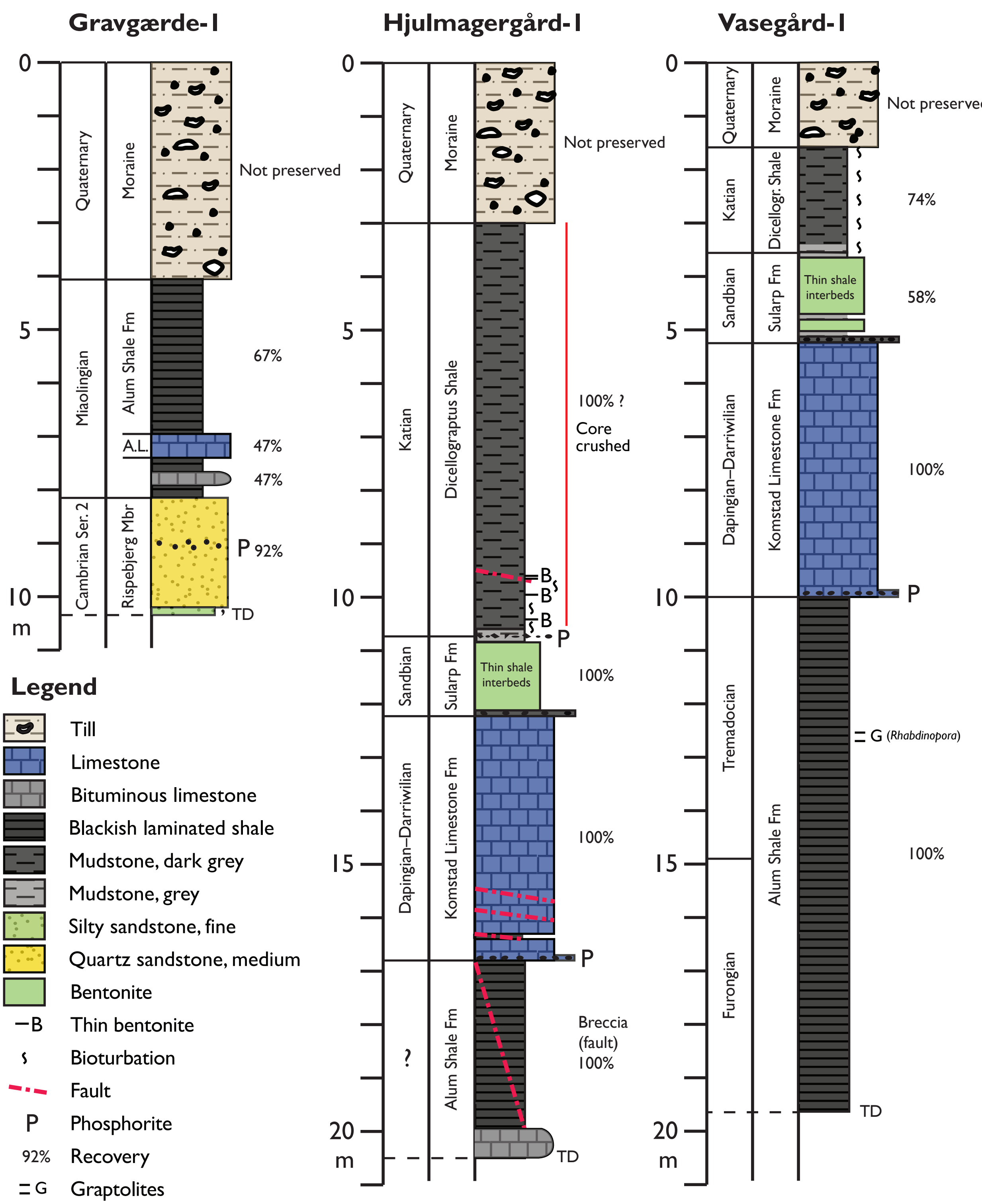

Fig. 2. Synoptic logs of the three boreholes described in this paper. For location of the boreholes, see Fig. 1.

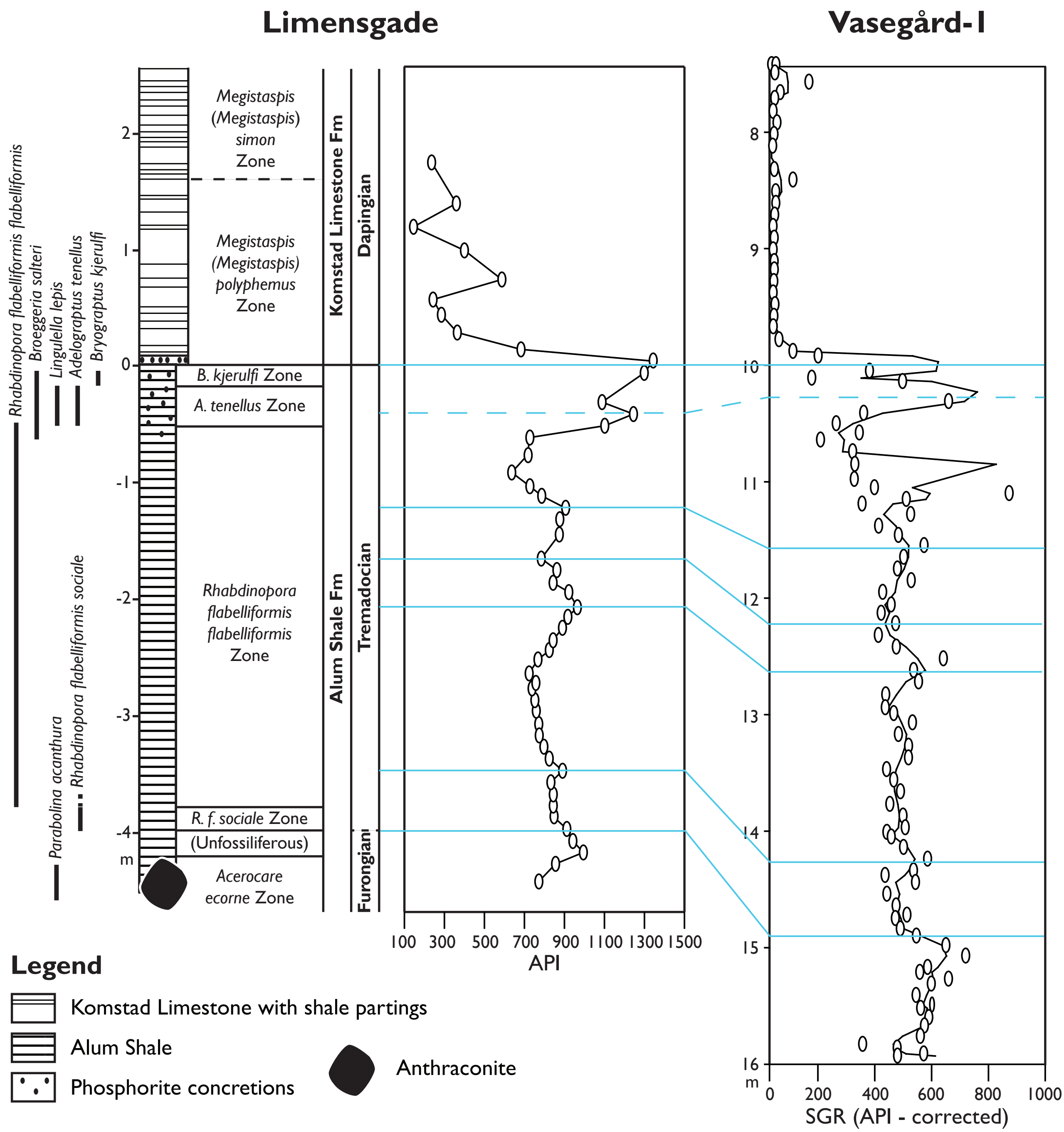

Fig. 3. Log of the Alum Shale and Komstad Limestone exposed in the abandoned limestone/shale quarry at Limensgade (for location, see Fig. 1). The Komstad Limestone log is adopted from Nielsen (1985), while the graptolite stratigraphy is taken from an unpublished study by von Jansson (1979). *Rhabdinopora flabelliformis sociale* is synonymised in modern literature with *R. canadensis* (see Maletz *et al.* 2023), which has its first appearance in the upper half of the *Rhabdinopora campanulatum* Zone. However, since the fossil material from Limensgade has not been re-examined by a graptolite expert, the original naming is retained. This also applies to the *R. flabelliformis* Zone, now included within the *Anisograptus matanensis* Zone (see Nielsen *et al.* 2023 for a brief review of the current graptolite zonation). Rare specimens of the trilobite *Parabolina acanthura* were reported from the site by Poulsen (1923); see also Nielsen & Andersen (2021). No anthraconite is currently exposed at this level in the abandoned quarry, not even after the site was extensively cleared in 2017. Accordingly, no limestone nodules were present where the gamma-ray profile was logged. The conodont zonation of the Komstad Limestone was investigated by Stouge (1974), and based on this, a correlation with the detailed trilobite zonation developed in the Skelbro Quarry by Nielsen (1995) has been established, as shown.

the strata dip more steeply, around 30–40°, increasing downwards. There is also a minor internal disturbance in the Komstad Limestone between 15.85 and 16.05 m, where the core is cut by small, oblique faults with slight crushing and smearing of Alum Shale along the fault planes. A larger fault, dipping *c.* 30°, truncates the Komstad Limestone at 16.3 m and is underlain by a breccia of crushed Alum Shale between 16.3 and 16.4 m. A lower slice of the Komstad Limestone then extends down to 16.78 m; this interval includes the characteristic basal conglomerate, 0.10–0.12 m thick. In this part of the core, the strata are obliquely oriented, dipping at *c.* 40°. Excluding the intervening brecciated Alum Shale, the total thickness of the Komstad Limestone is therefore *c.* 4.6 m; however, given the tectonic complications (and the strong dip of the lower part), this figure should be treated with caution.

Below 16.78 m, the core consists of brecciated Alum Shale with angular fragments generally < 2 cm (Fig. 5B). A few larger core pieces consist of anthraconite, also crushed and cut by mm-thick calcite-cemented veins. However, even so, the core quality on recovery was surprisingly good, although it has since disintegrated to the extent that it can no longer be removed from the boxes in a coherent state. The breccia also appears to dip at around 40°; this is obviously a fault zone. The breccia continues to 20.0 m, and the shale between 19.4 and 20.0 m is completely crushed and much more finely fragmented than the rest of the brecciated shale, presumably representing a discrete fault plane. The interval 20–20.5 m (TD) consists of an uncrushed anthraconite concretion. Drilling was terminated at 20.5 m, and it is therefore unknown whether the crushed fault zone continues below the anthraconite having a more resistant lithology.

The slight repetition of the lower part of the Komstad Limestone, together with the presence of smeared Alum Shale along minor fault planes, indicates modification of the fault by later reverse movements.

The Vasegård-1 borehole (DGU 246.913)

This borehole was drilled in the meadow adjacent to the Læså, north-west of Vasegård (Fig. 1). The approximate coordinates of the well site are N 55° 3'19.86", E 14°53'9.34". Vasegård is well known for the instructive exposures of Dicellograptus Shale

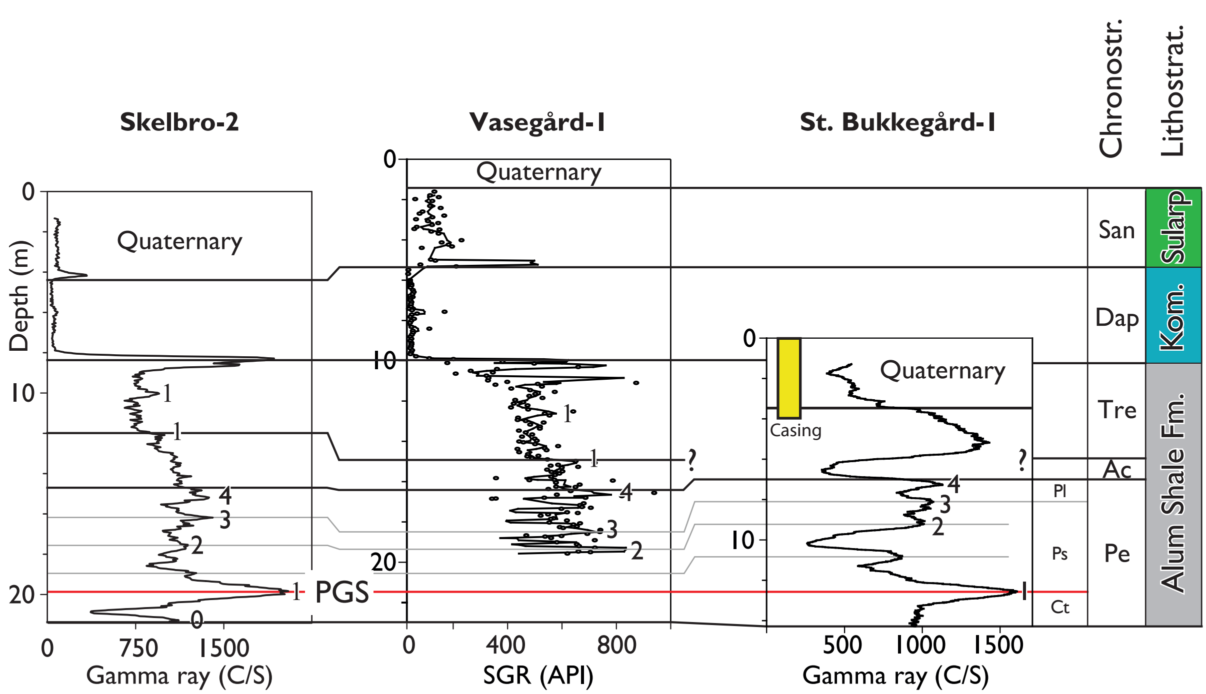

Fig. 4. Correlation of the Alum Shale in the Vasegård-1 borehole with the Skelbro-2 and St. Bukkegård-1 wells, based on gamma-ray logs. The small numbers adjacent to the curves identify correlatable gamma-ray maxima (see Nielsen *et al.* 2018 for details; location of the Skelbro-2 borehole is also shown in that paper). The Vasegård-1 gamma-ray log is constructed based on core hand-held XRF measurements (see text for details). Abbreviations: PGS: *Peltura* gamma-ray spike; C/S: Counts per second; SGR: Sum gamma-ray; Ct: *Ctenopyge tumida* Zone; Ps: *Peltura scarabaeoides* Zone; Pl: *Parabolina lobata* Zone; Pe: *Peltura* Superzone; Ac: *Acerocarina* Superzone; Tre: Tremadocian; Dap: Dapingian; San: Sandbian.

and Lindegård Mudstone in the southwestern bank of the Læså stream (Hadding 1915a,b; Poulsen 1936; Gry 1948; Bergström & Nilsson 1974; Vandenbroucke *et al.* 2013; for a review of the current lithostratigraphic nomenclature, see Nielsen *et al.* 2023). The underlying Sularp Formation was excavated and described by Funkquist (1919) (see also Nørregård 1925), and the upper part of the Komstad Limestone Formation is exposed across the meadow in a waterlogged abandoned quarry situated just east of the Læså, about 100 m NNE of the well site, as well as in the riverbed adjacent to the quarry (Fig. 1).

The Vasegård-1 borehole penetrated the basal part of the Dicellograptus Shale, the entire Sularp and Komstad Limestone formations, and was terminated at 19.64 m within the Alum Shale Formation. The core from the overlying till (0–1.58 m) was not preserved. The core recovery was low in the upper part of the borehole above the Komstad Limestone; this interval is illustrated by Pedersen (1989, fig. 8). It comprises the basal part of the Dicellograptus Shale (1.58–3.56 m), consisting of dark grey shale that is partly non-laminated (likely bioturbated, although the burrows are generally indistinct). Core recovery in this interval was 74%. This unit is underlain by the bentonite-rich Sularp Formation (3.56–5.23 m). The boundary is marked by a shift in colour to bioturbated light grey mudstone with a greenish tint and, shortly below, thick bentonites appear. No conglomerate was observed at the boundary, although Pedersen (1989, fig. 8) indicated such a layer. The core has rotated during drilling at this level, presumably resulting in some core loss. A conglomerate is present at the boundary in the nearby section excavated and described by Funkquist (1919), and the thickness of the Sularp Formation in the borehole closely matches that recorded in the excavated section. The core recovery within this unit was low (58%), owing to the numerous bentonite beds. The top of the basal conglomerate of the Sularp Formation is located at 5.11 m. The upper 50 mm contains black, rounded clasts (probably phosphorite) up to 25 mm in diameter. Below follows 30 mm of light grey shale with common black burrows, probably *Chondrites*, underlain by 40 mm of grey shale rich in small pyrite nodules. There are thus no black clasts in the 70 mm of shale between the conglomerate *sensu stricto* and the top of the Komstad Limestone, which is marked by a sharp, smooth surface. It remains an open question whether these 70 mm of grey shale represent a thin veneer of the Almelund Shale known from Skåne (see Nielsen *et al*. 2023 and references therein) or simply an atypical development of the conglomerate, which is up to 20 cm thick elsewhere on southern Bornholm (Grönwall 1916, p. 74). For the time being, the interval is assigned to the Sularp Formation.

The underlying Komstad Limestone Formation is 4.78 m thick (5.23–10.01 m) and represents the thickest development of this unit recorded on Bornholm (cf. Nielsen 1995; Nielsen *et al*. 2018, fig. 16). Core recovery from the Komstad Limestone and the underlying Alum Shale was essentially 100%. The upper part of the underlying Alum Shale was drilled between 10.01 and 19.64 m, including the entire Tremadocian part of the formation. Stipes of the graptolite *Rhabdinopora* were observed on surfaces at 12.53 m and 12.70 m. Drilling was terminated in the Furongian part of the formation (see below).

Fig. 5. Breccias in the 55 mm wide Hjulmagergård-1 core. **A**. Crushed and re-cemented Komstad Limestone, 15.45–15.65 m. **B**. Crushed Alum Shale, 17.9–18.1 m, photographed in a dry state so that the blackish shale appears grey.

Correlation of the Alum Shale in Vasegård-1

The Vasegård-1 core was analysed in 2018 using a handheld Niton™ XL3t GOLDD+ XRF device at the Subsurface Laboratory, GEUS. Element concentrations were measured at 214 levels in the core, corresponding to approximately every 80 mm in the interval 1.61–19.57 m. Details of the analytical procedure and applied corrections are provided by Schovsbo *et al*. (2018). The corrected U, K and Th concentrations were converted to American Petroleum Institute (API) units using the algorithm by Ellis & Singer (2007):

Sum gamma-ray (API units) = 4 × Th (ppm) + 8 × U (ppm) + 16 × K (wt%).

Three outliers with anomalous U concentrations were removed from the data before a running average of three data points was used to construct the gamma-ray curve shown in Fig. 3. The gamma-ray log is an excellent tool for correlating the Alum Shale due to its high and strongly variable uranium content (cf. Schovsbo *et al*. 2018; Nielsen *et al*. 2018).

Correlation with the Limensgade section

The abandoned shale/limestone quarry at Limensgade was cleared in the spring of 2017, resulting in excellent exposure of the Alum Shale and the overlying Komstad Limestone. Shortly afterwards, a survey of the section (with primary focus on the Alum Shale) was carried out in May 2017 using a Georadis GT-32 portable gamma-ray logger provided by the Department of Geosciences, University of Copenhagen. Measurements were acquired at approximately 10 cm intervals, with each data point representing a two-minute recording period. On this basis, the gamma-ray log shown in Fig. 3 was produced. Figure 3 also shows a detailed correlation of the log pattern with the unpublished graptolite zonation established by von Jansson (1979); for remarks on correlation with the current zonation, see the caption to Fig. 3. Von Jansson found that the Tremadocian Alum Shale at this locality is 4.0 m thick, not 2.6 m thick as originally reported by Poulsen (1922). The gamma-ray log obtained, which can be correlated with the Gislövshammar-2 borehole in Skåne and several wireline-logged wells on southern Bornholm (Nielsen *et al*. 2018), corroborates this conclusion (see further remarks below).

The basal conglomerate of the Komstad Limestone contains phosphorite and glauconite and is marked by a prominent spike on the gamma-ray log, which can also be clearly identified on the gamma-ray log of Alum Shale constructed for the Vasegård-1 core (Fig. 3). At Limensgade, this bed is underlain by 0.6 m of Alum Shale containing small phosphorite nodules (Fig. 3), as already noted by Poulsen (1922); these account for the high gamma-ray intensity in this interval. This upper interval of the Alum Shale with elevated gamma-ray readings is consistently double-peaked in all investigated sections on Bornholm, except in the Billegrav-2 borehole (cf. Nielsen *et al.* 2018, fig. 16), suggesting that two levels with more common phosphorite are present. This is unsurprising, given the very strong condensation of this interval (compare with the Gislövshammar-2 borehole in Skåne, see Nielsen *et al*. 2018, fig. 14). The lower 3.4 m of the Tremadocian Alum Shale include four moderate maxima that can be correlated between Vasegård-1 and Limensgade (Fig. 3). There are no obvious lithological differences between the shale at these levels and the remaining Alum Shale.

The basal part of the Tremadocian Alum Shale is incomplete on Bornholm, with most of the *Rhabdinopora campanulatum* Zone absent, representing a hiatus of approximately 2–2.5 million years (see Nielsen *et al.* 2023 for a brief review of the current graptolite zonation). Given this strong condensation, it is possible that the unfossiliferous interval separating the graptolite-bearing shale from the Furongian strata at the base of the section is, in fact, of Ordovician age (see Fig. 3). If this interpretation is correct, the Cambro–Ordovician boundary is marked by a small peak in gamma-ray values followed by a decline in gamma-ray intensity. However, in Scandinavia it is customary to place the boundary at the first occurrence of planktonic graptolites, a convention that is also followed here, as in Nielsen *et al*. (2018). Accordingly, the boundary is placed on the descending limb of the gamma-ray log curve above the minor maximum that marks the top of the Furongian *Acerocarina ecorne* Zone. In Skåne, an unfossiliferous interval included within the *Acerocarina* Superzone also separates the trilobitic uppermost Cambrian from the graptolite-bearing Ordovician shales (see Nielsen *et al*. 2018 and references therein). If the Cambro–Ordovician boundary is located at *c.* 14.9 m in Vasegård-1 as indicated, the Ordovician section of the Alum Shale is *c.* 4.9 m thick, which represents the thickest development recorded on Bornholm.

Comparison with Skelbro-2 and St. Bukkegård-1

The double gamma-ray peak marking the boundary between the Alum Shale and the Komstad Limestone in Vasegård-1 is also well developed in the Skelbro-2 gamma-ray log (Fig. 4). Below that, the moderate gamma-ray peak labelled 1 is likewise correlatable, whereas correlation of the smaller maxima at lower levels is less convincing. The gamma-ray log response across the Cambro–Ordovician boundary, marked by a minor peak followed by a slight decrease in intensity (as discussed above), is similar to that observed in the Skelbro-2 gamma-ray log. The upper part of the Furongian exhibits three gamma-ray peaks (Pe-2, Pe-3 and Pe-4) above the prominent PGS spike, which can also be correlated between Skelbro-2 and Vasegård-1 (see Nielsen *et al*. 2018 for details of the Alum Shale gamma-ray log stratigraphy). The Vasegård-1 borehole appears to terminate *c.* 2 m above the level of the PGS spike, while the overlying three peaks are well expressed.

In the Vasegård-1 gamma-ray log, there is a conspicuous peak at 11 m, overlain by a pronounced low (Fig. 4). This log pattern is not observed in the Skelbro-2 borehole or in any other boreholes on southern Bornholm (cf. Nielsen *et al*. 2018, fig. 16). Phosphorite nodules appear to be present in the interval with high gamma-ray readings just below 11 m. At 11.0 m, there is a thin limestone bed (*c*. 10 mm) with an erosive top overlain by small clasts (up to 5 x 15 mm), suggestive of a minor hiatus. Immediately above, small nodules of limestone occur between 10.86–11.0 m, which may account for the low gamma-ray intensity in that interval.

The gamma-ray log motif of the Ordovician and uppermost Furongian succession is atypical in the St. Bukkegård-1 well (Nielsen *et al*. 2018, fig. 12), complicating assessment of the total thickness of the Alum Shale Formation in the Læså area. The St. Bukkegård-1 well penetrated Alum Shale from *c.* 3.1 m directly below the Quaternary section to a depth of 37.8 m; hence, the Alum Shale Formation is at least 34.7 m thick at the drill site. The Tremadocian section of the Alum Shale in this borehole is probably at least 4 m thick, as at Limensgade, located *c.* 400 m south of St. Bukkegård. If the thickness of the Furongian *Acerocarina* Superzone – overlying the recognisable Pe-2 to Pe-4 peaks – is comparable to that in the Vasegård-1 borehole, located *c.* 750 m WNW of St. Bukkegård, where it measures *c.* 1.5 m (Fig. 4), the total thickness of the Alum Shale Formation in the Læså area may be estimated at ≥ 35.6 m.

Discussion

On unpublished draft maps made by the late Helge Gry (probably in the 1950s), occurrences of Alum Shale are indicated due north of Gravgærde as well as in the garden of Soldatergård (Fig. 1). Strangely, these observations were ignored when Gry (1960, 1969) compiled his geological map of Bornholm. The presence of Alum Shale in Gravgærde-1 is thus consistent with these earlier, unpublished observations. This implies that a belt of Alum Shale extends from Soldatergård to Gravgærde, which must be separated by a major fault from the Ordovician strata exposed farther north-east along the Læså stream, near Vasegård, and in the former Hjulmagergård and Vasegård limestone quarries. Parts of this succession are also encountered in the Hjulmagergård-1 and Vasegård-1 boreholes as described in this paper. Hjulmagergård-1 intersected the separating fault, which has a vertical displacement estimated at around 40–50 m and presumably strikes NW–SE (Fig. 1). The minor repetition of the Komstad Limestone in this well, separated by brecciated Alum Shale, indicates reverse reactivation of the fault. This interpretation accords with the orientation of the Komstad Limestone in the nearby Hjulmagergård quarry, which dips towards the fault, also indicating reverse drag (Fig. 1).

The upper part of the gamma-ray log is atypical in the St. Bukkegård-1 well (Nielsen *et al.* 2018, figs 12, 16; see also Fig. 4). The Alum Shale section cored in Vasegård-1 represents this interval, with the characteristic Pe-2, Pe-3 and Pe-4 gamma-ray log markers identifiable in both wells, providing robust tie-points for comparison. Correlation based on the gamma-ray logs shows that the Tremadocian succession is *c.* 4.9 m thick in the Vasegård-1 borehole, which – like the 4.8 m thick overlying Komstad Limestone – represents the thickest development of these units known from Bornholm. Somewhat surprisingly, the underlying *Acerocarina* Superzone is thinner (1.5 m) than in the Skelbro-2 core (2.7 m, see Nielsen *et al*. 2018). Adding the thickness of the *Acerocarina* Superzone, as recorded in the Vasegård-1 borehole, and the Tremadocian part of the Alum Shale, as observed in the old quarry at Limensgade, to the confidently correlated lower main part of the Alum Shale in the St. Bukkegård-1 well, suggests that the Alum Shale is at least 35.6 m thick in the Læså area. The maximum thickness may approach 38 m if the Tremadocian at St. Bukkegård is as thick as in the Vasegård-1 borehole and the *Aceroca-*

rina Superzone is as thick as in the Skelbro-2 borehole.

The Alum Shale section exposed at Limensgade provides a detailed tie between the gamma-ray log pattern and the graptolite zonation (Fig. 3). The gamma-ray log pattern, which can also be correlated with the Gislövshammar-2 borehole in Skåne, Sweden, and several wells on southern Bornholm (see Nielsen *et al*. 2018, fig. 14), corroborates the greater thickness of the Ordovician part of the Alum Shale, as identified by von Jansson (1979). The Cambro–Ordovician boundary on Bornholm is marked by a relatively inconspicuous gamma-ray peak followed by a slight decline in gamma-ray intensity. Reliable recognition of this subtle log pattern requires that the interval be viewed in context with the more prominent gamma-ray spikes in the upper Cambrian and at the base of the Komstad Limestone.

Conclusions

- The Cambro–Ordovician successions penetrated by the fully cored shallow boreholes Gravgærde-1, Hjulmagergård-1 and Vasegård-1, hitherto undescribed, are summarised.
- Alum Shale forms the bedrock in a belt from Soldatergård to north of Gravgærde, which is not shown on the existing geological map of the area.
- This belt is separated from Ordovician strata to the east by a NW–SE striking fault with an estimated vertical offset of around 40–50 m that appears to have undergone minor reverse reactivation.
- A gamma-ray log was constructed for the Vasegård-1 core, based on handheld XRF measurements, allowing correlation with wireline logged boreholes on southern Bornholm.
- The Alum Shale Formation is at least 35.6 m in the Læså area but may reach 38 m. These estimates are based on the succession encountered in the St. Bukkegård-1 well, supplemented by the new stratigraphic data from the Vasegård-1 borehole and the thicknesses known from Skelbro-2, correlated using gamma-ray logs.
- Maximum thicknesses on Bornholm of the Komstad Limestone Formation (4.8 m) and the Ordovician part of the Alum Shale (*c.* 4.9 m) are recorded in the Vasegård-1 borehole.
- A detailed tie between the gamma-ray log pattern and the graptolite zonation for the Ordovician part of the Alum Shale is established in the section exposed at Limensgade.

Acknowledgements

The authors thank referees Jon Ineson and Gunver Krarup Pedersen for their constructive comments on an earlier version of the manuscript, which helped to improve the final version.

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