Glauconitic deposits at Julegård on the south coast of Bornholm, Denmark dated to the Cambrian

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Bioturbated, glauconitic siltstones and sandstones are overlain by presumed Upper Triassic deposits at coastal exposures at Julegård on the south coast of Bornholm. These glauconitic deposits have not previously been dated. A ^{40}Ar-^{39}Ar dating of the glaucony gives an age of 493 ± 2 Ma suggesting the deposits belong to the Lower Cambrian Norretorp Member of the Læså Formation. The shallow marine deposits are strongly bioturbated, but only a single ichnoassociation is represented. The ichnogenus is referable to either *Trichophycus* Miller and Dyer, 1878 or *Teichichnus* Seilacher, 1955. Rare examples of *Rusophycus* Hall, 1852, probably trilobite trace fossils, are also represented.

Keywords: Bornholm, Cambrian, ^{40}Ar-^{39}Ar dating, trace fossils, *Tricophycus, Teichichnus, Rusophycus*

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The age and stratigraphy of the sediments on the landward edge of the down-faulted Arnager Block on the south coast of Bornholm at Julegård (Figs 1 and 2) have been open for more than one interpretation. Grönwall and Milthers (1916) and Gry (1969) mapped all the sediments cropping out between a point approximately 200 m east of Risebæk and a point aproximately 400 m west of Julegård, a coastal section of about 1.5 km, as Upper Triassic. Gravesen *et al.* (1982) mentioned that the stratigraphic position of the beds near Julegård is uncertain and that they may belong to the Lower Cretaceous Rabekke Formation. Hamann (1987), Jensen and Hamann (1989), and Graversen (2004a; 2004b; 2009) also placed these sediments in the Lower Cretaceous.

In most years the coastal exposures between Risebæk and Julegård are poor and only show minor outcrops of various white and greenish grey sandstones to a large degree covered by displaced red and green Triassic clay, or by down-wasted Quaternary deposits. In 2008 several storms, however, had removed large parts of the slope deposits and formed relatively large and well exposed coastal sections at Julegård (Figs 2 and 3). The newly exposed sections show glauconitic marine sediments at their base. These sediments, which are rich in trace fossils, are overlain by red and green clay of typical Late Triassic appearance and by light greyish to whitish fluvial sand and conglomerates.

None of these sediments have previously been described in detail and a first description of the glauconitic marine deposits at the base of the Julegård section is presented here. Their contact to overlying terrestrial deposits of presumed Triassic age appears gradational but as the trace fossil content in the shallow marine, glauconitic sediments is of Cambrian affinity, it was decided to carry out a ^{40}Ar-^{39}Ar dating of the glaucony to support the sedimentological studies.

Geological setting

The study area on the south coast of Bornholm is situated in the Fenno-Scandian Border Zone at the boundary between the Northwest European Craton and the Baltic Shield-East European Platform (Fig. 1; EUGENO-S 1987; Graversen 2004a; 2004b; 2009).

The studied section lies at the northeastern (land-

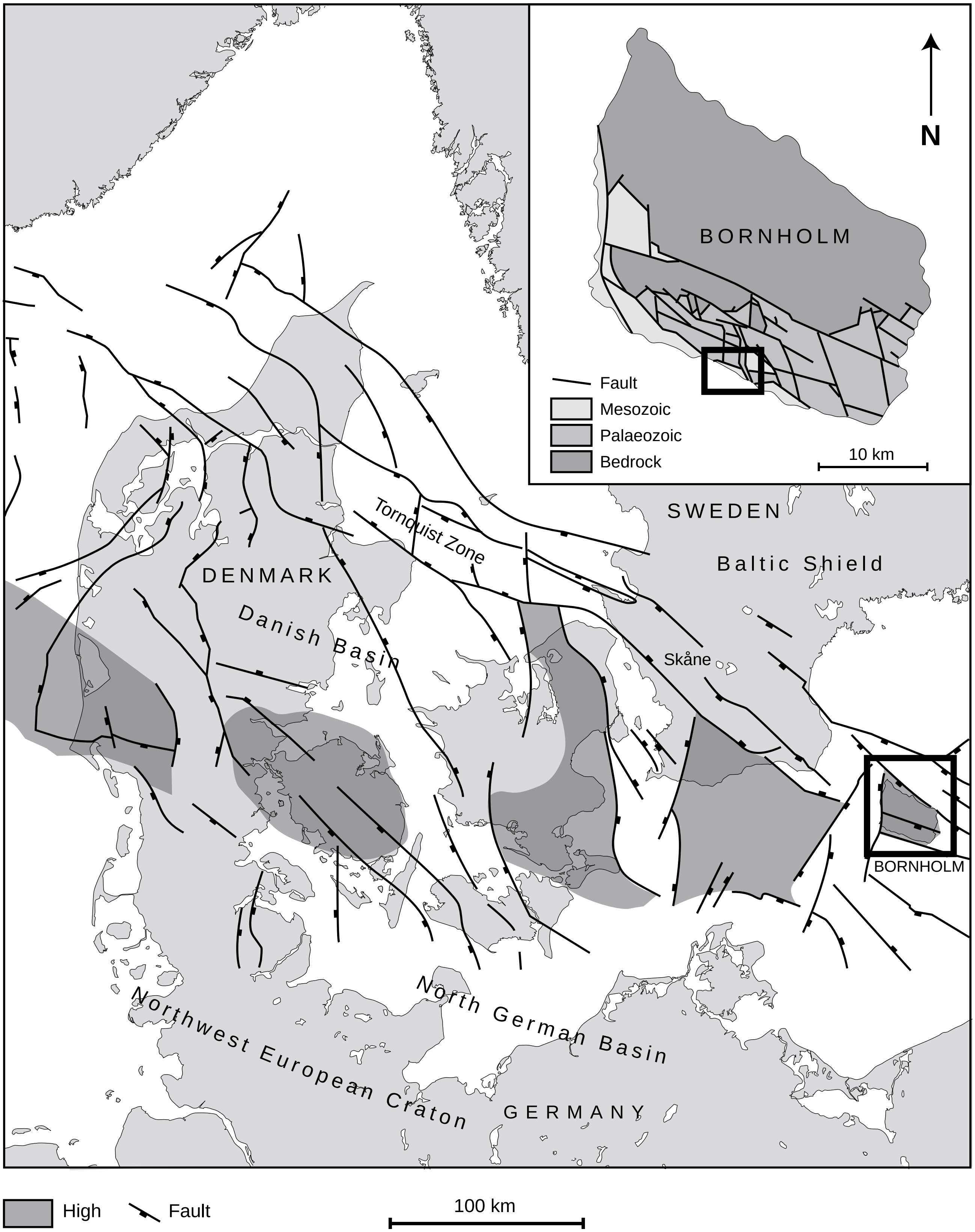

Fig. 1. Location map showing the position of Bornholm in a structural framework. Map based on Surlyk *et al.* (2008). Bornholm is composed of a Precambrian crystalline basement overlain by Palaeozoic and Mesozoic sediments that are broken down into a number of small fault blocks (Graversen 2009). The study site occurs in the down-faulted Arnager Block on the south coast of Bornholm (Fig. 2).

ward) edge of the Arnager Block and forms part of a small coastal strip of sediments between Julegård and Risebæk (Fig. 2; Gry 1969; Gravesen *et al.* 1982). The exposed sediments were mapped as Upper Triassic by Gry (1969). At Julegård these sediments are delineated shortly inland by a fault zone running WNW–ESE and separating the presumed Triassic deposits from uplifted Palaeozoic deposits of the Bornholm Block (Fig. 2; Gry 1969). This fault zone is well displayed some 300 m west of the Julegård section and Lower Cambrian deposits ("Green Shales") are exposed here in the steep cliff of the Bornholm Block (Fig. 2; Grönwall and Milthers 1916; Hansen 1936). The deposits, which belong to the Norretorp Member of the Læså Formation (Surlyk 1980; Nielsen & Schovsbo 2007) are glauconitic and relatively strongly lithified, contain numerous phosphorite nodules, and are strongly bioturbated. In contrast to the view of Gry (1969), Hamann (1987) and Jensen and Hamann (1989) placed a fault-bounded block of Lower Cretaceous sediments at Julegård. According to their view the Upper Triassic sediments are seen only in coastal outcrops near Risebæk and again in coastal outcrops west of

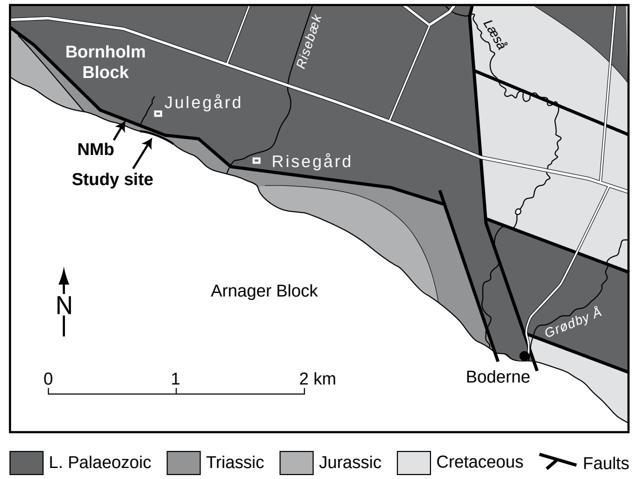

Fig. 2. Detailed location map of the south coast of Bornholm around Julegård. Based on Gry (1969). Glauconitic sediments of the Norretorp Member are exposed in the uplifted Bornholm Block at NMb (Grönwall and Milthers 1916; Hansen 1936). At the study site in the down-faulted block, sediments of the Norretorp Member also occur and are here overlain by sediments of presumed Upper Triassic age.

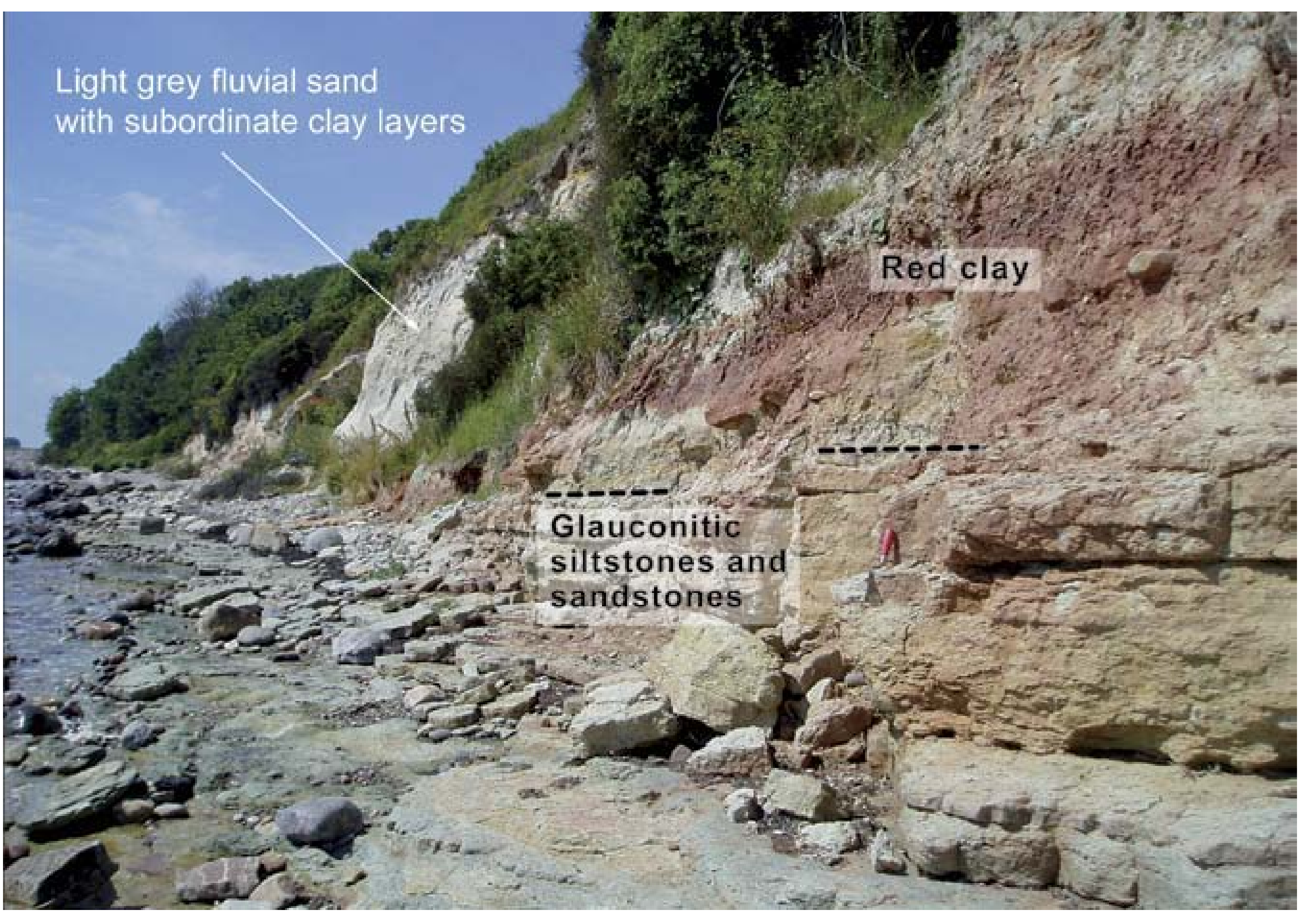

Fig. 3. General view of the studied outcrops at Julegård. Glauconitic, marine deposits of Cambrian age are overlain by red and green lacustrine clay and light greyish to whitish fluviatile sand and conglomerate of presumed Late Triassic age. The boundary between the two units is given by the discontinuous line. View is towards the west.

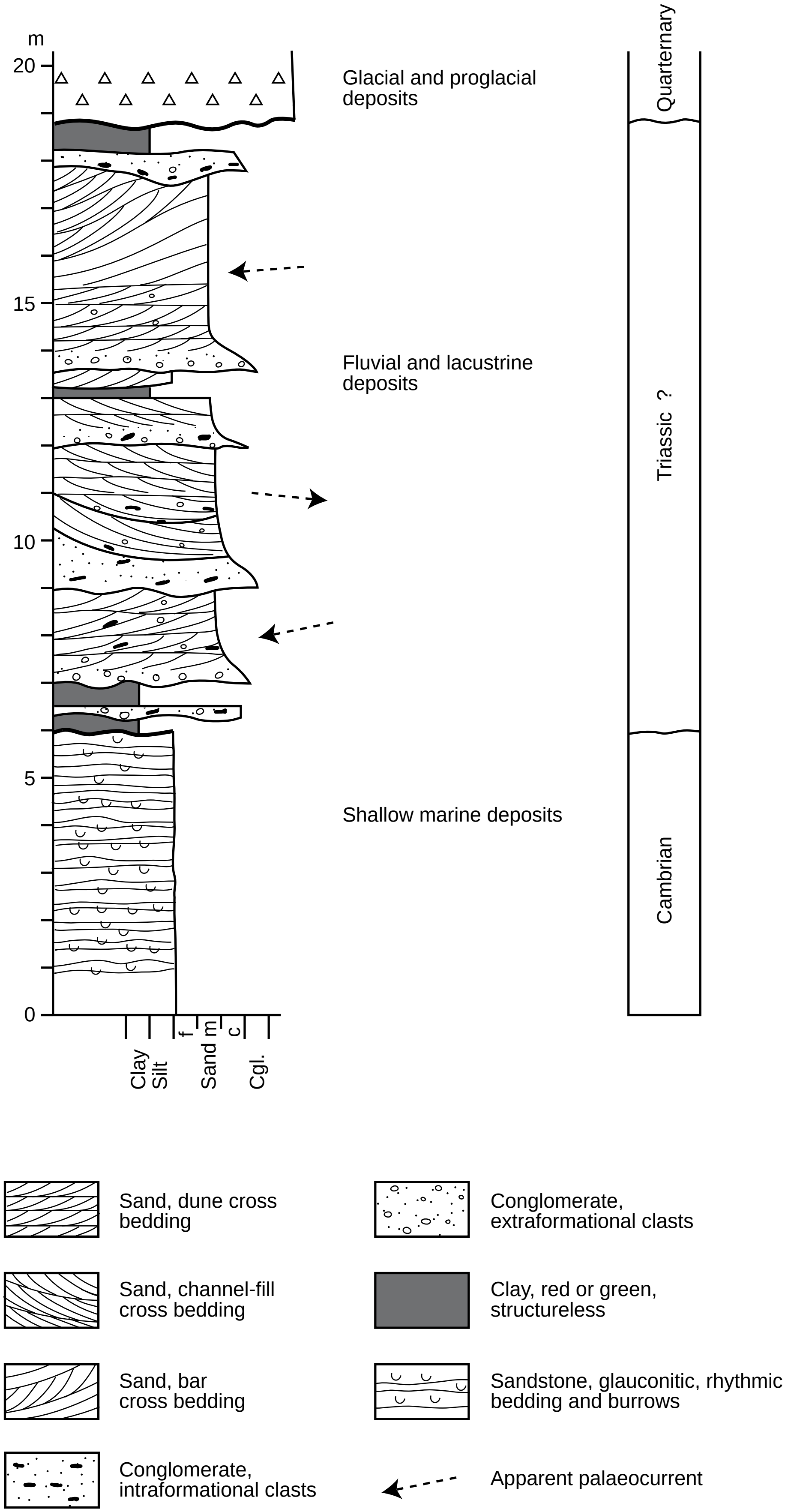

Fig. 4. The sedimentary succession at Julegård on the south coast of Bornholm.

Julegård. According to Hamann (1987) the lithology of the Mesozoic sediments at Julegård was similar to that of the Lower Cretaceous Rabekke Formation, but he also mentioned that the demarcation of the block was somewhat uncertain. Graversen (2004a; 2004b; 2009) followed the interpretation of Jensen and Hamann (1989) and also indicated the presence of Lower Cretaceous sediments at Julegård.

The Julegård section

The Julegård section described here belongs to the down-faulted Arnager Block and is composed of two different sedimentary units covered by Quaternary deposits (Figs 3 and 4). Glauconitic, greenish grey sandstone and siltstone with numerous trace fossils at the base are overlain by red or green clay and silt, and light greyish, kaolinitic fluvial sand and conglomerate. The glauconitic sediments, which have an exposed thickness of about 6 m, are exposed in the beach zone and in low coastal cliffs. In an eastward direction, towards Risebæk, the glauconitic sediments are replaced by well-stratified, greyish sandstones and multicoloured clay of presumed Triassic age. The contact between the two types of sediments is covered by Quaternary deposits and modern dune sand. The glauconitic sediments at Julegård dip gently towards the west and are overlain, without any major erosional surface, by multicoloured clay and light greyish sand and conglomerates also dipping towards the west. The glauconitic sediments described here at the base of the Julegård section are rich in trace fossils. These trace fossils have only received sporadic description in the literature. Gry (1969) noted the appearance of *Skolithos*-like burrows in some sandstones, and Gravesen *et al.* (1982) also noted the occurrence of bioturbated sandstones.

The age of the sediments at Julegård has not previously been examined and the existence of two different sedimentary units has not previously been reported.

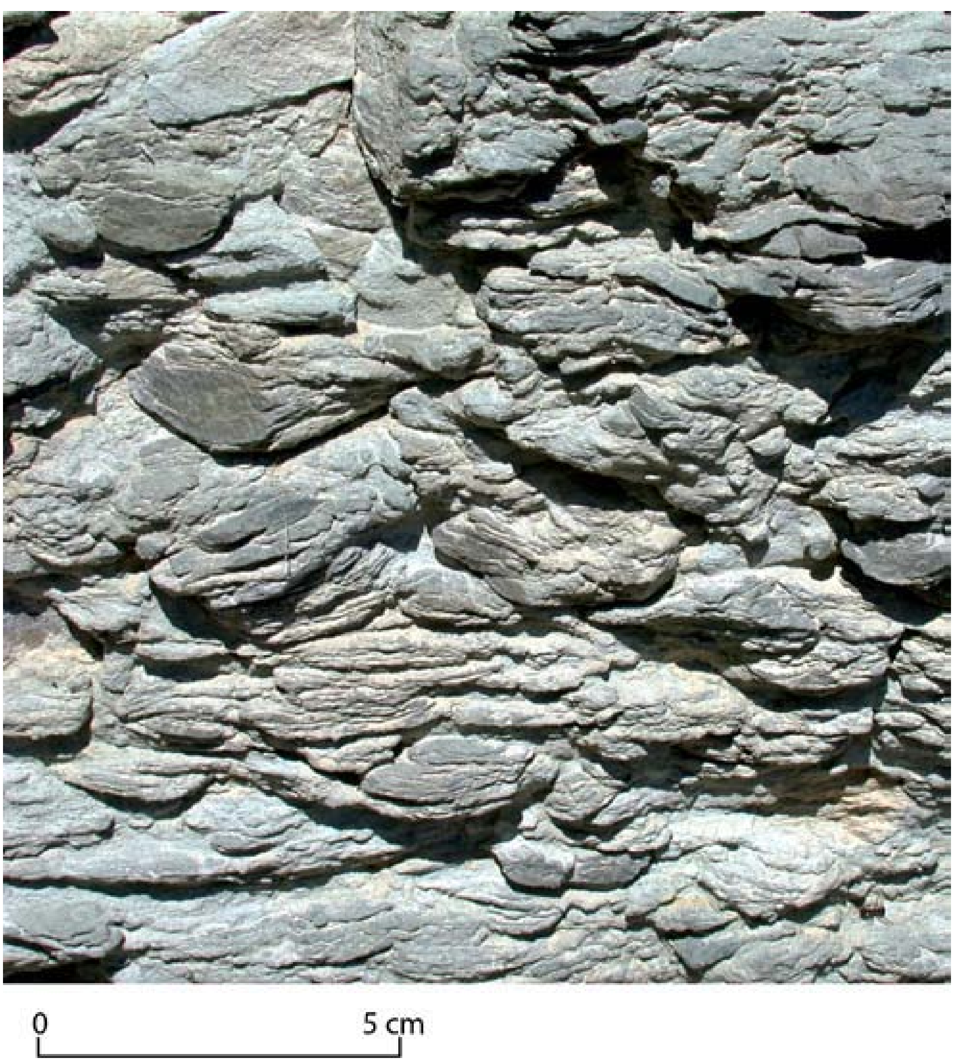

Fig. 5. General view of the glauconitic deposits extensively bioturbated with *Trichophycus/Teichichnus.*

Sparse ostracods in red clay facies at Risebæk, 0.8 km east of Julegård, indicate an Early to Middle Keuper (Late Ladinian – Carnian) age for these sediments (Christensen 1972; Gravesen *et al.* 1982). The uppermost unit at Julegård is dominated by light greyish to whitish fluvial sands and conglomerates but also contains thin red or green clay layers (Figs 3 and 4). The light greyish to whitish colour of the sand is most likely due to a content of kaolinitic clay. The clasts in the conglomerates are composed of intraformational clay lumps as well as extraformational pebbles and cobbles. The characteristic red and green colours of the thin clay layers suggest that the uppermost unit is of Late Triassic age (Figs 3 and 4). A red clay near the base of the terrestrial succession at Julegård was screened for pollen and spores, but proved to be barren. A dark grey mud layer in overlying terrestrial sediments was also barren (S. Piasecki, personal communication 2010). A definite proof of the age of this unit has to await further palynological investigation.

The glauconitic marine deposits at the base of the Julegård section have apparently been assigned Late Triassic as well as Early Cretaceous ages by previous authors, although the sediments have not been described in any detail. The marine deposits were sceened for microfossils and palynomorphs, but proved to be barren (S. Piasecki, personal communication 2009). It was decided therefore to carry out a ^{40}Ar-^{39}Ar age determination on the glaucony contained in the shallow marine deposits. This analysis, as discussed below, suggests that the deposits are of Cambrian age and belong to the Lower Cambrian Norretorp Member of the Læså Formation (Surlyk 1980; Nielsen & Schovsbo 2007).

The glauconitic deposits

Lithology

These sediments have an exposed thickness of about 6 m (Fig. 4). They are composed of a number of lightly cemented, greenish grey siltstones and fine-grained sandstones having a totally bioturbated ichnofabric (Figs 5 and 6). Physical sedimentary stuctures are very poorly preserved due to the extensive biotur-

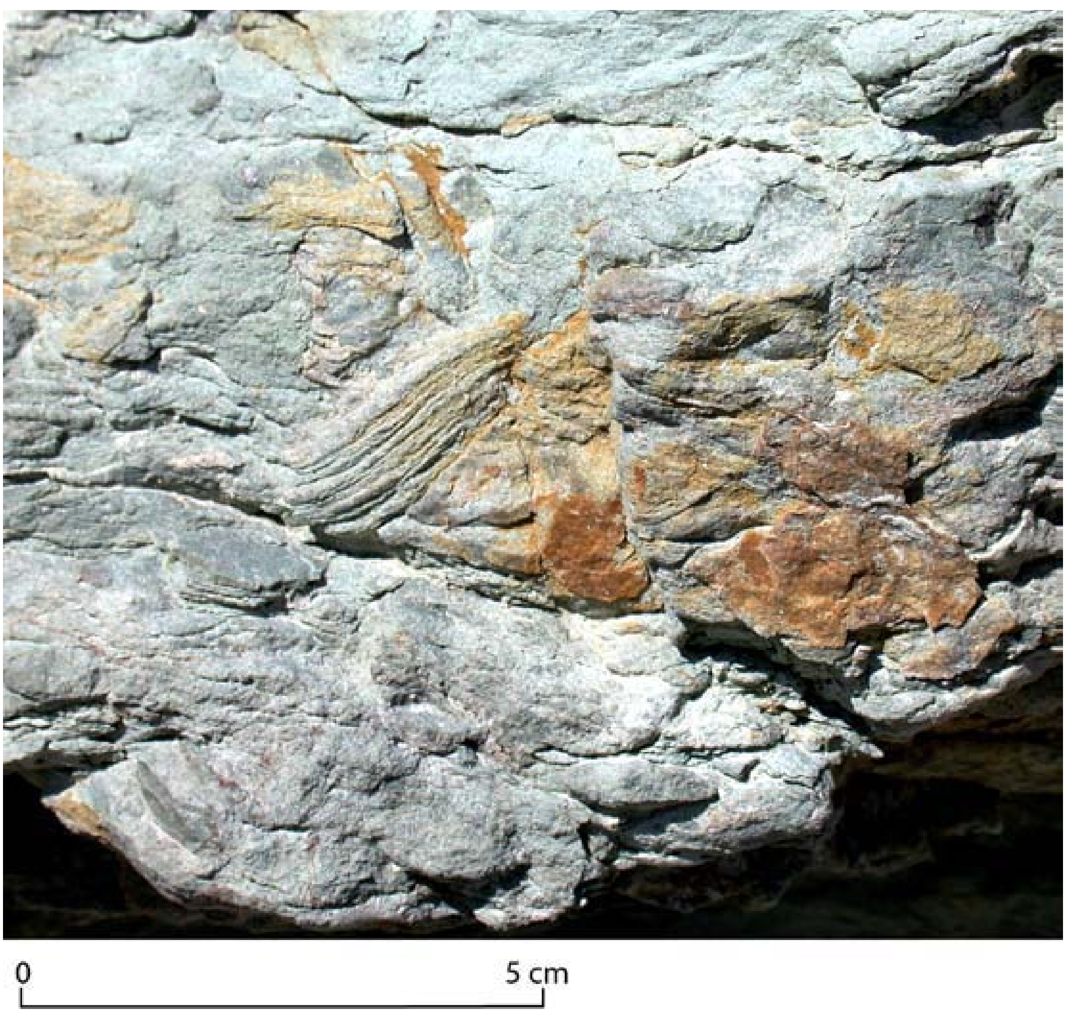

Fig. 6. Closer view of longitudinal section of the spreite structure attributable to *Trichophycus*/*Teichichnus.*


Fig. 7. Bedding plane exposure of *Trichophycus*/*Teichichnus*.

bation, ichnofabric index 4–5, but at some horizons, small-scale wave-generated structures are seen. This succesion is broken by a number of relatively well cemented sandstones with typical thicknesses between 5 and 20 cm. Some of these sandstones are well stratified, but most are massive and/or show evidence of bioturbation. One sample from the lightly cemented deposits had a carbonate content of 14%, but most of the carbonate probably originates from secondary fracture fillings. A thin section reveals that the sediment is composed of quartz (about 80–85 %), feldspars (10%), and bright green glaucony (5–10%). We follow Huggett and Gale (1997) and use the term glaucony and not glauconite for these green grains since the exact mineralogy of the grains is unknown. The glaucony grains are rounded to subangular and have almost the same grain-size distributions as the detrital grains with which they are mixed. An XRD-analysis indicates the presence of illite and kaolinite. There is a complete lack of phoshorite nodules.

The sediments are interpreted as a shallow marine deposit. The lithology suggests that the sediments were deposited between fair weather and storm wave base in the transition zone between the lower shoreface and the shelf. The presence of glaucony grains supports this interpretation as ideal conditions for glaucony formation are fully marine conditions, 10–30 m water depth, low sedimentation rate, and periodic winnowing (Huggett & Gale 1997).

Trace fossils

The trace fossils in the Norretorp Member have previously been described by Clausen and Vilhjálmsson (1986) from outcrops southwards from Snogebæk harbour to Broens Odde on the east coast of Bornholm. A diverse assemblage of trace fossils was described, representing seven ichnogenera, occurring in four ichnoassociations.

The trace fossils at the Julegård locality have a very different signature. Diversity is much reduced, and only a single ichnoassociation is represented. The ichnofabric is dominated by a spreite structure, possibly attributable to *Teichichnus* Seilacher, 1955, but

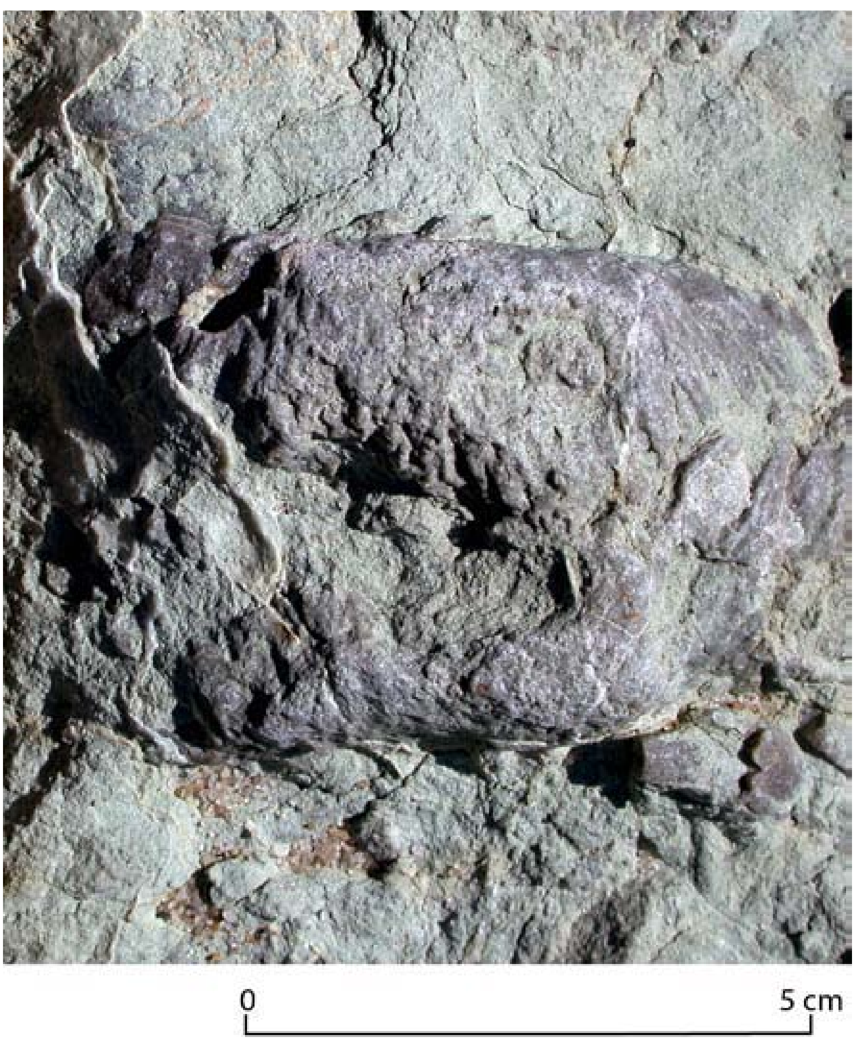

Fig. 8. *Rusophycus* isp., probably the resting trace of a trilobite.

possibly to *Trichophycus* Miller & Dyer, 1878 (Figs 5 and 6). Both of these cover more or less horizontal spreite structures. However, as Osgood (1970) indicated, the distinction between these two ichnogenera is not completely understood. Schlirf & Bromley (2007) applied *Teichichnus duplex* to spreite structures in Cambrian sandstones of nearby southern Sweden. This ichnospecies cannot be applied to the spreite structures at Julegård. However, A. Rindsberg, G. Mángano and L. A. Buatois have briefly visited the Julegård locality and all preferred to name the spreite structures as *Trichophycus* isp. This ichnotaxonomic problem will be addressed in the near future.

The density of bioturbation is so great that details of the morphology are hard to make out, despite the high-quality preservation (Fig. 7). This form may be the same as that called *Buthotrephis palmata* Hall, 1852 by Clausen & Vilhjálmsson (1986) at Broens Odde. Together with the spreite structure are seldom specimens of *Rusophycus* Hall, 1852, probably the resting traces of trilobites (Fig. 8).

Argon analysis of glaucony

Method

Jaw crushed material was sieved to a fraction of 200–300 μm. Bright green round glaucony grains were separated using a combination of heavy liquids and magnetic separation, and subsequently purified under an optical microscope by hand picking. The sample was irradiated in the TRIGA reactor at Oregon State University, Corvallis, USA. FCT-3 biotite was used as monitor assuming an age of 28.03 ± 0.01 Ma (2σ). The sample was dated using the incremental heating technique. Argon was released from the samples using a CO_2 integrated laser. The incremental heating was performed in 10 steps from 300°C to 1200°C and the released argon gas was introduced into a MAP 215-50 mass spectrometer after purification. Each measurement series includes 10 steps of measurements of the isotopes ^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar and ^{40}Ar. After every 3 or 4 steps, blanks were measured and corrections were made along with calculations of decay and corrections for mass fractionation and interference reactions between neutrons and isotopes of Ca, K and Cl (McDougall & Harrison 1988). Data were treated in the program ArArCALC (Koppers 2002) and an age from each step was calculated assuming an initial ^{40}Ar-^{36}Ar ratio of 295.5. All ages are reported with an uncertainty of 2σ. Further analytical and instrumental details are published by Duncan & Hogan (1994).

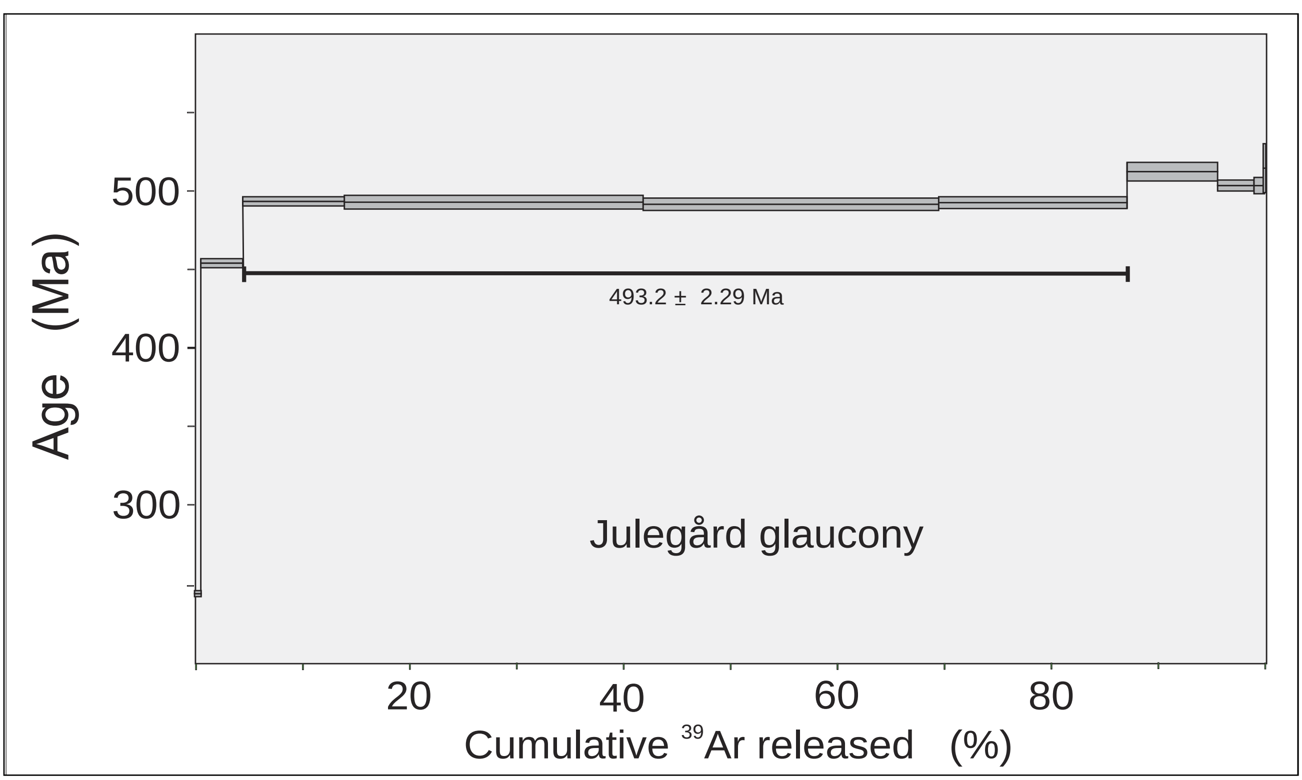

Fig. 9. Age spectrum for stepwise ^{40}Ar-^{39}Ar analysis of glaucony from the marine deposits at Julegård, south coast of Bornholm.

Results

Most of the released argon is present in four successive increments of the analysis (steps 3–6 representing 83% ^{39}Ar), Table 1. With their consistent calculated ages they constitute an age plateau of 493.2 ± 2.2 Ma (2σ) with an MSWD of 0.3 (Fig. 9). The two low-temperature increments yield lower ages, and the four steps at the highest temperatures yield increasing ages with a maximum of 515 ±15 Ma. The total of the released argon results in a calculated age of 492. 4 ± 2.2 Ma (2σ). An isochron for the same four increments 3–6 results in an age of 494.0 ± 3.1 Ma (2σ) statistically identical to the plateau age. The small non-radiogenic component of the argon (0.3 – 4.3 % of the ^{40}Ar) is indistinguishable from atmospheric argon, and no excess Ar is indicated. The plateau age result, which analytically is a highly significant age of 493 ± 2 Ma (2σ), is preferred.

Interpretation

The glaucony of the Julegård sample is considered to have retained the radiogenic argon that accumulated from at least the time of its maturation some few million years after its formation as an authigenic mineral (Odin 1982). However, glaucony has been shown to lose argon during irradiation in the sample preparation for ^{40}Ar-^{39}Ar isotope analysis (Foland *et al.* 1984; Smith *et al.* 1993). This is due to the habit of glaucony to crystallize as laminae thinner than the recoil distance of ^{39}Ar formed during irradiation. Therefore the calculated age would be expected to be higher than the geological age if recoil took place. Detected ^{39}Ar losses may amount to 27–64% (Smith *et al.* 1993) or 17–29% (Foland *et al.* 1984), resulting in correspondingly too high calculated ages. The release of Ar from glaucony during heating is probably related to dehydration of the crystals. For the Julegård sample this occurred over a considerable temperature interval of 275°C and this could indicate that recoil either was extremely uniform or did not occur. In case of the latter, the calculated age of 493 ± 2 Ma is also the geological age. However, if recoil occurred, the formation age may be between Carboniferous and Jurassic.

It is interesting to note that ^{40}Ar-^{39}Ar analysis of glaucony from the Middle Cambrian Kalby Clay (Poulsen 1966) which formed from the erosion of the Exsulans Limestone Bed resting on the Læså Formation yielded three high-temperature steps constituting 42% of the ^{39}Ar with Middle Cambrian ages of 491–513 Ma (Fig. 10; Holm 1984). If indeed these two argon analyses both have age significance, the Julegård deposit is indicated to be Cambrian.

We note that the age calculated for the Julegård

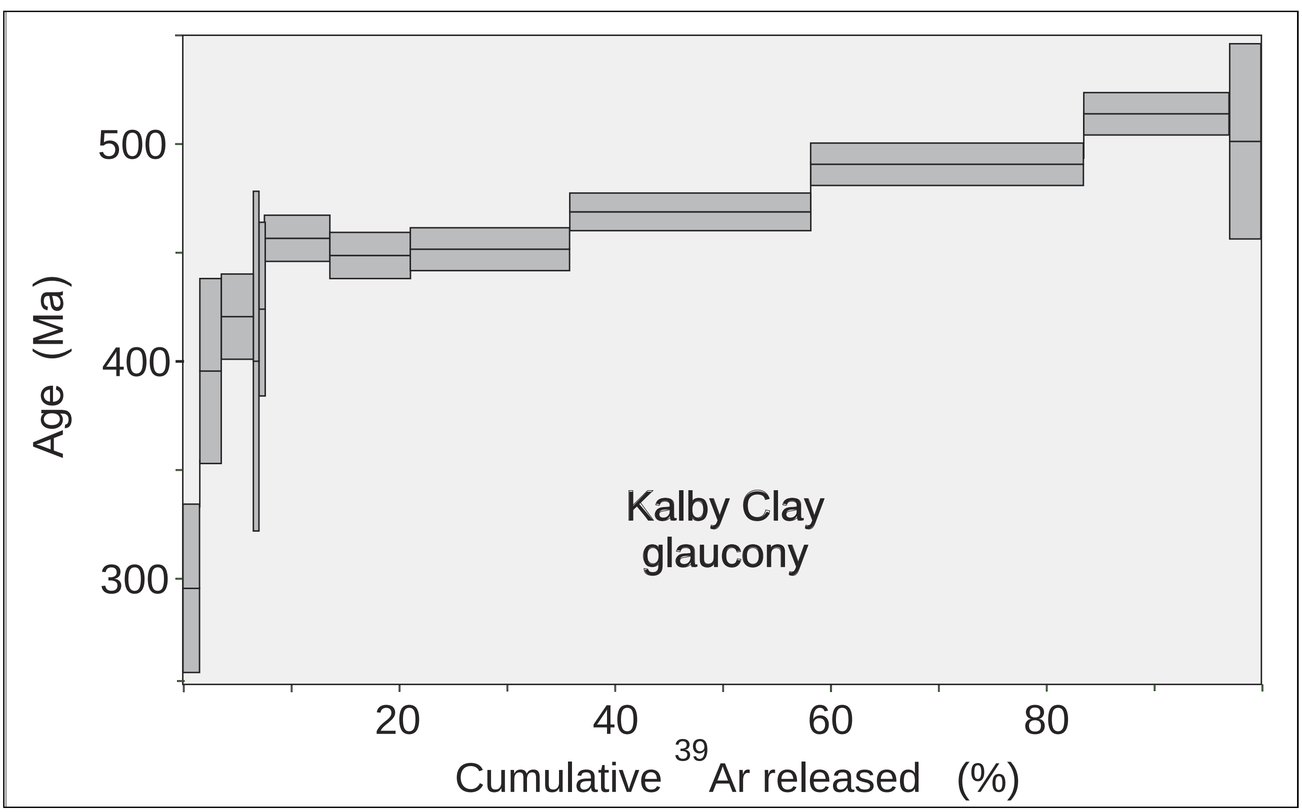

Fig. 10. Age spectrum for stepwise ^{40}Ar-^{39}Ar analysis of glaucony from the Kalby Clay (Exsulans Limestone Bed) of the Middle Cambrian of Bornholm (from Holm 1984).

glaucony is both younger than the previously reported age of 510 ± 5 Ma for calcite concretions in Middle Cambrian black shales in southern Sweden (Israelson *et al.* 1996) and biostratigraphic information that indicates an Early Cambrian age for the Norrretorp Member (Poulsen 1967). Therefore, the glaucony may have suffered an Ar loss. The considerable indicated systematic error on the Ar analysis thus precludes a more precise interpretation of the age.

Discussion and conclusions

Coastal exposures at Julegård on the south coast of Bornholm have so far only received little attention. The outcrops described here belong to the Arnager Block. They are formed by two very different lithological units, shallow marine siltstone and sandstone at the base and fluvial sand and conglomerates with subordinate multicoloured clay layers at the top.

The shallow marine deposits in the lower unit are densely bioturbated. Most trace fossils are attributed to the ichnogenus *Teichichnus* or possibly to *Trichophycus* but the sediments also contain rare specimens of *Rusophycus* probably the resting traces of trilobites. The shallow marine deposits contain glaucony, and a ^{40}Ar-^{39}Ar dating of the glaucony yields a calculated age of 493 ± 2 Ma, which is a Late Cambrian (Furongian) age (cf. Israelson *et al.* 1996), but because of the lithology of the studied unit, it most likely belongs to the Early Cambrian Norretorp Member of the Læså Formation (Surlyk 1980; Nielsen & Schovsbo 2007). The lithology of the studied unit suggests that it may belong to the upper, more sand-rich, part of the Norretorp Member (cf. Nielsen and Schovsbo 2007). The fluvial sand and conglomerates with subordinate multicoloured clay layers in the upper unit have been interpreted to belong to the Lower Cretaceous Rabekke Formation (Jensen and Hamann 1989), but these sediments are here considered to be of Upper Triassic age in agreements with the descriptions of Grönwall and Milthers (1916) and Gry (1969).

The recognition of Cambrian deposits of the Norretorp Member below presumed Upper Triassic sediments in the down-faulted block at Julegård is new and suggests that the displacement along the main fault zone that runs a little inland is less than the thickness of the Norretorp Member or less than 100 m (cf. Nielsen and Schovsbo 2007).

During the winter of 2009–2010, violent storms largely covered the Cambrian exposure at Julegård with off-shore sand and also caused extensive burial by collapse of the overlying Triassic sediments. These conditions may represent the normal situation, thereby explaining the lacking report of Cambrian exposure at the Julegård study site by previous stratigraphers.

Acknowledgements

Ichnologists A. Rindsberg (University of Western Alabama), and G. Mángano and L.A. Buatois (Saskatoon) briefly visited the locality and provided valuable advice on the ichnotaxonomy of the spreite trace fossils. We are grateful for the analytical assistance of John Huard at the Argon laboratory in Oregon, and we like to thank Finn Surlyk and reviewers Arne Thorshøj Nielsen and Gunver Pedersen for constructive comments on the manuscript.

Table 1.
Results of ^{40}Ar-^{39}Ar analysis of Julegård glaucony.

Incremental Heating		36Ar(a)	37Ar(ca)	38Ar(cl)	39Ar(k)	40Ar(r)	Age ± 2σ (Ma)	40Ar(r) (%)	39Ar(k) (%)	39(k)/40(a+r) ± 2σ	36(a)/40(a+r) ± 2σ
1	300 °C	0.000021	0.000118	0.000002	0.003279	0.243317	244.23 ± 1.88	97.49	0.49	0.013137 ± 0.000071	0.000085 ± 0.000020
2	400 °C	0.000056	0.000997	0.000067	0.026575	3.898078	454.53 ± 1.96	99.58	3.98	0.006789 ± 0.000033	0.000014 ± 0.000002
3	500 °C	0.000116	0.001964	0.000123	0.063170	10.186094	494.00 ± 2.49	99.66	9.47	0.006181 ± 0.000036	0.000011 ± 0.000001
4	600 °C	0.003169	0.007112	0.000000	0.186282	30.002479	493.49 ± 3.56	96.97	27.93	0.006021 ± 0.000049	0.000102 ± 0.000002
5	700 °C	0.003141	0.008633	0.000214	0.184080	29.549727	492.06 ± 3.16	96.95	27.60	0.006040 ± 0.000043	0.000103 ± 0.000003
6	775 °C	0.002882	0.012251	0.000059	0.118050	18.987092	492.90 ± 3.50	95.71	17.70	0.005951 ± 0.000048	0.000145 ± 0.000004
7	850 °C	0.000201	0.005776	0.000230	0.055918	9.403260	512.43 ± 5.39	99.37	8.38	0.005909 ± 0.000071	0.000021 ± 0.000001
8	925 °C	0.000115	0.003292	0.000111	0.023417	3.859033	503.48 ± 2.99	99.13	3.51	0.006015 ± 0.000041	0.000030 ± 0.000002
9	1050 °C	0.000041	0.001789	0.000032	0.005688	0.937941	503.72 ± 5.04	98.73	0.85	0.005988 ± 0.000066	0.000043 ± 0.000010
10	1200 °C	0.000004	0.000623	0.000004	0.000569	0.096303	515.26 ± 14.83	98.91	0.09	0.005845 ± 0.000125	0.000037 ± 0.000085
Total fusion (total of 10 increments)							492.41 ± 2.19				
								MSWD			
Weighted plateau of 4 increments 3-6							**493.23 ± 2.19**	0.33	82.69		
											40/36 ± 2σ
Isochron (inverted) of 4 increments 3-6							**494.02 ± 3.09**	0.23		Non-radiogenic Ar:	272 ± 64

a = atomospheric, ca = calcium, cl = chlorine, k = potassium, r = radiogenic

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