Upper Cambrian trilobite biostratigraphy and taphonomy at Kakeled on Kinnekulle, Västergötland, Sweden

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Terfelt, F. 2003. Upper Cambrian trilobite biostratigraphy and taphonomy at Kakeled on Kinnekulle, Västergötland, Sweden. *Acta Palaeontologica Polonica* 48 (3): 409–416.

A section through the Upper Cambrian black shales and limestones at Kakeled on Kinnekulle, Västergötland, Sweden, extends from the lower–middle part of the *Agnostus pisiformis* Zone into the *Peltura scarabaeoides* Zone. Fossils are usually preserved only in the stinkstones, but in the *A. pisiformis* Zone trilobites can be found also in the shales. Lithologically, the stinkstones can be subdivided into primary coquinoid limestone, which include the majority of the fossils, and early diagenetically formed limestone. The orientation of cephala and pygidia of *A. pisiformis* were measured on four shale surfaces and one stinkstone surface. The majority of the shields were deposited with the convex side up and showed a preferred orientation, suggesting that their positions were affected by currents. Above the *A. pisiformis* Zone the section comprises the *Olenus/Homagnostus obesus* Zone (0.30 m), the upper part of the *Parabolina spinulosa* Zone (0.05 m), the *Peltura minor* Zone (1.15 m), and the *Peltura scarabaeoides* Zone (2.50 m). The *Leptoplastus* and *Protopeltura praecursor* zones are missing. The *Olenus/H. obesus* Zone is represented only by the *O. gibbosus* and *O. wahlenbergi* subzones, whereas the *O. truncatus*, *O. attenuatus*, *O. dentatus*, and *O. scanicus* subzones are missing.

Key words: Trilobita, biostratigraphy, alum shale, depositional environment, Upper Cambrian, Kakeled, Kinnekulle, Sweden.

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Introduction

The pioneering papers on the succession of trilobites and other faunal elements in the Upper Cambrian of Scandinavia were published in the second half of the nineteenth century (e.g., Linnarsson 1868; Nathorst 1869, 1877; Tullberg 1882). The most comprehensive study is that by Westergård (1922), who thoroughly investigated a great number of sections in Sweden and subdivided the Upper Cambrian into six biozones. In ascending order these are the *Agnostus pisiformis* Zone, the *Olenus* Zone, the *Parabolina spinulosa* and *Orusia lenticularis* Zone, the *Leptoplastus* and *Eurycare* Zone, the *Peltura*, *Sphaerophthalmus* and *Ctenopyge* Zone, and the *Acerocare*, *Cyclognathus*, and *Parabolina* Zone.

The zonation was subsequently refined by Westergård (1947). In that paper, the Upper Cambrian was subdivided into six zones and 24 subzones. Henningsmoen (1957) monographed the olenid trilobites based mainly on Norwegian material, and introduced an even more refined zonation for the Upper Cambrian of Scandinavia by subdividing it further, into eight zones and 32 subzones. In that zonation Henningsmoen (1957) split the *Peltura* Zone into three zones; the *Protopeltura praecursor* Zone, the *Peltura minor* Zone, and the *P. scarabaeoides* Zone. The latter were formerly treated as subzones by Westergård (1947). The *Leptoplastus/Eurycare* Zone was subdivided into five subzones by Westergård (1947), in ascending order the *Leptoplastus paucisegmentatus* Subzone, the *L. raphidophorus* Subzone, the *L. ovatus/Eurycare latum* Subzone, the *E. angustatum* Subzone, and the *L. stenotus* Subzone. A sixth Subzone, *L. crassicorne*, was added by Henningsmoen (1957) between the *L. raphidophorus* and the *L. ovatus* subzones. He also inserted two new subzones in the lowermost part of the *Peltura* Zone, the *Protopeltura broeggeri* Subzone and the *P. holtedahli* Subzone. Recently, however, Nielsen and Schovsbo (1999) showed that these three subzones should be abandoned, and a revised zonation is shown in Fig. 2.

The Middle and Upper Cambrian of Scandinavia are dominated by kerogen-rich black shales and mudstones, known as alum shales, together with lenses and beds of dark grey, organic-rich limestones referred to as stinkstones or orsten (anthraconite). In Scandinavia the alum shale facies extends from the very north of Norway to the southernmost parts of Sweden and Bornholm, Denmark, and varies in thickness from a few metres up to almost a hundred metres (Andersson et al. 1985; Thickpenny 1984, 1987). Throughout the Middle and Late Cambrian Scandinavia was covered by an epicontinental sea. The influx of terrigenous material was generally extremely low (1–10 mm/1000 years) and basically restricted to reworking of eolic sediments and re-deposition of older strata (Buchardt et al. 1997). Alum shales are generally believed to have been formed in anoxic to dysoxic conditions. However, periods of anoxic conditions were apparently relatively short, and dysoxic conditions

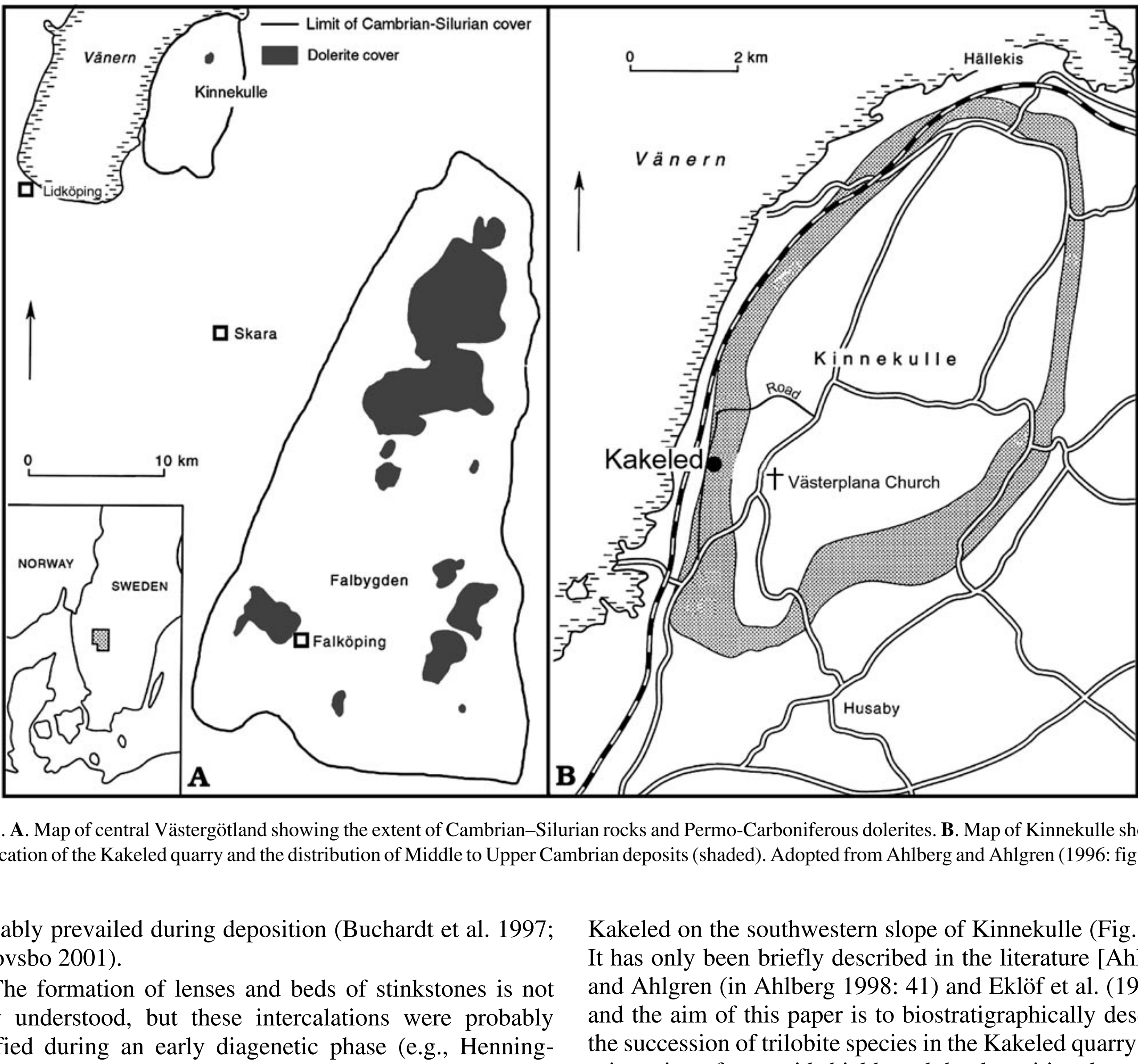

Fig. 1. **A**. Map of central Västergötland showing the extent of Cambrian–Silurian rocks and Permo-Carboniferous dolerites. **B**. Map of Kinnekulle showing the location of the Kakeled quarry and the distribution of Middle to Upper Cambrian deposits (shaded). Adopted from Ahlberg and Ahlgren (1996: fig. 1).

probably prevailed during deposition (Buchardt et al. 1997; Schovsbo 2001).

The formation of lenses and beds of stinkstones is not fully understood, but these intercalations were probably lithified during an early diagenetic phase (e.g., Henningsmoen 1974; Dworatzek 1987). The growth of carbonate concretions was presumably a result of the activity of sulphate reducing bacteria, increasing the alcalinity in the pore water, coupled with an input of bicarbonate from dissolved shell material (Buchardt et al. 1997).

In Västergötland, Lower Palaeozoic sedimentary rocks are represented in four major areas: Billingen-Falbygden, Kinnekulle, Halle-Hunneberg, and Lugnåsberget. With the exception of Lugnåsberget, these hills or mountains are capped by dolerite intruded as sills during Permo-Carboniferous times (Andersson et al. 1985). The most complete Lower Palaeozoic successions are found on Kinnekulle and in the Billingen-Falbygden district (Fig. 1A) where the strata are more or less horizontal and tectonically undisturbed. The Upper Cambrian (the Olenid Series) of Västergötland has a thickness of between 12 and 16 metres (Westergård 1922). It is well exposed on Kinnekulle and in the Billingen-Falbygden area.

On Kinnekulle, Upper Cambrian strata are exposed in a number of old quarries. One of these quarries is situated at Kakeled on the southwestern slope of Kinnekulle (Fig. 1B). It has only been briefly described in the literature [Ahlberg and Ahlgren (in Ahlberg 1998: 41) and Eklöf et al. (1999)], and the aim of this paper is to biostratigraphically describe the succession of trilobite species in the Kakeled quarry. The orientation of agnostid shields and the depositional environment is also discussed.

Locality

Kakeled is situated 14 km northeast of the city of Lidköping and about 1 km west of Västerplana Church (Fig. 1B). It is an old quarry where local farmers used to burn shale together with limestone in a big field oven to produce lime for agricultural purposes. The measured section is located in the eastern part of the quarry. It has a thickness of 6.2 m and extends laterally for about 30 m. The most complete succession is found in the central part of the exposure. The section extends stratigraphically from the lower–middle part of the *Agnostus pisiformis* Zone into the middle *Peltura scarabaeoides* Zone. It consists of finely laminated alum shale with lenses and beds of dark grey limestone (stinkstone or orsten), and a few thin sand bodies. In the *A. pisiformis* and *Olenus*/*H. obesus*

Zones		Subzones
Acerocare		*Acerocare ecorne*
		Westergaardia
		Peltura costata
		Peltura transiens
Peltura Zones	*Peltura scarabaeoides*	*Peltura paradoxa*
		Parabolina lobata
		Ctenopyge linnarssoni
		Ctenopyge bisulcata
	Peltura minor	*Ctenopyge affinis*
		Ctenopyge tumida
		Ctenopyge spectabilis
		Ctenopyge similis
	Protopeltura praecursor	*Ctenopyge flagellifera*
		Ctenopyge postcurrens
		Leptoplastus neglectus
Leptoplastus		*Leptoplastus stenotus*
		Leptoplastus angustatus
		Leptoplastus ovatus
		Leptoplastus raphidophorus
		Leptoplastus paucisegmentatus
Parabolina spinulosa		*Parabolina spinulosa*
		Parabolina brevispina
Olenus Zones	*Homagnostus obesus*	*Olenus scanicus*
		Olenus dentatus
		Olenus attenuatus
		Olenus wahlenbergi
		Olenus truncatus
		Olenus gibbosus
	Agnostus pisiformis	

Fig. 2. Zonation of the Upper Cambrian of Scandinavia. Modified from Henningsmoen (1957), following Nielsen and Schovsbo (1999).

zones there is a 1.50 m thick stinkstone bed referred to as "The Great Stinkstone Bed". It comprises a lower part measuring 0.30 m and a upper part measuring 1.20 m. These are separated by a thin (0.10 m) bed of shale. Nine other stinkstone beds, with thicknesses between 0.10 and 0.55 m (Fig. 3), are present above "The Great Stinkstone Bed". The shale is more or less uniform throughout the section but can differ somewhat in the degree of lamination. Due to weathering, the preservation of the shale in the upper parts (above "The Great Stinkstone Bed") is not as good as in the lower parts. Fossils are usually preserved only in the stinkstone beds, but in the *A. pisiformis* Zone trilobites can be found also in the shales.

Lithology and biostratigraphy

The exposed lithological succession has a thickness of 6.2 m and ranges stratigraphically from the *Agnostus pisiformis* Zone into the *Peltura scarabaeoides* Zone. The base of "The Great Stinkstone Bed" was selected as reference level (0.0 m; Fig. 3). Seventeen species of trilobites and one brachiopod (*Orusia lenticularis*) were identified, and these can be used for a biostratigraphical subdivision of the succession. Their ranges are shown in Fig. 3, and selected characteristic species are shown in Fig. 4.

***Agnostus pisiformis* Zone (1.20 m to 1.00 m)**.—The lower 1.20 m consists of black alum shale with a few fine-grained, grey to light grey stinkstone lenses. The alum shale is unweathered and finely laminated. The only fossil found is the zonal index, *A. pisiformis* (Fig. 4A), which occurs in large numbers on some bedding planes. The fossils are generally poorly preserved in the shale. Three complete specimens were recovered. Although the preservation in the stinkstone lenses is excellent, no articulated specimens were found. In the lower part agnostids in the stinkstone lenses are found as 0.5 to 5 cm thick coquinas. A few specimens were found in the non-coquinoid limestone. The upper 1.00 m of the *A. pisiformis* Zone forms part of "The Great Stinkstone Bed". The fossils occur in up to 0.10 m thick coquinoid layers. There is a 0.10 m thick alum shale bed 0.30 m above the reference level. Two thin sandstone wedges are present near the top of the *A. pisiformis* Zone. The stinkstones adjacent to the sandwedges are lithologically identical with the non-coquinoid parts of the "The Great Stinkstone Bed". No fossils were found in the 0.10 m thick shale or the sandstone.

***Olenus* and *Homagnostus obesus* Zone (1.00 m to 1.30 m)**.—The lower 0.20 m belongs to the *Olenus gibbosus* Subzone. The subzonal index fossil *O. gibbosus* (Fig. 4E, F) is very common (several complete or nearly complete cranidia and pygidia, four more or less complete librigenae, and innumerable fragments) and it co-occurs with *Homagnostus obesus* (numerous complete or nearly complete cephala and pygidia; Fig. 4B), *A. pisiformis* (several pygidia and cephala) and *O. transversus* (one complete pygidium and one nearly complete cranidium). One fragmentary shield of *Glyptagnostus* cf. *reticulatus* was recovered. The upper 0.10 m belongs to the *O. wahlenbergi* Subzone and includes *O. wahlenbergi* (five more or less complete librigenae, several cranidia, and a few pygidia; Fig. 4C, D) and *H. obesus*. All specimens are found in 0.5 to 10 cm thick irregular, wavy "*Olenus* coquinas". Some of the coquinas in the *O. gibbosus* Subzone consist exclusively of fragments of the index fossil.

***Parabolina spinulosa* and *Orusia lenticularis* Zone (1.30 m to 1.35 m)**.—This zone occurs directly above the *Olenus wahlenbergi* Subzone. Three pygidia of *Parabolina spinulosa* were found on bedding planes otherwise completely covered by the brachiopod *Orusia lenticularis* (Fig. 4G, H).

***Peltura minor* Zone (1.35 m to 2.50? m)**.—The lower 0.25 m forms the top of "The Great Stinkstone Bed". The remaining 0.80 m consist of three stinkstone beds and three beds of alum shale. All three alum shale beds contain stinkstone lenses. The major part of the *P. minor* Zone is represented by the *Ctenopyge tumida* Subzone. The most common trilobites are *Sphaerophthalmus alatus* (hundreds of complete cranidia, several more or less complete librigenae, and a thorax) and *Peltura acutidens* (fifteen pygidia and ten cranidia).

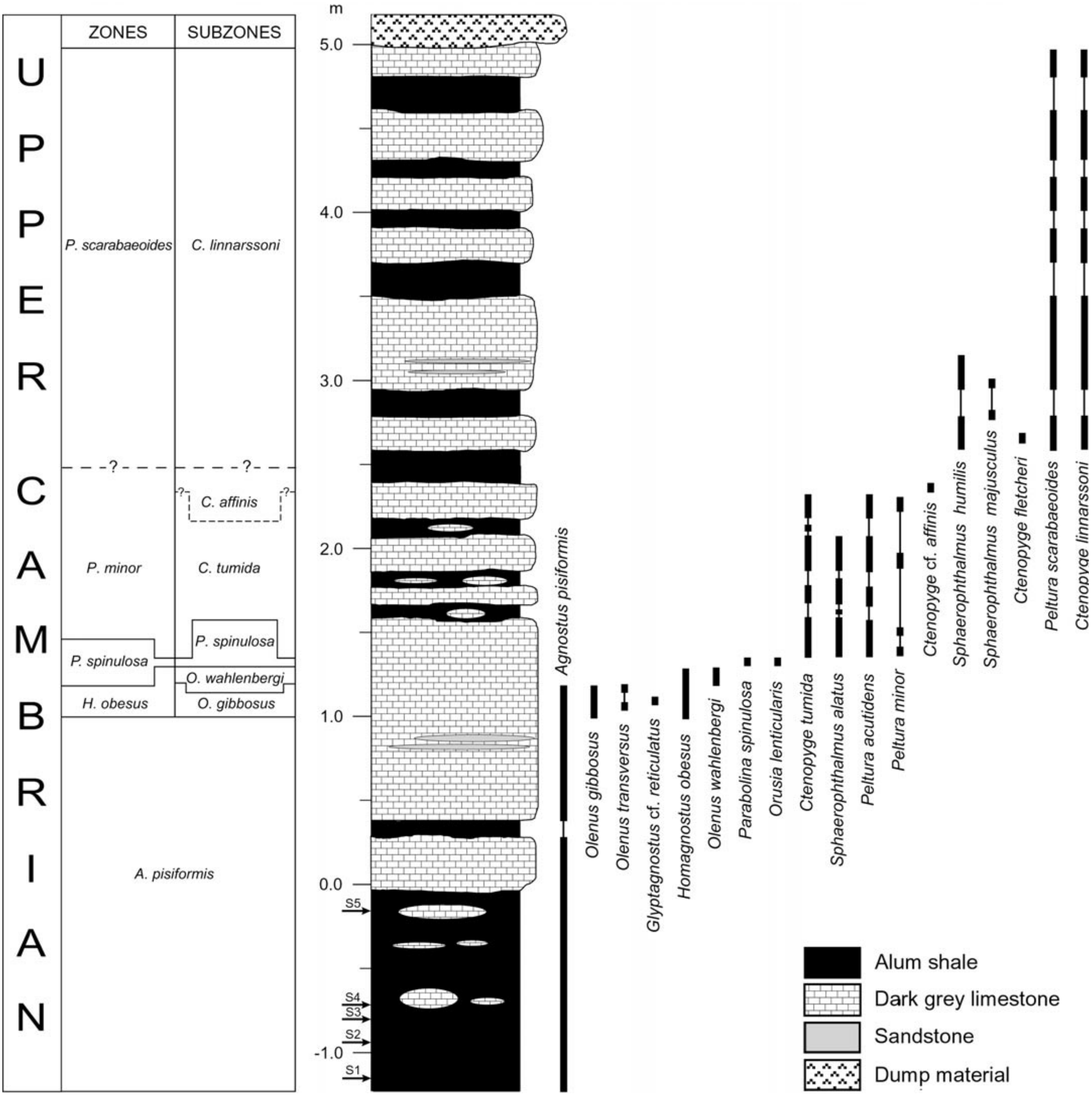

Fig. 3. Lithological succession, biostratigraphical zonation, ranges of trilobite and brachiopod taxa, and sample levels for surfaces 1 to 5 (see also Fig. 5) in the Upper Cambrian at Kakeled, Kinnekulle, Västergötland.

Less common are *P. minor* (three cranidia and internal moulds of four cranidia; Fig. 4K) and *C. tumida* (ten cranidia, two librigenae and a thoracic segment with a spine; Fig. 4J). Four specimens assigned to *C.* cf. *affinis* (Fig. 4L–N) were found in the uppermost part of this zone, suggesting the presence of the *C. affinis* Subzone. In the upper part of the zone the fossils were found in thin coquinoid layers in contrast to the lower part, where specimens occur in few numbers in an otherwise nonfossiliferous limestone.

***Peltura scarabaeoides* Zone (2.50? m to 5.00 m)**.—This interval comprises six stinkstone beds and six beds of alum shale. The entire interval belongs to the *Ctenopyge linnarssoni* Subzone. Species found in this subzone are: *P. scarabaeoides* (one nearly complete specimen, several pygidia, cranidia, librigenae, and thoracic segments; Fig. 4I), *C. linnarssoni* (ten incomplete librigenae, several fragmentary librigenae and one poorly preserved cranidium; Fig. 4O), *Sphaerophthalmus humilis* (several cranidia and five

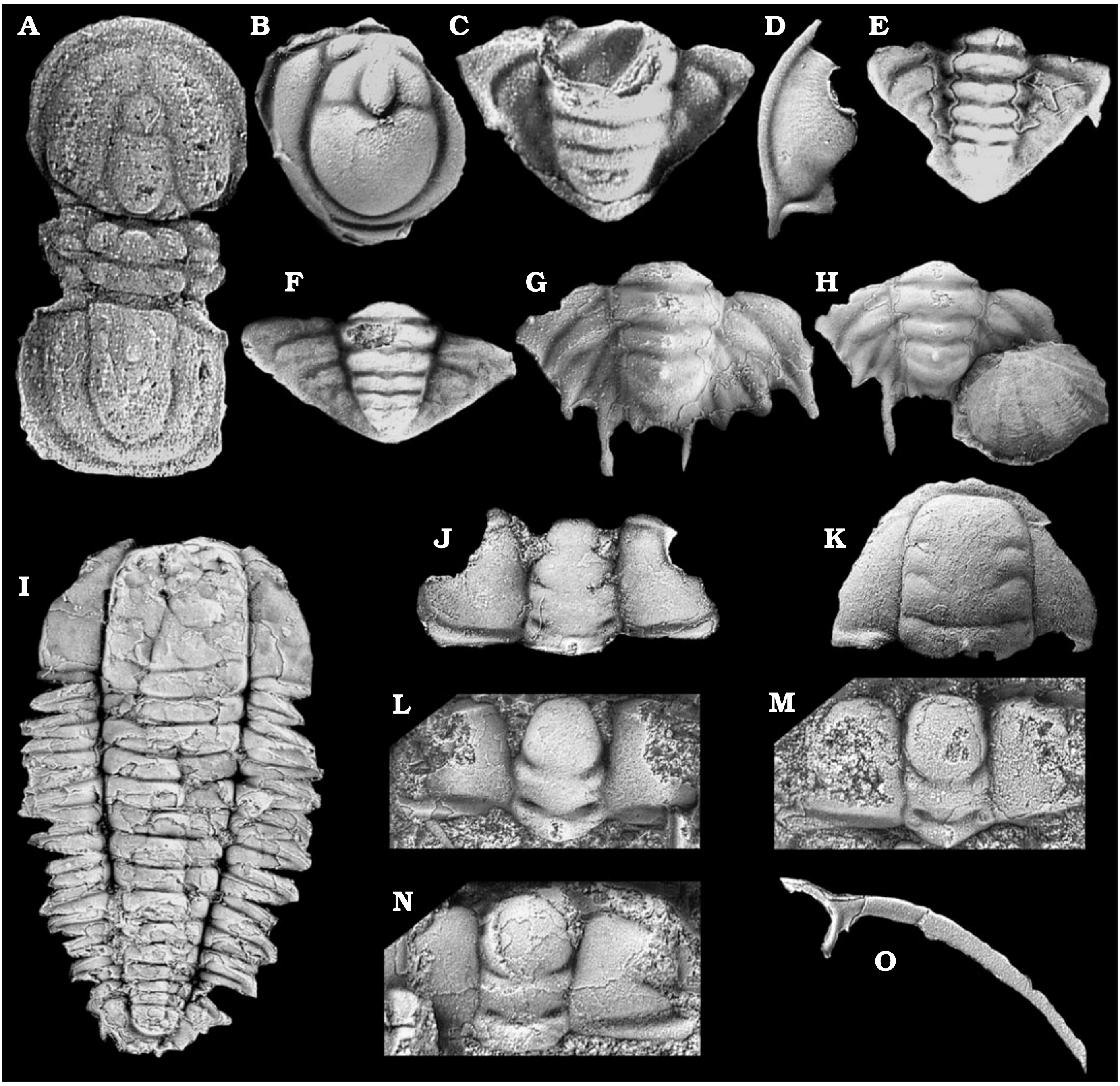

Fig. 4. **A**. *Agnostus pisiformis* (Wahlenberg, 1818), nearly complete specimen from the *A. pisiformis* Zone, LO 8930t, × 22. **B**. *Homagnostus obesus* (Belt, 1867), pygidium from the *Olenus*/*H. obesus* Zone, LO 8931t, × 6. **C**, **D**. *Olenus wahlenbergi* Westergård, 1922, from the *O. wahlenbergi* Subzone. **C**. Pygidium, LO 8932t, × 13. **D**. Librigena, LO 8933t, × 8. **E**, **F**. *Olenus gibbosus* (Wahlenberg, 1818) from the *O. gibbosus* Subzone. **E**. Narrow pygidium, LO 8934t, × 4.5. **F**. Wide pygidium, LO 8935t, × 5. **G**, **H**. *Parabolina spinulosa* (Wahlenberg, 1818) from the *P. spinulosa* Subzone. **G**. Pygidium, LO 8936t, × 7.5. **H**. Pygidium together with the brachiopod *Orusia lenticularis* (Wahlenberg, 1818), LO 8937t, × 7. **I**. *Peltura scarabaeoides* (Wahlenberg, 1818), nearly complete specimen from the *P. scarabaeoides* Zone, LO 8938t, × 5.5. **J**. *Ctenopyge tumida* Westergård, 1922, cranidium from the *C. tumida* Subzone, LO 8939t, × 10.5. **K**. *Peltura minor* (Brögger, 1882), cranidium from the *P. minor* Zone, LO 8940t, × 5. **L**–**N**. *Ctenopyge* cf. *affinis* from the *Peltura minor* Zone, *C. affinis* Subzone? **L**. Cranidium, LO 8941t, × 13. **M**. Cranidium, LO 8942t, × 12.5. **N**. Cranidium, LO 8943t, × 13.5. **O**. *Ctenopyge linnarssoni* Westergård, 1922, librigena from the *C. linnarssoni* Subzone, LO 8944t, × 5.5. All illustrated specimens are from the Kakeled quarry and housed in the Department of Geology, Lund University (LO).

pygidia), *S. majusculus* (three incomplete cranidia), and *C. fletcheri* (one librigena). At or near the base there is a 0.20 m thick stinkstone bed containing *P. scarabaeoides*, *S. humilis*, *C. linnarssoni*, *C. fletcheri*, and *S. majusculus*. This stinkstone bed is overlain by a 0.15 m thick alum shale bed succeeded by a 0.55 m thick stinkstone bed with two thin sandstone wedges in the lower part. The stinkstone adjacent to the sandwedges does not show any lithological features different from the non-coquinoid parts of the stinkstone bed. Fossils found in this stinkstone bed are *P. scarabaeoides*, *C. linnarssoni*, *S. humilis*, and *S. majusculus*. The four remaining stinkstone beds in the upper part of the zone yielded *P. scarabaeoides* and *C. linnarssoni*. Fossils were generally found in thin (< 0.5 cm) biogenic layers with bioclasts less than 1 mm.

As a result of quarrying, the top of the succession has been removed. The present surface has subsequently been covered, at least partly, by deposits from the adjacent cultivated field.

Remarks.—The succession of trilobite species shows that there are several gaps in the sequence. There is no evidence for the presence of the *Olenus truncatus*, *O. attenuatus*, *O. dentatus* and *O. scanicus* subzones in the *Olenus*/*Homagnostus obesus* Zone. Furthermore, the lower subzone of the *Parabolina spinulosa* Zone, the *Parabolina brevispina* Subzone is missing, as well as the *Leptoplastus* and *Protopeltura praecursor* zones. The *P. minor* Zone lacks the *Ctenopyge similis* Subzone and the *C. spectabilis* Subzone (the two lowermost subzones). In the *P. scarabaeoides* Zone, there is only evidence for the presence of the *C. linnarssoni* Subzone, whereas the *C. bisulcata*, the *Parabolina lobata* and the *Peltura paradoxa* subzones are missing. Moreover, there are no fossils indicative of the *Acerocare* Zone.

The boundary between the *P. minor* Zone and the *P. scarabaeoides* Zone can not be precisely established, since there is a 0.2 m thick interval with unfossiliferous shales between the last appearance of fossils indicative of the *P. minor* Zone and the first appearance of fossils indicative of the *P. scarabaeoides* Zone.

The fossils are generally found in coquinoid limestones. The few fossils preserved in non-coquinoid layers (i.e., specimens in the lower part of the *P. minor* Zone and fossils preserved in some shale/stinkstone levels in the *A. pisiformis* Zone) probably represent *in situ* faunas.

Taphonomy

The only fossil encountered in the *Agnostus pisiformis* Zone at Kakeled is the zonal index. It is preserved both in the alum shales and the stinkstones. Shields of this species occur in abundance and several surfaces are completely covered by them (Fig. 5). Preservation is generally poor (probably due to dissolution) in the shale and the specimens are almost exclusively disarticulated (only three complete specimens were found). The latter is also true for the specimens in the stinkstone, but their preservation is generally excellent. The disarticulation may indicate transport prior to deposition (Öpik 1979). This deviates from the general conception of the depositional environment in which alum shale is formed, i.e., anoxic–dysoxic conditions in fairly deep, stagnant waters below storm wave base (e.g., Dworatzek 1987; Bergström and Gee 1985; Buchardt et al. 1997). In such environments one would expect the shields to sink to the bottom with the convex side down and with their polar angle randomly oriented. In environments with horizontal water movement the shields would flip over and rest with the convex side up. With only one prevailing current direction (unimodal water current) the shields would be oriented with their articulating margin downcurrent (Nagle 1967; Eklöf et al. 1999). A bi-directional water current (waves or tides) would orient the shields with their longitudinal axis perpendicular to the current directions (Nagle 1967; Eklöf et al. 1999).

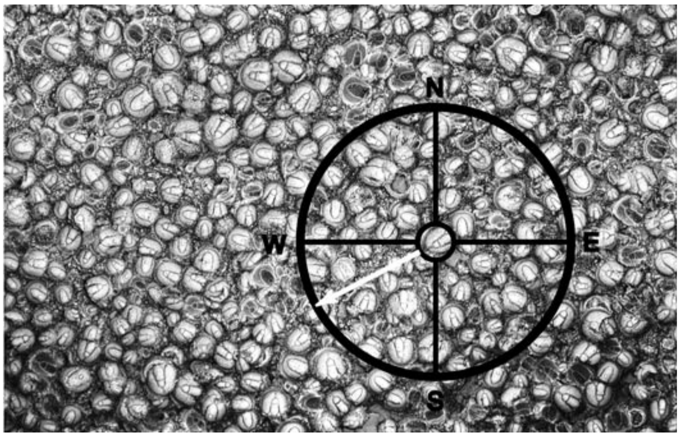

Fig. 5. Stinkstone surface (S5) with densely packed shields of *Agnostus pisiformis*, and the principal procedure when measuring the orientation of a cephalon or a pygidium. For further details, see main text.

To evaluate whether the alum shale was deposited during calm conditions in deep, stagnant water or in an environment affected by water movements, four alum shale slabs (S1–S4) and one stinkstone lens (S5) were collected for further investigation and measurements (Fig. 3). The polar angle was measured for both cephala and pygidia on each surface (Fig. 5), and the distribution of convex up and convex down was counted (Fig. 6). Polar angles for convex down shields were not measured as they give a result close to random (Eklöf et al. 1999).

The majority of the shields were deposited with the convex side up on all five surfaces (on average 84.2%) thus indicating deposition in non-stagnant water. Furthermore, the shields showed a preferred distribution towards the south. The fact that some shields were deposited with their convex sides down can be explained by irregularities in the bottom sediment where shields can rest unaffected by water movements (Eklöf et al. 1999). Two surfaces (S1 and S5) showed a significantly unipolar distribution; in S1 the orientation was strongly directed towards the south and in S5 towards the south-southwest. The remaining three surfaces (S2–S4) showed bipolar distributions with orientation towards the south and the east.

The shield orientation in S1 and S5 indicates a southerly wind-driven current, as wave and tidal currents are considered to give rise to bipolar distribution patterns. Wind-driven

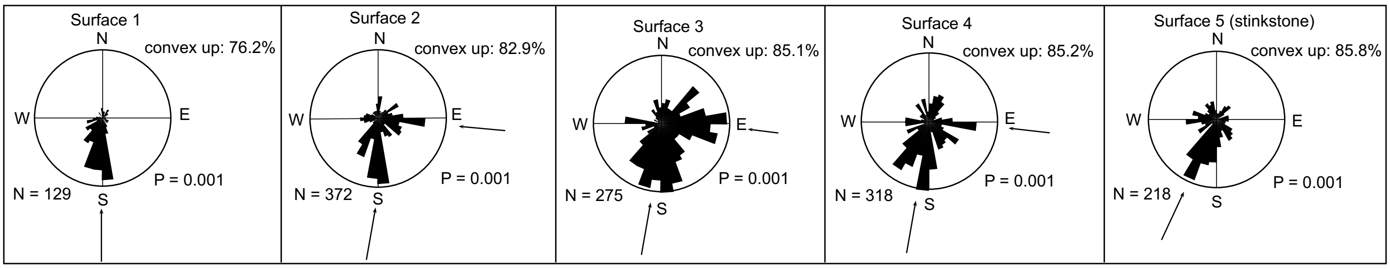

Fig. 6. Polar angle distribution of *Agnostus pisiformis* shields in four alum shale surfaces (S1–S4) and one stinkstone surface (S5) in the Kakeled quarry. Also shown is the percentage of shields with their convex side up, the number of measured shields (N), and the significance level (P). Arrows indicate inferred current directions.

currents rarely reach depths below 100 m (Skinner and Porter 1987: 380), thus indicating a fairly shallow water environment. Surfaces 2, 3, and 4 show a more complex pattern with bipolar distributions towards the south and east, respectively, suggesting a two-current system with one component acting from the south and another component acting from east. Although it is difficult to obtain unambiguous interpretations concerning the current directions in this material, the orientations of the shields were obviously caused by water currents, strongly indicating deposition in a shallow water environment. This is in accordance with a previous study on the orientation of cephala and pygidia in the Kakeled quarry (Eklöf et al. 1999).

In the Kakeled stinkstones, most fossils were found in coquinoid layers. The Upper Cambrian coquinas are believed to represent single depositional events (Dworatzek 1987), such as storms. This supports the idea of a shallow water environment in Kakeled. Moreover, the siliciclastic sand bodies, which probably were laid down during storms, indicate a shallow/near shore environment. No evidence of infiltrating of sand between limestone blocks could be found, thus the sand was probably deposited in irregularities on the stinkstone bed. The section contains several stratigraphical gaps, which may indicate erosion during storm events.

The Kakeled succession is undoubtedly a shallow water deposit. Dworatzek (1987) discriminated two types of lithological sequences (type I and type II), where type I is characterized by, for instance, a higher proportion of limestone, more coquinas, and less concretionary lenses than in type II. According to Dworatzek (1987) the Upper Cambrian of the Kinnekulle and Öland areas are characterised under type I, whereas for example the Billingen and Närke areas are characterised under type II. The type I sequence is associated with stronger currents and wave energies, reflecting the presence of intrabasinal highs. The Kakeled section corresponds well to the lithological sequence type I.

Concluding remarks

The section at Kakeled is representative for the Upper Cambrian of Kinnekulle. In terms of stratigraphical completeness it is comparable to other sections in the area (see Westergård 1922, 1943, 1947). The *A. pisiformis* Zone is at least 2.2 m thick at Kakeled and probably only the lowermost part is unexposed. The *Olenus*/*H. obesus* Zone is remarkably thin (0.3 m) in the Kakeled section. As in most other localities on Kinnekulle the *P. spinulosa* Zone is very thin. The *Leptoplastus* Zone is generally present, but very thin on Kinnekulle (Westergård 1922). This zone has not been recorded at Kakeled. The *Peltura* beds (the *P. minor* and *P. scarabaeoides* zones) are represented by 3.65 m at Kakeled, and the upper part is obviously missing.

The percentage of stinkstones appears to be much higher at Kakeled than in most other sections on Kinnekulle, comprising about 70% of section thickness. On northern and eastern Kinnekulle the Upper Cambrian generally consists of less than 40% stinkstones, increasing to 50–60% towards southwest. The Kakeled section show a number of features (a high percentage of coquinoid limestones, thin sand wedges, current oriented agnostid shields, and numerous gaps in the succession) that associate it with a shallow water environment, reflecting the presence of intrabasinal highs.

Acknowledgements

I would like to thank Professor Per Ahlberg for his constant advice and suggestions, Dr. Mats Eriksson for his engagement in the late version of the manuscript, and Dr. Claes Bergman for advices concerning the palaeocurrent section. I thank the reviewers Professor Euan Clarkson and Dr. Niels Schovsbo for their valuable comments on the manuscript. I am also grateful to Dr. Anita Löfgren, Dr. Sofie Lindström and Professor Per Ahlberg for reading a draft of the manuscript.

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