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Article

Late Ordovician (Katian) spores in Sweden: oldest land plant remains from Baltica

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Abstract: A palynological study of the Ordovician–Silurian boundary (Katian–Rhuddanian) succession in the Röstånga-1 drillcore, southern Sweden, has been performed. The lithology is dominated by mudstone and graptolitic shale, with subordinate limestone, formed in the deeper marine halo of southern Baltica. The palynological assemblages are dominated by marine microfossils, mainly chitinozoans and acritarchs. Sparse but well-preserved cryptospores, including *Tetrahedraletes medinensis*, *Tetrahedraletes grayii* and *Pseudodyadospora* sp., were encountered in the Lindegård Formation (late Katian–early Hirnantian), with the oldest record just above the first appearance of the graptolite species *Dicellograptus complanatus*. This represents the earliest record of early land plant spores from Sweden and possibly also from Baltica and implies that land plants had migrated to the palaeocontinent Baltica by at least the Late Ordovician.

Keywords: stratigraphy; palynology; thermal alteration index; Ordovician; Silurian; Röstånga-1 drillcore; Skåne; Sweden.

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Introduction

Evidence of early land plant spores have been dated back to at least the Mid-Ordovician (Vavrdová 1990; Strother et al. 1996; Le Hérissé et al. 2007; Rubinstein et al. 2010) and are all from Gondwana, from where they possibly originated (Rubinstein et al. 2010). The earliest known cryptospores are from Middle Ordovician (Dapingian) strata of Argentina (Rubinstein et al. 2010). Other early records include findings from late Darriwilian deposits in the Czech Republic (Vavrdová 1990) and Saudi Arabia (Strother et al. 1996; Le Hérissé et al. 2007). Fragments of the earliest land plants with *in situ* cryptospores have been described from Oman, and studies of the spore-wall ultrastructure suggest a liverwort affinity for these plants (Wellman et al. 2003). The so far oldest cryptospores described from Baltica are of latest Katian–Hirnantian age from the Valga-10 core in southern Estonia (Vecoli et al. 2011). The dating of these spores, however, is uncertain and the spores described in the present study are slightly older than the spores described from the Valga-10 core. Previous palynological studies from Swedish Palaeozoic successions have identified spores in strata of Silurian age (Wenlock–Pridoli) both from Skåne and Gotland (Gray et al. 1974; Hagström 1997; Hagström & Mehlqvist 2012; Mehlqvist et al. 2012, 2014).

In this pilot study, the palynology of the Röstånga-1 drillcore has been analysed in order to investigate the occurrence of land plant-derived spores. The Röstånga-1 core was drilled in west-central Skåne (Scania), the southernmost province of Sweden (Fig. 1), and is considered to comprise the stratigraphically most complete Upper Ordovician through lowermost Silurian succession from this area of Sweden (Bergström et al. 1999). Palaeogeographically, this location is within the slowly subsiding cratonward side of the German–Polish Caledonian foreland basin (Fig. 1; the Scanian Confacies Belt of Jaanusson (1995); see Erlström et al. (1997) and Calner et al. (2013) for reviews of the tectonic evolution of Skåne), and the studied succession is therefore relatively thin.

Materials and methods

The Röstånga-1 core was drilled by Borrbolaget, Västra Frölunda, in 1997 and has previously been studied by Bergström et al. (1999), Pålsson (2002), Koren' et al. (2003), Bergström et al. (2014) and Maletz et al. (2014). The core has a diameter of 71 mm down to a depth of 40.13 m, and a diameter of 52 mm in the interval 40.13–132.59 m. The succession in the core dips 35°. The stratigraphic interval discussed herein corresponds to a depth of 108.84–49.00 m and comprises, in ascending order, the Skagen Limestone, the Mossen Formation, the Fjäcka Shale, the Lindegård Mudstone and the lowermost part of Kallholn Formation. The lithologies range from dark grey limestone to light grey mudstone and black, organic-rich shale.

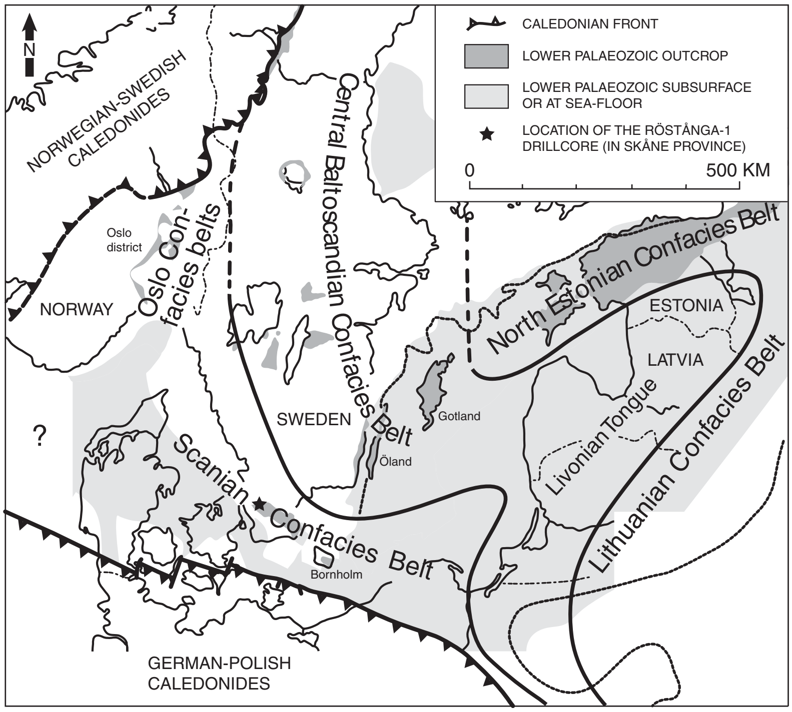

Fig. 1. Palaeogeography of Baltoscandia and distribution of Palaeozoic strata in the region. The Late Ordovician depth zonation of the Baltoscandian basin is shown (confacies belts of Jaanusson 1995) as well as the location of the Röstånga-1 drillcore in the shale-dominated Scanian Confacies Belt.

For the palynological analysis, a total of 21 samples were collected from the Fjäcka Shale, the Lindegård Mudstone and the Kallholn Formation, corresponding to the interval between 91.0 and 49.0 m (Fig. 2). The samples were processed palynologically at Global Geolab Limited in Canada, according to standard palynological processing methods. The reference for colour measurements for assessing the thermal alteration index (TAI) is the colour standards of Philips Petroleum Company. The core and the palynological slides with illustrated specimens (numbered with the prefix LO) are housed at the Department of Geology, Lund University.

Stratigraphy and lithologies

The Skagen Formation in the Röstånga-1 drillcore consists of a grey to greenish skeletal limestone, rich in trilobite fragments, alternating with calcareous mudstone. Regionally, it shows a substantial lateral variation in thickness, and it has been suggested that this unit reflects a eustatic sea level fall (Bergström et al. 1997). In the Röstånga-1 core, a relative shallowing of sea-level at this level is supported by facies and the overall stratigraphic development, and the presence of a discontinuity surface with angular- to round-shaped solution structures at the top of the Skagen Limestone (Fig. 3). This irregular surface most likely correlates with the conglomerate previously reported at the top of the Skagen Limestone in the Borenshult core, Östergötland (Bergström et al. 2011), the unconformable boundary at the top of the Kullsberg mud mounds in the Siljan district (Calner et al. 2010a), and with the sequence boundary reported at the Keila–Oandu stage boundary in the East Baltic area by Ainsaar et al. (2004, p. 122–123; for a discussion of Katian sea-level, see Calner et al. 2010a). Accordingly, this disconformity is associated with substantial erosion and a hiatus not only in the northern Estonian shelf sections but also across large parts of Baltoscandia.

The presence of the Skagen Limestone and the associated discontinuity surface in the core show that this early Katian shallowing resulted in carbonate deposition even along the margins of the continent where the depositional environment usually was much deeper. There is, however, no macroscopical evidence for subaerial exposure at this level in the core, and the discontinuity surface is inferably associated with submarine dissolution that took place after the maximum lowstand due to sediment starvation and transgression. This transgression is marked by the overlying Mossen Formation that constitutes glauconite-rich limestone and strongly bioturbated grey mudstone. The basal portion of the overlying Fjäcka Shale is generally laminated suggesting low oxygen levels and a prolonged transgression. This unit is a basin-wide marker bed that locally caps the truncated Kullsberg mud mounds in the Siljan district (Calner et al. 2010a) or a coeval regional palaeokarst surface elsewhere in southern Sweden and the East Baltic area (Calner et al. 2010b).

The contact between the Lindegård Mudstone and the Kallholn Formation is gradational from light grey mudstone to dark grey and graptolitic mudstone and shale, and the boundary is arbitrarily placed at a depth of ca. 56 m at the top of the *Metabolograptus persculptus* graptolite Zone, recognized in the core by Koren' et al. (2003) and Maletz et al. (2014). The Kallholn Formation represents a new transgression, most likely associated with a late Hirnantian deglaciation.

Palynology

Cryptospores

The palynological assemblages are dominated by marine microfossils but we have here for the first time also identified spores from land plants represented by cryptophytes (*sensu* Edwards et al. 2014). The presence of a sparse but well-preserved cryptospore assemblage including *Tetrahedraletes*

Fig. 2. Lithological succession, stratigraphic subdivision and sample levels of the Röstånga-1 drillcore. Based on Bergström et al. (1999, 2014), Pålsson (2002), Koren' et al. (2003) and Maletz et al. (2014). SB, sequence boundary. Abbreviations of stratigraphic names: SuF, Sularp Formation; SkF, Skagen Formation; MF, Mossen Formation.

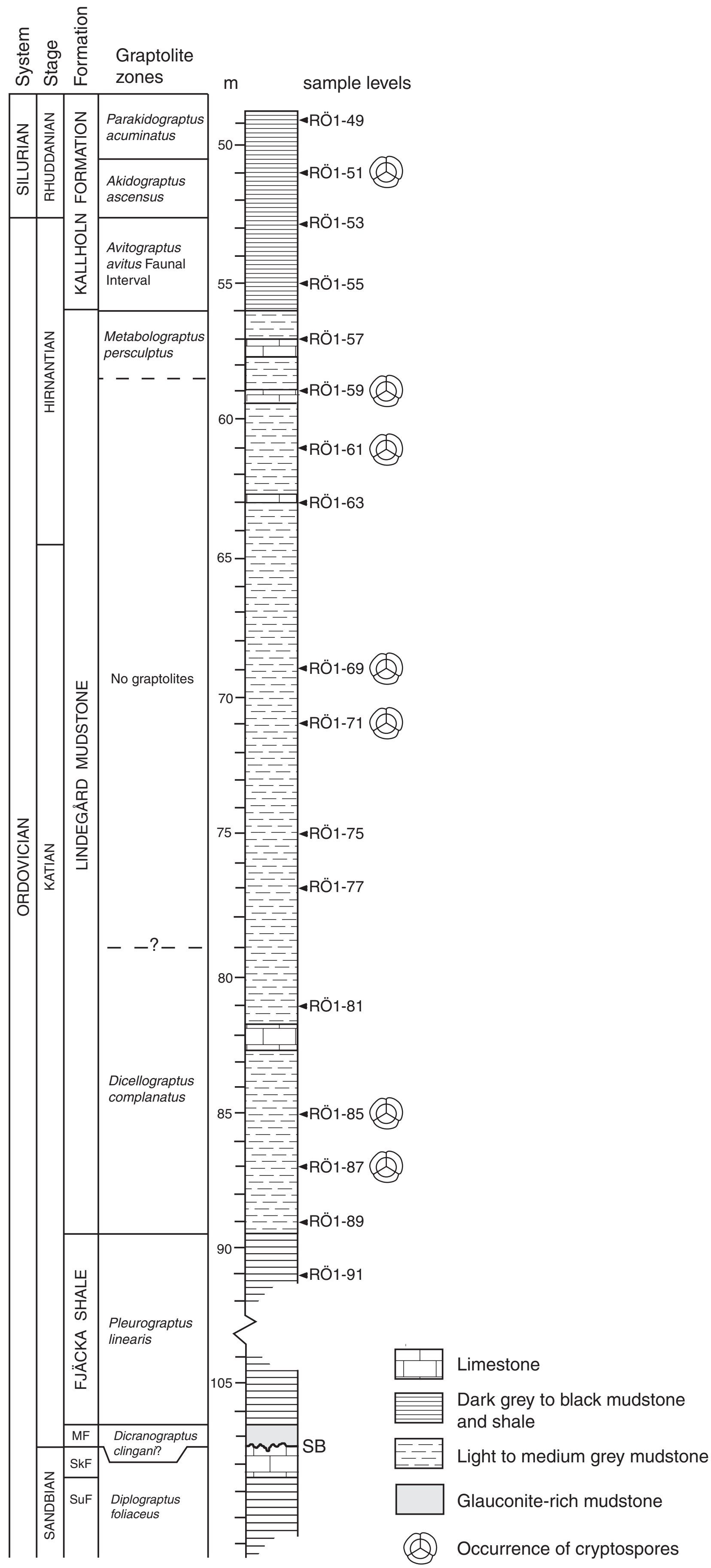

Fig. 3. Thin section of the drillcore showing the disconformity and solution structures at the top of the Skagen Limestone. Note brownish infill with fine skeletal hash of the Mossen Formation. Photo courtesy: Oliver Lehnert.

medinensis (Fig. 4L,N,O), *Tetrahedraletes grayii* (Fig. 4M) and *Pseudodyadospora* sp. possibly provides the oldest evidence of early land plants in Baltica and definitely the oldest spore record from the Lower Palaeozoic of Sweden.

The crypotospores of this study were recovered from the Lindegård Mudstone at the following core depths: 87.0, 85.0, 71.0, 69.0, 61.0, 59.0 and 51.0 m (Fig. 2). The oldest record is just above the appearance of the early Katian graptolite species *Dicellograptus complanatus*, recognized in the core by Pålsson (2002; i.e. Ka4 Stage Slice of Bergström et al. 2009). The presence of cryptospores in the Röstånga-1 core shows that land plants had migrated to Baltica by at least the Late Ordovician.

T. medinensis, *T. grayii* and *Pseudodyadospora* sp., have been reported globally from coeval assemblages, possibly indicating homogeneous land plant assemblages that tolerated a wide range of climatic conditions (e.g. Vecoli et al. 2011).

Acritarchs

Three well-preserved and diverse acritarch assemblages were recovered. The assemblage recovered from the upper Fjäcka Shale (lower Katian; sample RÖ1-91) and the lower–middle Lindegård Mudstone (lower–upper Katian; samples RÖ1-89 to RÖ1-75) is characterized by the occurrence of the key acritarchs *Baltisphaeridium* spp., *Buedingiisphaeridium balticum* and *Orthosphaeridium* spp. The record of diagnostic Early–Middle Ordovician acritarchs, e.g. *Striatotheca* (Fig. 4D), *Coryphidium* (Fig. 4H) and *Acanthodiacrodium–Coryphidium* (Fig. 4J), indicates that reworking of older sediments has occurred, possibly suggesting an Avalonian detrital sediment provenance in a foreland basin system. This assemblage is possibly coeval with assemblages described from Anticosti Island, Québec, Canada (Jacobson & Achab 1985), Jordan (Keegan et al. 1990), Iran (Ghavidel-Syooki 1997) and Estonia (Delabroye et al. 2011a).

The assemblage from the upper Katian–Hirnantian portion of the Lindegård Mudstone (samples RÖ1-69 to RÖ1-57) is characterized by the occurrence of long-ranging acritarchs [e.g. *Veryhachium* (Fig. 4A,B), *Micrhystridium* (Fig. 4I) and *Leiosphaeridia*] and by the appearance of several taxa with Silurian affinity, e.g. *Ammonidium* spp. (Fig. 4G), *Diexallophasis denticulata* (Fig. 4F) and *Tylotopalla* sp. (Fig. 4E). This assemblage seems to mark a global event, possibly related to the initial stage of the Hirnantian glaciation with a major palaeoenvironmental stress (e.g. Delabroye et al. 2011b). The age of this assemblage is probably comparable to assemblages described from northern Gondwana (Vecoli & Le Hérissé 2004), southern Turkey (Paris et al. 2007), Estonia (Delabroye et al. 2011a) and Anticosti Island, Québec, Canada (Delabroye et al. 2011b).

The assemblage from the lower Kallholn Formation (uppermost Hirnantian–lower Rhuddanian; samples RÖ1-55 to RÖ1-49) is characterized by the presence of sphaeromorph acritarchs together with a relatively high abundance of graptolites and rare cryptospores. Acritarchs are scarce throughout this interval, which agrees with palynological studies from coeval strata in other parts of the world. The acritarch assemblage from the Kallholn Formation may also in part be correlated with assemblages from acritarch zone 'AS4' in the Valga-10 core, southern Estonia (Delabroye et al. 2011a). It is also comparable to assemblages described from Jordan (Armstrong et al. 2009).

The acritarchs recovered from the Röstånga-1 drillcore are brownish black in colour, indicating a TAI of 4, which is considered post-mature with respect to oil generation. The high thermal maturity is probably the result of a combination of relatively deep burial in a foreland basin setting and extensive magmatic activity during the early Permian.

Conclusions

Palynological studies through the Katian–lowermost Llandovery succession of the Röstånga-1 core, southern Sweden, have been performed. The palynological assemblages are strongly dominated by marine microfossils and reveal an off-shore depositional environment. The presence of cryptospores, representing the earliest evidence of land plants in Sweden and possibly in Baltica, provides additional evidence for the timing of terrestrialization of plants and the spreading patterns of early land plants. The occurrence of older, Early–Middle Ordovician acritarchs indicates that reworking has occurred, possibly suggesting an Avalonian detrital sediment provenance in a foreland basin system.

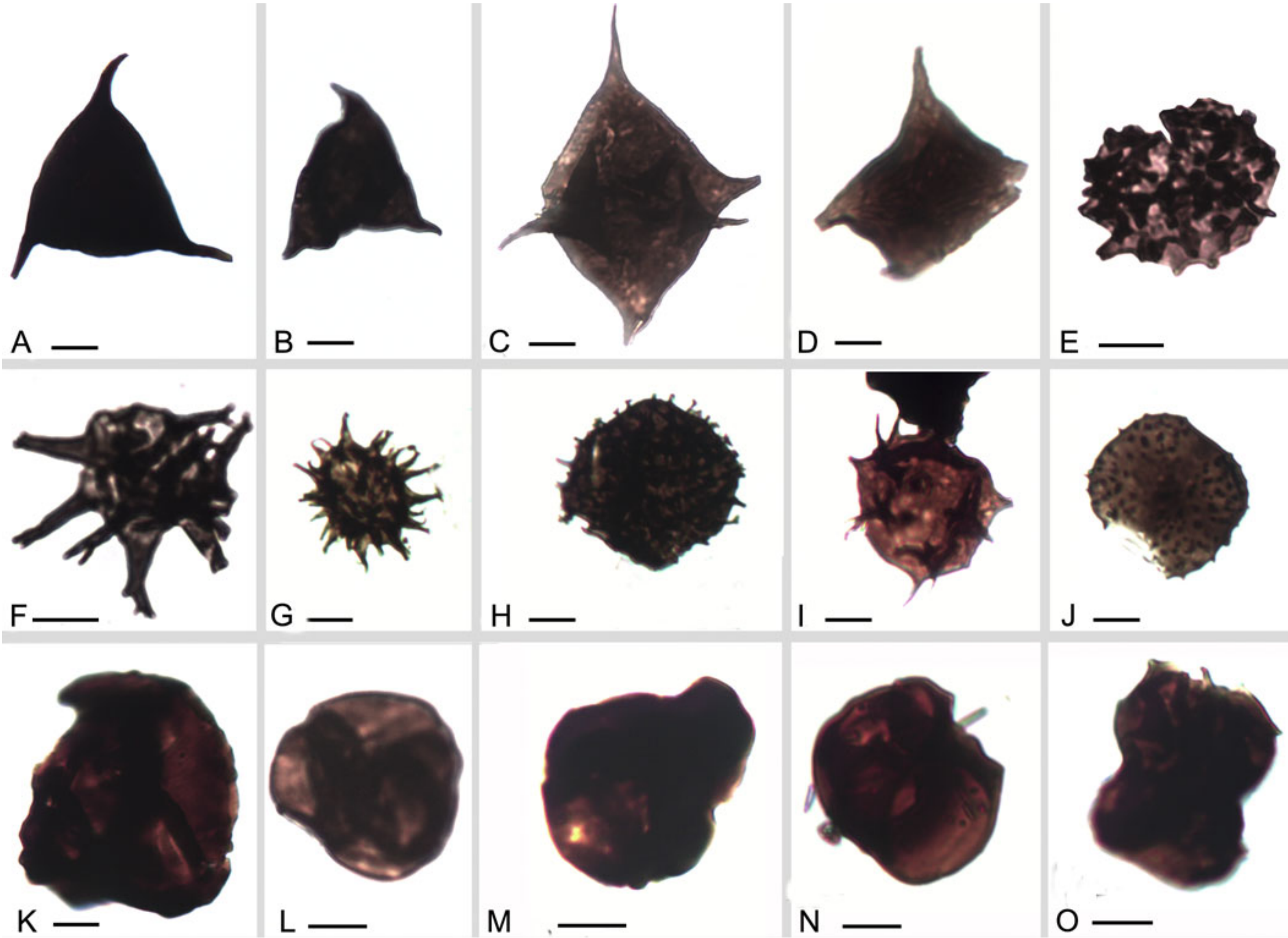

Fig. 4. Light micrographs of representative palynomorphs from the studied samples, scale bars = 10 μm. Taxa, sample number, England Finder Reference (EFR) and LO numbers. **A**. *Veryhachium* sp., RÖ1-69, EFR: M29/3, middle Lindegård Mudstone, 69.0 m, LO11883 t. **B**. *Veryhachium* sp., RÖ1-69, EFR: U27, middle Lindegård Mudstone, 69.0 m, LO11884 t. **C**. *Veryhachium?* sp., RÖ1-59, EFR: G10, upper Lindegård Mudstone, 59.0 m, LO11885 t. **D**. *Striatotheca* sp., RÖ1-77, EFR: X40/1, middle Lindegård Mudstone, 77.0 m, LO11886 t. **E**. *Tylotopalla* sp., RÖ1-69, EFR: H41, middle Lindegård Mudstone, 69.0 m, LO11887 t. **F**. *Diexallophasis denticulata* (Stockmans & Willière) Loeblich, RÖ1-69, EFR: T44, middle Lindegård Mudstone, 69.0 m, LO11888 t. **G**. *Ammonidium* sp., RÖ1-69, EFR: V47, middle Lindegård Mudstone, 69.0 m, LO11889 t. **H**. *Coryphidium* sp., RÖ1-77, EFR: L34/3, middle Lindegård Mudstone, 77.0 m, LO11890 t. **I**. *Micrhystridium* sp., RÖ1-71, EFR-D24, middle Lindegård Mudstone, 71.0 m, LO11891 t. **J**. *Acanthodiacrodium-Coryphidium*, RÖ1-77, EFR: M38, middle Lindegård Mudstone, 77.0 m, LO11892 t. **K**. Cryptospore gen. et sp., indet, RÖ1-51, EFR: W13, Kallholn Formation, 51.0 m, lower Rhuddanian Stage (Llandovery), *Akidograptus ascensus* Zone, LO11893 t. **L**. *Tetrahedraletes medinensis* (Strother & Traverse) Wellman & Richardson, RÖ1-87, EFR: O32, lower Lindegård Mudstone, *Dicellograptus complanatus* Zone, 87.0 m, LO11894 t. **M**. *Tetrahedraletes grayii* Strother, RÖ1-71, EFR: U13/2, middle Lindegård Mudstone, 71.0 m, LO11895 t. **N**. *T. medinensis* (Strother & Traverse) Wellman & Richardson, RÖ1-61, EFR: F19, upper Lindegård Mudstone, 61.0 m, LO11896 t. **O**. *T. medinensis* (Strother & Traverse) Wellman & Richardson, RÖ1-69, EFR: V41/1, middle Lindegård Mudstone, 69.0 m, LO11897 t.

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