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Upper Ordovician $\delta^{13}C_{org}$ chemostratigraphy, K-bentonite stratigraphy, and biostratigraphy in southern Scandinavia: A reappraisal

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ABSTRACT

A pioneer $\delta^{13}C_{org}$ study through the upper Sandbian and Katian (Upper Ordovician) succession in the Röstånga 1 drill core in the classical geological outcrop area at Röstånga in southernmost Sweden produced a wealth of new carbon isotope data which are useful for local and regional correlations. Among the Upper Ordovician positive $\delta^{13}C$ excursions, the Guttenberg (GICE), Waynesville (Saunja), Whitewater (Moe), Paroveja, and Hirnantian (HICE) isotopic carbon excursions are recognized but the Kope (Rakvere) $\delta^{13}C$ excursion is missing, suggesting a stratigraphic gap. All these isotopic excursions are tied closely to biostratigraphy, especially graptolite biostratigraphy, and in the case of the Waynesville (Saunja) and Whitewater (Moe) excursions, for the first time anywhere in the world. The Röstånga GICE $\delta^{13}C_{org}$ curve from the upper Sularp Shale shows a striking similarity to that of the Katian GSSP in Oklahoma, suggesting the potential of trans-Atlantic correlation. Based on a projection from the Katian GSSP, the previously poorly constrained position of the base of the Katian in southern Sweden appears to be in the uppermost Sularp Shale in strata of the upper *Diplograptus foliaceus* Zone. Previous interpretations of the relations between K-bentonite successions in southern Scandinavia are somewhat revised and the Kinnekulle K-bentonite is recognized for the first time in Scania. Based on new radiometric dates, this very prominent and widespread ash bed appears to be slightly older than the Deicke and Millbrig K-bentonites in eastern North America.

1. Introduction

There are many outcrops of Upper Ordovician strata in the Provinces of Västergötland and Dalarna, and a few in the Province of Östergötland, in south-central Sweden. However, in the Province of Skåne (Scania) in southernmost Sweden, and on the Island of Bornholm in Denmark, exposures of rocks of that age are restricted to a few localities, which in Scania are mainly located in the Fågelsång, Röstånga and Tommarp-Järrestad areas (Fig. 1). Also in the latter areas, the Upper Ordovician outcrops do not expose long stratigraphic intervals but rather consist of limited exposures of short successions that are separated by significant covered intervals. Attempts to describe in detail the stratigraphic succession through this part of the Ordovician therefore have to be based on drill cores. The most significant drill cores currently available are the Röstånga 1 in the Röstånga area (e.g. Bergström et al., 1999, 2014; Pålsson, 1996, 2002), and the Koängen (Nilsson, 1977) and Lindegård (Glimberg, 1961) drill cores from the Fågelsång area. The Upper Ordovician succession on the Danish island of Bornholm in the Baltic Sea is known from a few stratigraphically limited outcrops (e.g. Hadding, 1915a,b) and the Billegrav 2 and two other drill cores. Whereas the Fågelsång Upper Ordovician succession has become relatively well known through the work by Nilsson (1977) and Glimberg (1961), that of the Röstånga area was quite incompletely described prior to the drilling of the Röstånga 1 well in the summer of 1997. This well provided the first continuous succession from the upper Sandbian through the top of the Hirnantian stages (Upper Ordovician) as well as through much of the lower and middle Llandovery (Lower Silurian) in this area (Bergström et al., 1999). Subsequent work on this drill core has resulted in several publications (Pålsson, 2002; Koren' et al., 2003; Grahn and Nõlvak, 2007; Badawy et al., 2014; Bergström et al., 2014; Maletz et al., 2014; Kiipli et al., 2015) but some aspects of this drill core, such as the pre-Hirnantian $\delta^{13}C_{org}$ chemostratigraphy, have not been studied previously. The latter research topic is the primary focus of the present study. As will be shown below, this chemostratigraphic study produced some unexpected results that initially were confusing but later, combined with other types of evidence, proved useful for a regional reappraisal of the stratigraphy of the upper Sandbian and Katian successions in southern Scandinavia.

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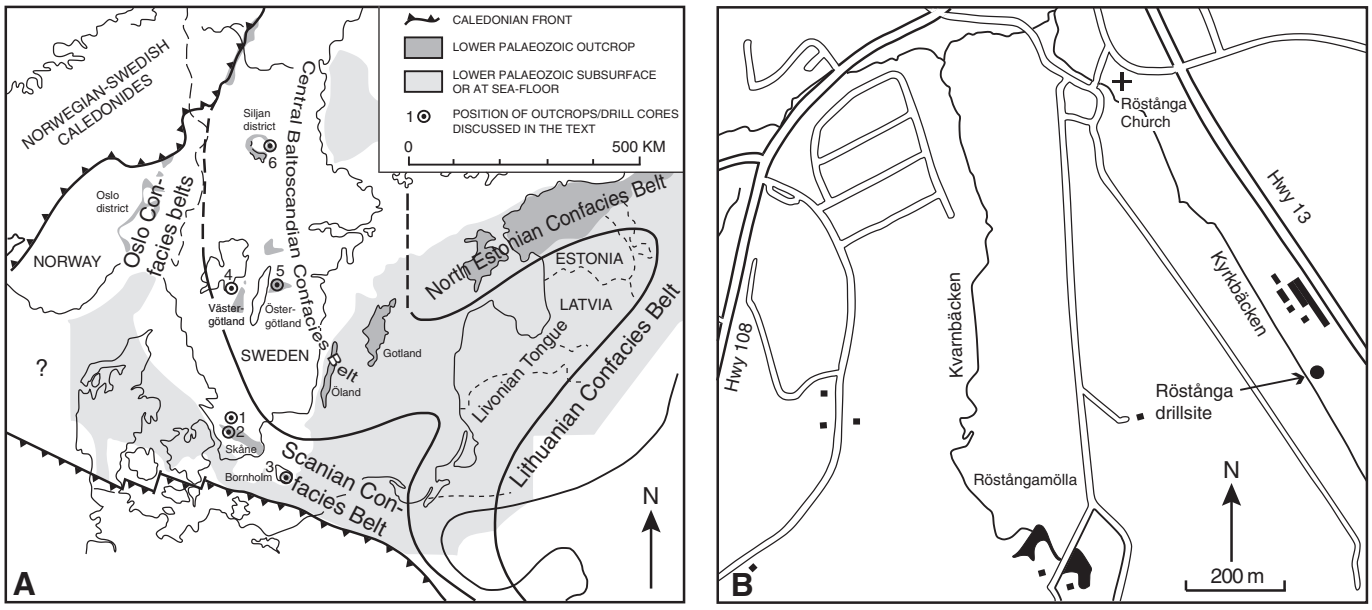

Fig. 1. A, sketch-map of Baltoscandia showing the distribution of confacies belts and the location of localities discussed in the text. 1. Röstånga; 2. Fågelsång; 3. Billegrav; 4. Mossen, Kinnekulle; 5. Borenshult; 6. Solberga. B, Detailed map of part of the Röstånga area west of Highway 13 showing the location of the Röstånga 1 drill site and the Kyrkbäcken outcrop, which is situated a couple of hundred m from the drill site along the western side of the brook opposite the name Kyrkbäcken.

2. Geologic setting and stratigraphy

Ordovician strata in the Röstånga area have a long exploration history, the earliest publications dating back to the 1870s (for a useful summary of the early work, see Moberg, 1910). The previous papers on the Röstånga 1 drill core and the adjacent outcrop along Kyrkbäcken (Church Brook) published by Bergström et al. (1997, 1999, 2014) and by Pålsson (1996, 2002) provide general reviews of past stratigraphic and paleontological work on the Upper Ordovician in the Röstånga area and reference to these publications is made for such information. As is also the case with the succession in the Fågelsång area, which is located approximately 32 km south of Röstånga (Fig. 1), the Ordovician succession at Röstånga was deposited in an outer shelf or upper slope environment near the margin of the Baltic platform. This part of Scania is located within the structurally complex Tornquist Zone that separates the Baltic Shield from the European continent (Fig. 1). In the terminology of Jaanusson (1976, 1995), the Ordovician rocks in Scania represent the Scanian confacies (or lithofacies) belt that is characterized by dominantly clastic sediments deposited in relatively deep water. The Scanian successions, which contain diverse graptolite faunas, differ conspicuously from the carbonate-dominated successions in the more central parts of the Baltic Shield, especially in the East Baltic region, which yield abundant shelly faunas but few graptolites.

With a single exception, we use the same formation classification of the Upper Ordovician pre-Hirnantian succession in the Röstånga 1 drill core and the adjacent exposures along Kyrkbäcken as in Bergström et al. (1997). The only difference is that the term Skagen Formation, which has been employed previously for the calcareous interval between the Sularp Shale and the Mossen Formation, is replaced by the term Freberga Formation. As will be shown below, the principal reason for this change is the fact that the present chemostratigraphic study indicates that much of this unit is substantially younger than the Skagen Formation in south-central Sweden. Because the present study deals not only with the Röstånga succession but also with some other Scandinavian successions, the Upper Ordovician stratigraphic terminology used herein is summarized in Fig. 2. In the case of global Ordovician stages and stage slices, we follow the terminology of Bergström et al. (2009a).

The biostratigraphic work carried out on Upper Ordovician strata in the Röstånga area has been reviewed by Bergström et al. (1997) and Pålsson (1996, 2002) and we summarize only some pertinent data. The Sularp Shale in its outcrop along Kyrkbäcken has yielded about a dozen conodont species but the fauna is dominated by coniform taxa of little biostratigraphic significance and diagnostic index species have not been found. The absence of *Baltoniodus* species, which are very common, and used as subzonal index fossils, in the Dalby Limestone in south-central Sweden (Bergström, 1971) suggests that the upper Sularp Shale is younger than the Dalby Limestone, which is in agreement with the aspect of the fauna, which is similar to that of the Freberga Formation, which overlies the Dalby Limestone in south-central Sweden. In general, the conodont fauna appears to represent an interval around the *Amorphognathus tvaerensis*/*A. superbus* zonal boundary but in the absence of the index taxa, the position of this horizon cannot be located. Bergström et al. (1997) recorded more than a dozen chitinozoan species from the Sularp Shale of the Kyrkbäcken section and essentially the same species association was listed by Grahn and Nõlvak (2007) based on samples from the same locality. Although composed of mainly long-ranging taxa, this chitinozoan fauna was interpreted as representing the *Spinachitina cervicornis* Zone that ranges from the upper Sandbian *Baltoniodus alobatus* conodont Subzone into the lower Katian. We conclude that the available microfossil data from the upper Sularp Shale are not very diagnostic biostratigraphically. A few graptolites have been recorded from the Sularp Shale in the Kyrkbäcken outcrop (Moberg, 1910) but these are in need of taxonomic revision. Comparison with the similar succession in the Koängen drill core (Nilsson, 1977) clearly suggests that the top part of the Sularp Shale corresponds to part of the *Diplograptus foliaceus* Zone. Although the thin Mossen Formation at Röstånga has not yet yielded diagnostic graptolites, comparison with the Koängen drill core succession indicates that in all likelihood this unit is also referable to the *Dicranograptus clingani* Zone. This is supported by the fact that it has yielded a trilobite fauna (Pålsson, 1996) that includes the stratigraphically important species *Tretaspis ceriodes* (Angelin) that in Västergötland is characteristic of, and restricted to, the Mossen Formation (e.g. Skoglund, 1963). The Mossen Formation at Röstånga has also yielded the characteristic conodont *Hamarodus brevirameus* (formerly *H. europaeus*) that elsewhere first appears in the *A. superbus* Zone (Fan et al., 2015) in strata equivalent to the *D. clingani* Zone. The biostratigraphically diagnostic graptolite succession in the Fjäcka Shale and Lindegård Formation described by Pålsson (2002) will be further discussed below. Whereas the Fjäcka Shale has yielded graptolites of the *Pleurograptus linearis* Zone, this