[PS]High Life on the Seafloor during an Ocean Anoxic Event - the Sedimentology of SPICE (Middle to Late Cambrian Alum Shale, Sweden)*

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Search and Discovery Article #50615 (2012)**
Posted June 18, 2012

*Adapted from poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012

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Abstract

The Alum Shale in Scandinavia, one of the most prominent Early Paleozoic source rocks in Northern Europe, consists of mostly black organic-rich mudstones and some intercalated carbonate beds. The unit has been previously interpreted as being deposited on a deep anoxic shelf because it contains high TOC contents (<17 wt%). δ13C and δ34S curves from Alum cores (work of others) shows that part of the succession correlates to the SPICE (Steptoean Positive Carbon Isotope Excursion) event, a time of interpreted worldwide anoxic conditions in Middle to Upper Cambrian strata. This study, using cores and outcrops in southern Sweden and Norway, aims at examining the mudstone microfacies over the entire SPICE stratigraphic interval to test how this postulated Cambrian anoxic event is reflected in sediments deposited on the deep shelf.

Alum mudstones are dominantly clay-rich but locally contain abundant silt-size quartz and carbonate grains, commonly arranged in distinct laminae that vary laterally in thickness. Locally, clay rip-up clasts are common, and mud ripples have been observed. Throughout the succession, the mudstones are highly bioturbated with ubiquitous vertical burrows and very common horizontal burrows.

The ichnofossil distribution follows a gradient with greater diversity in more proximal settings and decreasing diversity on more distal parts of the shelf. This distribution pattern is observed throughout the Alum in the study area. The trace fossil diversity gradient points to a downslope decrease in the oxygen content of bottom or near bottom seawater. However, the constant presence of benthic activity also indicates that the seafloor was most likely never persistently anoxic during Alum deposition. The presence of silt laminae and mudstone ripples further suggests

that the deep shelf, even during SPICE times, was occasionally supplied with sediment and possibly oxygen-rich waters from the shallow shelf. Overall, the facies did not change throughout the stratigraphic interval that contains the SPICE event. Therefore, the deep shelf remained largely oxic to dysoxic, which calls into question the existence of any persistent anoxia during Alum deposition. Nevertheless, large quantities of organic matter could have been trapped in “marine snow” (organo-clay floccules) during the SPICE interval, which could provide a mechanism by which the observed changes in geochemical values could have occurred without requiring worldwide anoxic oceans.

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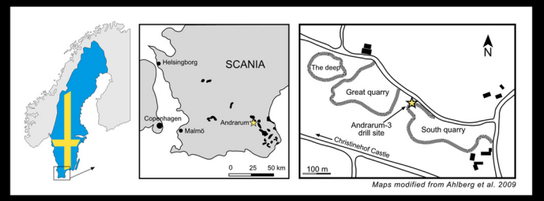
Motivation

- SPICE = Steptoean Positive Carbon Isotope Excursion, which is equivalent to a postulated ocean anoxic event (e.g. Gill et al. 2011)
- Document how this Early Paleozoic anoxic event is expressed in Aum Shale sediments
- Anoxic events tend to produce reducing conditions on the deep shelf. Is the Alum Shale deep shelf on Baltica anoxic during the SPICE event?

Alum Shale Drill Core & Facts



Maps modified from Ahlberg et al. 2009

Fig. 1: Location of the study area in Scania, southern Sweden; the core was drilled in the western corner of an old Alum Shale quarry. Black areas in "B" represent outcrop occurrences of Alum Shale.

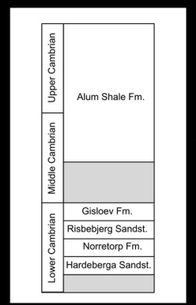
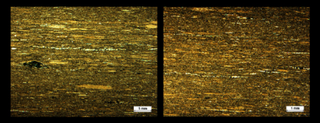


Fig. 2: Generalized stratigraphy of the Alum Shale in Scania (Ahlberg 1998) which is mostly Cambrian but extends upwards into the basal Tremadocian (Lower Ordovician); limestones in the unit are partly to entirely diagenetic in origin.

Fig. 3: (A) Core as available for measuring and sampling, not slabbed, with late diagenetic healed vertical fractures; (B) horizontal fractures in Alum Shale sediments, healed with gypsum, occur throughout the Andrarum core. The Alum Shale shows TOC values of up to 18% in southern Sweden and is the most important Early Paleozoic source rock in Europe (cf. Andersson et al. 1985).

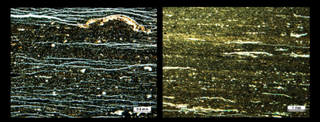
Alum Shale Facies

Facies 1: mudstones with horizontal burrows



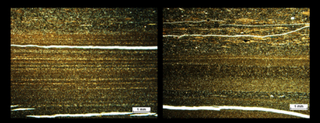
- mudstone with 2-5% silt, finely dispersed & arranged as remnant sub-millimeter-thick laminae with irregular lateral geometry
- Abundant horizontal ichnofossils and clay clasts; also multidirectional traces
- Some sub-millimeter laminae with little to no TOC (Total Organic Carbon)
- "Background" sedimentation, partly by bed load processes (silt)

Facies 2: mudstones with fossil debris

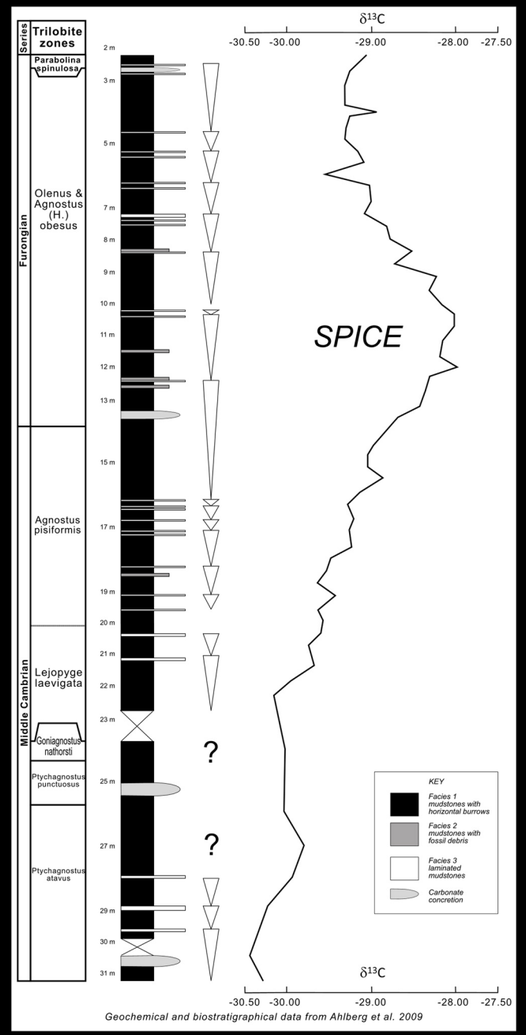


- Mostly massive mudstone with 2-5% carbonate and quartz silt and sand, arranged in laminae crosscut by trace fossils
- Some horizontal and abundant multidirectional traces
- Trilobite and brachiopod (?) fossils and fossil debris, recrystallized and arranged parallel to bedding
- Some lag concentrations of storms, some *in situ* remains of benthic organisms living on the sea floor

Facies 3: laminated mudstones



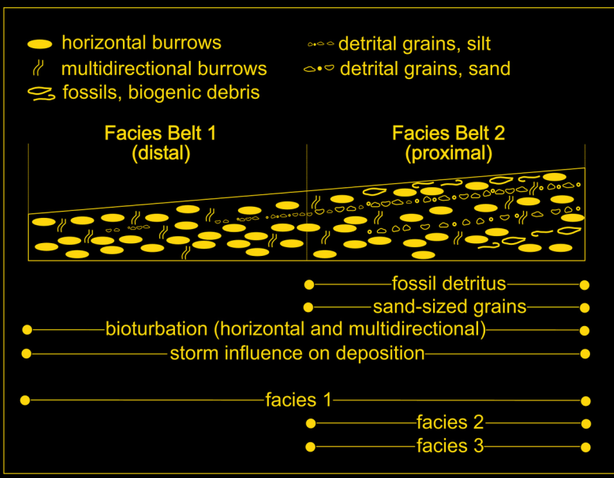
- Sub-millimeter-scale horizontal irregular siltstone laminae, and mostly high- with minor low-TOC massive mudstone laminae
- Little bioturbation; only multidirectional burrows, no horizontal ones
- TOC content overal low; few horizontal calcite-/gypsum-filled fractures
- Bed load deposition, either ripples or upper flow regime planar bed sedimentation; most likely storm events



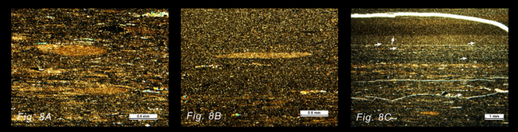
Geochemical and biostratigraphical data from Ahlberg et al. 2009

Alum Shale Succession

- Little facies variety over seven trilobite and conodont biozones - relatively monotonous deep shelf succession
- Shorter-term trends expressed in dm- to m-scale parasequences
- Bioclasts, and complete fossils occur in black shale; discontinuous silstone laminae common in all facies
- Bioturbations occur throughout the investigated Alum interval
- Onset of SPICE not time-equivalent to transgression; climax not recorded as lowstand as no significant change in facies occurs
- SPICE not associated with major anoxic even on the deep shelf indicated by abundace of traces
- Benthic life indicated by fossils with calcareous shells, and abundant traces



Living conditions on deep shelf during SPICE



Two types of burrows:

- Horizontal, oval to roundish in cross-section, filled with mudstones with low TOC content (Fig. 8A and B)
- "Multidirectional" filled with mud containing similar amounts of TOC as surrounding matrix (Fig. 8C)

Implications:

- No persistent anoxia in the water column as reflected in sedimentology on deep shelf environment during Alum Shale deposition
- At least dysoxic conditions also a few millimeters down into the sediment indicated by multidirectional burrows

Conclusions

- Middle to Upper Cambrian succession in Andrarum drill core shows distinctive parasequences/sequences; however, the overall facies is monotonous throughout studied interval
- Two mudstone facies belts can be distinguished; a completely homogenized distal mudstone with burrows (facies 1), and a more proximal one with shells and silt- to sandstone laminae (facies 2 and 3).
- The Alum Shale in the Andrarum drill core was deposited in part above, and in part probably below storm wave base.
- Facies is thoroughly bioturbated; this argues against persistent anoxic conditions on the Alum deep shelf; water column and uppermost millimeters of sediment must have been at least dysoxic.
- Interestingly, the SPICE event does not influence facies expression in Scandinavian offshore sediments; it is not reflected in the formation of e.g. an widespread anoxic zone

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