Utrecht University

Faculty of Earth Sciences

Master thesis

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*Palynological investigation of the mid-Sinemurian (Early Jurassic) carbon cycle perturbation*

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Author
Hendrik Aalpoel

Supervisors
1st: dr. Bas van de Schootbrugge
2nd: Carolien van der Weijst

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# Abstract

A high-resolution palynological investigation was performed on the Sinemurian sediments of the German Schandelah core. Roughly 60 meters of core material was sampled in 1-meter intervals, and the resulting samples were processed to yield palynological slides. The resulting assemblages are characterised by a remarkable stability. Terrestrial palynomorphs greatly dominate over marine palynomorphs, and within terrestrial palynomorphs pollen dominate over spores consistently. The marine record is characterised by two acmes of the dinoflagellate cyst *Liasidium variabile*, in the Obtusum and Oxynotum ammonite zones of the Upper Sinemurian. In order to better quantitively asses these palynomorph records, a Sporomorph Ecogroup (SEG) model, and several SEG and palynomorph based proxies are used. Once more, records appear relatively stable, but variations in the Upland SEG group and spore/bisaccate (S/BP) ratio indicate the probable occurrence of relative sea level rise during intervals in the Lower and Upper Sinemurian. The apparent stability of the palynoflora contrasts reports from Lincolnshire (UK), where Riding et al. (2013) report a global warming event of a few hundred thousand years, based on palynological and stable isotope data. However, the results of this study, and studies performed on other localities, makes the possibility of a global warming event during deposition of the Upper Sinemurian strata highly unlikely. The need for this interval to be studied out of Europe is acknowledged, though, and definitive conclusions can only be made if a global database of palynological and stable isotope data is compiled. Until a such research is conducted, the image of stable vegetation in the Sinemurian, after rapid floral changes during the preceding Rhaetian and Hettangian stages, still remains viable.

## Introduction

Generally, early Jurassic climate is seen as relatively stable, with warm surface-air temperatures and monsoons which dominate the mid-latitudes based on modelling results. (Chandler et al., 1992). Thus, a report of a geographical significant warming phase in both the terrestrial and marine realm during the Sinemurian stage of the Jurassic Epoch (Riding et al., 2013) warrants further investigation.

In this report, the results of a palynological investigation of Sinemurian core material from Schandelah, Germany, are covered. Using high resolution sampling (<1 meter scale), an attempt will be made to uncover the development in Sinemurian vegetation dynamics, as well as possible changes in the marine realm. A comparison will be made to the results of Riding et al. (2013) and other sources, to test the viability of a Sinemurian global warming period. Additionally, the results from this study will be combined with results of previous studies, including Van der Weijst (2015), to create a continuous palynological record which spans the Late Triassic Rhaetian stage to the early Jurassic Sinemurian stage, enabling an overview of long-term vegetation changes.

## Background information

### Geologic and climatic background

In the early Jurassic, the continents were still aggregated in the Pangean supercontinent (Figure 1), spread roughly equally over the northern and southern hemisphere, it ranged from 85°N to 83°S, and spanning 180° of longitude (Chandler et al., 1992). Northern Pangea, Laurasia, compromised of the North American and Eurasian plates was connected to southern Pangea, Gondwana, which consisted of the African, Antarctic, Australian, Indian and South American plates. To the East these continents were separated by the Tethys ocean.
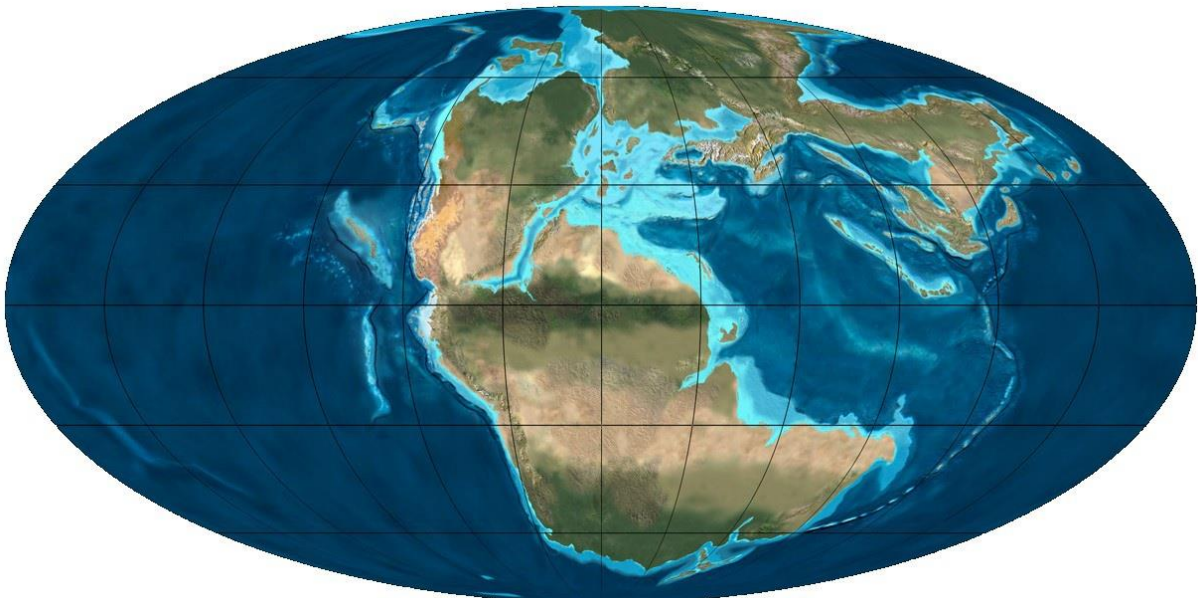


*Figure 1: Continental landmass distribution during the Early Jurassic (200 MA). Obtained from: Blakey, 2014.*

The studied material from the Schandelah core originate from the epicontinental sea margin of this ocean (Figure 2). Sediments found in the Schandelah core specifically originate from the Central European basin, this basin formed as intensified Late Triassic to Early Jurassic rifting of northern Pangea contributed to sea level rise. Consequently, this ensued in flooding of the peri-Thethyan epicontinental lowlands, much like the Central European Basin (Ziegler, 1990).

The break-up of the Pangea supercontinent is also linked to the emplacement of the Central Atlantic Magmatic Province (CAMP) (Marzoli et al., 1999). This magmatic province extended over $7*10^6$ km$^2$, with an estimated volume of at least $2*10^6$ km$^2$ (Marzoli et al., 1999). The massive volcanic eruptions associated with the CAMP are generally believed to be the cause of the end-Triassic extinction event, one of the five major extinction events in the Phanerozoic (Bambach et al., 2004). Greenhouse gasses emitted from CAMP volcanism have likely had an influence on the carbon cycle throughout most on the Hettangian and the Early Sinemurian (Van de Schootbrugge et al., 2008).

The climate associated with the super-continental configuration as in the Early Jurassic has generally been described from model results as warm, up to 5°-10° warmer than modern times (Chandler et al., 1992), with high surface-air temperatures and extreme continental aridity in the low and middle latitudes of western Pangea (Chandler et al., 1992). The mid-latitudes coasts of the Tethys ,and the continent bounding, Panthalassa oceans were dominated by monsoons, which also affected conditions deep into continental interior in some regions (Chandler et al., 1992). Seasonality was likely also high (Kutzbach & Gallimore, 1989; Chandler et al., 1992), with temperatures ranging approximately 45° over high latitude continental interiors, a value comparable to modern day Siberia (Chandler et al., 1992).
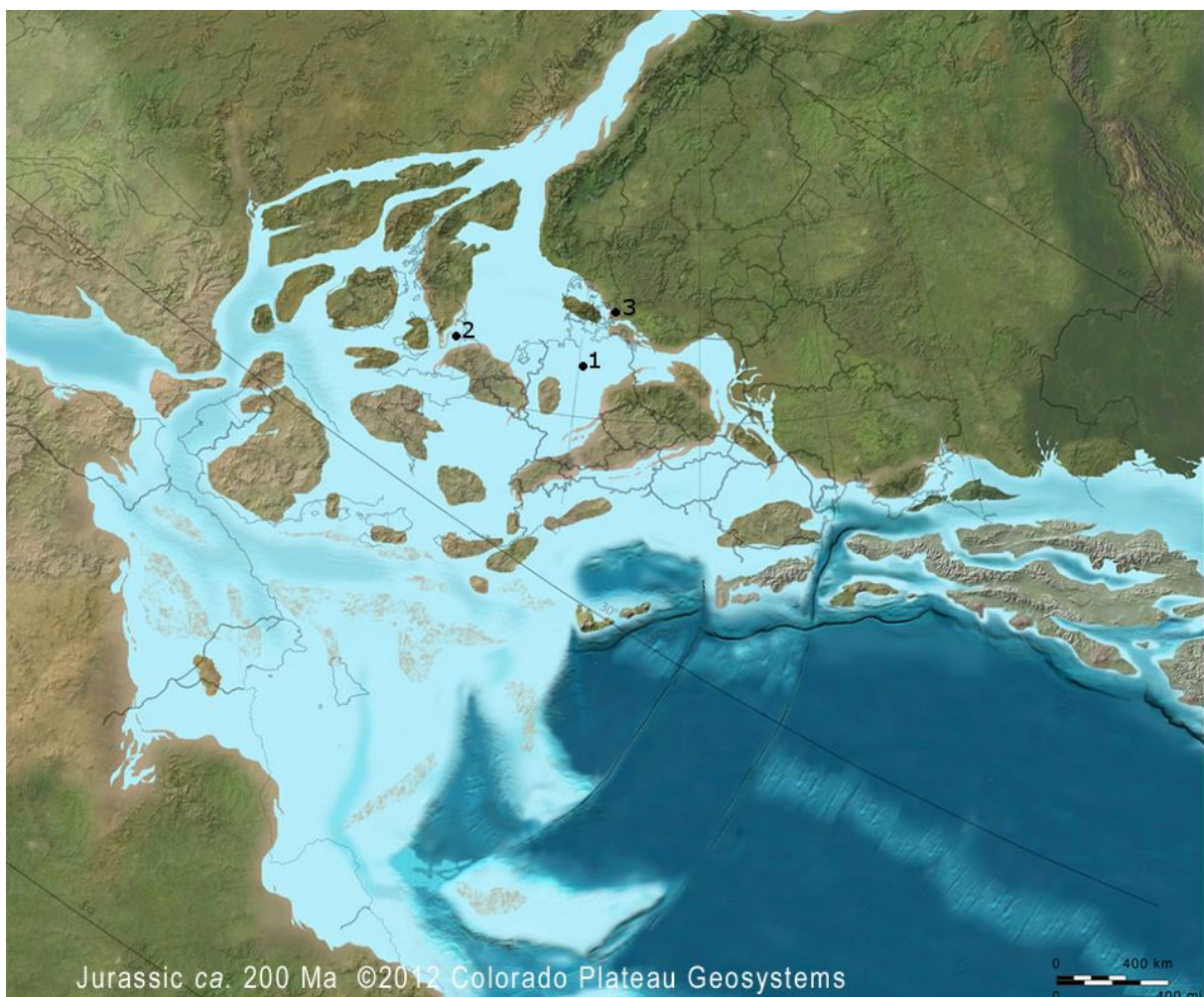


*Figure 2: Location of localities discussed in text. 1) Schandelah. 2) Copper Hill. 3) Höllviken. Map obtained from: Blakey, 2012.*

**Previous research**

The Sinemurian stage has been discussed in an number of different cores from the Central European basin. One such succession of cores, originating from the Höllviken Halfgraben between Denmark and Sweden, has been investigated by Lindström et al. (2017). The entire succession ranges from the Middle Triassic to Lower Jurassic, reaching into the Early Sinemurian stage. Palynology in the

Sinemurian was characterised by the presence of the *Cerebropollenitis macroverucosus* taxon, and dominated by *Deltoidospora spp.*, and abundant presence of *Perinopollenitis elatoides* and *Pinuspollenitis minimus* (Lindström et al., 2017). In terms of plant groups, those dominantly found after the extinction interval were pinacean conifers, corystosperms, ginkgo/cycads and tree ferns (Lindström et al., 2017). In addition, Lindström et al. (2017) noted the post extinction interval (Hettangian to Early Sinemurian) palynoflora appears relatively stable. Other detailed terrestrial palynomorph records of the Sinemurian are relatively scarce. Riding et al. (2013) do report relative abundances from a borehole in eastern England (discussed further below), from which a dominance of *P. elatoides* and abundant presence of *Classopollis classoides* and undifferentiated bisaccate pollen. Several marine palynological records of the Sinemurian are also available. Dinoflagellate cysts found in Lower Sinemurian belong in the *Dapcodinium priscum* dinoflagellate cyst zone of Poulsen & Riding (2003), while the cysts in the Upper Sinemurian almost exclusively belong to *Liasidium variabile* (Van de Schootbrugge et al., 2005). The Upper Sinemurian is thus the *L. variabile* zone (Poulsen & Riding, 2003), although *Mancodinium semitabulatum* and *Valvaeodinium armatum* are also known to be found in this time period (Feist-Burkhardt, 2009).

**The late-Sinemurian global warming event**

In their 2013 paper, Riding et al. discuss palynological, carbon and oxygen isotope data from the Copper Hill Borehole, eastern England. They found a 2-3‰ negative excursion in both marine and terrestrial Total Organic Carbon (TOC) $\delta^{13}$C records, lasting approximately several hundred thousand years. In addition, an acme of *Classopollis* pollen from the terrestrial realm, and *L. variabile* dinoflagellate cysts from the marine realm were found. These acmes occurred during the same time as the Sinemurian Carbon Isotope Excursion (S-CIE). Because of the affinity of *Classopollis* with warm paleotemperatures (Pocock & Jansonius, 1961), as well as the affinity of *L. variabile* with warm water conditions, Riding et al. (2013) interpreted this data as being linked. Furthermore, they considered this evidence of a major biogeochemical perturbation, which they associated with injection of isotopically light carbon in the ocean and atmosphere, resulting in global warming. Similarities between the S-CIE event and the Cenozoic Paleocene-Eocene thermal maximum (PETM) have been found (Riding et al., 2013), although in particular the sudden appearance of *L. variabile* has been found reminiscent of the appearance of the *Apectodinium* dinocyst event during the PETM (Feist-Burkhardt, 2009). This distribution pattern, the peridinialan affinity of *L. variabile* and autofluorescense analysis have been used as arguments to suggest a heterotrophic character to the dinoflagellate producing *L. variabile*, making it the oldest candidate of a heterotroph dinocyst in the fossil record (Feist-Burkhardt, 2009). As the name implies, a number of morphotypes of *L. variabile* have been found, with at least ten variations of this "species" (Van de Schootbrugge et al., 2005). Palliani & Riding (2000) encountered two distinct variations (Figure 3) in the Brown Moor Borehole from New Yorkshire (United Kingdom). Specimens from the Obtusum and part of the Oxynotum ammonite zone had relative short apical and antapical horns (Figure 3A). Morphotype b (Figure 3B), with a long apical horn and a rounded left antapical protuberance as well as a pronounced right lateral 'shoulder' on the hypocyst was confined to the Oxynotum zone (Palliani & Riding, 2000).
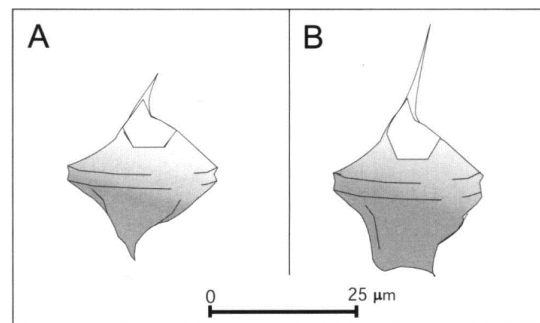


*Figure 3: Line drawings of two L. variabile morphotypes (A&B), as described by Palliani & Riding (2000). Refer to text for description. Obtained from: Palliani & Riding, 2000.*

## Material and methods

### Core details
For this research project, a total of 46 samples were processed from the Sinemurian interval of the Schandelah core. This core was drilled in the municipality of Lehre, Lower Saxony, near the town of Schandelah (52°18'23"N, 10°42'66"W) in August and September of 2008. Drilled to a maximum depth of 338 meters below surface (m.b.s.), it spans the Rhaetian (Upper Triassic) to Toarcian (Lower Jurassic). More detailed methodology can be found in Van de Schootbrugge et al. (in press).
The age model for the core was constructed using ammonite zonation. Because of the lack of ammonite specimen in the record, and their incomplete or poor preservation, the stratigraphic record has been improved using ostracods, benthic foraminifera, calcareous nannofossils and palynomorphs (Van de Schootbrugge et al., in press). Lithological columns and ammonite zonation used in figures henceforth are as defined by Van de Schootbrugge et al.(in press).

### Sinemurian deposit lithology
The Sinemurian section of the Schandelah core spans roughly 60 meters, from 233.30-230.20 m.b.s. at the base to 170.20 at the top, at which the base of the Pliensbachian is defined (Van de Schootbrugge et al, in press) . The lithology of the Schandelah core has been described extensively by Van de Schootbrugge et al. (in press). In summary, the Lower Sinemurian is mostly consistent of generally well laminated organic-rich black to dark grey shales and claystones. The base consists of two calcareous sandstone beds, separated by a grey claystone. Further upcore, a regional marker bed known as the "Konglomerat Bank" occurs, called so due to its conglomeratic nature. It can be found from 188.10 to 187.70 m.b.s., placing it in the Oxynotum ammonite zone. Another regional marker bed can be found near the top of the Sinemurian (177.27 – 176.94 m.b.s.), which is a conglomeratic sandy limestone, known as the "Raricostatum Bank".

### Sample processing
Palynological processing was performed in the Gemeenschappelijk Milieulaboratorium (GML) building, Utrecht University, the Netherlands. The process was started by scraping selected samples, after which samples were ground and weighted. 10 Grams of sediment were then heat dried of 24 hours at 60 degrees. After drying, a Lycopodium tablet was added (in order to count and calculate absolute palynological data). The sediment was then treated with 10% HCl, in order to remove carbonates. Then, samples were rinsed with 30% HF for the removal of silicates, after which they were shaken for two hours. After sharing, the samples were once again rinsed with HCl. The HF rinsing, shaking and subsequent HCl rinsing were then repeated. The residue was then sieved with a 250 μm and a 10 μm sieve to filter out large and very fine residue respectively. During the sieving process, an ultrasonic tub was used to break up material. The sieved residue was then stored in vials. In order to prepare microscope slides, a homogenous droplet of this residue was transferred to a slide plate, along with a small amount of glycerine jelly. After placing a cover slip, it was fixed in place using varnish.

### Sample analysis
Up to 300 palynomorphs per sample were counted using a light microscope, using a 10*40 magnification. Lycopodium spores added during processing were also counted independently to asses absolute abundances. Amongst other material, plates provided by Wall (1965) and Lindström et al. (2017) were used to aid in the identification of palynomorphs. A number of palynomorphs were also identified with the help of Van de Schootbrugge and Van Konijnenburg-van Cittert (personal communication, 2017-2018).

**The Sporomorph Ecogroup model**

In order to realistically interpret changes in Jurassic sporomorph assemblages, information on the ecology of the parent plants of quantitively important spores and pollen is needed (Abbink et al., 2004). The same paper, Abbink et al. (2004) explore a palaeocommunity model to facilitate interpretation of quantitative sporomorph distribution patterns, applicable to the Jurassic and Early Cretaceous of NW Europe. The resulting "Sporomorph Ecogroup (SEG) Model" will also be used in this thesis, in order to infer changes in sea level and climate.

The basis of the model is grouping different types of dispersed spores and pollen of land plants, to reflect the composition of a source community. In order to do this, an ecological framework is needed. This framework was established by Grime (1979), in which two factors were determined to define the type of specific vegetation: stress and disturbance. Variations in these two factors defined three different plant strategies: competitive (low stress, low disturbance), stress tolerating (high stress, low disturbance) and ruderal (low stress, high disturbance), a fourth option (high stress, high disturbance) was not found to be viable as a plant habitat (Grime, 1979).

Translating these strategies into the SEG model, the following SEGs were established by Abbink et al. (2004), and described in detail in Table 1. The lowland SEG presents itself as an area with optimum of nutrients and fresh water, making it a low stress and low disturbance niche fitting competitive plants (Abbink et al., 2004). The other SEGs follow either a stress-tolerating or ruderal strategy. Stress inducing factors might include salt water influence (tidally influenced SEG), salt spray (coastal SEG) or lack of fresh water and nutrients (upland SEG) (Abbink et al., 2004). A ruderal strategy might be employed by plants living along rivers, possibly being periodical submersed or experiencing erosion of the river banks (river SEG). Pioneers or first colonisers will also follow this ruderal strategy (Pioneer SEG). These SEGs have been schematically plotted in Figure 4. Palynomorphs found in the Sinemurian stage of the Schandelah core have been affiliated with a SEG, as well as their known or probable parent plant in table 2. Known or probable parent plant affinity and SEG assignments are per Abbink et al. (2004), Lindström et al. (2017) and Van der Weijst (2015).
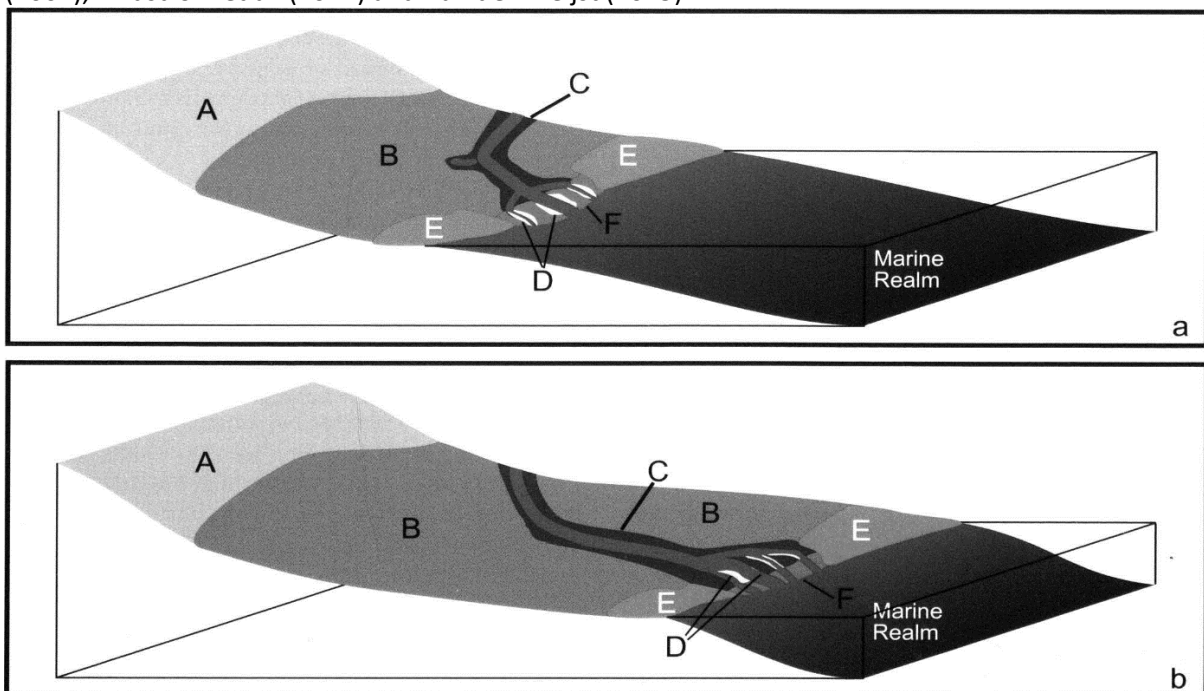


*Figure 4: Schematic depiction of the spatial distribution of the SEG. Upper timeslice a represents a sea-level high, while the lower timeslice b represents a sea level low. A - Upland, B - Lowland, C - River, D - Pioneer, E - Coastal & F - Tidally influenced SEG. Obtained from: Abbink et al., 2004.*

*Table 1: Description of SEGs as cited from Abbink et al. (2004).*

| SEG | Description of flora reflected in SEG |
|---|---|
| **Upland** | Upland communities: vegetation on higher terrain well above groundwater level that is never submerged by water |
| **Lowland** | Lowland communities: vegetation on plains and/or in fresh water swamps; the plans may (periodically) be submerged by fresh water, resulting in the possible presence of 'wetter' (Lowland – Wet) and 'drier' (Lowland – Dry) taxa in this group; there is no influence of (sea) salt, except, perhaps, under extreme conditions. |
| **River** | Riverbank communities, vegetation on river banks which are (periodically) submerged and subject to erosion. |
| **Pioneer** | Pioneer communities, vegetation at instable and recently developed eco-space (e.g. vegetation growing at places that had been submerged by the sea for a longer period). |
| **Coastal** | Coastal communities, vegetation growing immediately along the coast, never submerged by the sea but under a constant influence of salt spray. |
| **Tidally-influenced** | Tidally influenced communities, vegetation that is daily influenced by tidal changes (regularly submerged at high tide). |

**Changes in SEGs as proxies for environmental changes**

The relative abundance of SEGs and the quantitative abundance of individual SEGs are expected to be indicative of changes om geography and/or climate (Abbink et al., 2004). Sea level fluctuations are a major geographical factor, and changes therein are recorded in various ways in the distribution of the SEGs. During sea level rise, the sea water invades the coastal/delta plain, and thus reduces the area reflected by the vegetation of the Lowland SEG, while this same Lowland SEG will expand during sea level fall (Observe Figure 4 for the difference in situations). During sea level rise, coastal vegetation will be forced back and replace the Lowland SEG, and as such, the ratio between the Lowland SEG and the Coastal SEG is deemed a proxy for sea-level fluctuations (Abbink et al., 2004).

The boundary between the Upland SEG and the Lowland SEG is relatively stable, however changes in river drainage patterns cause an increase of Upland SEG related palynomorphs (mainly alete bisaccates). Consequently, during rising sea level at the flooding surface, Upland SEG levels are thought to be relatively high (Abbink et al., 2004).

As climate change impacts a number of factors, including humidity levels, precipitation and temperature. These factors, in turn, impact the competitive strategy of plants, causing the constituents, or abundances thereof, of SEGs to change (Abbink et al., 2004). The Lowland SEGs assigned plants have a competitive strategy. Thus, the Lowland SEG is considered most sensitive to climate change (Abbink et al., 2004). Plants within other SEGs might also follow a competitive strategy, and in particular the Coastal and Upland SEGs are thought to be affected by climate change. Within a SEG, climate change can be recognised by categorising and plotting wet vs. dry elements and warm vs. cold elements (Abbink et al., 2001). The remaining SEGs are not considered to experience a major influence of climate change (Abbink et al., 2004).

*Table 2: Known/probable plant affinity and assigned SEG for pollen and spore taxa, as well as higher (functional) taxon of marine palynomorphs. N/A = not attributable.*

| Palynomorph | Known/Probable parent plant/affinity | SEG |
| --- | --- | --- |
| **Pollen** | | |
| **Alisporites spp.** | Seed fern, Corystospermales | Upland |
| **Bisaccate pollen (undifferentiated)** | Conifers/Corystospermales | Upland |
| **Cerebropollenites macroverrucosus** | Conifer | Pioneer |
| **C. mesozoicus** | Conifer | Pioneer |
| **C. thiergartii** | Conifer | Pioneer |
| **Chasmatosporites hians** | Cycads/Ginkgos | Lowland - Dry |
| **C. apertus** | Cycads/Ginkgos | Lowland - Dry |
| **C. major** | Cycads/Ginkgos | Lowland - Dry |
| **C. elegans** | Cycads/Ginkgos | Lowland - Dry |
| **Classopollis classoides** | Conifer, Cheirolepidiaceae | Coastal |
| **Cycadopites sp.** | Cycadopyta/Ginkophyta | Lowland - Dry |
| **Monosulcites spp.** | Cycads/Ginkos/Bennittales/Peltaspermales (Seed ferns) | Upland |
| **Perinopollenites elatoides** | Conifer, Cupressaceae/Taxodiaceae | Lowland - Wet |
| **Pinuspollenites sp.** | Conifer, Pinaceae | Upland |
| **Podocarpus sp.** | Conifer | Upland |
| **Pollen indet** | N/A | N/A |
| **Protoabietipites** | Conifer | Upland |
| **Quadraeculina** | Unknown gymnosperm | Upland |
| **Sulcate pollen** | ? | ? |
| **Vitreisporites** | Seed fern, Caytoniales | River |

| | | |
| --- | --- | --- |
| **Spores** | | |
| **Anapiculatisporites spp.** | Fern | Coastal |
| **Baculatisporites spp.** | Fern, Osmundaceae | River |
| **Calamospora spp.** | Equisetales | River |
| **Conbaculatisporites spp.** | Fern | N/A |
| **Concavisporites** | Fern | Lowland - Wet |
| **Convolutispora** | ? | N/A |
| **Deltoidospora spp.** | Fern, Dipteridaceae | Lowland - Dry |
| **Densoisporites** | Lycophyte, Pleuromeiaceae | Coastal |
| **Enzonalasporites** | Conifer, Voltziales, ?Majonicaceae | Lowland - Dry |
| **Gordonispora spp.** | Bryophyte | River |
| **Ischyosporites** | Ferns, Schizaceae | Lowland - Wet |
| **Kekryphalospora** | ? | ? |
| **Lycospora spp.** | Lycophyte | ? |
| **Neoraistrickia spp.** | Fern | River |
| **Osmundicites** | Fern, Osmundaceae | River |
| **Polypodiisporites spp.** | Fern, Schizaceae, Polypodiaceae | N/A |

| | | |
|---|---|---|
| **Retitriletes spp.** | Fern | River |
| **Semiretisporites** | ? | N/A |
| **Spores Indet** | N/A | N/A |
| **Stereisporites** | Bryophytes | River |
| **Trachysporites spp.** | Fern | N/A |
| | | |

| | | |
|---|---|---|
| **Aquatics** | | |
| **Acritach indet** | Acritarchs | Aquatic - Marine |
| **Algae/Phytoplankton indet** | N/A | N/A |
| **Baltiphaeridium** | Acritarchs | Aquatic - Marine |
| **Dinocyst indet** | Dinoflagellates | Aquatic - Marine |
| **Foramifera linings** | Foraminifera | Aquatic - Marine |
| **Liasidium variabile** | Dinoflagellates | Aquatic - Marine |
| **Mancodinium spp.** | Dinoflagellates | Aquatic - Marine |
| **Micrhystridium spp.** | Acritarchs | Aquatic - Marine |
| **Nanoceratopsis spp.** | Dinoflagellates | Aquatic - Marine |

# Results

**General palynological stratigraphy of the Sinemurian section**

In general, the palynological assemblage in the Sinemurian can be described as consistent. Almost all notable taxa found, span the entire interval, varying only in relative abundance trough time. Pollen taxa with major presence in the assemblage include *Alisporites spp., Classopollis spp., Pinuspollenitis spp.* And *Perinopollenitis elatoides*. Spores have a less diverse assemblage throughout, notable taxa include *Deltoidespora spp., Retitriletes spp*. and *Trachysporites spp*. The only marine palynomorphs which could be confidently determined were either dinoflagellate cysts (*Nanoceratopsis spp., Liasidium variabile* and *Mancodinium spp.)* and acritarchs (*Micrhystridium spp.* and *Baltispaeridium*), and all of these taxa are very irregularly present. The ranges of all species determined in this interval can be found in Figure 5. As can be inferred from this chart, constructing biozones using the species present is greatly hampered by the lack of first and last occurrences in the record, as few species have a first (FO) and last occurrences (LO), and the ones which do not appear to be reliably found to use as a stratigraphic marker. The major exception to this is are the FO and LO of *L. variabile*, at 213.00 and 178.00 m.b.s., respectively. This range belongs to the Obtusum and Oxynotum ammonite zones, consistent with other reports of a strictly Upper Sinemurian age for this species (e.g. Poulsen & Riding, 2003).

*Figure 5: Stratigraphic range chart of all palynological taxa. Depth in m.b.s.*

## General trends in the palynological assembly

When plotted (Figure 6), it quickly becomes evident that the palynological assemblage is dominated by terrestrial palynomorphs (spores and pollen). Terrestrial and marine palynomorph taxa are well preserved in the studied samples, allowing consistent identification of (at least) the major taxa found in the assemblage. Contrary to the abundance of terrestrial sporomorphs, aquatic palynomorphs rarely attain a relative abundance above 10%, except for some conspicuous intervals. These intervals have a relatively high share of acritarchs (e.g. at ~223 and ~174 m.b.s.) or dinoflagellate cysts (e.g. at ~183 m.b.s.). This is also evident in the calculated ratio of terrestrial and aquatic palynomorphs (T/A), which rarely attains values below 0.9, and averages 0.94, indicating an assemblage extremely influenced by terrestrial input. Naturally, the previously discussed intervals of dinocyst/acritarch input notwithstanding. Pollen abundance greatly dominates over spores, which typically only occur with abundances of ~15%. Aquatic palynomorphs are rare, and as such the relative presence in these taxa are not as reliable as the estimates of terrestrial pollen and spore taxa abundance. At about 180 m.b.s. and upward, the onset of a gradual declining trend can be found in the abundance of pollen, while the abundance of spores increases gradually with approximately the same magnitude, this is also observed in the pollen/spore (P/S) ratio.
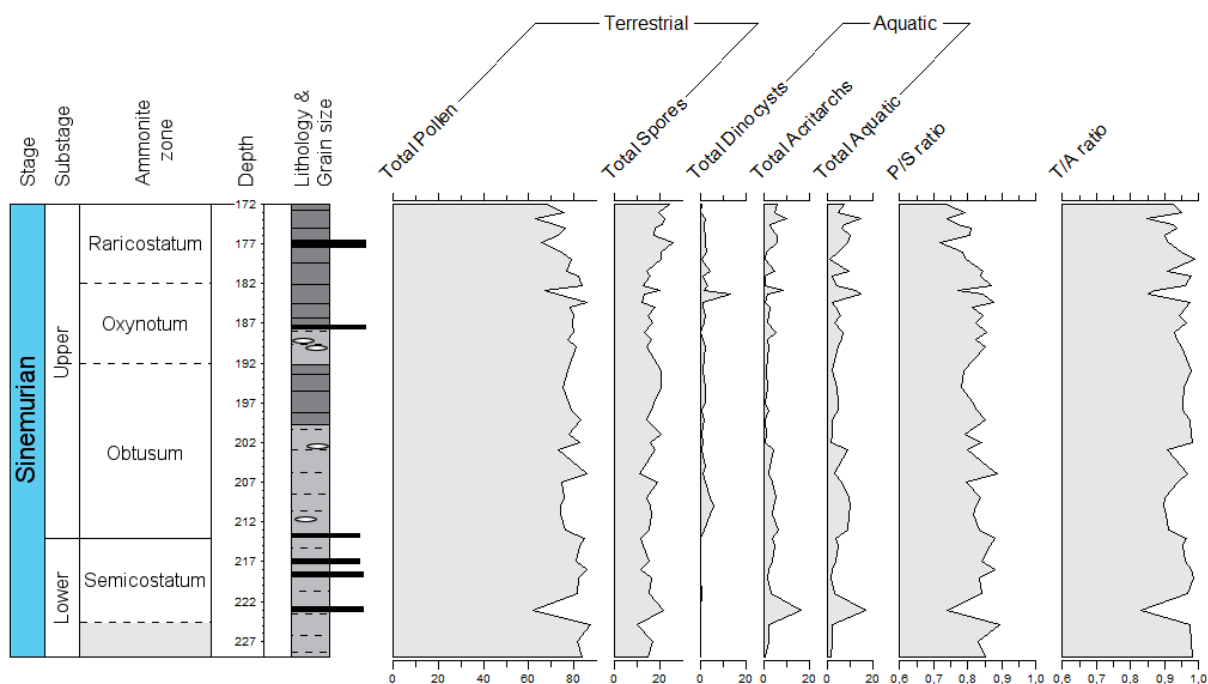


*Figure 6: Main palynomorph groups in the studied material. Depth in m.b.s, abundances in percentages. P/S ratio: ratio of pollen over spores. T/A ratio: ratio of terrestrial palynomorphs over marine palynomorphs.*

## Common sporomorph data

A selected number of common palynomorphs has been plotted in Figure 7. The most abundant is *Perinopollenitites elatoides*, which is especially prolific at 227, 219, 209 and upwards of ~185 m.b.s.. Another common taxa is the bisaccate *Alisporites spp.*, with acmes at 225, 214 and 190 m.b.s. *Classopollis classoides* also occurs regularly, and has acmes at 227-223 and 188-185 m.b.s.. Other common pollen have no notable acmes, but do contribute to the variety of taxa found.

Spore assemblages are dominated by *Deltoidospora spp.* (3,8% on average, of the total assemblage), *Retitriletes spp.* (2,6%) and *Trachysporites spp.* (4,2%) which are the only taxa found with a regular presence that are (on average) more abundant than 1%. *Kekryphalosphora* is also commonly found, but contributes just 0,6% to the total assemblage. A relatively large amount of indeterminable spores have been found, as the preservation of spores, while still adequate, in most occasions was not good enough to assign a taxon with enough certainty.

The dinocyst *Liasidium variabile* occurs in an interval between 213-178 m.b.s, and has two acmes, at 210 and 183 m.b.s.. This palynomorph will be discussed in greater detail in a following section. The acritarchs *Micrhystridium spp.* and *Baltisphaeridium spp.* can be found in most, but not all, samples. *Micrhystridium spp*. has a notable acme of 11.6% at 223.1 m.b.s., abundances not found at any given point in the assemblage. However, a gradual increase of *Micrhystridium spp.* in the top 10 meters of the Sinemurian stage is still notable. Except for the semi-regular incidence of foraminifera test linings, no other aquatic taxa are commonly present.
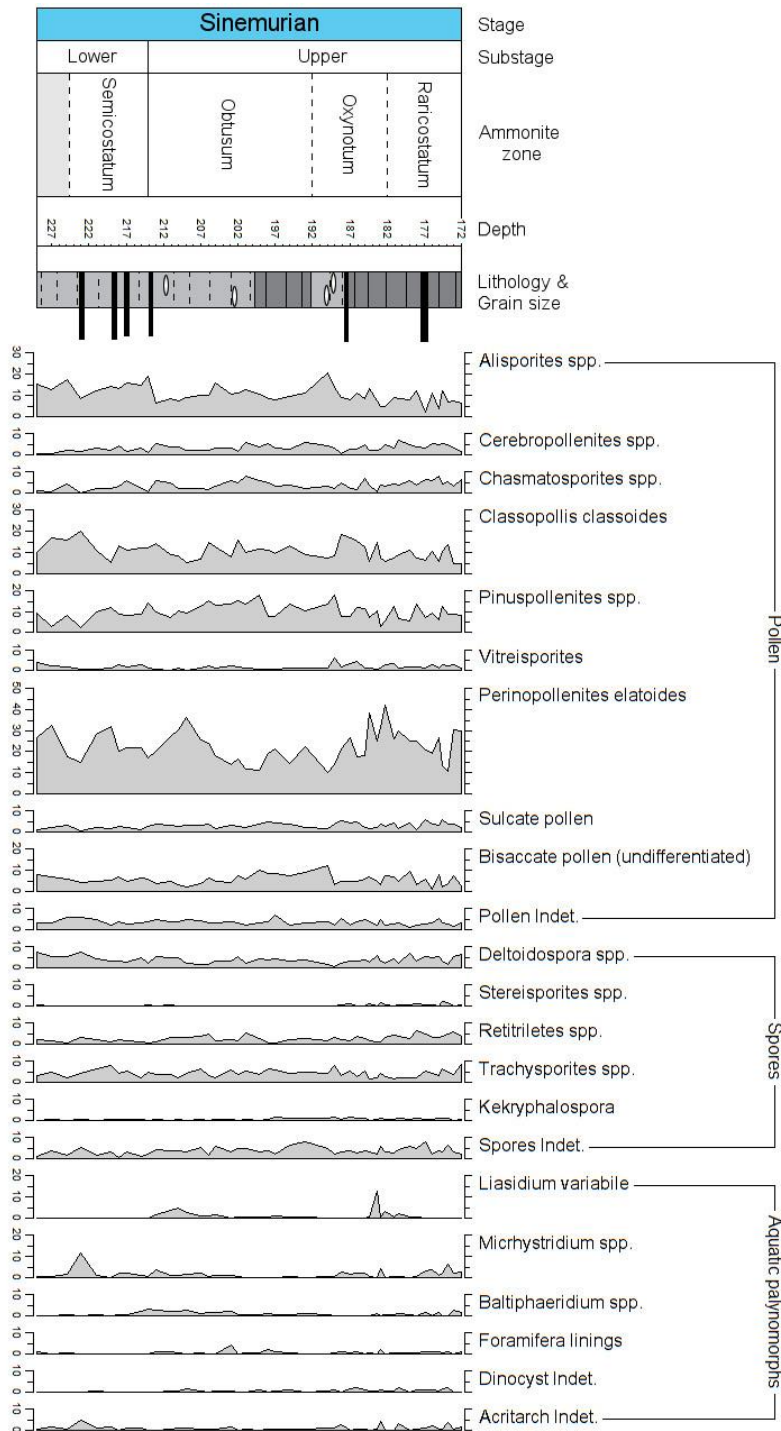


*Figure 7: Common palynomorphs, organised by pollen, spores and aquatic palynomorphs. Depth in m.b.s. Abundances in percentages.*

## Sporomorph Ecogroup data

The relative abundances of palynomorphs have been accumulated to their respective SEG as per Table 2. The resulting graph, with all the available SEG data, can be found in Figure 8. As can be inferred from the graph, the River and Pioneer SEGs are typically only present in low abundances, averaging a 5-7% share. As the constituents of the Aquatic – Marine SEG are the same as the Total Aquatic group of Figure 6, the same patterns discussed previously are observed in Figure 8. With an average share of 10%, the Coastal SEG is relatively present in the Sinemurian. High abundance of the Coastal SEG can be found though, especially in the first few meters of Sinemurian stratigraphy (229-220 m.b.s.), in which the Coastal SEG is more prominently present, reaching values of up to 20% at 223 m.b.s.. The combined Lowland and the Upland SEG are most present in the assemblage, averaging about 30% but in certain intervals reaching a share of 50% each. Within the Lowland SEG, the Wet share is dominant over the Dry share in the entire studied interval. The Upland SEG has 3 notable intervals of increased abundance (highlighted yellow in Figure 8). These intervals are especially relevant because of earlier discussed relation between the Upland SEG and the maximum flooding surface/sea level rise (Abbink et al., 2004). Interestingly, as the Upland SEG has a sharp decrease in abundance at the top of the third interval (~188 m.b.s.), the Lowland – Wet SEG has a gradual increase in abundance. This is also apparent after the other two intervals, though after the first one more notably so (with a relatively high peak of ~36% at 209 m.b.s.) than after the second (middle) interval.
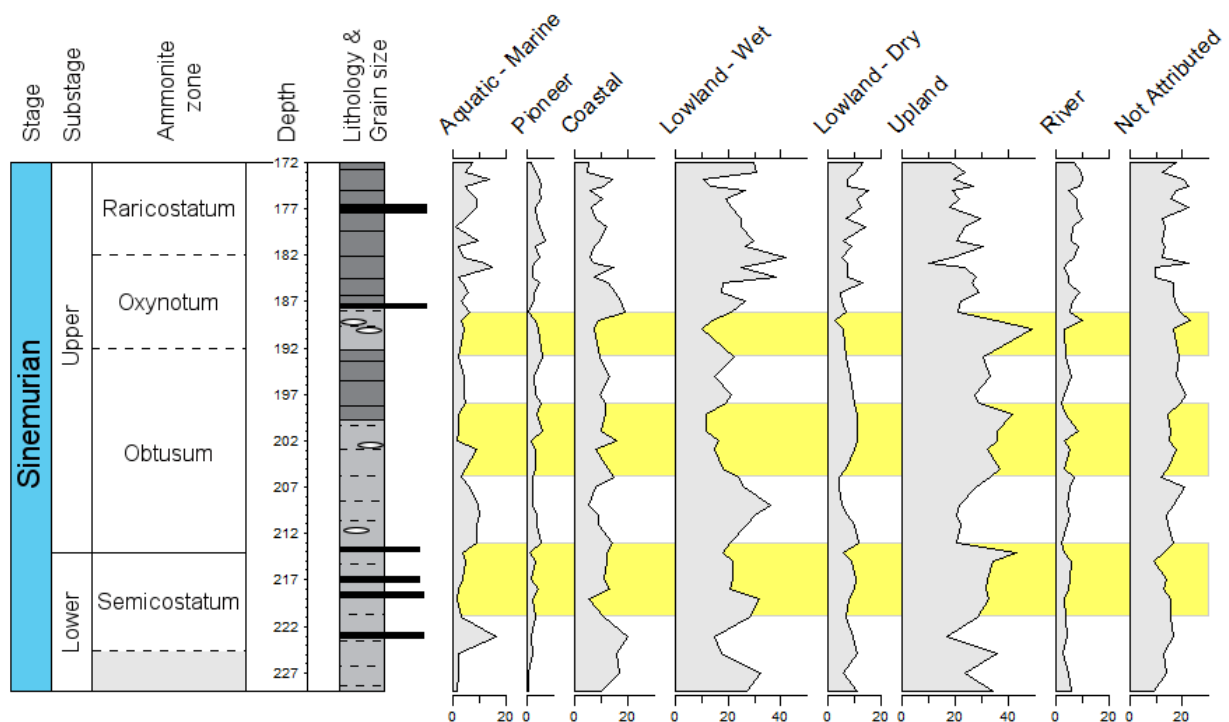


*Figure 8: Relative abundances of the SEGs. Yellow bars represent intervals of increased Upland SEG abundance. Depth in m.b.s., abundances in percentages.*

## Sporomorph and SEG derived proxies

The SEG and sporomorph data can be used as proxy for sea level change. The ratio of the Coastal SEG to the Lowland SEG is an indicator of relative sea level change (Abbink et al., 2004), this ratio is plotted in Figure 9. The yellow intervals are the intervals of increased Upland SEG abundance. It is apparent the Coastal/Lowland (C/LL) ratio slightly elevated during these intervals, and in particular the first and second interval, during which values of ~0.35 are reached. The increase in abundance continues between the middle and top interval. After the top interval, the ratio sharply declines to values closer to ~0.2. The ratio of spores and bisaccate pollen can also be used as a proxy for coastal proximity, as spores are water-transported, while bisaccates are air-transported. Bisaccates thus have a larger

potential to be distributed offshore, while spores are more commonly found offshore (Pieñkowski & Waksmundzka, 2009). The calculated ratio of spores and bisaccate pollen (S/BP) is also plotted in Figure 8 The S/BP ratio is noticeably decreased during times increased Upland SEG presence. After each interval, there is a marked increase in the S/BP ratio, up to values of ~0.4. After the third, topmost interval, the increase of the SP ratio is gradual but steady, and at the top of the Sinemurian, values of 0.5 and more are common.

The ratio between the Lowland – Wet (LL Wet) SEG and the Lowland – Dry (LL Dry) was also calculated and graphed in Figure 9. Overall, with values ranging between approximately 0.5 and 0.9, the LL Wet/LL Dry ratio is highly variable. While variable, there is no noticeable in- or decreasing trend in the ratio, until just prior to the second increased Upland SEG abundance interval, marked by an increase in the LL Wet/LL Dry ratio, reaching an acme of 0.87 at 209 m.b.s.. Values then remain stable until 206 m.b.s, but then sharply decrease, until values of 0.5 are reached. However, by the end of the second interval values remain variate, with a mean of 0.7. As was before the onset of the second interval, no in- or decreasing trend in the data is observed. It thus appears that, while the composition of the Lowland SEG is highly variate on the short term, the long term record remains relatively stable, with a general dominance of the LL Wet SEG over the LL Dry SEG.
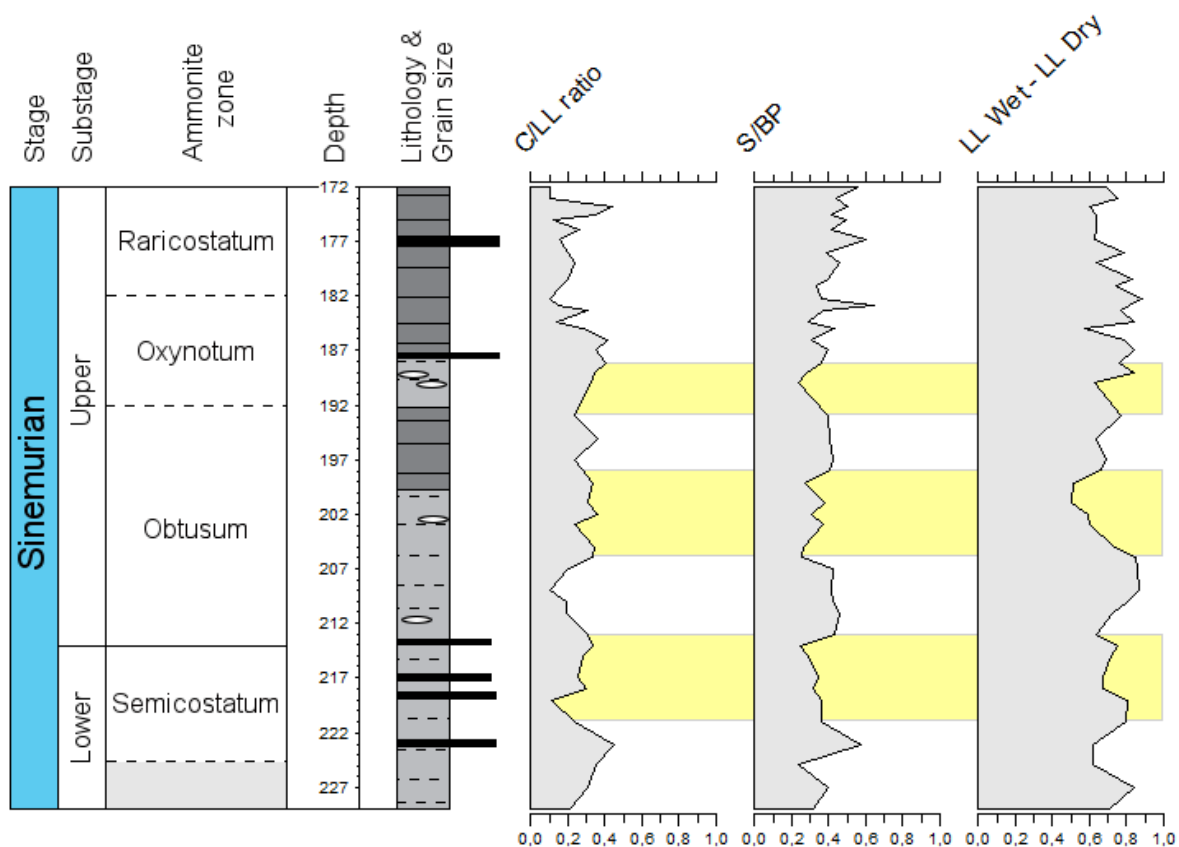


*Figure 9: SEG and sporomorph derived ratios. Yellow bars indicate intervals of increased Upland SEG presence as in Figure 7. C/LL ratio: Ratio of Coastal SEG over total Lowland SEG. S/BP: ratio of spores over bisaccate pollen. LL Wet – LL Dry: ratio of the Lowland – Wet SEG over the Lowland – Dry SEG. Depth in m.b.s.*

**Parent plant abundance**

Aside from the SEG model, further palaeoecological and palaeoclimatological information from palynological assemblages can be obtained from categorisation according to known or probable parent plant affinity (Lindström et al., 2017). The abundances of parent plant have been plotted in Figure 10, in accordance with the affinities as in Table 2. Immediately obvious is the dominance of conifers in the

assemblage, varying between ~40-60%. Ferns and seed ferns are moderately abundant, at roughly 10-20% each. Equisetales, Bryophytes, Lycophytes and Cycads/Ginkgo's only account for a few percent of the assemblage each, with the former three taxa only appearing irregularly altogether. As it appears, none of the major plant groups present, (seed) ferns or conifers, display large or erratic shifts in abundance, but instead appear to be largely stable in abundance throughout the studied interval.
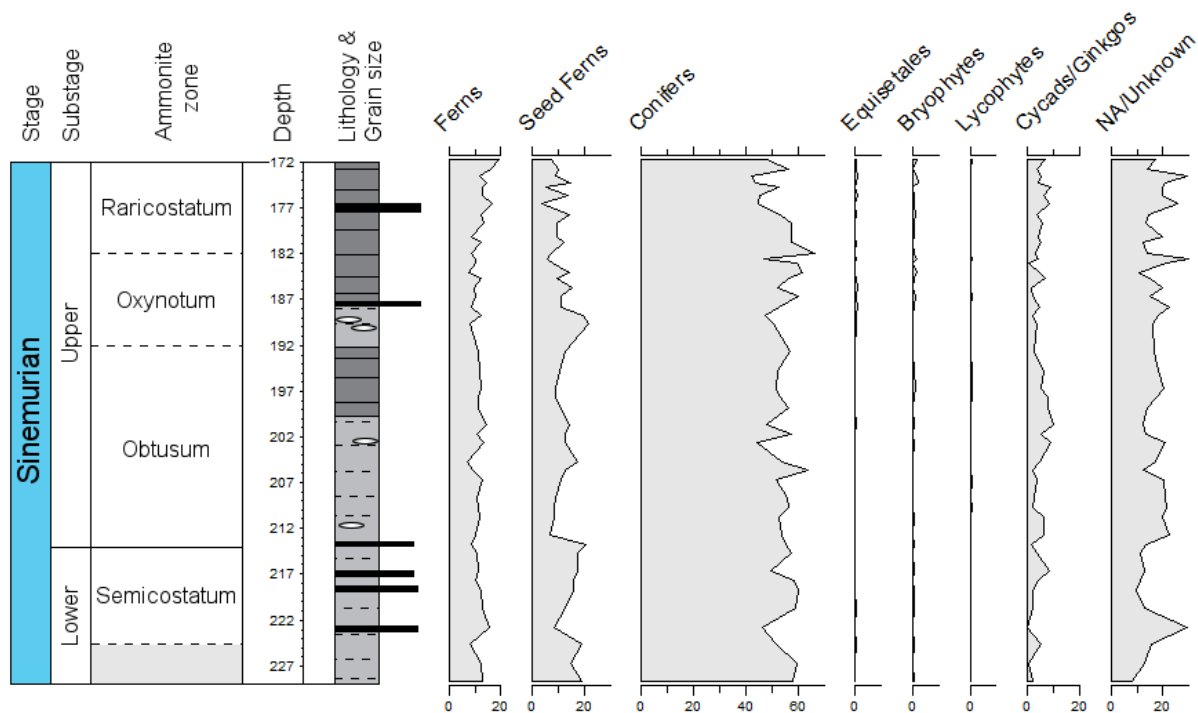


*Figure 10:Abundance of known parent plants/affinities in the Sinemurian. Depth in m.b.s. Abundances in percentages.*

## Sinemurian event palynological & δ¹³C$_{org}$ data

In the Copper Hill Borehole data analysed by Riding et al. (2013), a negative Carbon isotope excursion Was found diachronous with an acme in both *Classopollis classoides* pollen and *Liasidium variabile* dinoflagellate cysts. As both palynomorphs are found in the Schandelah core, this section will de dedicated to these two taxa, as well as the δ¹³C$_{org}$ data, originally published by Van de Schootbrugge et al. (In press). Both the palynomorph data and the δ¹³C$_{org}$ data are plotted in Figure 11. *C. classoides* pollen appear continuously in the section, with abundances varying between roughly 5% and 15%. Acmes occur at the bottom of the Sinemurian, between 221 and 229 m.b.s, and 189 to 184 m.b.s. Interestingly, in this interval the Konglomerat Bank lithology can also be found. While there are more abundance shifts in the record, the general trend of the *C. classiodes* pollen data is relatively stable. *L. variabile* appears suddenly in the record at 213 m.b.s., has a peak occurrence of 4.9% at 210 m.b.s, and then has abundances of ~1% up to 192 m.b.s.. At 184.3 m.b.s. it reappears in the record, and attains a maximum abundance of 12.4% at 183.3 m.b.s.. After this peak abundance, it once again decreases in abundance, to about 1-2%, and its last found occurrence is at 178 m.b.s.. The twofold nature of the *L. variabile* acmes is striking, and might suggest the occurrence of two events in the marine realm.

δ¹³C$_{org}$ data from Van de Schootbrugge et al. (In press) is also provided. Measurements were preformed on Total Organic Carbon (TOC), and reported relative to the Vienna-Pee Dee belemnite standard (VPDB). For detailed methodology, refer to Van de Schootbrugge et al. (In press). Values in the Sinemurian range between -27‰ and -24‰, considered to be normal values for Mesozoic hemipelagic marlstones (Van de Schootbrugge et al., In press). Two positive as well as one negative excursion can be found in this time period. The positive excursions occur between 212-214 m.b.s. and 183-178 m.b.s., the negative excursion of -2‰ occurs at 185 m.b.s.. No other notable trends can be found, and the

entire Sinemurian has a average value of -25.3‰. Interestingly, the major negative excursion at 185 m.b.s. is found during an acme of *C. classoides*, while it precedes the second influx of *L. variabile*.

The Upland SEG abundance have also been plotted in Figure 11, along with the intervals of increased Upland SEG abundance, as previously discussed, as this is one of the few SEGs that shows a discernible amount of change during the interval, possibly indicating sea level changes. The topmost interval of increased Upland SEG abundance just precedes the top (189-184 m.b.s.) acme of *C. classoides*. During the other two intervals, *C. classoides* appears to be relatively stable. There is no apparent relation between the intervals of increased Upland SEG abundance and *L. variabile* abundance. Comparing the $\delta^{13}C_{org}$ data to the increased Upland SEG intervals, the bottom interval coincides with the lower positive $\delta^{13}C_{org}$ excursion found in the record.
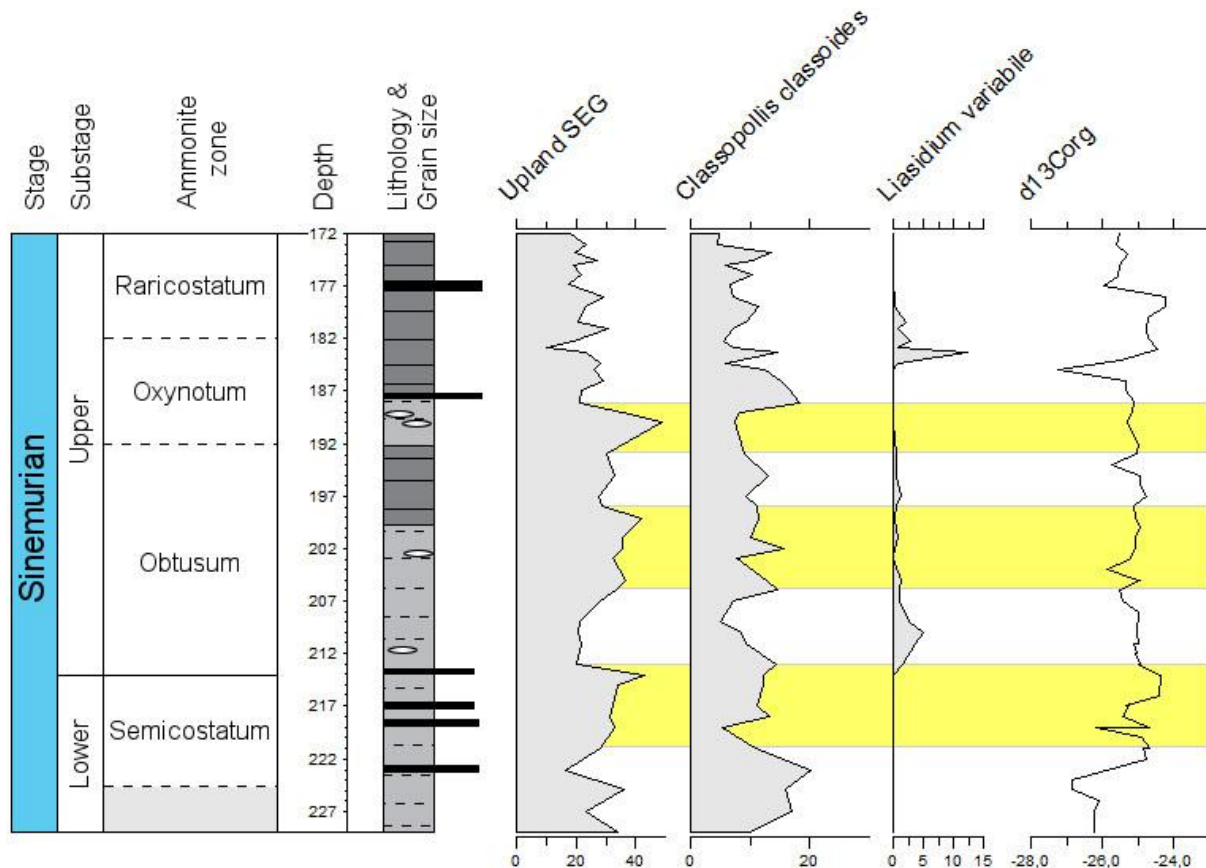


Figure 11: Upland SEG, C. classoides and L. variabile abundances, $\delta^{13}C_{org}$ isotope curve. Yellow bars indicate intervals of increased Upland SEG abundance. Depth in m.b.s. Abundances in percentages. $\delta^{13}C_{org}$ (d13Corg) in ‰ (VPDB).

**Combined Rhaetian-Sinemurian palynology of the Schandelah core**

The data of this study have been integrated in previous work done by Van der Weijst (2015) and Van de Schootbrugge et al. (in press), to generate a record spanning the Late Triassic Rhaetian stage to Early Jurassic Sinemurian stage. Selected data from this record is plotted in Figure 12, including $\delta^{13}C_{org}$ data of Van de Schootbrugge et al. (in press). The boundary between the Rhaetian and Hettangian is observable at 318,60 m.b.s., being placed there based on palynological results (Van de Schootbrugge et al., in press). The boundary between the Hettangian and Sinemurian is less conspicuous, however several spore peaks occur during the Hettangian, which are noticeably absent in the Sinemurian

Compared to the previous Hettangian stage, spore and pollen levels are relatively stable, with increased presence of *Alisporites spp.*, *Pinuspollenites spp.* and *Chasmatosporites spp.* pollen taxa in the Sinemurian. *P. elatoides* abundances increased in the Hettangian, and remain high throughout the Hettangian-Sinemurian, except of some conspicuous intervals during the Angulata ammonite zone. As previously noted, *C. classoides* abundance remains stable in the Sinemurian, however the extension of

the record downward shows these stable levels are a continuation of *C. classoides* abundances in the Hettangian, with only a noticeable excursion right after the Triassic-Jurassic boundary.
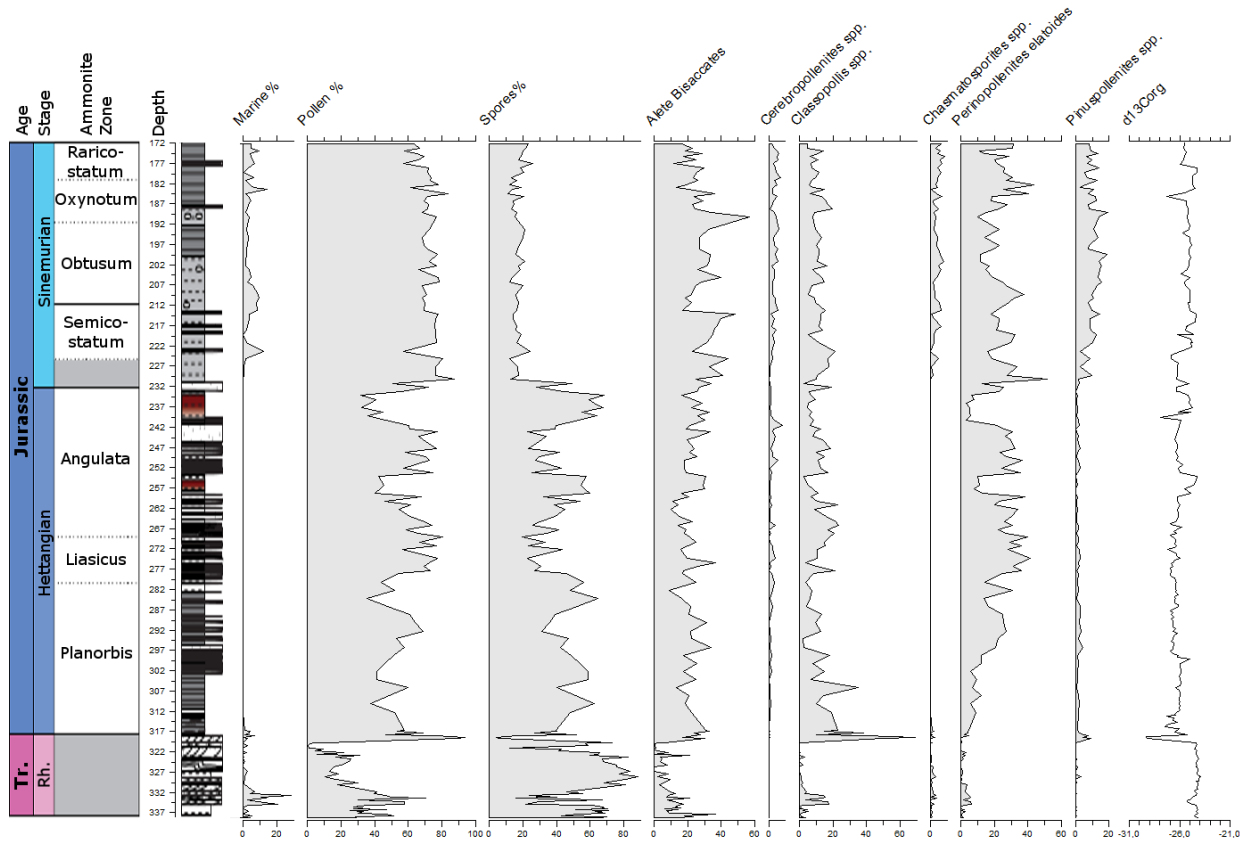


*Figure 12: Selected palynomorph groups and taxa, as well as δ¹³C$_{org}$ (d13Corg) data from the Rhaetian - Sinemurian interval of the Schandelah core. Tr.: Triassic. Rh. Rhaetian. Depth in m.b.s. Abundances in percentages, δ¹³C$_{org}$ in ‰ (VPDB).*

## Discussion

**Sinemurian palynological developments**

Overall, the palynology in the Sinemurian section of the Schandelah core is stable, only a few taxa have LO's. The taxa which do, are generally spore taxa low in abundance, making them unreliable indicators for floral changes. Overall though, these results are in agreement with the notion that the Early Jurassic post-extinction interval was a period of relatively stable vegetation (Barbacka et al., 2017; Lindstöm et al., 2017). In Höllviken, the early Sinemurian assemblage is dominated by *Deltoidospora spp.,* and *Perinopollenites elatoides* and *Pinuspollenites minumus* (Lindström et al., 2017). Compared to the preceding Hettangian stage, a slight increase in *Alisporites spp.* and *Classopollis torosus* was noted Lindström et al., 2017). The palynological assemblages between Höllviken appear relatively similar in terms of taxa found, and it is noted the dominant plant groups post-extinction interval were (pinacean) conifers, corystosperms (seed ferns), ginkgo//cycads and tree ferns (Lindström et al., 2017), much like in the Sinemurian of Schandelah (Figure 10), although it should be noted in particular ferns appear more abundant in the Höllviken succession.

In a previous study, Van der Weijst (2015) investigated the Hettangian and Sinemurian palynology of Schandelah, and inferred from spore peaks in the Hettangian the presence of a mega-monsoon system. In this study, the palynology of the Sinemurian was sampled at a greater resolution compared to Van der Weijst (2015), yet spore abundances remain relatively constant in the Sinemurian stage compared to the previous Hettangian (Figure 12). The mega-monsoonal circulation thus either failed to develop in the Sinemurian, or did not reach high latitudes, which might be related to changing boundary conditions in the form of falling $CO_2$ concentrations and restoration of the carbon cycle post-CAMP vulcanism (Van der Weijst, 2015).

Interpretation of the SEG data starts with the combined Lowland SEGs, which are thought to be most sensitive to climate change. This is due to the competitive strategy used by the vegetation assigned to these SEGs (Abbink et al., 2004). While the Lowland – Wet SEG remains relatively stable throughout the studied interval, the Lowland – Dry SEG shows major shifts in abundance. Coupled to variances in Upland and Coastal SEG abundance, these shifts have been interpreted to be caused by relative sea level rise in the Sinemurian. This will be discussed in greater detail in the following section.

Unfortunately, lack of species which can be attributed to "warm" of "cold" categories inhibit further determination of Sinemurian clime. While a Lowland – Wet to Lowland – Dry was constructed, this ratio showed larger variance but no major trends, except for a sharp decrease at roughly 206 m.b.s., although values recover thereafter. Overall though, based on the Lowland – Wet/Lowland – Dry ratio, the Sinemurian was mostly a stage favoured by wet vegetation in the Lowland SEG.

The marine component of the assemblage typically reaches abundances of only a few percent throughout the Sinemurian. Exceptions are peaks of *L. variabile* in the Late Sinemurian, discussed in a section below, and a peak of the *Micrhystridium spp.* acritarch in the Lower Sinemurian. While *L. variabile* has been found abundantly in the European Upper Sinemurian (i.e. Riding et al., 2013; Feist-Burkhardt, 2009), no reports of an acritarch-acme have been found for this time period, indicating it was probably a regional event of unknown origin.

**Sinemurian sea level changes**

In the Jurassic-Early Cretaceous, sea level changes are generally accepted to be the major geographical factor controlling paleoenvironmental changes (Abbink et al., 2004). In fact, a majority of big and lesser extinction events alike coincide with large eustatic inflections (Hallam & Wignall, 1999). The concept of a possible global warming event in the Sinemurian can thus not be fully grasped without comprehensive information on sea level changes. In the Schandelah record of the Sinemurian, three intervals of sea level rise appear to be present, as indicated by intervals of increased Upland SEG presence. Palynomorphs in this group are (mainly) air transported, and thus provide a constant influx, while other, water transported palynomorphs are condensed due to a decrease in sediment supply (Abbink et al., 2004). This phenomenon is further quantified in the calculated Spore/Bisaccate (S/BP)

ratio, which is a measure of proximity to the coast (Pieñkowski & Waksmundzka, 2009). During times of increased Upland SEG abundance, the S/BP ratio is relatively decreased (Figure 9), indicating a relative decrease of sporomorph input and this a greater proximity to the coastline. The reasoning behind this interpretation are as follows: sporomorphs are vulnerable to dynamic transporting factors, such as tides or waves, and are thus mechanically destroyed in high energy nearshore environments ( Pieñkowski & Waksmundzka, 2009). As spores are more robust, they preferentially settle in these zones, while bisaccates are most buoyant and easily transported of all sporomorphs, and can thus be found even in distal settings (Pieñkowski & Waksmundzka, 2009). During periods of increase in sea level, an increase in the ratio between the Coastal SEG and the Lowland SEG (C/LL ratio) is expected, as the increase in sea level will take up the space of the Lowland SEG's vegetation, while the vegetation in the Coastal SEG remains relatively constant (Abbink et al., 2004). While values are slightly elevated during the Upland SEG abundance intervals,  the continued increase between the second and third interval, pointing to increased sea level rise, is not observed in the other sea level proxies. In contrast, the decreased C/LL values are expected, pointing towards increased Lowland SEG abundance. The decrease in Upland SEG abundance and C/LL ratio, as well as increase in S/BP ratio from ~188 m.b.s. and upward, suggest the onset of relative sea level lowering. Altogether, the palynomorph related proxies for sea level change paint a complex picture of change during this time period, with the onset of multiple sea level rise pulses, followed by a relative sea level lowering. The first sea level rise interval, falls almost entirely in the Semicostatum ammonite zone. Eustatic sea level rise in this zone is well supported from sites in Europe, North America and eastern Asia (Hallam, 1981). In contrast, there is evidence found for a shallowing during the mid-Sinemurian Obtusum and Oxynotum ammonite zones, although the evidence thereof is inadequate outside of Europe (Hallam, 1981). There is good evidence for a deepening event in the late Sinemurian Raricostratum zone, probably controlled by eustasy (Hallam, 1981), which fits the deepening trend in the upper section (~188 m.b.s) and upwards, although the onset of this trend is already in the Oxynotum zone, as the Raricostatum zone is placed approximately 16 meters upward. In a recent study, Barth et al. (2018) found evidence for transgression during the Semicostatum and Oxynotum/Obtusum zone, as well as regression during the Raricostatum zone, based on a sequence stratigraphical investigation of several wells in Central Europe, including Germany. These results are in accordance with the observed changes in palynomorph related proxies and SEG models. The observed records contradict Hallam (1981) at least regionally, as Hallam (1981) rather discussed changes in a global window.

**The Sinemurian Event**
Comparing the known data of Riding et al. (2013) to the results of this study yields remarkable results. While the acmes of *L. variabile, C. classoides* and the negative carbon isotope excursion neatly align in the Copper Hill Borehole data (Figure 13), such an alignment is lacking in the data from the Schandelah core (Figure 11). While there is a negative isotope excursion found in Schandelah, it is not persistent in the Oxynotum subzone, but is rather followed by a positive excursion. It should be noted detailed comparison is hampered, as the zonal completeness of each locality is unknown. The occurrence of *L. variabile* in the Schandelah core is also of a different nature compared to the date of Riding et al. (2013). The double-peaked nature of the *L. variabile* acmes is not found in the Copper Hill Borehole, this might be caused by the reduction of the Obtusum ammonite zone in this core compared to the Schandelah core, thereby causing it to possibly miss this acme of *L. variabile*. While this is still speculative, the precise nature of *L. variabile* needs to be addressed nonetheless.  First described by Drugg (1978), from Upper Sinemurian deposits from Germany, *L. variabile* has been described to be the oldest representative of the order Peridiniales (Fensome et al., 1993). Based on autofluorescence analysis, the dinoflagellate producing *L. variabile* is thought to be heterotrophic (Feist-Burkhardt, 2009). The sudden appearance of this dinocyst in the fossil record has been attributed to palaeoceanographical change, possibly linked to the opening and flooding of the Hispanic Corridor (Van de Schootbrugge et al., 2005), an seaway connecting the western Panthalassa to the Tethys.
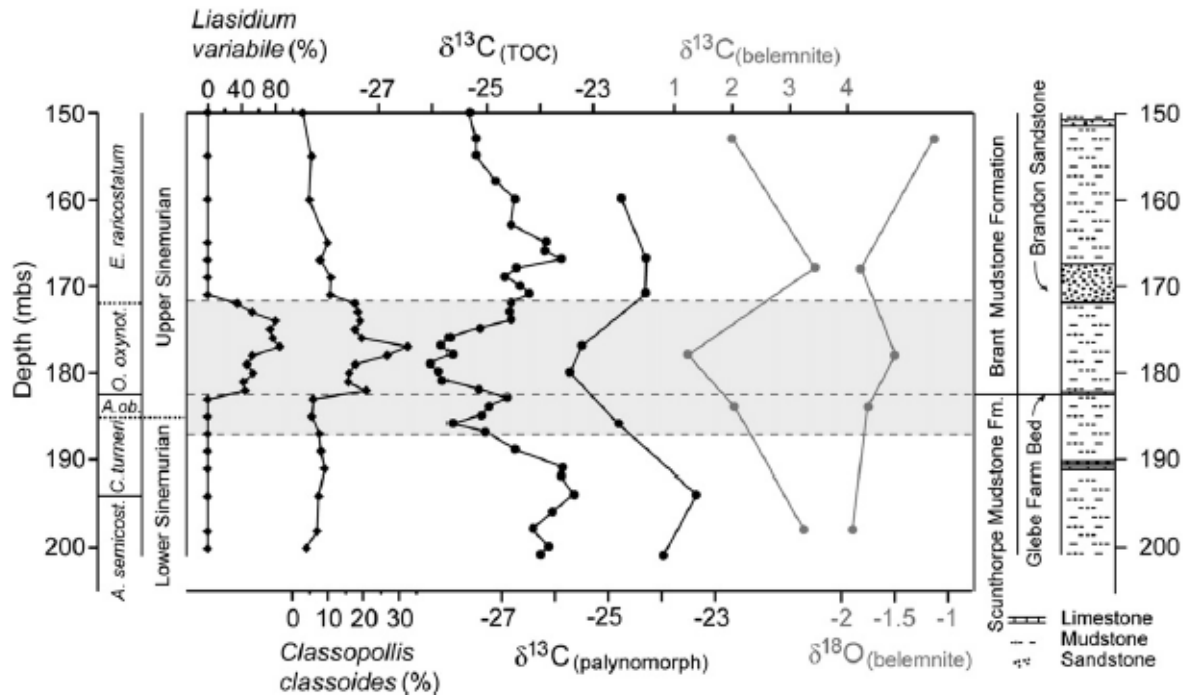
*Figure 1: Copper Hill Borehole data. Ammonite biozonation on the left, lithostratigraphy and a lithological summary based on a unpublished description of N.G. Berridge on the right. Left hand graph depicts the Liasidium variabile curve, expressed as percentages of the entire marine palynoflora. Right thereof, percentages of Classopolis classoides expressed as percentages of the terrestrially derived palynomorphs. The remaining curves depict stable isotope records (black: organic, grey: carbonate. Light grey shading indicates de extend of the S-CIE event. Dashed line in centre of shaded area indicates the base of L. variabile which is coincident with the second δ$^{13}$C pulse. Obtained from: Riding et al. (2013).*

Riding et al. (2013) refuted this suggestion, because of the lack of *L. variabile* records from Central America and the eastern Pacific. Instead, Riding et al. (2013) propose a north western directed migration from the western Tethys under the influence of changing circulation patterns due to sea-level highstand. Furthermore, Riding et al. (2013) suggest it might have followed warmer waters poleward, possibly indicating *L. variabile* is a thermophilic species. In the Schandelah core, however, there is a discrepancy between the sea level highstand and the occurrence of *L. variabile* acmes, best illustrated in Figure 11. Here, the peaks in Upland SEG abundance are a proxy for sea level rise, and it is apparent neither *L. variabile* acme occurs in proximity of intervals of increased Upland SEG abundance, with the bottom acme occurring between two such intervals and the top *L. variabile* acme above all three intervals. There is , however, evidence of widespread transgression in the CEB, based on sequence stratigraphy (Barth et al., 2018). Based on ammonite records, flooding during this time period took place via the south and west (Barth et al., 2018 and references therein), indicating the viability of the hypothesis suggested by Riding et al. (2013) of poleward migration by *L. variabile*. This hypothesis does not adequately explain double-peaked nature of the *L. variabile* influx, and more in-depth palynological research of this interval is needed in this, and other locations, in order to infer the mechanisms at play.

**δ$^{13}$C$_{org}$ data**

Based on δ$^{13}$C from palynomorphs, total organic carbon and belemnites, Riding et al. (2013) inferred the extend of a possible warming event was likely in both the marine and terrestrial realm. While δ$^{13}$C data from the marine realm is not available from the Schandelah core, Van de Schootbrugge et al. (in press) do present δ$^{13}$C data from total organic carbon (Sinemurian: Figure 11, Rhaetian – Sinemurian: Figure 12). While there is a noticeable negative in the lower Obtusum zone of the Schandelah core, it

does not reach the temporal extend of the excursion described from the Copper Hill Borehole by Riding et al. (2013), although the magnitude (~-2‰) is similar. In general though, values in the Schandelah record match the generally relatively positive ( around -24‰) values found in the Copper Hill Borehole during the lowermost Sinemurian Turneri zone (Van de Schootbrugge et al., in press).

Sinemurian $\delta^{13}C_{org}$ values from the Mochras core, Wales (UK), are generally increasing to values of -23,8‰ (VPDB) in the Obtusum zone, after which a sharp decline to -28,0 ‰ sets in in the Oxynotum to the Pliensbachian Ibex zone (Van de Schootbrugge et al., 2005). These values compare tolerably well to values obtained from Dorset (southern England, UK) (Jenkyns & Weedon, 2013). Values in the Lower Sinemurian Turneri zone of Dorset are generally rising, while values in the Copper Hill Borehole are dominantly falling. The best agreement is in the lower part of the Raricostatum zone, were similar positive trends and absolute values are found (Jenkyns & Weedon, 2013).

Overall, comparisons are hampered due to the unknown completeness of the zonal intervals in all sections. While some sections of some localities do show similar trends ,e.g. the lower Raricostatum zone in Dorset and the Copper Hill Borehole, some intervals are missing, e.g. the Oxynotum zone in Dorset (Jenkyns & Weedon, 2013). In the Mochras core, the Obtusum zone is present, but characterized by relatively high values (Van de Schootbrugge et al., 2005), while the negative excursion in the Copper Hill Borehole also took place during this period (Riding et al, 2013). Due to this discrepancy, and the lack of notable excursion in the Schandelah record, the claimed global impact of the S-CIE reported by Riding et al. (2013) remains questionable. More $\delta^{13}C_{org}$ measurements of the Sinemurian, especially from out of Europe, are needed to confidently asses the presence of a global excursion.

# Conclusion

The Sinemurian palynology of the Schandelah core is characterised by a remarkable stability of the terrestrially derived palynomorphs. Pollen to spore ratios are high and show no large shifts or trends. All notable terrestrial taxa span the entire studied interval. The SEG model used shows no large shifts between ecogroups, however peaks in the abundance of the Upland SEG, coupled with low spore to bisaccate (S/BP) ratios are indicative of relative sea level rise in the Lower and beginning of Upper Sinemurian (Abbink et al., 2004; Pieñkowski & Waksmundzka, 2009). This is consistent with the sequence stratigrapical records established for this region (Barth et al., 2018), and might have been the driver for the sudden appearance of the marine palynomorph *Liasidium variabile* dinocyst (Riding et al., 2013; Barth et al., 2018). Riding et al. (2013) reported the acme of *L. variabile* in the Sinemurian Obtusum and Oxynotum zones in relation to a global warming event. The possible presence of such an event was inferred from negative excursions in $\delta^{13}C$ of total organic carbon, palynomorph residue and belemnites, and a peak in *Classopollis classoides* pollen, thought to be indicative of warm paleotemperatures (Pocock & Jansonius, 1961). While *L. variabile* was present in the Schandelah core, there is no indication in the terrestrial realm of an impactful global warming event. *C. classoides* abundances during the Obtusum and Oxynotum zones remain stable as well. The $\delta^{13}C_{org}$ is stable as well, with the exception of one short, negative excursion during the Oxynotum zone. On the basis of this record, and comparison with palynological and/or stable isotope records in Wales (Mochras, Van de Schootbrugge et al., 2005), Bristol (Jenkyns & Weedon, 2013) and Höllviken (Lindström et al., 2017), a global warming event during the Upper Sinemurian could not be proven present. Instead, the Sinemurian can best be described as the final recovery phase of an ecosystem which devastated by continuous CAMP volcanism, and was still enduring the consequences of this volcanism in the Hettangian. The regional viability of the S-CIE discussed by Riding et al. (2013) has not been ruled out, although those authors themselves noted that the marine and terrestrial geochemical and palynological signals in the Copper Hill Borehole cannot be attributed to local factors.

While it was beyond the scope of this study to go in-depth on the full Rhaetian-Sinemurian palynological record, the presence of high resolution, long term records will prove invaluable reference data when discussing the possibility of smaller scale, possibly regional, events such as the S-CIE.

Some questions thus still remain. Especially the origin of *L. variabile* still remains enigmatic, and more localities, especially non-European, might be needed to adequately explain the sudden appearance of this dinocyst in this and other records.

# Acknowledgements

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