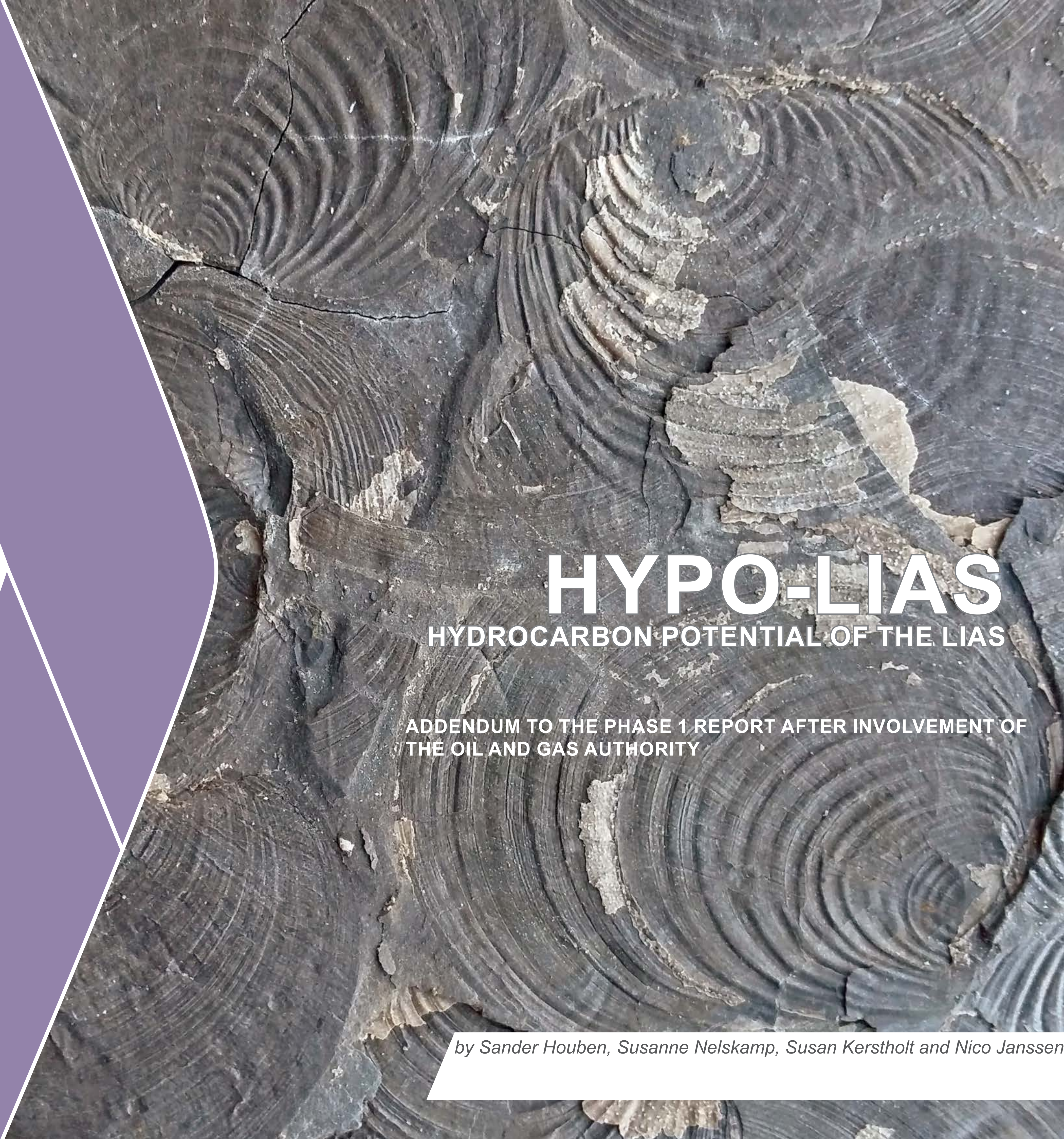
TNO innovation for life



HYPO-LIAS

HYDROCARBON POTENTIAL OF THE LIAS

ADDENDUM TO THE PHASE 1 REPORT AFTER INVOLVEMENT OF THE OIL AND GAS AUTHORITY

by Sander Houben, Susanne Nelskamp, Susan Kerstholt and Nico Janssen

TNO Report 2017 R10380

Addendum to Hydrocarbon Potential of the Lias: HYPO-Lias

Date: 01-11-2017
Authors: Sander Houben, Susanne Nelskamp, Susan Kerstholt and Nico Janssen
Number of pages: 35
Sponsors: Oil and Gas Authority, UK, EBN B.V., NAM B.V., Statoil ASA.
This project is executed with subsidy from the Ministry of Economic Affairs, National Regulations EA-subsidies, Topsector Energy executed by the Netherlands Enterprise Agency.
Report Number: TNO 2017 R11374

HYPO-Lias is a collaboration between:

1. INTRODUCTION AND SCOPE

2. THE TOARCIAN OCEANIC ANOXIC EVENT IN THE EAST SHETLAND PLATFORM AREA

3. SOURCE ROCK POTENTIAL OF THE WESTERN APPROACHES AREA

4. SUMMARY AND CONCLUSIONS

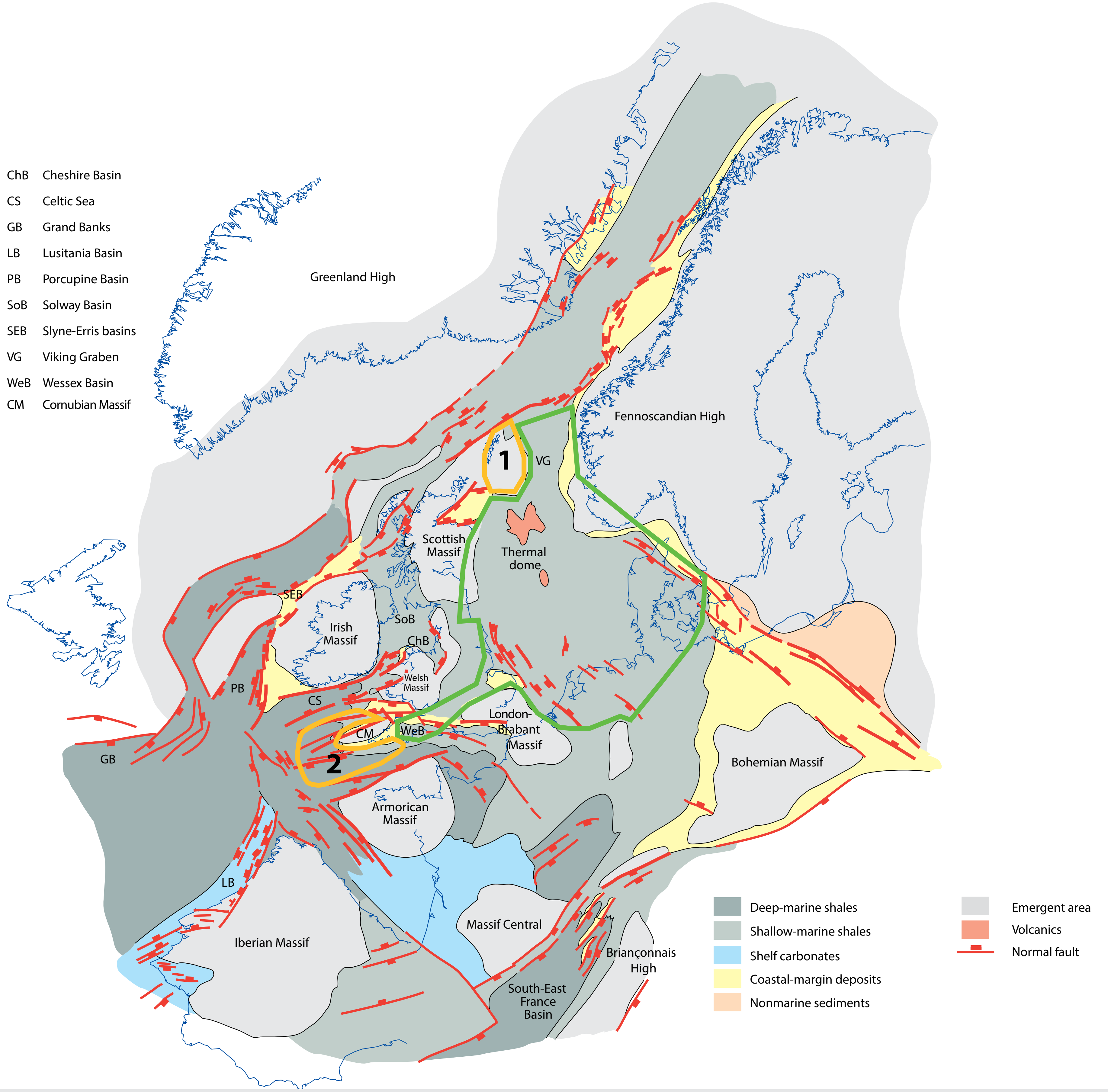
1. INTRODUCTION AND OBJECTIVES

1.1 Introduction to HYPO-Lias

The Early Jurassic (174-201 Million years ago, Ma) was a period during which oceanic anoxia occurred repeatedly, affecting the production and preservation of organic-matter in marine sediments. Therefore the Early Jurassic boasts important hydrocarbon source rocks, worldwide, and in Northwestern Europe specifically. Marine sediments of Early Jurassic age have historically been referred to as the Liassic.

In 2015 and 2016 TNO has performed a regional multi-client study, named the HYPO-Lias (Hydrocarbon Potential of the Liassic) Project. The full report of this study will become public in 2019. The study area comprises the North Sea area and extends into the Southern Norwegian Sea to the north. The northern part of the Viking Graben Area of Norway forms the northern boundary of the study area (**Figure 1.1**). The onshore exposures of the Cleveland Basin of Yorkshire, UK form the western extremity, whereas the southwestern boundary is the Wessex Basin of Dorset in the UK. The eastern boundary of the study area lies in Denmark and is part of the Norwegian-Danish Basin. The HYPO-Lias project specifically focused on cross-border comparisons, and to construct a novel integrated stratigraphic framework. Outcrop localities in the UK were sampled in high resolution for organic-carbon isotope and palynological analyses. These outcrops are important reference sites for ammonite zonations and thus provide a firm 'chronostratigraphic backbone'. Collectively the analyses provide insight into **(1)** the paleoclimatic and depositional development and **(2)** the drivers that affect source-rock potential.

The HYPO-Lias results revealed a close correspondence between carbon cycle perturbations as revealed by the carbon isotope trends and changing climate, run-off, development of anoxia and eventually organic-matter enrichment. The study elucidated that the Toarcian Oceanic Anoxic Event (T-OAE) stood out in terms of environmental impact. This relatively transient phase climate change is accompanied by a conspicuous carbon isotope excursion that can be traced globally. In the Southern North Sea it represents the only extensive source-rock interval of the Lower Jurassic, whereas in other parts of the study area, its environmental fingerprint is noted in a wide array of depositional environments. In addition, the Earliest Jurassic (Hettangian - Early Sinemurian) was a phase of remarkable warm and dynamic climatic conditions, following a major episode of large-scale volcanism associated with the Triassic-Jurassic (T/J) boundary, and is associated with excellent source-rock formation in the Wessex Basin. In other areas this interval did not yield substantial organic enrichment, albeit this view might be somewhat biased by a general paucity of well penetrations in these strata.



▲ **Figure 1.1: Map for the Early Jurassic showing the distribution of active structures and sediment facies.** The location of the Mid-Jurassic thermal dome in the central North Sea is also shown. Modified after Coward et al. (2003). The green outlineshows the geographic scope of the first phase of HYPO-Lias, which will become public in December 2019. The orange outline shows the scope of the present study, which is directly publically available.

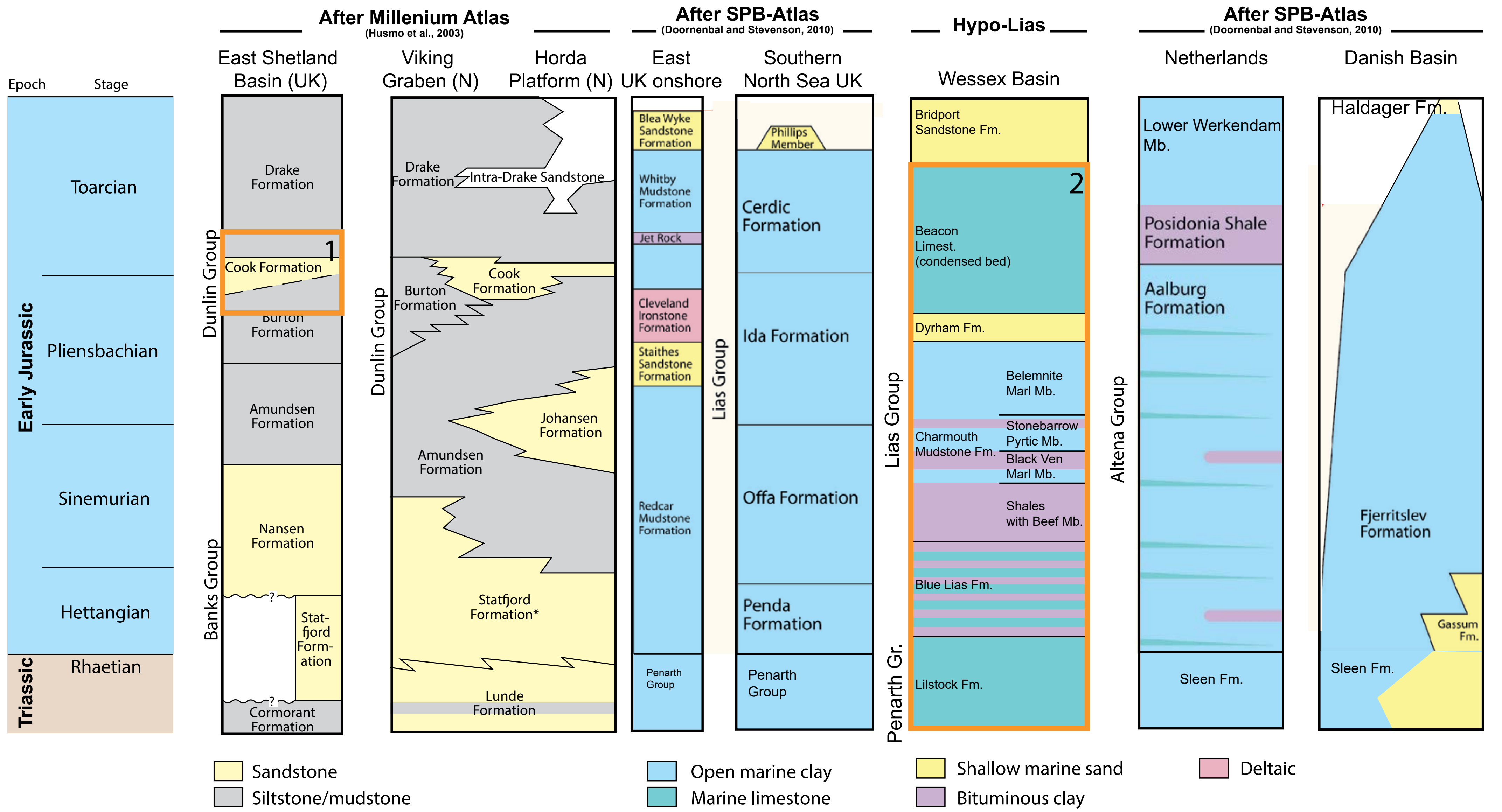
1.2 Context and objectives of this Addendum to Hypo-Lias

This addendum to the HYPO-Lias project was funded by UK's Oil and Gas Authority (OGA) and focuses on two research topics, related to the findings of the first HYPO-Lias-study.

1. The T-OAE stands out as a climate perturbation that led to the formation of excellent oil-prone source rocks in the epeiric basin of the Southern North Sea (e.g., on- and offshore Netherlands, west and southwest Germany and in the Paris Basin, France). However, further to north into the Norwegian sector of the Viking Graben, deposits of exactly this age are sandstones of the upper Cook Fm. (in the Norwegian blocks 30 and 34). Based on a petrophysical log inventory we have observed that the T-OAE, further towards the west, in UK-territory may correspond to a finer-grained deposits (in blocks 210, 211, 2 and 3). These sediments in that case should be classified as Drake Fm., which is like the Cook Fm., part of the Lower Jurassic Dunlin Group (see Figure 1.2). These finer-grained deposits are much more prone to develop into source facies due to lower clastic accumulation rates and less dynamic depositional conditions, favoring the accumulation of organic-carbon. However, the precise stratigraphic relationships across the UK-Norway border are hitherto underexplored. Through applying a combination of stable isotope analyses and palynostratigraphy we evaluate how the T-OAE is expressed in the British East Shetland Platform area. By evaluating the Total Organic Carbon (TOC) content and the Hydrogen-Index (HI) of the kerogens, we furthermore evaluate the source-rock potential of these strata. Through compiling petrophysical log patterns we aim to elucidate lateral stratigraphic trends.

2. In the southwestern margin of the study area of the HYPO-Lias Project (the Wessex Basin and Somerset Basins), we encountered excellent cyclical source rocks of the Blue Lias Fm. and Charmouth Mudstone Fm., of Hettangian to Sinemurian age (Figure 1.2). Coeval sediments source a major onshore oilfield (Wytch Farm Oil Field). Substantially further offshore, in the Western Approaches Region (Melville and Brittany Basins, Figure 1.1) and in the South Celtic Sea Basin, on the basis of well-log pattern comparable deposits are encountered in the few wells that penetrate Lower Jurassic strata. We here evaluate the stratigraphic position, paleo-environmental setting and source-rock potential of two offshore Lower Jurassic wells. Through integrating literature and petrophysical log data from other wells we refine trends in the development and distribution of the Lower Jurassic in this distant corner of the UK-territory.

These research topics will be presented in two separate chapters of this report. The report is concluded with a summary-chapter as part of which the results of this 2nd phase study are integrated with the regional results of the 1st phase of HYPO-Lias.



▲ **Figure 1.2: Overview of the lithostratigraphic and facies relations across part of the study area.** The information from the northern parts of the study area (East Shetland Basin, Viking Graben and Horda Platform) are derived from the Millenium Atlas (Husmo et al., 2003), whereas the information from the UK, Netherlands and Denmark is after the Southern Permian Basin (SPB) Atlas (Doornenbal and Stevenson, 2010). The facies variation for the Wessex Basin is a result from the HYPO-Lias study, its lithostratigraphic subdivision is after Cox et al. (1999).

Concretion in Jet Rock near Kettleness, Yorkshire

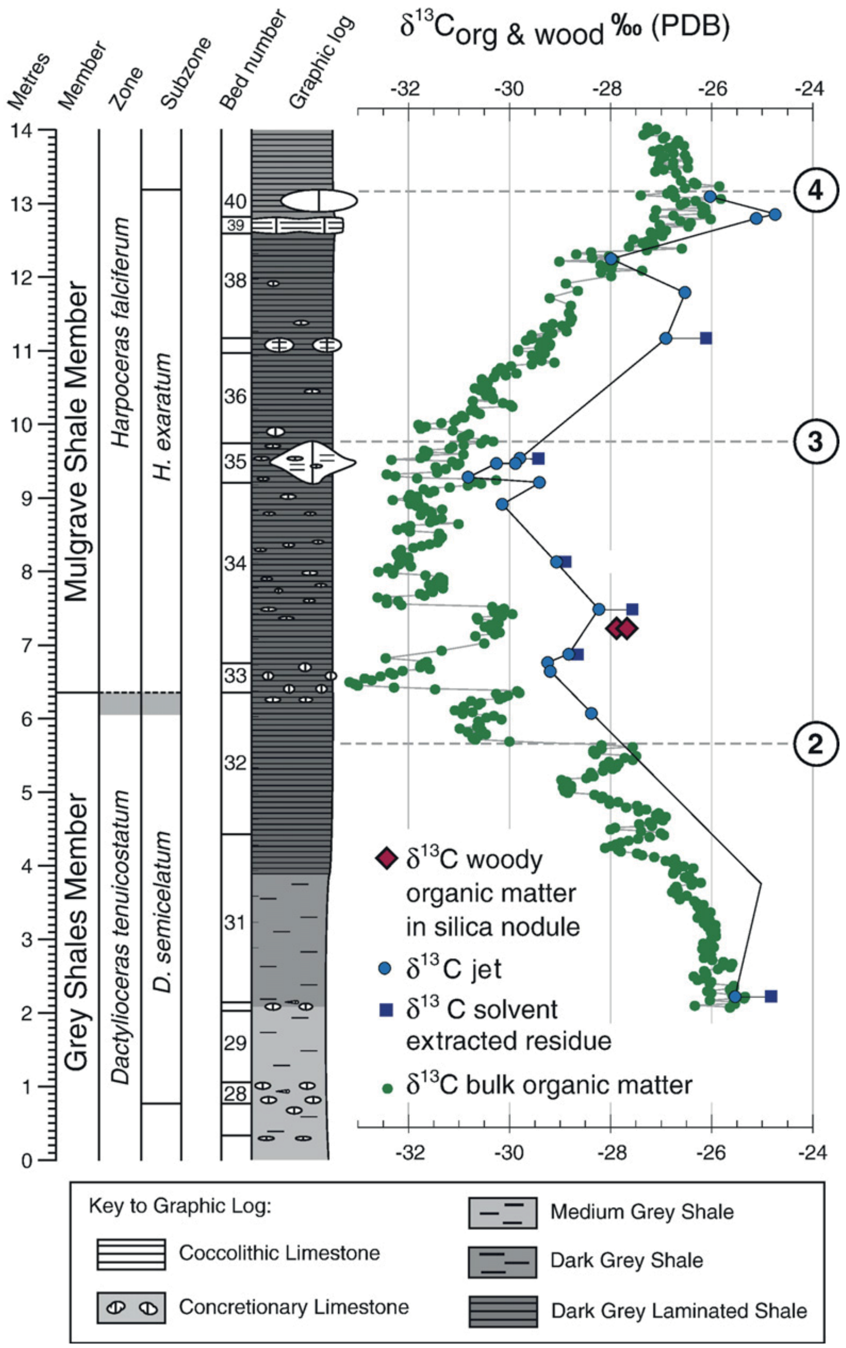
》02

The Toarcian Oceanic Anoxic Event in the East Shetland Platform area

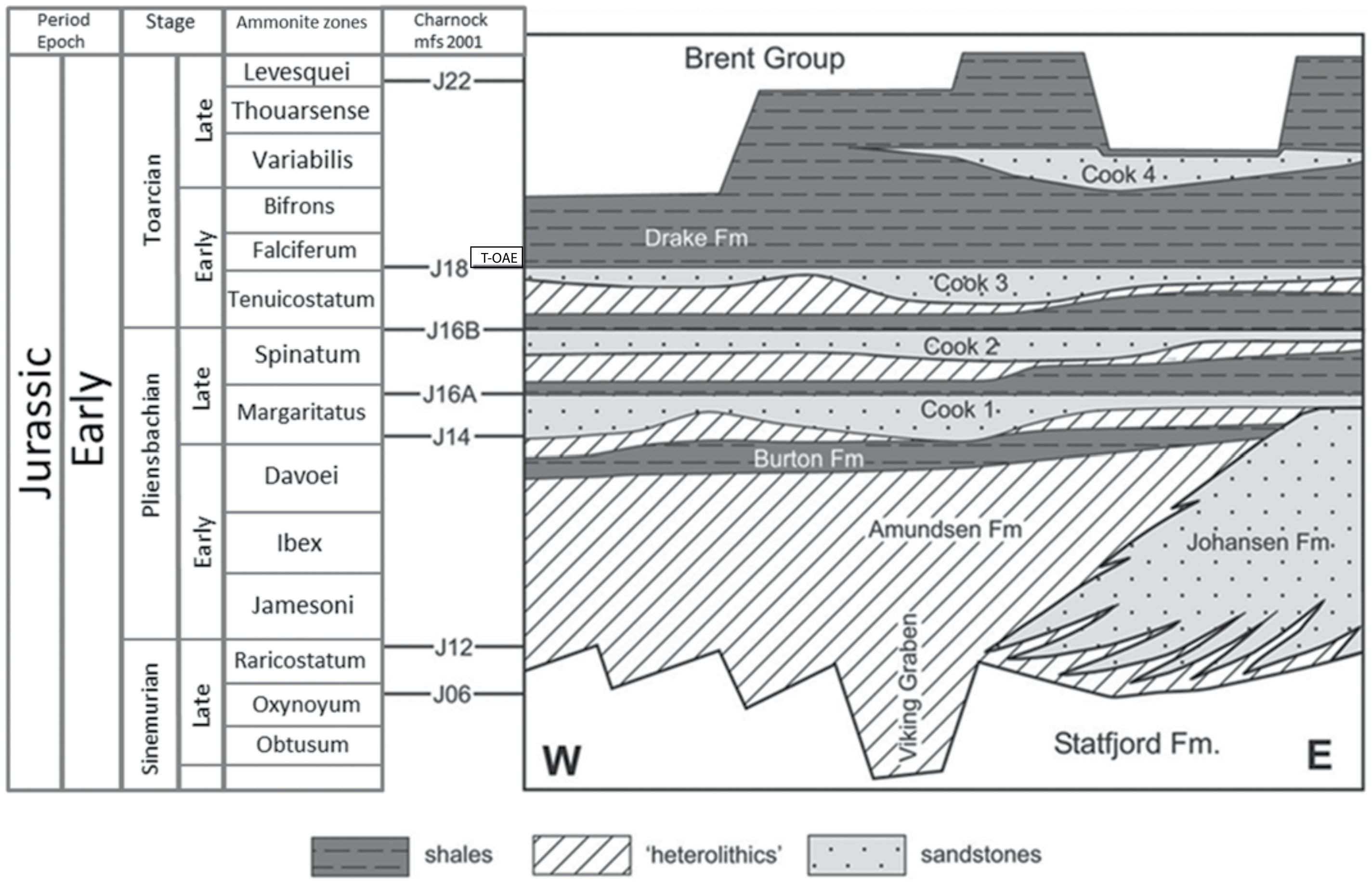
2.1 Background and objectives

The Toarcian Oceanic Anoxic Event (T-OAE)

A distinct phase of black shale deposition occurred during the Toarcian Stage of the Early Jurassic, more specifically near the boundary between the tenuicostatum and falciferum Ammonite Subzones (Jenkyns, 1988; Hesselbo et al., 2000). Associated organic-rich shales are prominent throughout NW-Europe (e.g., the Posidonia Shale in Germany and the Netherlands, the Jet Rock of the Whitby Mudstone Fm. of Yorkshire, UK and the Schiste Carton in France) and constitute important source-rocks. This phase of black-shale deposition is now commonly known as the Toarcian Oceanic Anoxic Event. Analyses from shallow marine epicontinental sedimentary successions from NW-Europe have revealed a striking negative carbon isotope excursion (CIE) in bulk organic carbon and/or carbonate coeval with the T-OAE (see e.g., Jenkyns, 1988; Jimenez et al., 1996; Röhl et al., 2001, **Figure 2.1**). A similar negative carbon isotope excursion is also recorded in fossil wood (Hesselbo et al., 2000; Korte and Hesselbo, 2011), leading to the hypothesis that this widespread and substantial (2-8‰) negative carbon isotope excursion (CIE) was caused by exogenic addition of a ^{12}C-enriched carbon source to the ocean-atmosphere reservoir, for example via thermal oxidative metamorphism of organic deposits (McElwain et al., 2005) or methane hydrates (Hesselbo et al., 2000). Consequently, anoxia, enhanced preservation and the installation of an anoxygenic photosynthetic community (including sulfur bacteria) are thought to have led to substantial organic enrichment and TOCs locally exceeding 20%.



◄ **Figure 2.1: Organic carbon isotope profiles across the Grey Shales Mb. and Mulgrave Shale Mb. in the Yorkshire outcrops.** This Figure is after Hesselbo et al. (2007). The bulk organic carbon isotope data are after Kemp et al. (2005). The carbon isotope excursion (CIE) is characterized by an initial to negative values, maximum excursion values and a reovery to more postive values.



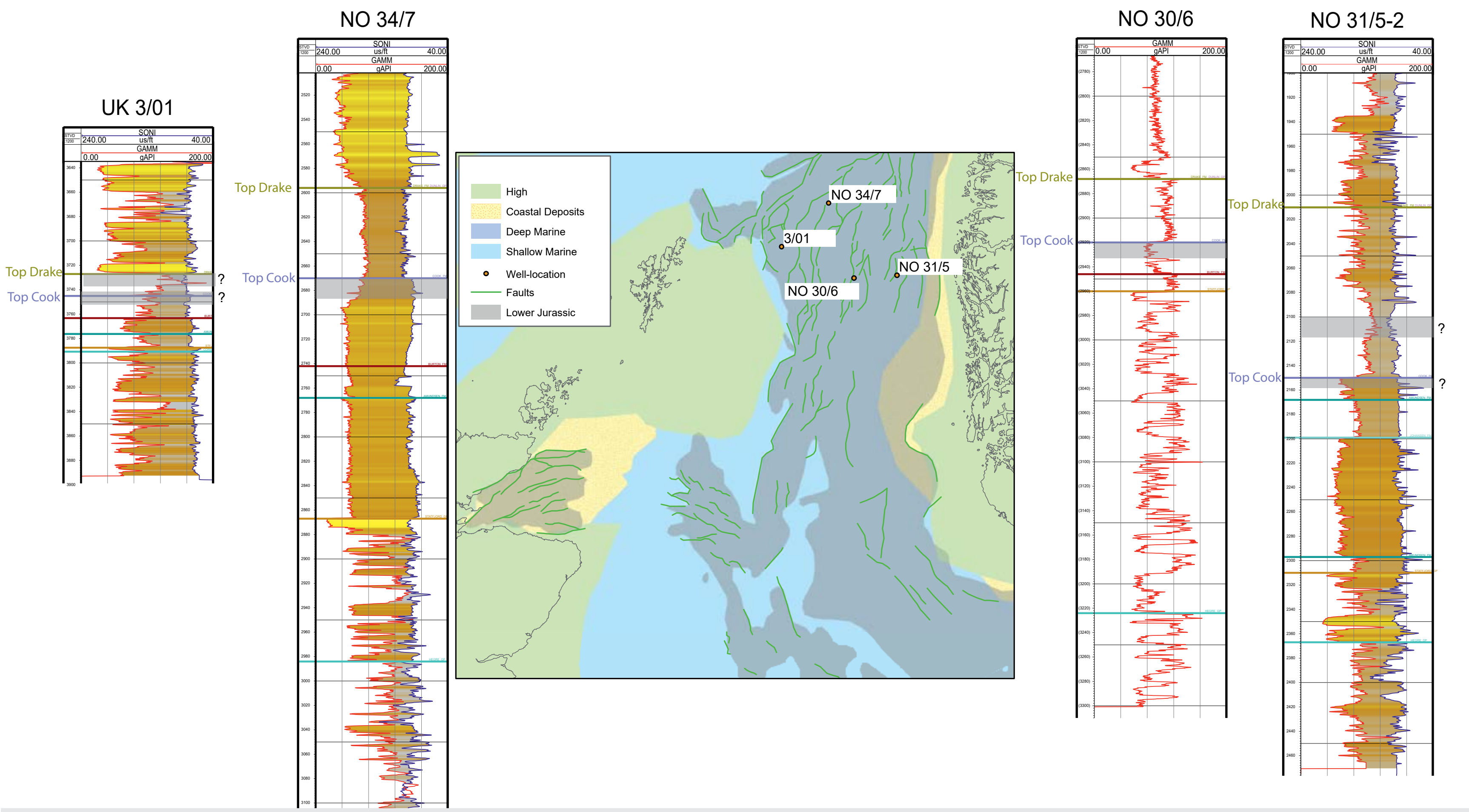
▲ **Figure 2.2: Stratigraphic architecture of the Dunlin Group across the northern North Sea.** This Figure is after Churchill et al. (2016). The J sequence maximum flooding surfaces (MFS) are after Charnock et al. (2001). Note that the Cook Fm. consists of a series of stacked sandstone levels. Lateral shaly facies equivalents are demoninated as Drake Fm. The upper Cook Fm. is used to describe the upper two to three sandstone intervals (Cook 3, Cook 4 and/or Cook 5, which sometimes also recognized). The T-OAE corresponds to the base of the Falciferum Ammonite Zone.

Dunlin Group heterogeneity

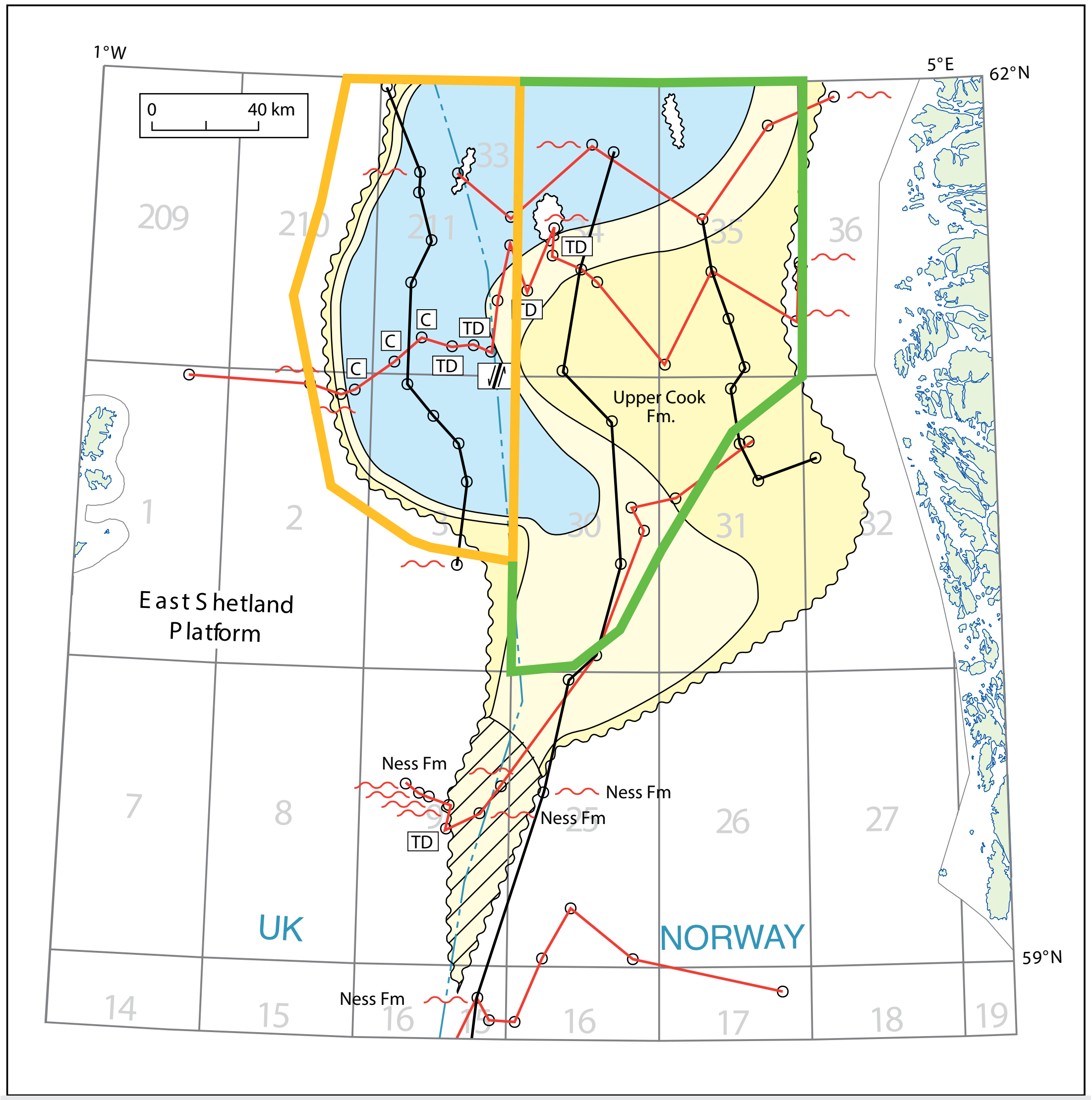
The Cook Formation of the Dunlin Group represents a series of sequential sandstone tongues that occur at four distinct stratigraphic levels (Marjanac and Steel, 1997). Each tongue consists of a lower heterolithic part and an upper sandstone part. The lower heterolithic parts (Cook-I and Cook-II) are interpreted as shoreface deposits created during falling relative sea level and are characterized by gentle basinward progradation and downlap/offlap onto the underlying offshore shales of the Burton Formation (**Figure 2.2**). The Cook sandstones have sharp erosive bases, are laterally restricted, and are interpreted as largely estuarine deposits. Thus, they form combined lowstand and transgressive systems tracts. The overlying shales (of the Drake Formation) are considered the highstand deposits (Marjanac and Steel, 1997).

In a recent study by Churchill et al. (2016), the Cook Formation within the Knarr Field (Blocks 34/2 and 34/3 in Norway) is divided into Sands 1, 2 and 3 and consists of a complex mosaic of tide-dominated facies. The division between the Upper and Lower Cook Fm. is dated as Late Pliensbachian (Spinatum or Margaritatus Zone, the J15 Maximum Flooding Surface, MFS). The Upper Cook is divided into Sands 4 and 5, which are composed of shoreline-to-shelf deposits. Consequently, the Late Pliensbachian J15 MFS reflects a major change in depositional system and reflects the gradual transgression of the system, which is finally drowned at the base of the Toarcian, the J16B MFS in the Knarr area, thus leading to deposition of Drake Fm. shales, substantially prior to the T-OAE (Base Falciferum Zone, **Figure 2.1**). This also invokes that the T-OAE here locally may correspond to a shale-rich facies, which is substantially more likely to develop into a prosperous source-rock, analogues to the T-OAE strata in the Netherlands and onshore Yorkshire.

During the Hypo-Lias study, wells from the Norwegian sector (blocks 34/7, 34/10 and 30/06, **Figure 2.3**) of the Viking Graben area were studied in terms of palynology and carbon isotope stratigraphy. The results indicated that the T-OAE and its characteristic CIE are consistently part of shoreface sandstone facies of the Upper Cook Formation (i.e., Cook-IV and/or 5th sand). Perhaps not surprisingly, in those high-energy sedimentary regimes, no substantial organic-enrichment was recorded, albeit the palynological assemblages did reveal indications for photic zone anoxia.



▲ Figure 2.3 Log characteristics and locations of selected wells from the Northern UK North Sea and Norwegian Viking Graben.
The grey intervals mark the position of the T-OAE in the wells. Detailed view of the palaeogeographic map of the Lower Jurassic in the Northern North Sea area. Grey: Present-day extent of the Lower Jurassic sediments, Green: Major faults of the Jurassic (compiled from Evans et al., 2003). In the wells from block 34/7 and block 30/6, the stratigraphic position was constrained using a combination of carbon isotope stratigraphy and palynostratigraphy (HYPO-Lias study). In the other two wells, two hypotheses are presented based on the log-signature.



▲ Figure 2.4: Palaeoenvironmental map of the northern North Sea during the Early Toarcian.
This Figure is after Coward et al. (2003). A clastic wedges builds outward from the Norwegian mainland. Sediments transported from the East Shetland Platform are less well documented. Note that this predates the buildout of the Middle Jurassic Brent Group, from the south in relation to uplift of the North Sea Thermal Dome. The map illustrates the deposition of the Drake Formation in the west across the East Shetland Platform area. The orange outline shows the scope of this study. The green outline that of the first phase of HYPO-Lias.

However, as can be deduced from the preceding section, the Cook sandstones and Drake shales are known to be diachronously dispersed throughout the British and Norwegian sectors of the Viking Graben area (**Figure 2.4**).

Hence, if the T-OAE corresponds to the offshore mudstone facies of the Drake Formation, it may impose possible source rocks (**Figure 2.4**). This could be the case further to the south (e.g., in the Knarr Field, Norway 34/2-34/3), but specifically further to the west, in the UK quadrants 2, 3, 210 and 211). Hence, the primary research objective of this study is to evaluate how the T-OAE is expressed in the UK-quadrants 2, 3, 210 and 211, in a stratigraphic and depositional context.

Note that we follow the division of Marjanac and Steel (1997) in distinctly recognizing four Cook sandstone cycles (Cook I to Cook-IV) occurring below the main Drake Fm. shales. The fifth cycle (see Cook-4 in **Figure 2.2**) is not always recognized.

Paleogeographic setting and basin restriction

The Viking Graben and adjacent East Shetland Platform area are located in an interesting area with respect to the Southern North Sea Basin. During much of the Hettangian and Sinemurian, deposition of the Statfjord Gp. and Amundsen Fm. is characterized by very coast-proximal to continental fluviodeltaic settings. Under these circumstances connectivity of the Southern North to Arctic (boreal) water-masses was likely strongly restricted. The Burton-Cook-Drake sequence provides the first truly marine depositional nature (see also Charnock et al., 2001) and may as such herald a record of establishment of enhanced connectivity. Based on the distribution of dinoflagellate cysts, the epeiric seas south of the ESP were continuously and persistently dominated by Tethyan influenced water-masses (e.g., Palliani and Riding 2003) preceding the T-OAE. In addittion, recent studies have indicated a strong degree of restriction during deposition of the T-OAE black shales (Montero-Serrano et al., 2015). Consequently, by also considering the biogeographic significance of the palynological patterns observed, insight can be obtained of links between paleoceonographic connectivity, basinal restriction and black-shale formation.

Summary of objectives

The objectives of the study presented in this chapter are to:
1. Assess the depositional nature of the T-OAE in the area spread across Quadrants 2, 3, 210 and 211. This will be achieved by applying a combination of carbon isotope, palynostratigraphy and petrophysical log-correlation.
2. Evaluate whether the T-OAE represents a potential source-rock, in parts of the study area. To this end TOC and Rock Eval analyses are performed.
3. Evaluate the timing and role of deepening of the Viking Graben Conduit by evaluating biogeographic patterns of dinoflagellate cysts.

2.2 Approach and Methodology

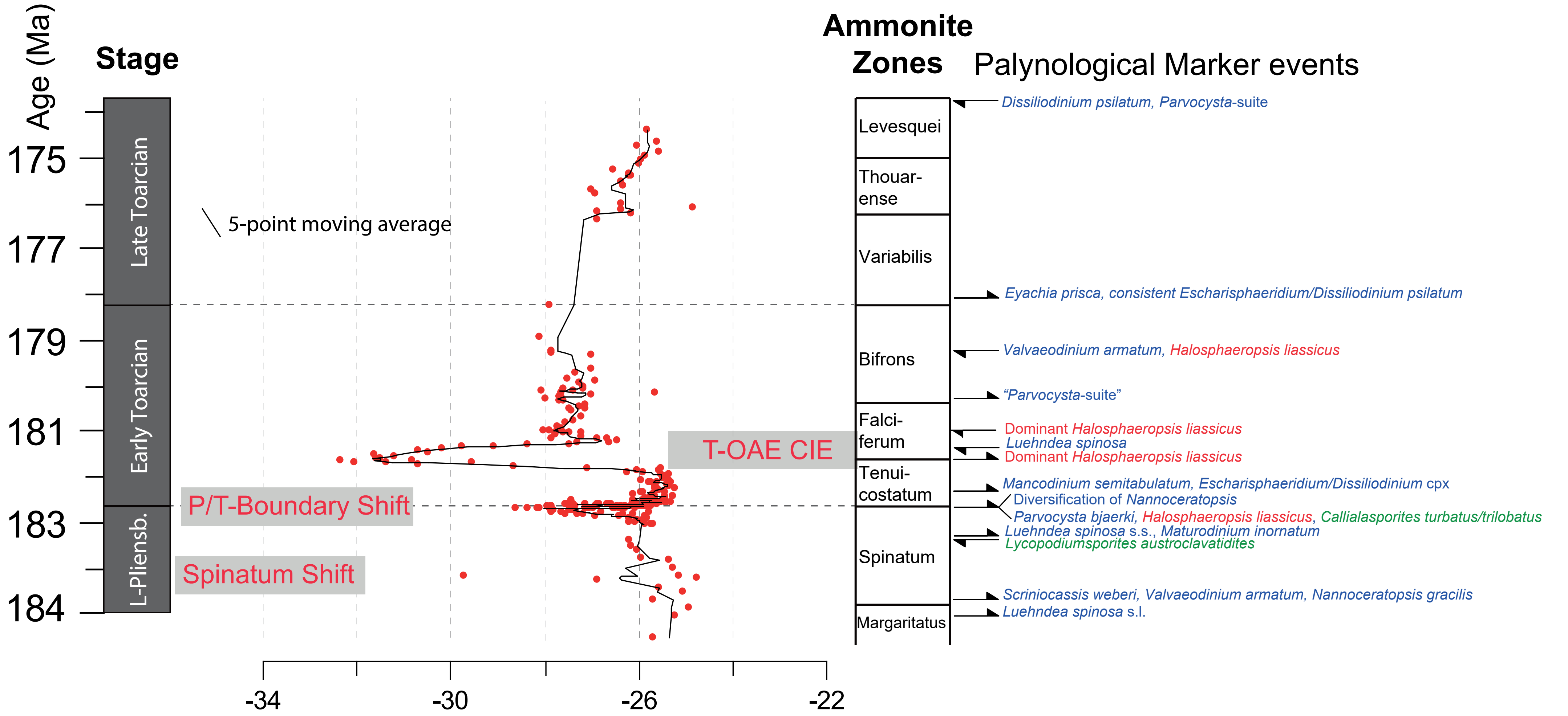
In order to evaluate the potential presence of prolific source-rocks of Early Toarcian age in the East Shetland Platform Area we have employed a work-flow combining bio- and isotope stratigraphic analyses, log correlation and rock eval analyses.

Stratigraphic framework

The characteristic ~6-8 ‰ negative Carbon Isotope Excursion (CIE) at the base of the Falciferum Zone (the Exaratum Subzone) provides the opportunity to stratigraphically assess the position of the T-OAE. 'Precursor CIEs' in the Late Pliensbachian have recently been recorded in the Yorkshire outcrops (HYPO-Lias-study, Littler et al., 2010; Ruhl et al., 2016). These are primarily related to (local) changes in organic-substrate (Suan et al., 2015). Of course, carbon isotope stratigraphy has the highest success-rate if positioned samples (e.g., from cores or outcrops) are available. This is only rarely the case when working with offshore wells where sample material comes predominantly from cuttings. The substantial Toarcian CIE nevertheless is expected to be recorded in material derived from cuttings, albeit the signal might be smeared out and/or diluted. Therefore, for detection of the T-OAE i, it is also of great importance to have independent, biostratigraphic information available.

As part of the HYPO-Lias study, the biostratigraphic ranges of palynomorphs in the reference section of the Yorkshire Coast were re-evaluated. Integration with existing scientific publications (e.g., Riding, 1983; Bucefalo-Palliani and Riding, 2003; Van de Schootbrugge et al., 2005) have elucidated that the Early Toarcian and the T-OAE in particular was a period during which the composition of marine palynological assemblages changed significantly and abruptly.

Already in the Late Pliensbachian Spinatum Ammonite Zone, a major introduction and diversification of organic-walled dinoflagellate cysts (dinocysts) is noted. These comprise the Tethyan taxa *Nannoceratopsis* and *Luehndea spinosa*. During the T-OAE, dinoflagellate cysts are temporarily disappearing or largely declining in abundance. This is considered a consequence of adverse conditions during the T-OAE. *Luehndea spinosa* goes extinct during the T-OAE. Subsequently, dominance of small sphaeromorph algal cysts like *Halosphaeropsis liassicus* and prasinophyte algal cysts like *Tasmanites* and *Pleurozonoria* mark the T-OAE interval, essentially corresponding to the Exaratum Ammonite Subzone of the Falciferum Zone. The proliferation of these taxa is related to strongly stratified water conditions and/or anoxia shoaling into the photic zone (Van de Schootbrugge et al., 2013). Subsequently, the dinoflagellate cysts that characterize the pre-T-OAE interval return in abundance and *Halosphaeropsis liassicus* is no longer recorded. Later in the Early Toarcian, near the base of the Bifrons Ammonite Zone, a series of distinct taxa abruptly appears, with taxa like *Parvocysta nasuta*, *Wallodinium cylindricum*, *Susadinium scrofoides* and *Phallocysta elongata*. These morphologically closely related species are often referred to as the "*Parvocysta* suite" and range to the top of Toarcian. The appearance of gonyaulacean taxa with complex and/or apical archaeopyles, such as *Dissiliodinium* and *Escharisphaeridia* also occurs after the T-OAE.

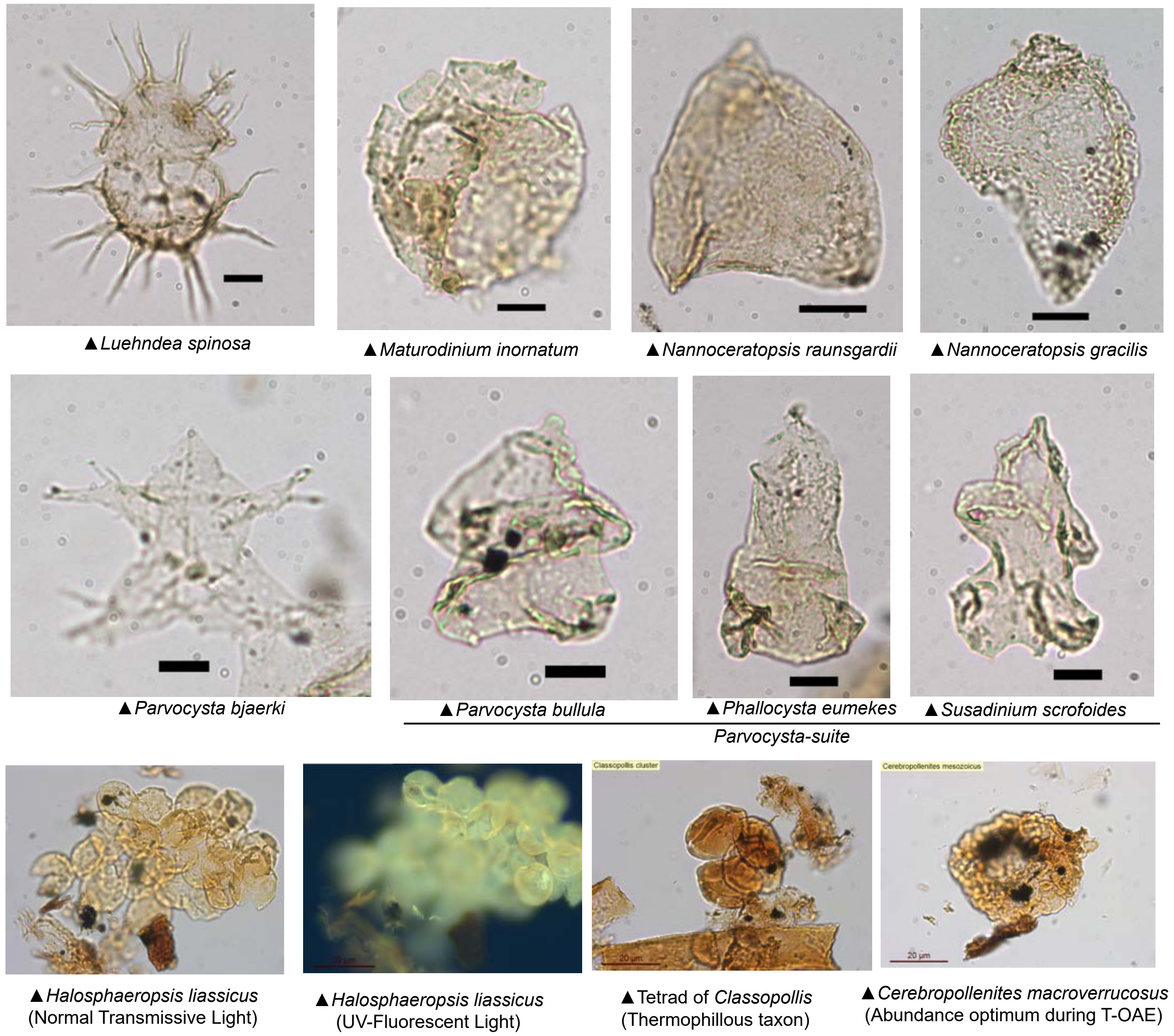


▲ **Figure 2.5: Summary of the stratigraphic framework for the Late Pliensbachian and Toarcian.** This Figure is modified after the HYPO-Lias study. The carbon isotope data from the Cleveland Basin (Yorkshire,red dots) are scaled against the timescale of Gradstein et al. (2012), following the Ammonite Zones of Page, 2003. The main "isotope events" are indicated. At the right the most important palynological marker events as recognized in the outcrop reference sections are indicated. Names written in green are sporomorphs, in blue dinocysts and in red prasinophyte algae.

Figure 2.5 provides a summary of the bio- and isotope stratigraphic considerations used in this study. We acknowledge that performing 'classical' range-top-based palynostratigraphy is also tedious when relying on cuttings material. However, by quantitatively performing analyses, the abovementioned trends and events can be confidently assessed in the absence of core material.

Palynological processing

The organic matter is extracted from the rock using standard laboratory processing procedures. During the first step, the sedimentary rock is crushed and treated with hydrochloric acid (30%) to digest the carbonate. After that, the mineral bonds of the silicates are destroyed by using hydrofluoric (35%) acid, thus releasing the acid-resistant organic matter. The organic residue is then concentrated by sieving over a 10 μm mesh. The organic matter particles larger than 10 μm are brought on a glass slide, fixed by a mounting medium (glycerine jelly), and covered by a thin glass cover slip. The slide is studied using a transmitted light microscope with magnifications varying between 100 and 1000 microns. Up to 100 specimens were counted using the 40x objective. Illumination with ultra violet light is applied for the identification of small acritarchs and other palynomorphs (**Figure 2.6**).



▲ **Figure 2.6: Photomicrographs of stratigraphically relevant palynomorphs.** The scale bar represents 10 μm unless indicated otherwise. The uppermost row displays dinoflagellate cyst taxa that are relevant in the Late Pliensbachian and Toarcian. The middle row displays members of the *Parvocysta*-suite. *Parvocysta bjaerki* is the only species of this genus that occurs in substantially older strata predating the T-OAE. The T-OAE marker *Halosphaeropsis liassicus* is particularly recognizable using UV-fluorescence microscopy.

Stable carbon isotope analysis

Isotopes are variants of a chemical element with a similar number of protons, but differing in the number of neutrons. Therefore, two isotopes of the same element display similar chemical behaviour, but differ in the molecular weight. Isotopes can be radioactive, like ^{14}C, or stable like ^{12}C and ^{13}C. For this project the stable carbon isotopic composition of bulk organic material was analyzed ($\delta^{13}C_{org}$). In this type of stable isotope analysis, these two stable carbon isotopes, ^{12}C and ^{13}C are measured and expressed as a ratio against a standard (the Vienna Pee Dee Belemnite, VPDB). Note that it is also possible to assess $\delta^{13}C$ on the calcite of fossils (e.g. belemnites) or on the bulk carbonate fraction of the sediment ($\delta^{13}C_{carbonate}$).

The technique used for isotope analysis is the Elemental Analyser - Isotope Ratio Mass Spectrometry (EA-IRMS). For this technique, samples and reference materials are weighed into tin capsules, sealed and then loaded into an automatic sampler on a Europa Scientific Roboprep-CN sample preparation module. From there, they are dropped into a furnace held at 1000 °C and combusted in the presence of oxygen. The tin capsules flash combust, raising their temperature in the region of the sample to ~1700 °C. The combusted gases are swept in a helium stream over a combustion catalyst (Cr_2O_3), copper oxide wires (to oxidize hydrocarbons) and silver wool to remove sulphur and halides. The resultant gases (N_2, NO_x, H_2O, O_2, and CO_2) are swept through a reduction stage of pure copper wires held at 600 °C. This removes any oxygen and converts NO_x species to N_2. A magnesium perchlorate chemical trap removes water. Carbon dioxide is separated from nitrogen by a packed column gas chromatograph held at an isothermal temperature of 100 °C. The resultant CO_2 chromatographic peak enters the ion source of the Europa Scientific 20-20 IRMS where it is ionised and accelerated. Gas species of different mass are separated in a magnetic field then simultaneously measured using a Faraday cup collector array to measure the isotopomers of CO_2 at m/z 44, 45, and 46. Both references and samples are converted and analysed in this manner. The analysis proceeds in a batch process, whereby a reference is analysed followed by a number of samples and then another reference. The output voltages of the IRMS, combined with careful weighing of the sample, also provide the means to reconstruct weight percent total organic carbon (TOC).

The application of stable isotope analysis is based on the assumption that the measured ratio between ^{12}C and ^{13}C in a sediment sample reflects the atmospheric ratio at the time of deposition. Variations in the stable carbon isotope composition reflect changes in the isotopic composition of the global carbon pool (i.e., the exchange between the oceanic, terrestrial and atmospheric reservoirs). Most organisms exhibit preferential uptake of light carbon (^{12}C), due to chemical interactions at molecule level. As a consequence, during geological times when excessive burial of organic matter occurs, the oceanic background ratio will become enriched in heavy carbon (^{13}C). During times of excessive oxidation of organic matter, or other mechanisms that lead to ^{12}C-enrichment of the ocean-atmosphere reservoirs, negative excursions in $\delta^{13}C$ develop. These shifts can be correlated for stratigraphic purposes.

Rock Eval Pyrolysis

Rock Eval Pyrolysis analyses were performed by Geo-Lab in Garbsen, Germany.

During Rock-Eval pyrolysis ca. 100 mg of ground and homogenised sample is subject to a pyrolysis step followed by the complete oxidation of the residual sample. A FID detector measures the hydrocarbon released during pyrolysis, while CO_2 and CO are detected by infrared absorbance during both steps. In the here applied standard cycle for “whole rock” (IFP 2001), pyrolysis starts isothermally at 300°C for 3 minutes, after which the sample is heated to 650°C. The oxidation step starts isothermally at 400°C (3 min) and then heats up to 850°C. Organic carbon decomposition results in 4 main peaks: the S 1 peak (hydrocarbons released during the isothermal phase), the S2 peak (hydrocarbons produced between 300 and 650°C), the S3 peak (CO_2 from pyrolysis of OM up to 400°C), and the S4 peak (CO_2 released from residual OM below ca. 550°C during the oxidation step). Mineral carbon decomposition is recorded by the S3’ peak (pyrolysis-CO_2 released above 400°C), and the S5 peak (oxidation-CO_2 released above ca. 550°C).

These peaks are used to calculate the amount of total organic carbon (TOC) and the amount of mineral carbon (MINC). In addition, the so-called hydrogen index (HI = S2/TOC) and oxygen index (OI = S3/TOC) are calculated. The HI and OI indices are proportional to the H/C and O/C ratios of the organic matter, respectively, and can be used for OM classification in Van-Krevelen-like diagrams (Espitalie et al. 1977). The calibration standard used was the IFP-55000 (Institut Francais du Petrole; IFP 2001), a Jurassic marine sediment.

Petrophyiscal log correlations

On the East Shetland Platform 44 wells from blocks 2, 3, 210 and 211 were used for the well correlation. Mainly the Gamma Ray (GR) and Sonic (DT) logs are used for the correlations. The GR is scaled from 0 – 200 gAPI, the DT is scaled from 40 – 240 μS/ft. Well formation tops from OGA were used as guidelines for the correlation. If available the biostratigraphic interpretation of the Toarcian OAE was added to the logs. All reported depths are measured down-hole.

2.3 Results and Interpretation

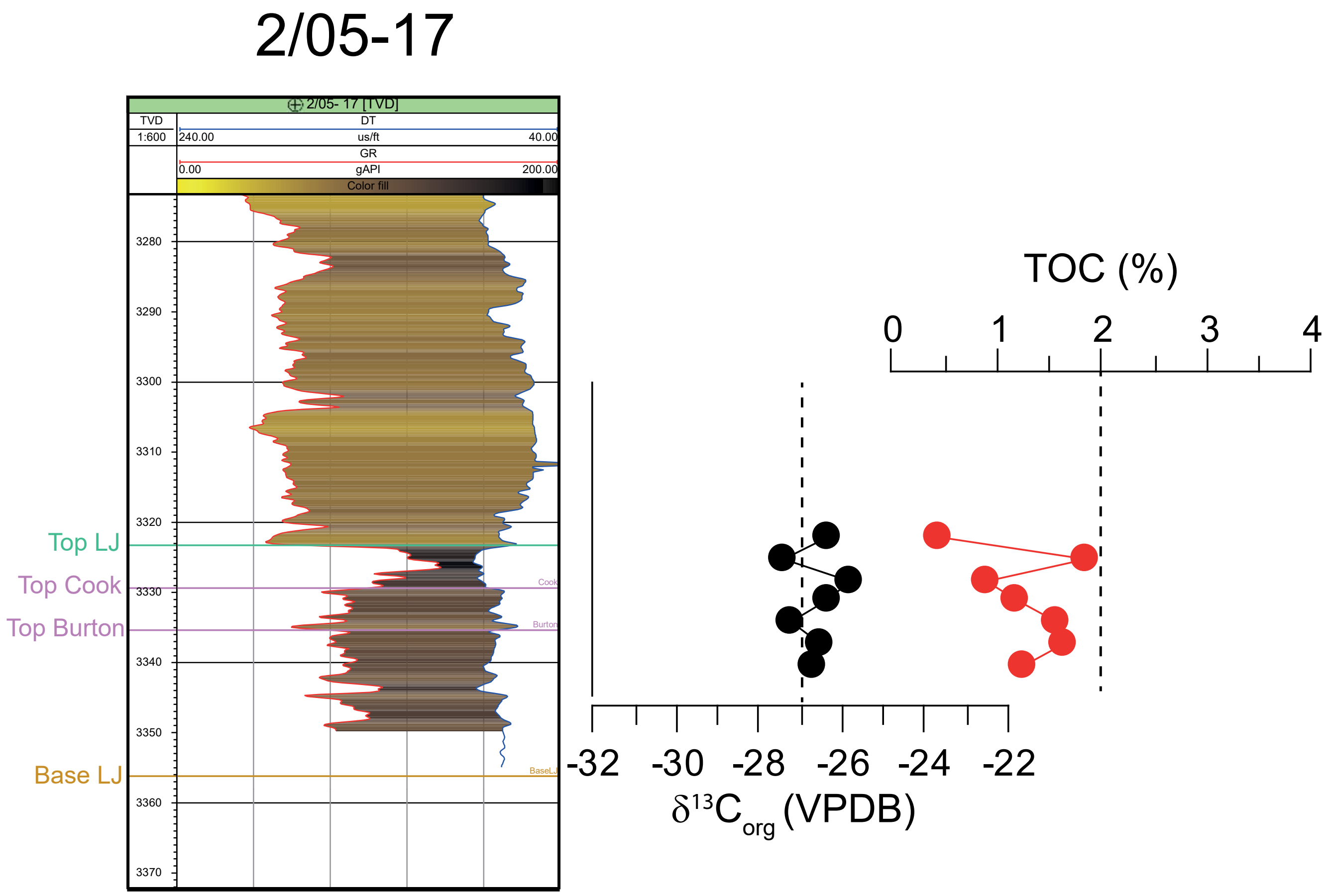
Bio- and Isotope stratigraphy

In total 112 samples from eight wells were analyzed for bulk organic carbon isotopic composition. In addition, 26 samples from seven wells were analyzed for palynology, with the aim of refining stratigraphic assessment and/or understanding organic-composition (**Table 2.1**). The results are plotted alongside the petrophysical (gamma and sonic) log panels, including the available well-tops according to the OGA-website[1].The results per well are described and discussed in the respective figure captions.

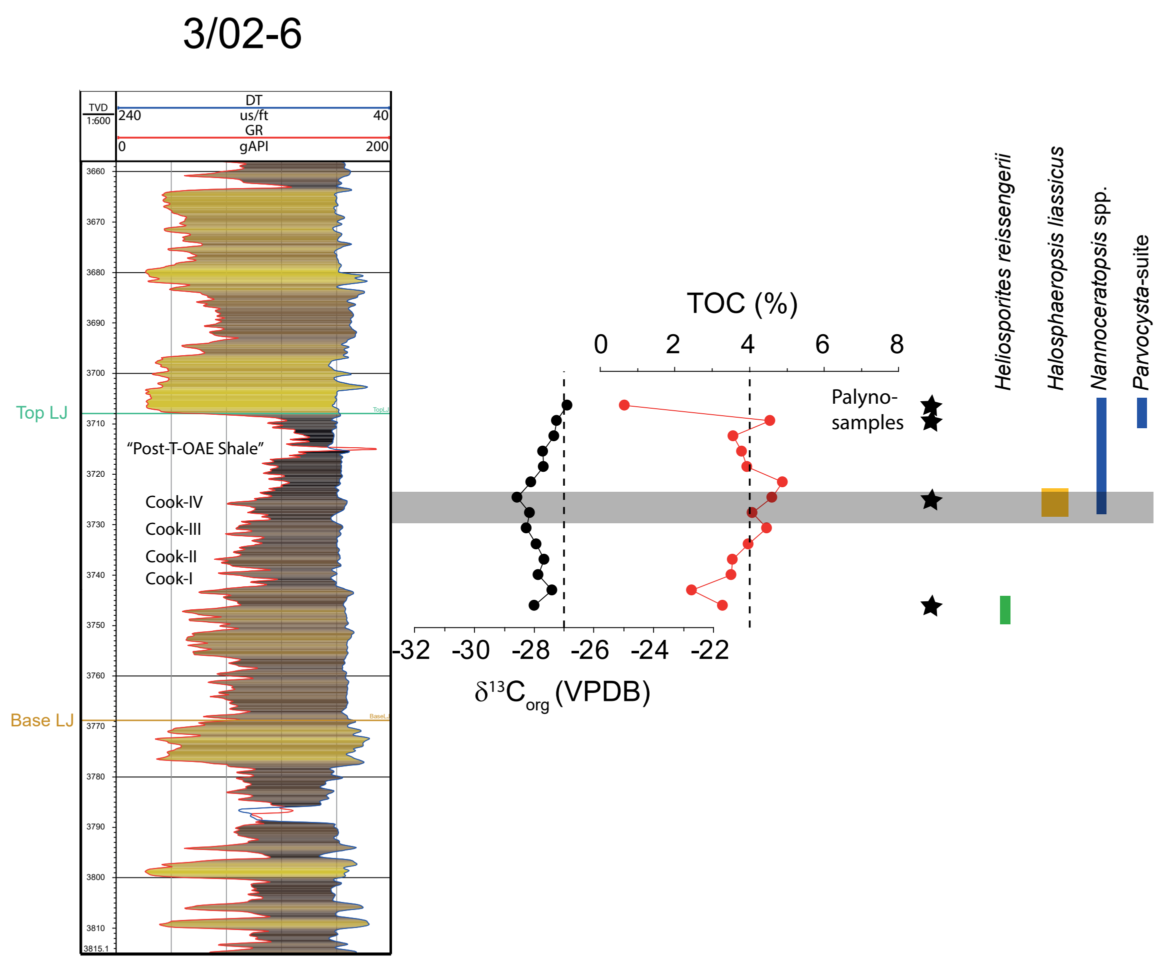
Table 2.1 Sampling for isotope and palynostratigraphic analysis. CO=Core, CU=Cuttings

Well	Interval (ft)	Interval (m)	$\delta^{13}C_{org}$	Paly
211/21-7 (CU)	9612-9665	2930-2946	7	2
3/02-6 (CU)	12155-12286	3705-3745	14	4
211/18b-25 (CU)	11161-11361	3402-3463	22	5
211/27-9 (CO)	11867-11926	3617-3635	11	4
211/02-1 (CU)	11581-11778	3530-3590	8	3
2/05-17 (CU)	10899-10958	3322-3340	7	0
210/20-2 (CO&CU)	9698-9747	2956-2971	12	4
3/01-2 (CU)	12506-12664	3812-3860	13	4

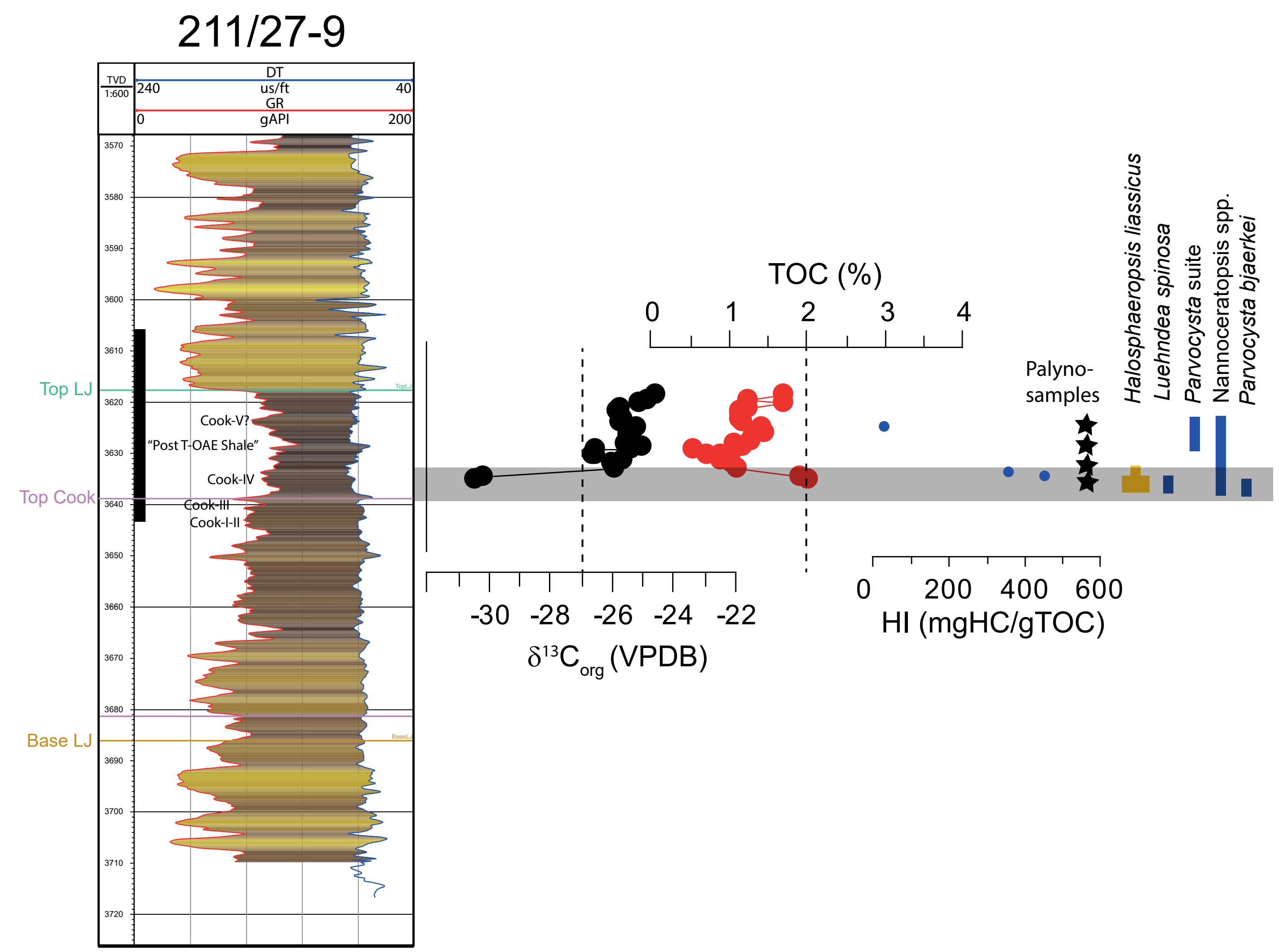
[1]: https://itportal.ogauthority.co.uk/information/well_data/bgs_tops/geological_tops/geological_tops.html



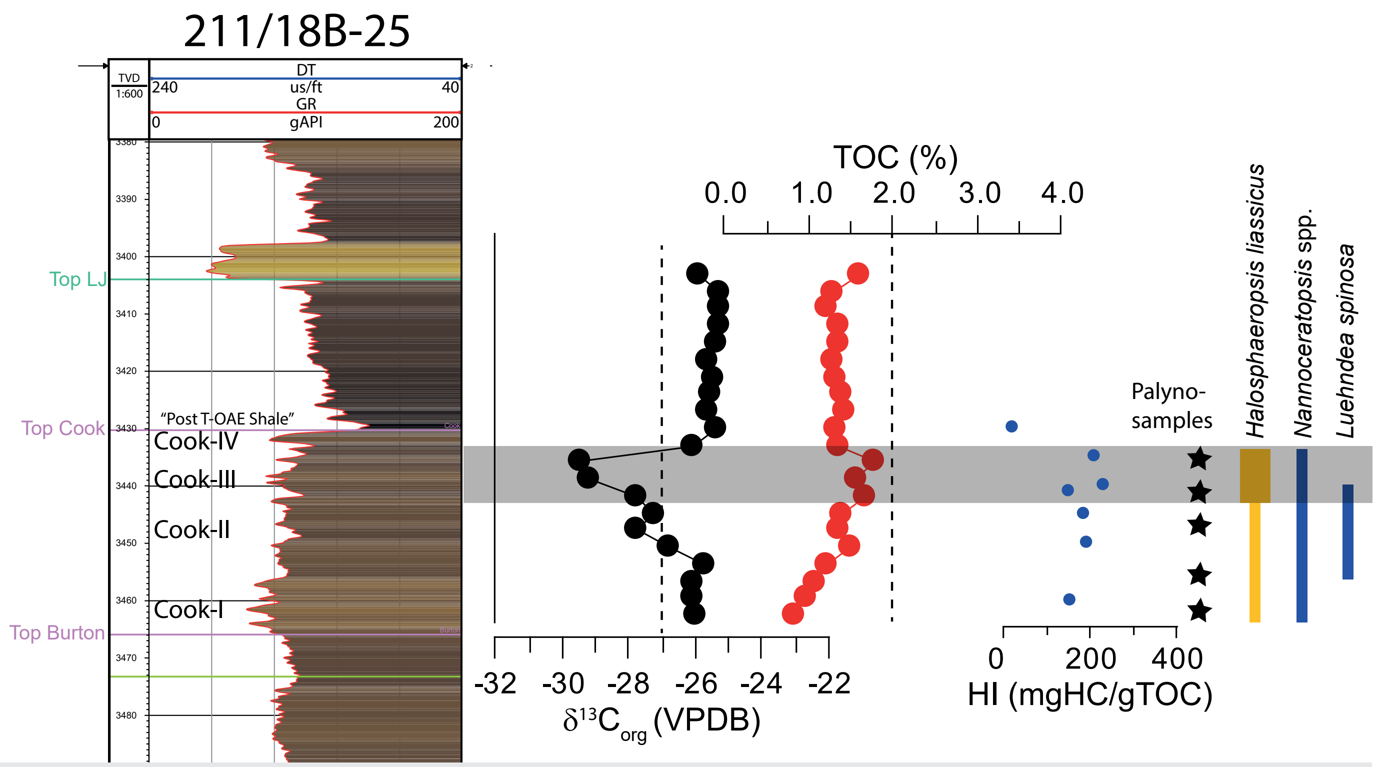
◄ Figure 2.7: Stable isotope carbon isotope and TOC-data from cuttings from Well 2/05-17, plotted along composite gamma (note color shading) and sonic log. The base and top of the Lower Jurassic (LJ) and of the Burton and Cook Fm. are after the OGA-well top database. In this well the Dunlin Gp. is incomplete or substantially condensed (see also Figure 2.15) . The carbon isotope data do not display a clear carbon isotope excursion (CIE). The characteristic high GR-interval above the Cook Fm. does not seem to correspond to the T-OAE. Because of the carbon isotope results, this well was not selected for further palynostratigraphic or rock eval evalution.



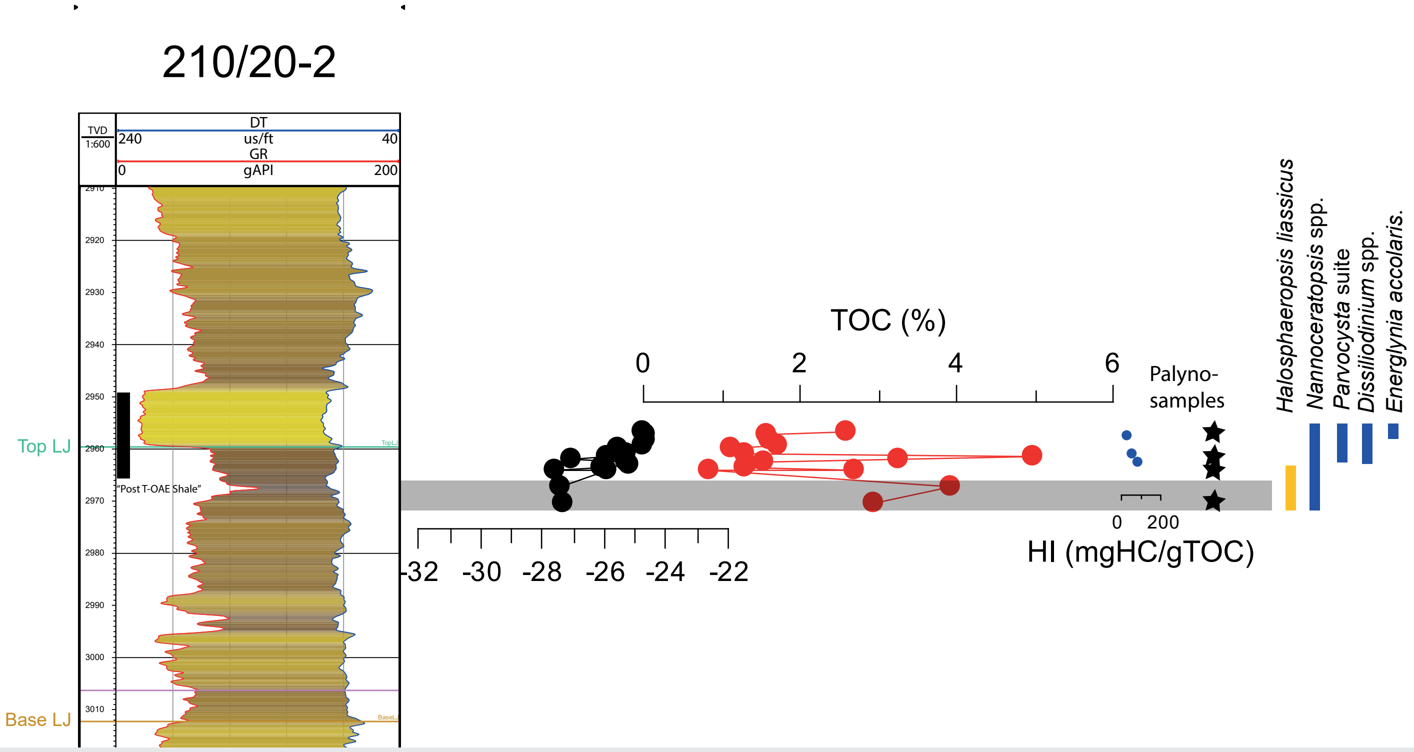
◄ Figure 2.8: Stable isotope carbon isotope, TOC- and palynostratigraphic data from cuttings from Well 3/02-6, plotted along composite gamma (note color shading) and sonic log. The base and top of the Lower Jurassic (LJ) is after the OGA-well top database. The log-pattern clearly indicates four Cook Fm. sandstones and an overlying shaly facies of the Drake Fm. The isotope data display a gentle upsection negative shift followed by a gentle recovery. The most negative value corresponds to the uppermost conspicuous Cook Fm. sandstone. To evaluate if this gentle isotope profile corresponds ot the T-OAE (grey shading), four palynological preparations were analyzed. The lowermost sample, below the Cook Fm. likely corresponds to the Amundsen Fm. The abundance of the sporomorph Heliosporites reissengerii and the absence of dinoflagellate cysts indicates a Late Sinemurian or older age. The sample with the most negative carbon isotope value contains abundant *Halosphaeropsis liassicus*. In addition, dinoflagellate cysts of the genus *Nannoceratopsis* are present. Luehndea spinosa, which goes extinct in association with the T-OAE is not recorded. Nevertheless, the palynological associations and the isotopes collectively clearly indicate that the T-OAE is position at about 3725 m (12221') depth. This is further supported by the appearance of the *Parvocysta*-suite in the uppermost samples. This implies that the T-OAE is positioned in the Upper Cook (4th unit) and that the on log-pattern conspicuous shale interval between 3712 and 3717 m (12178-12195') depth does not correspond to the T-OAE. Note that the Hydrogen Index (HI) data for this are not depicted because the Rock Eval results reveal contamination by allochtonous hydrocarbons (see Figure 2.18). This may also explain the remarkably high TOC-content (3-5%).



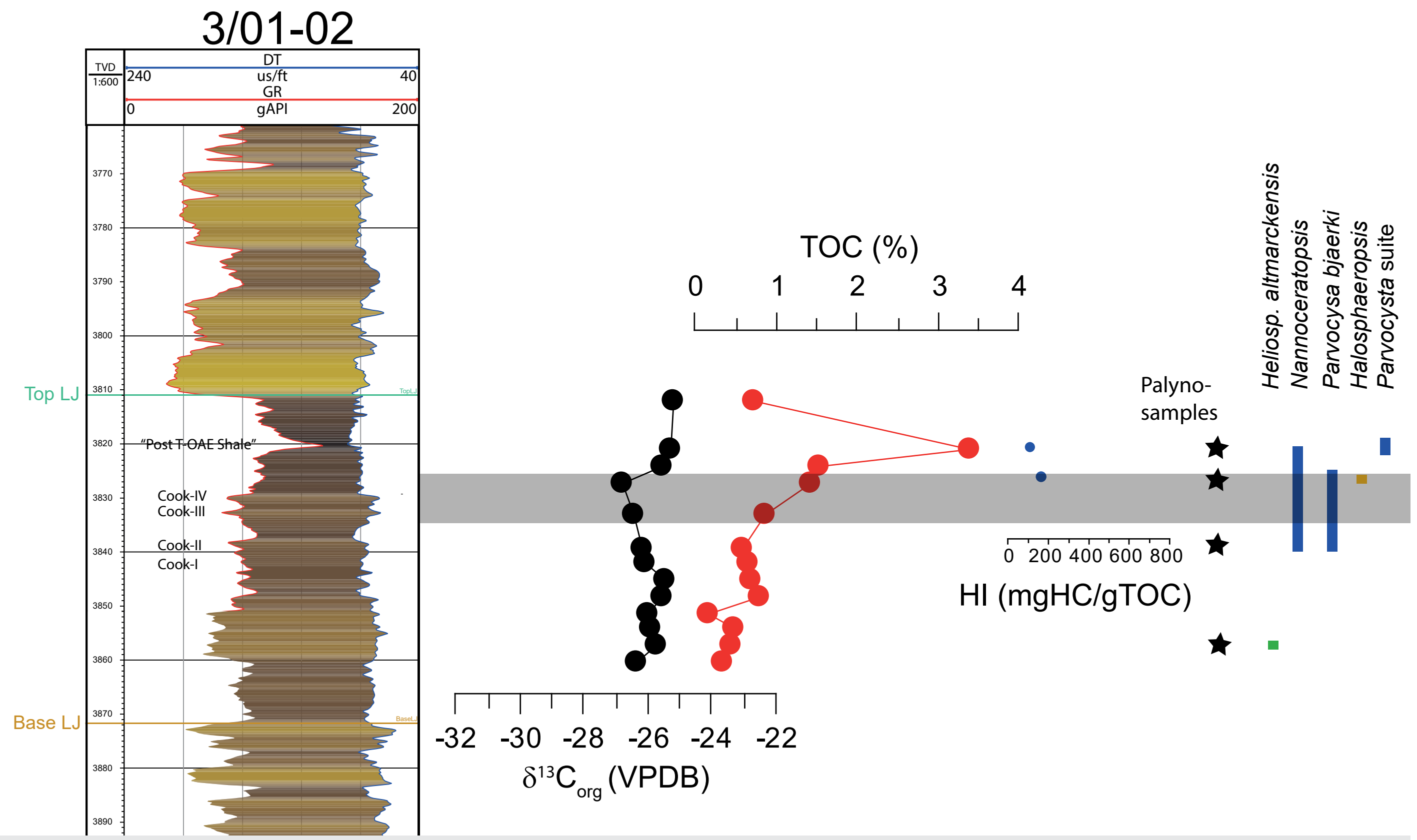
▲ Figure 2.9: Stable isotope carbon isotope, TOC- (IRMS-based), Hydrogen Index and palynostratigraphic data from core samples from Well 211/27-9, plotted along composite gamma (note color shading) and sonic log. The base and top of the Lower Jurassic (LJ) and of the Cook Fm. are after the OGA well top database. The black vertical profile indicates the cored section. The core starts in the upper part of the Cook Fm., spans the entire Drake Fm. and continuous into the overlying Brent Group. The Cook sandstones appear less-pronounced than in some other wells (e.g., Figure 2.8). The lowermost two samples clearly capture the carbon isotope excursion and subsequent recovery. Also the palynostratigraphic results support the conclusion that the T-OAE is positioned at about 3635 m (11926') depth, with abundant *Halosphaeropsis liassicus*, presence of *Nannoceratopsis* spp., *Parvocysta bjaerki* and importantly the concomitant exinction of *Luehndea spinosa*. Evaluation of the log-pattern subsequently give rise to recognition of the four Cook sand units. The shaly interval at 3628 m (11903') corresponds to the introduction of the *Parvocysta*-suite. Three rock eval analyses were performed. Albeit TOC is relatively throughout, a maximum of about 2% is recorded in correspondence to the T-OAE. Importantly, the Hydrogen Index is substantially higher (400-500 mgHC/gTOC) in this T-OAE interval of the Cook-IV facies than in the overlying Drake Fm. mudstones.



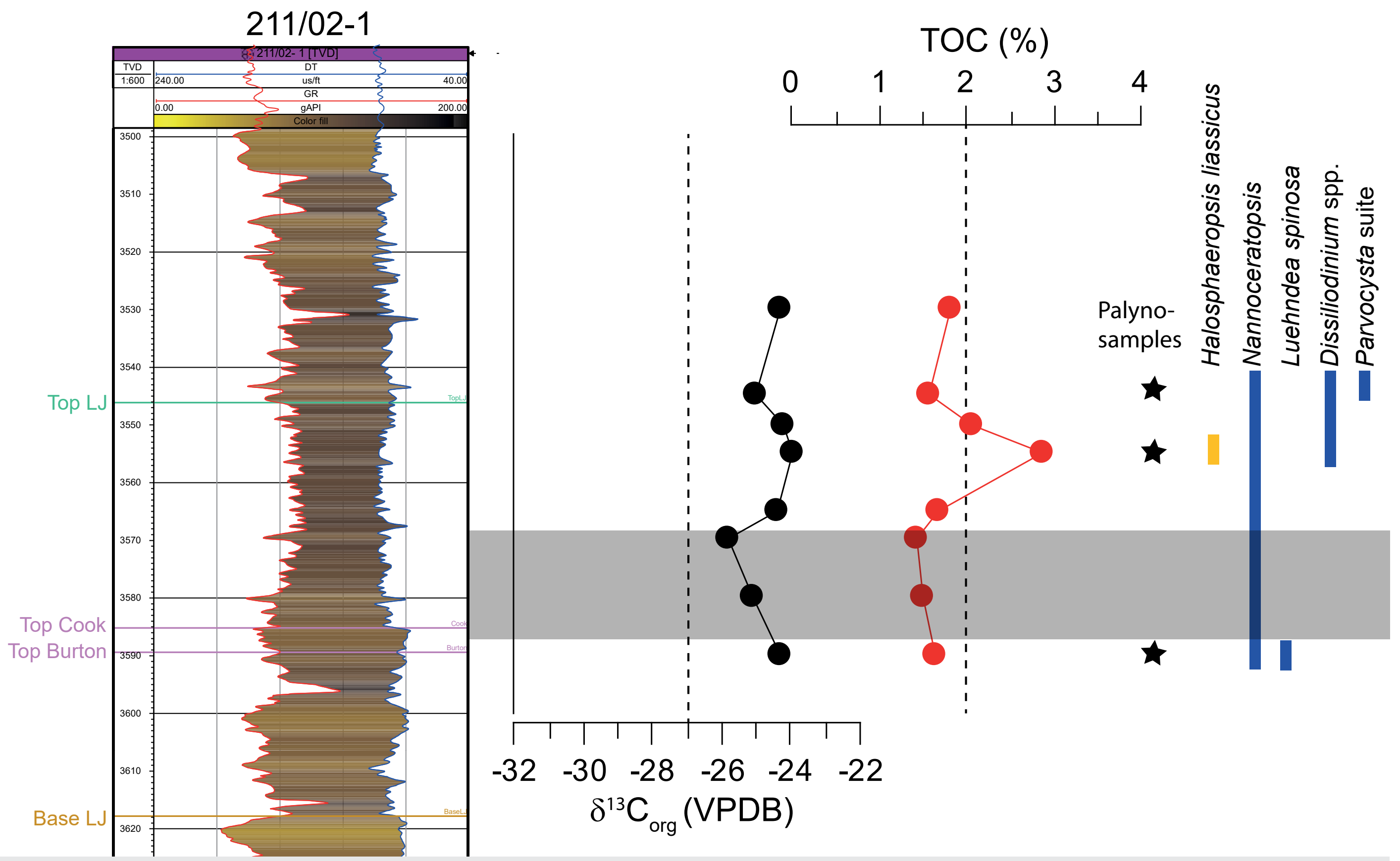
▲ Figure 2.10: Stable isotope carbon isotope, TOC- (IRMS-based), Hydrogen Index and palynostratigraphic data from cutting samples from Well 211/18b-25, plotted along composite gamma (note color shading) and sonic log. The base and top of the Lower Jurassic (LJ) and top of the Burton and Cook Formations are after the OGA well database. Despite this dataset was generated based on cuttings material, a very complete and conspicous carbon isotpe excursion are recorded, The base of the CIE is positioned at 3450 m (11319') depth and the maximum excursion is positioned at 3435 m (11270') depth, again responding to fourth Cook Sand. the The palynostratigraphic data undoubtedly support the position of the T-OAE (grey shading). *Halosphaeropsis liassicus* is very abundant in the samples with the most negative values. *Luehndea spinosa* goes extinct corresponding to the initial negative excursion phase, much akin to the Yorkshire records. TOC-values remain below 2%. Also the Hydrogen Index data are not indicative a good Type-II source rock (see also Figure 2.16 and 2.17). This is likely due to a large degree of mixing with terrestrial organic matter supplied from the east. Again a rather prominent shale interval overlies the T-OAE, which is according to the Hydrogen-Values of a prominent terrestrial Type III to Type IV organic origin. There are not palynological data at hand to evaluate whether this corresponds to the incursion of the *Parvocysta*-suite.



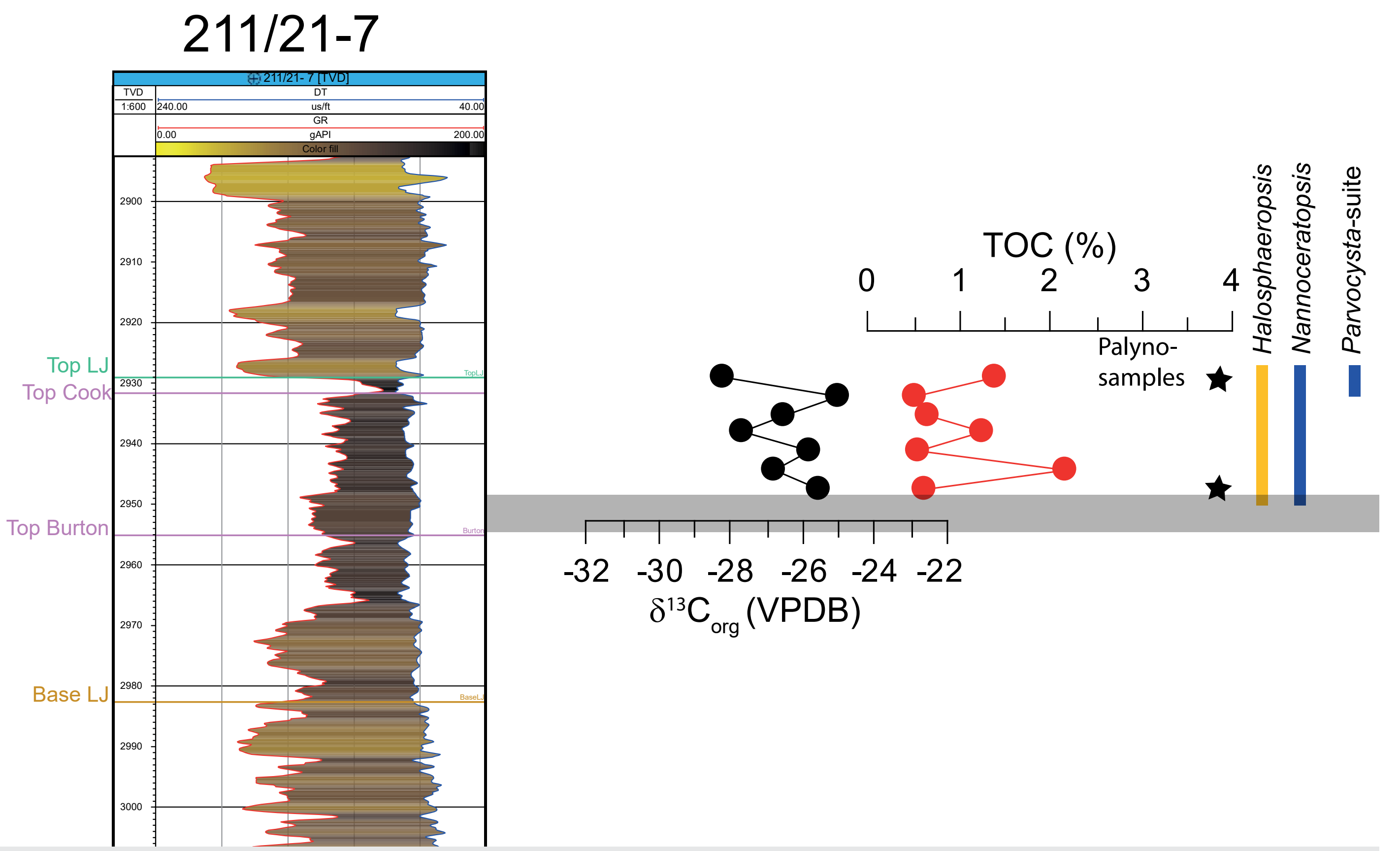
▲ **Figure 2.11: Stable isotope carbon isotope, TOC- (IRMS-based), Hydrogen Index and palynostratigraphic data from core and cuttings samples from Well 210/20-2, plotted along composite gamma (note color shading) and sonic log.** The base and top of the Lower Jurassic (LJ) are after the OGA well top database. The black vertical profile indicates the cored section. According to the general log-pattern the base of the core is within the Drake Fm, and continuous into the overlying Brent Group. Below the core, characteristic shale horizon is noted. The Cook sandstones appear less-pronounced than in some other wells. The basal two samples derived from cuttings are somewhat more negative than those recorded further up-section. Very negative values of -30 per mille are however not recorded. The palynostratigraphic lend support to these lowermost cuttings samples approximating the T-OAE (grey shading), with the presence of *H. liassicus* and AOM-dominated palynofacies. Overlying, a clear Upper succession is recovered as reflected by the occurrence of the *Parvocysta* suite and *Energlynia accolaris*. The TOC-pattern is rather variable, with values reachin 5% in the Upper Toarcian section. Hydrogen Index data however, suggest a terrestrial origin.



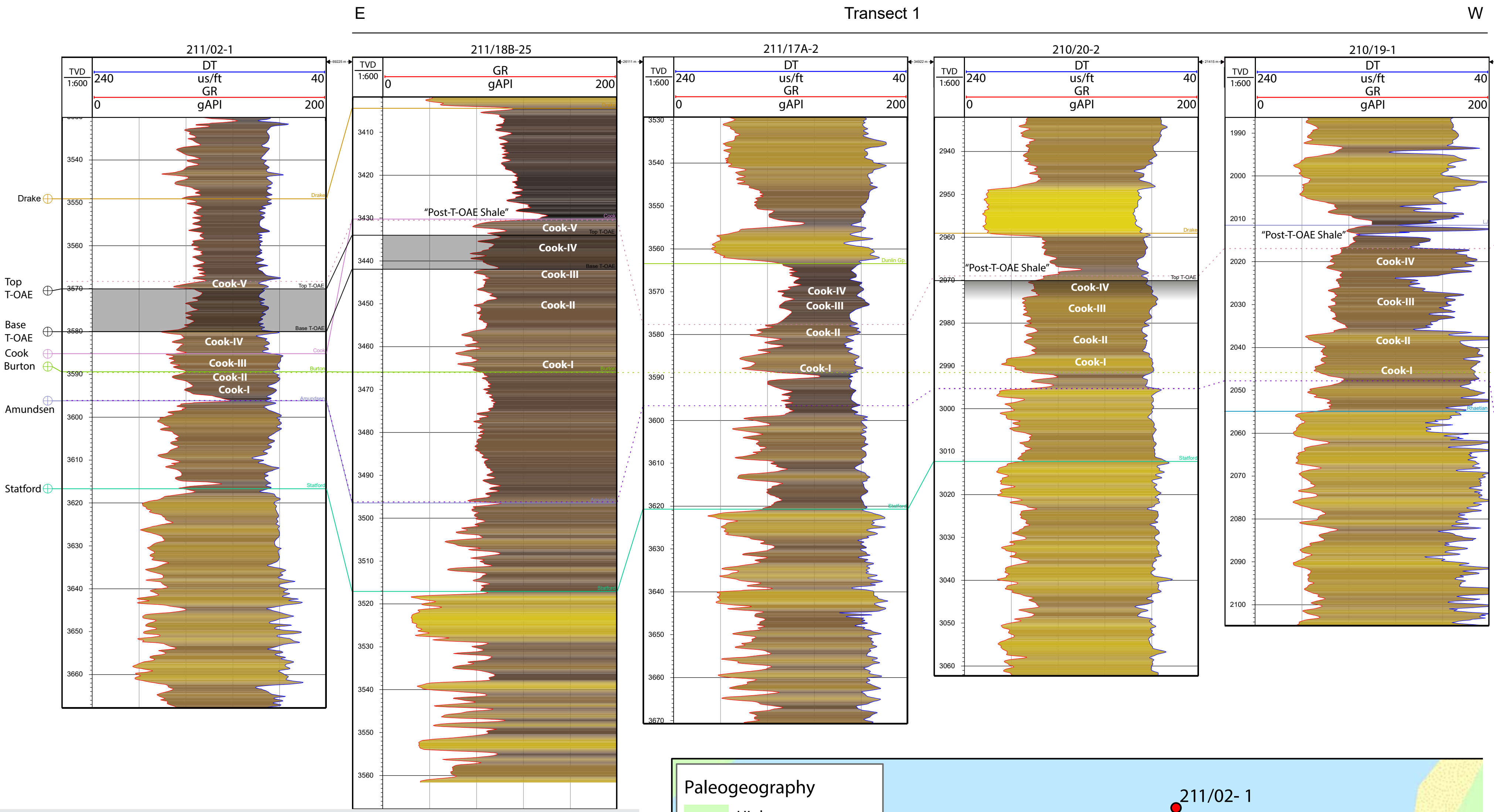
▲ **Figure 2.12: Stable isotope carbon isotope, TOC- (IRMS-based), Hydrogen Index and palynostratigraphic data from cuttings samples from Well 3/01-2, plotted along composite gamma (note color shading) and sonic log.** The base and top of the Lower Jurassic (LJ) are after the OGA well top database. The carbon isotope data reflect a gentle decrease from -26 to -27 per mil between 3840 and 3826 m (12549'-12552') depth. The palynostratigraphic results aid to elucidate the level of the T-OAE. The basal sample contains *Heliosporites reissengerii*, thus confirming a Sinemurian or older age. The gentle isotope shift is accompanied by the presence of *Nannoceratopsis* spp. and *Parvocysta bjaerki*, both occurring in the Latest Pliensbachian. *Halosphaeropsis jurassica* is recorded in the sample with the most negative values. Hence, it seems plausible that the T-OAE is positioned as indicated by the grey shading, thus underlying the characteristic post-T-OAE shale in the Drake Fm., likely within the Cook-IV Sand. The TOC in the post T-OAE shale is enriched reaching about 3%. The low Hydrogen Index values suggest a Type III-IV organic matter with a terrestrial origin.

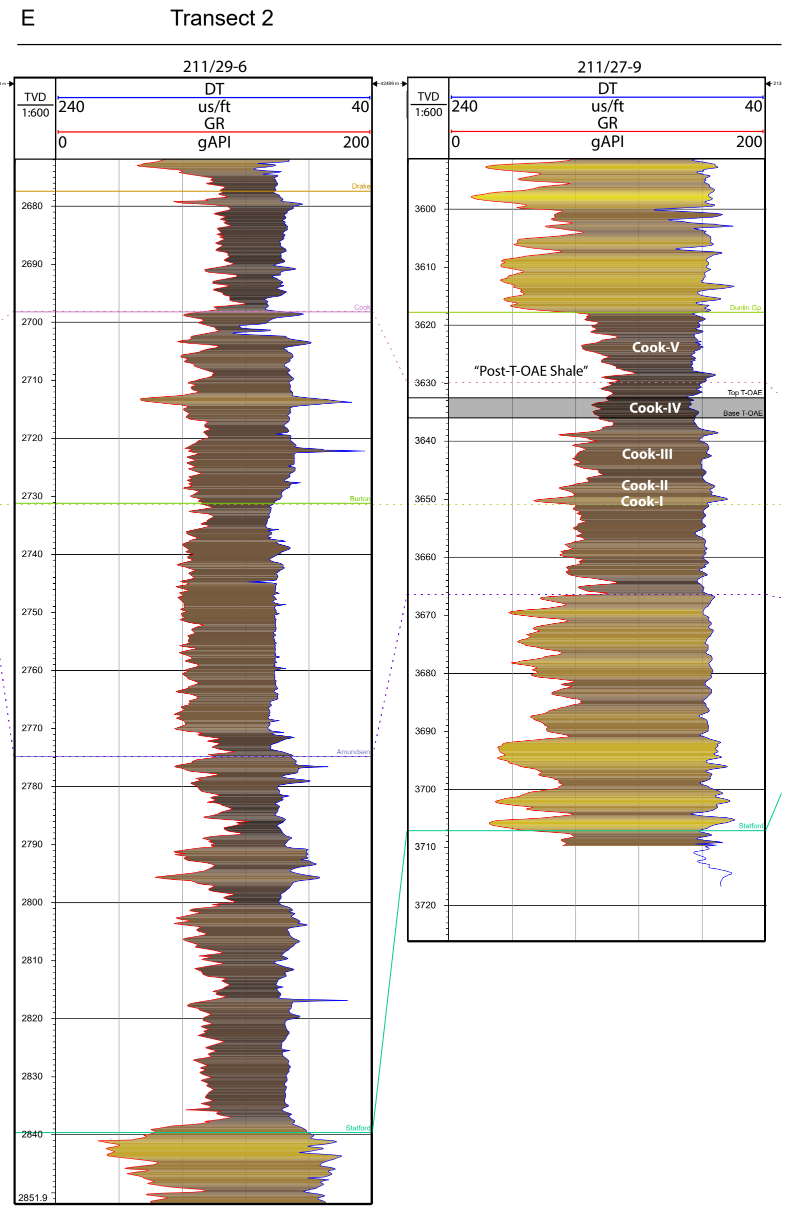


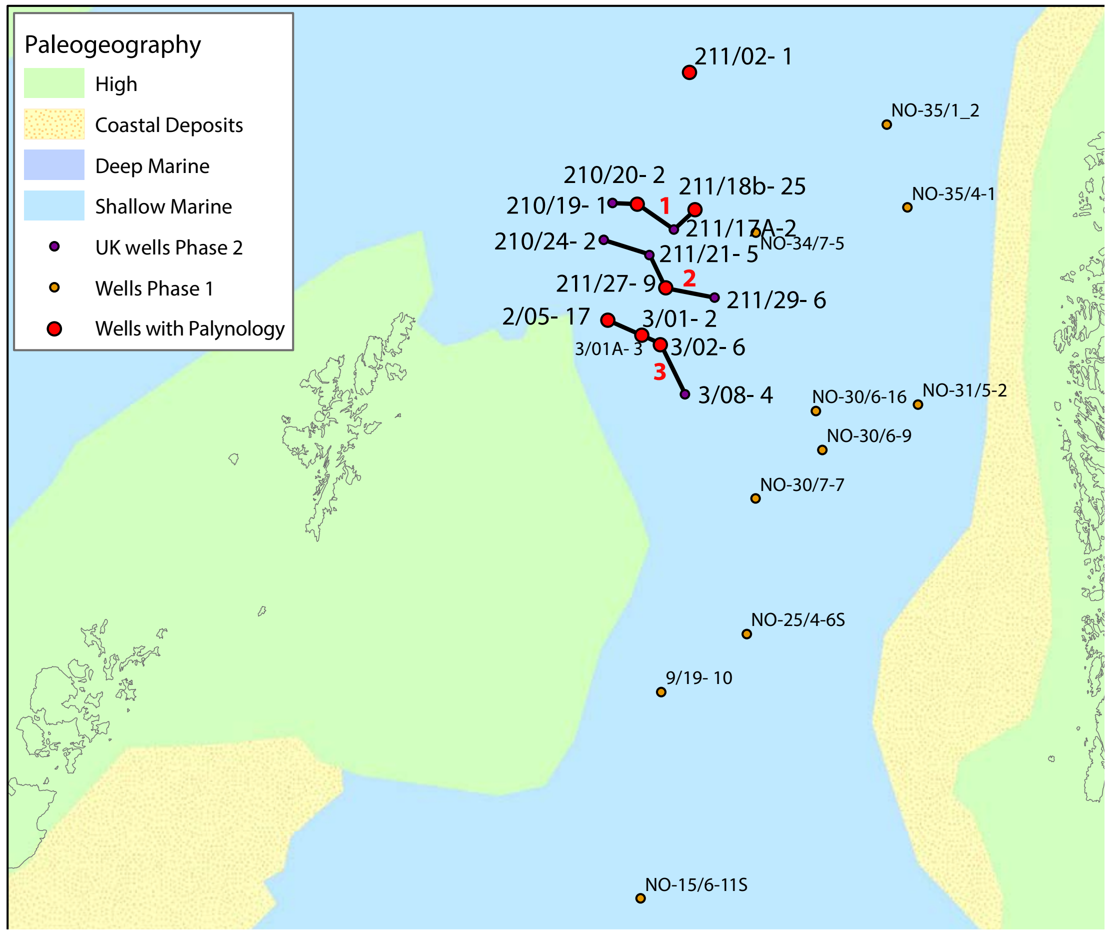
▲ **Figure 2.13: Stable isotope carbon isotope, TOC- (IRMS-based)and palynostratigraphic data from cuttings samples from Well 211/02-1, plotted along composite gamma (note color shading) and sonic log.** The base and top of the Lower Jurassic (LJ) and the top of the Cook and Burton Fm. are after the OGA well top database. This well has fairly extended shaly interval above the Cook Fm. the actual top seems to be positioned somewhat higher than provided by the OGA well top database. The carbon isotopes are characterized by minor decrease in the lower three samples. The palynostratigraphy prescribes an evident Upper Toarcian succession above 3555 m (11663') depth and an Latest Pliensbachian to Earliest Toarcian age based on the presence of Luehndea spinosa in the basal sample (3590 m, 11778') depth. Hence, the T-OAE is positioned somewhere between these levels, likely at the most negative isotope value. Due to a scarcity of available sample material, rock eval analyses could not be performed.



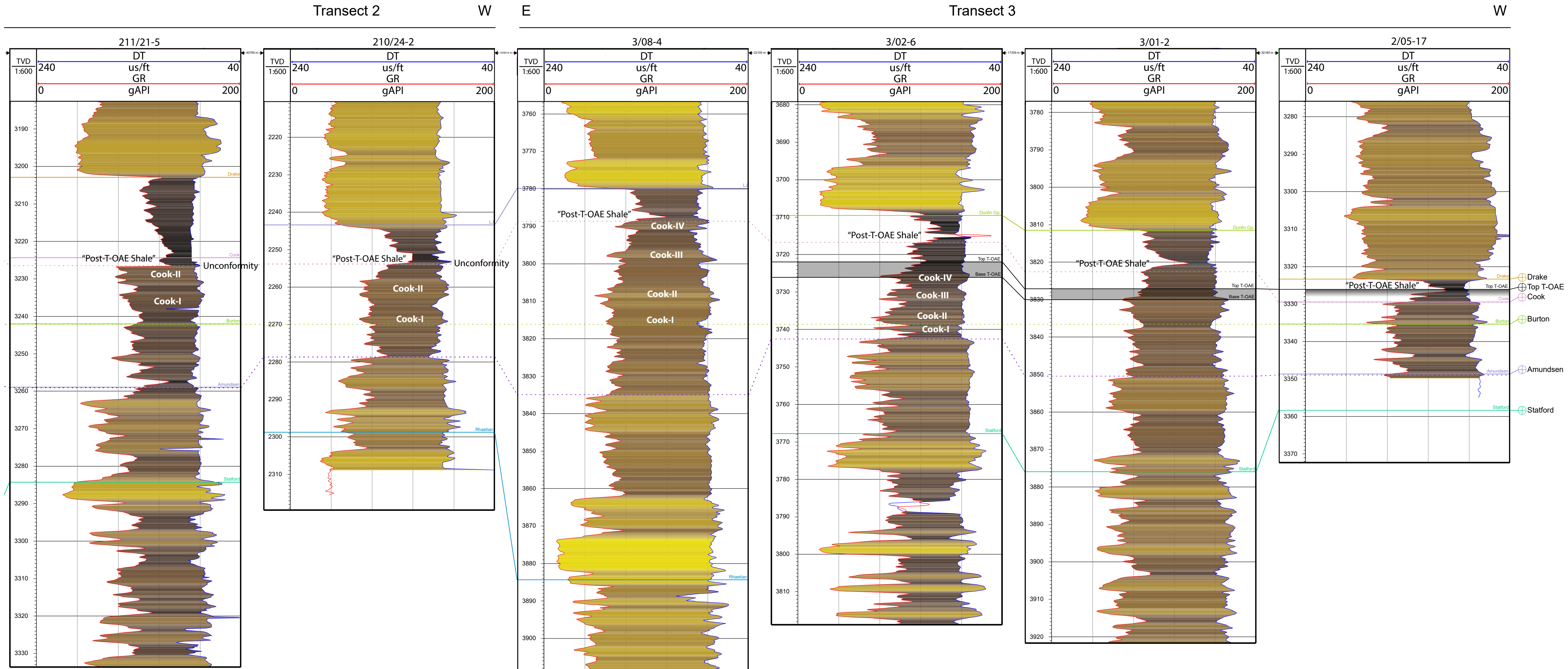
▲ **Figure 2.14: Stable isotope carbon isotope, TOC- (IRMS-based)and palynostratigraphic data from cuttings samples from Well 211/21-7, plotted along composite gamma (note color shading) and sonic log.** The base and top of the Lower Jurassic (LJ) and the top of the Cook and Burton Fm. are after the OGA well top database. The carbon isotope data from this well do not display a noteworthy signal. The palynological data indicate that the *Parvocysta*-suite appears at the level of a pronounced shale within the Drake Fm. Hence, albeit no record of the T-OAE could be obtained, its expected stratigraphic position is within the Cook Fm. Because of the stratigraphic uncertainty, no additional rock eval data were generated.







▲ Figure 2.15: Well-log correlation panels of three west-transects across the study area (see map at right), using gamma- and sonic velocity logs) . For the log correlation the Gamma and Sonic logs were used. Well formation tops indicated by coloured lines are after the OGA-well top database. The interpreted stratigraphic position of the T-OAE is indicated by grey shading. The log expression of the Burton formation is shows higher GR and DT values which can be interpreted as a shaly lithology. In some wells a very high GR peak could be observed within the lower part of the formation. It is overlain in most cases by the Cook formation, which consists of 4 characteristic cycles (marked in white). In 211/21-5 and 211/24-2, only the lower two Cook sands are present. The upper part of the Cook Fm. appears erosionally truncated. According to the results of this study, the T-OAE is positioned in somewhat more shaly 4th unit of the Cook Formation. Consistently above this level, we record a rather pronounced high-GR, unit here referred to as the "Post-T-OAE Shale". This transition is consistently marked by the incursion of the *Parvocysta*-suite. Towards the top of the formation the GR and DT values slowly decrease. Note that well 211/02-1 lies to the north of the other wells and is not included in the E-W transects. Its lithology is also a bit different, as the conpicuous "Post-T-OAE shale" is not developed here.



▲ **Figure 2.15: ...Continued**

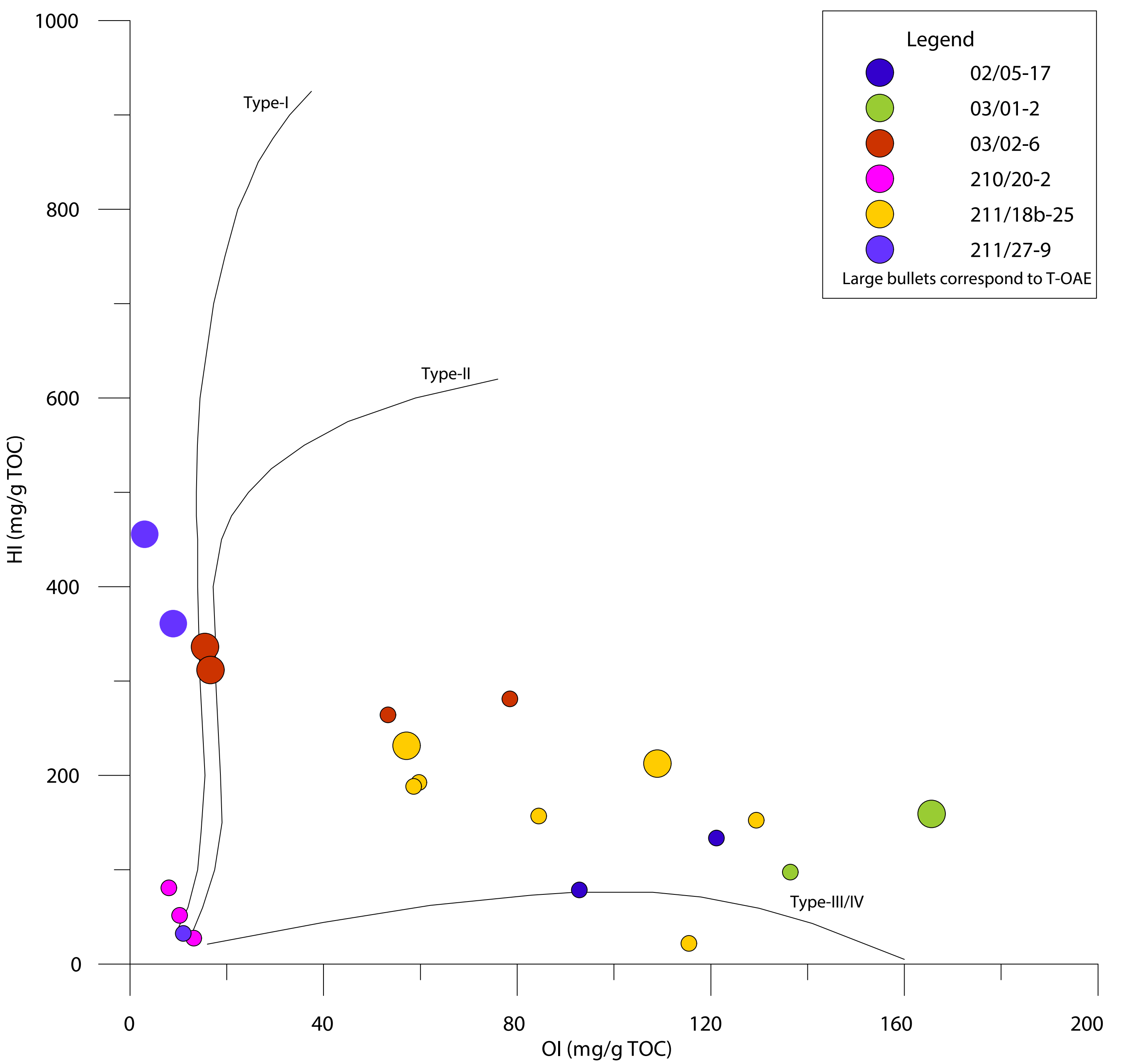
Regional correlation and biogeography

The well transects depicted in **Figure 2.15** provide insight into the regional correlation of the Cook and Drake Fm. interval. Overall, the results suggest a rather homologous stratigraphic position of the T-OAE (**Figure 2.15**). The T-OAE consistently corresponds the relatively low GR strata, interpreted as the Cook-IV. In some cases a 5th Cook-V sand is also recorded, occurring substantially up in to the Late Toarcian (**Figure 2.15).** Marjanac and Steel, 1997, Charnock (2001) and Churchill et al. (2016) suggest the division between the Upper and Lower Cook Fm. (between the Cook-II and Cook-III unit) as being of Late Pliensbachian age (Spinatum or Margaritatus Zone) and thus corresponding to the J15 MFS. This implies that the Cook-III sand is of Earliest Toarcian age (base Tenuicostatum Zone and thus pre-dating the T-OAE, see **Figure 2.2**). This is in-line with the observations from ths study. Consequently, the Late Pliensbachian J15 MFS reflects a major change in depositional system and reflects the gradual transgression of the system. The T-OAE (Base Falciferum Zone, see **Figure 2.2**) apparently correlates to the Cook-IV sand, and hence it is not the associated J18-flooding that leads to transgression and proliferation of Drake Fm. shale deposition. Hence, we have not observed the T-OAE to correlate with prominent shale facies, therefore also limiting the source-potential of this time-interval.

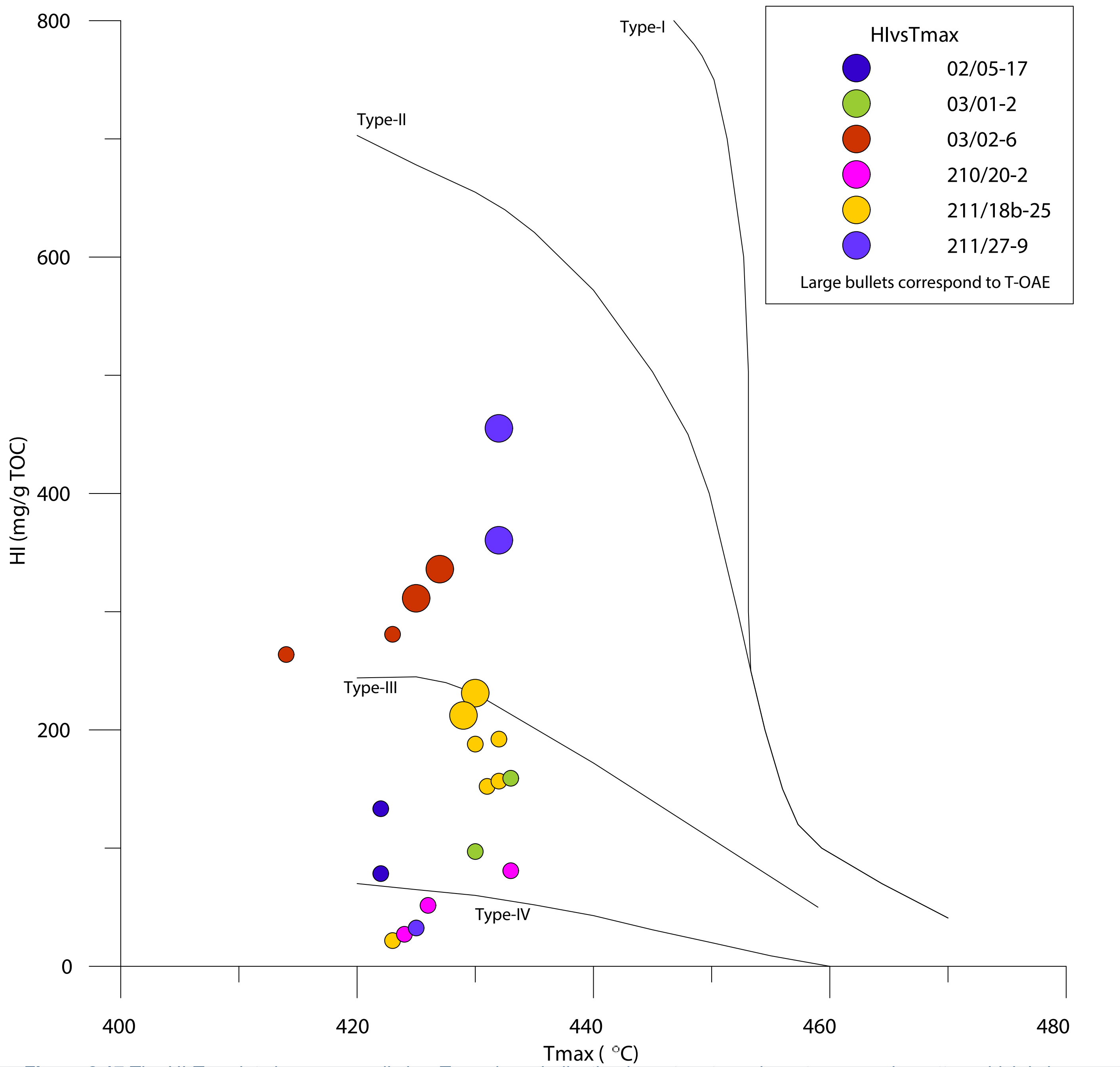
In contrast, the deposition of a conspicuous shaly lithology post-dates the T-OAE, giving rise to the designation of the "post T-OAE shale". This shale relates to the introduction of the *Parvocysta*-suite. A group of dinoflagellate cysts that is present in Arctic water masses, already since Late Pliensbachian times (see e.g., Zakharov et al., 2006). A similar reorganisation has also been observed in macrofossil distribution patterns (Dera et al., 2011). Consequently, its introduction into the East Shetland Platform area suggests the establishment of a connection with northerly sourced water masses coming through the Viking Strait. Hence, it seems that this post-T-OAE transgression established a connection with the Southern North Sea. In turn providing a mechanism for the termination of severe water-mass restriction and anoxia that contributed to the distribution of organic-rich deposition beyond the T-OAE in the Southern North Sea.

Rock Eval and TOC analysis

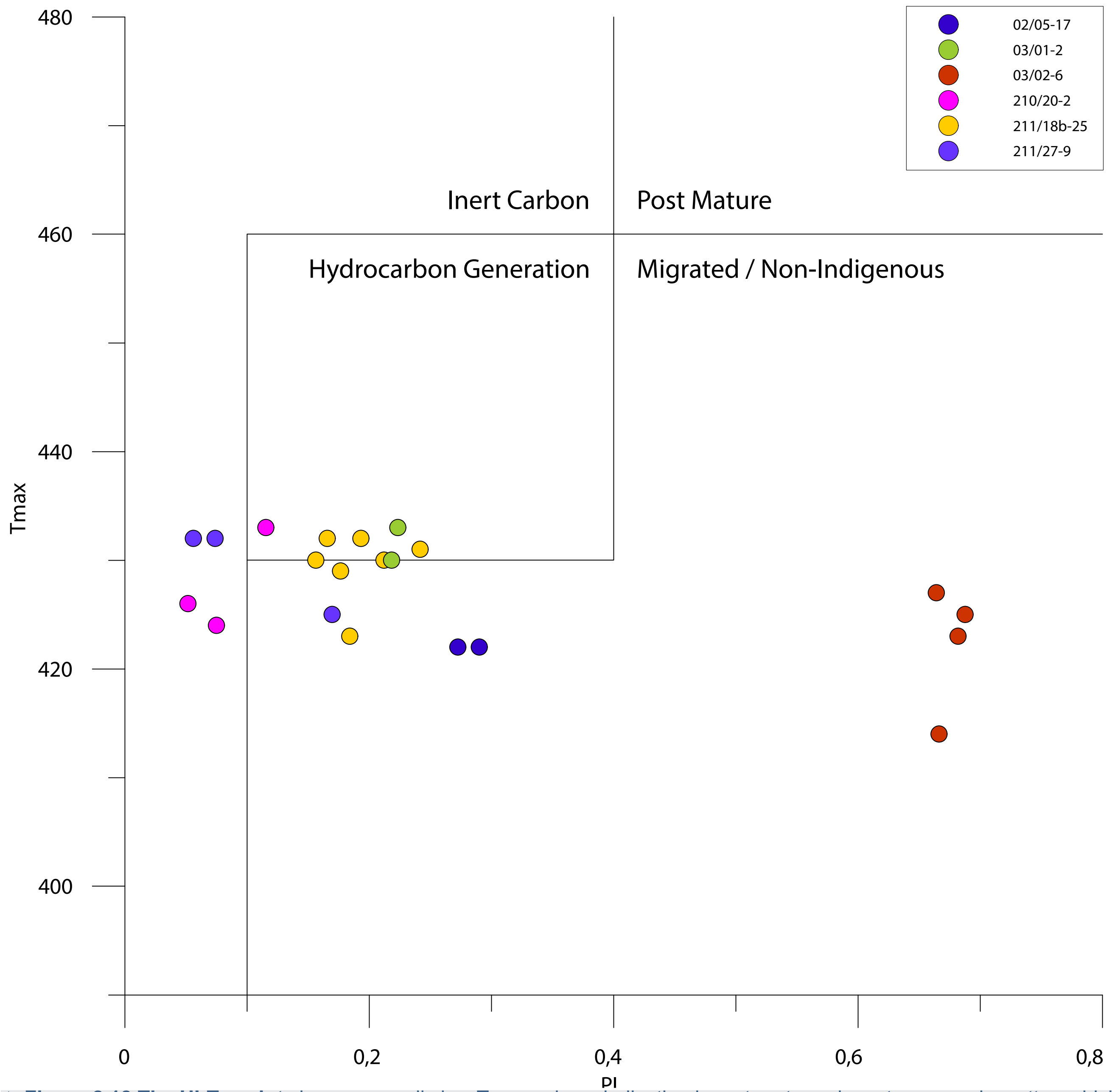
In order to evaluate the qualtity and character of the organic-matter contained in the interval of interest we have generated Rock Eval data on selected samples (**Figure 2.7 -2.14**). This selection focused either on evaluation of organic-matter trends in the now recognisable T-OAE or to evaluate changes in other conspicuous intervals as recognized on the petrophysical logs. Note that due to scarce availability of the cuttings material, we could not always perform analyses for all desired intervals. The results are discussed in the respective figure captions of **Figure 2.16 - 2.18**. In general the results of the Rock-Eval analyses show poor source-rock quality with mostly immature to early mature type III organic matter **Figure 2.16 & 2.17**). Two samples from well 211/27-9, corresponding to the T-OAE appear to be of higher quality with a type II-III source-rock with HI values of around 400 and TOC of more than 2%.. Collectively this suggests that the T-OAE indeed stands out as a prosperous time-interval for source-rock genesis, even in the study area. However, due to high sedimentation rate and compared to the Southern North Sea, limited or short-lived phases of anoxia no major Toarcian source rock is to be expected in the area. Importantly, also the shaly interval above the T-OAE of the Drake Fm., which based on log profiles looks very prominent is not a prosperous source rock. It is merely the effect of deepening of the Viking and/or rapidly rising relative sea-level by about Late Toarcian times. The organic-matter is low in concentration and of a Type III-IV origin.



▲ **Figure 2.16 Rock-Eval analysis results from the wells in the northern offshore blocks 2, 3, 210 an 211 of the UK.** This pseudo-van Krevelen diagram shows that the type of organic matter is mainly type III. The results show hydrogen indices (HI) mainly below 300 and high oxygen indices (OI > 40). Two exceptions are two samples from well 03/02-6 and two samples from well 211/27-9 which show HI values of 300 to 450 and low OI values, usually interpreted as mature type I or II organic matter. These correspond ot the T-OAE stratigraphically. However, their TOC-content remains relatively low (<2%) and for Well 03/02-6 we suspect the presence of migrated or contaminated hydrocarbons (see **Figure 2.18**). An excellent Toarcian source-rock cannot be invoked.



▲ **Figure 2.17** The HI-T_{max} plot shows generally low T_{max} values, indicating immature to early mature organic matter, which is in agreement with the palynological observations, that are consistently characterized by a minimal degree of brown coloration and overall good preservation. The samples from the T-OAE interval consistently have elevated hydrogen index values. The measured TOCs are between 0.5 and 2%, only well 03/02-6 has TOC values of around 4%.



▲ **Figure 2.18 The HI-T$_{max}$ plot** shows generally low Tmax values, indicating immature to early mature organic matter, which is in agreement with the palynological observations, that are consistently characterized by a minimal degree of brown coloring and overall good preservation. The samples from the T-OAE interval consistently have elevated hydrogen index values. The Measured TOC are between 0.5 and 2%, only well 03/02-6 has TOC values of around 4%.

2.4 Conclusions and implications

1. The T-OAE event was successfully traced through isotope and palynostratigraphy.

2. The T-OAE does not correspond to a conspicuous shale facies in any of the wells, as is the case in the Southern North Sea Basin. In contrast, the T-OAE corresponds to the Upper Cook Formation (i.e., the Cook-IV unit).

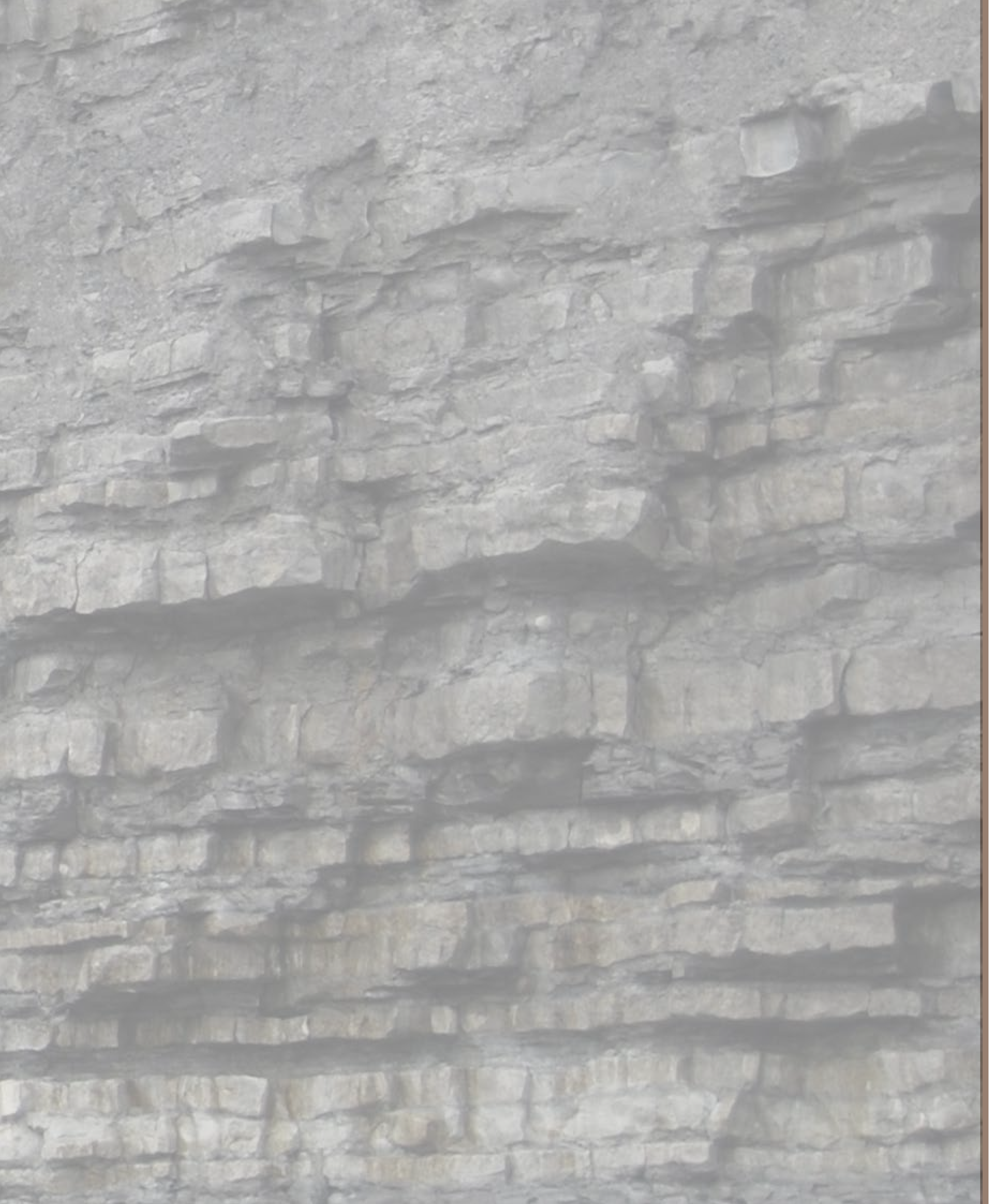
3. In such a dynamic, high accummulation sedimentary regime, sediment accumulation outpaces organic enrichment thus not leading to prolific source rocks, albeit rock eval data suggest a Type-II kerogen in some wells (211/27-9).

4. The latter is in-line with the palynological assemblages that indicate photic zone anoxia.

5. Above the T-OAE correlative Cook-IV unit, we note a conspicuous shale interval. The onset of this Drake Fm. shale, corresponds to the introduction of boreal/arctic dinoflagellates. In Yorkshire (UK) and the Netherlands this introduction of taxa corresponds to the late Early Toarcian (Bifrons Ammonite Subzone), where it is accompanied by a demise in overall TOC-values. Hence, the establishment of a boreal connection through the Viking Strait by late Early Toarcian times seems to have ended the restricted anoxic settings that led to good source rock formation further to the south.

6. The maturity of all samples from the East Shetland Platform area is low, Tmax values indicate that the organic matter is immature to early oil generation.

Hettangian-Sinemurian Blue Lias Fm. near Lyme Regis, Dorset



03

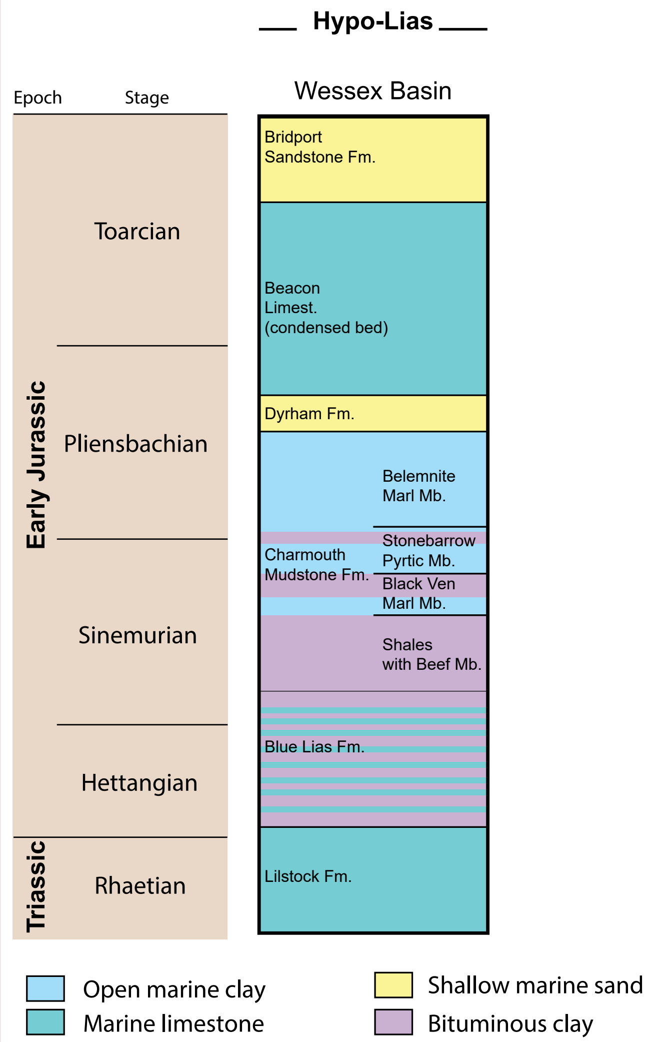
Source rock potential of the Western Approaches area

3.1 Background and objectives

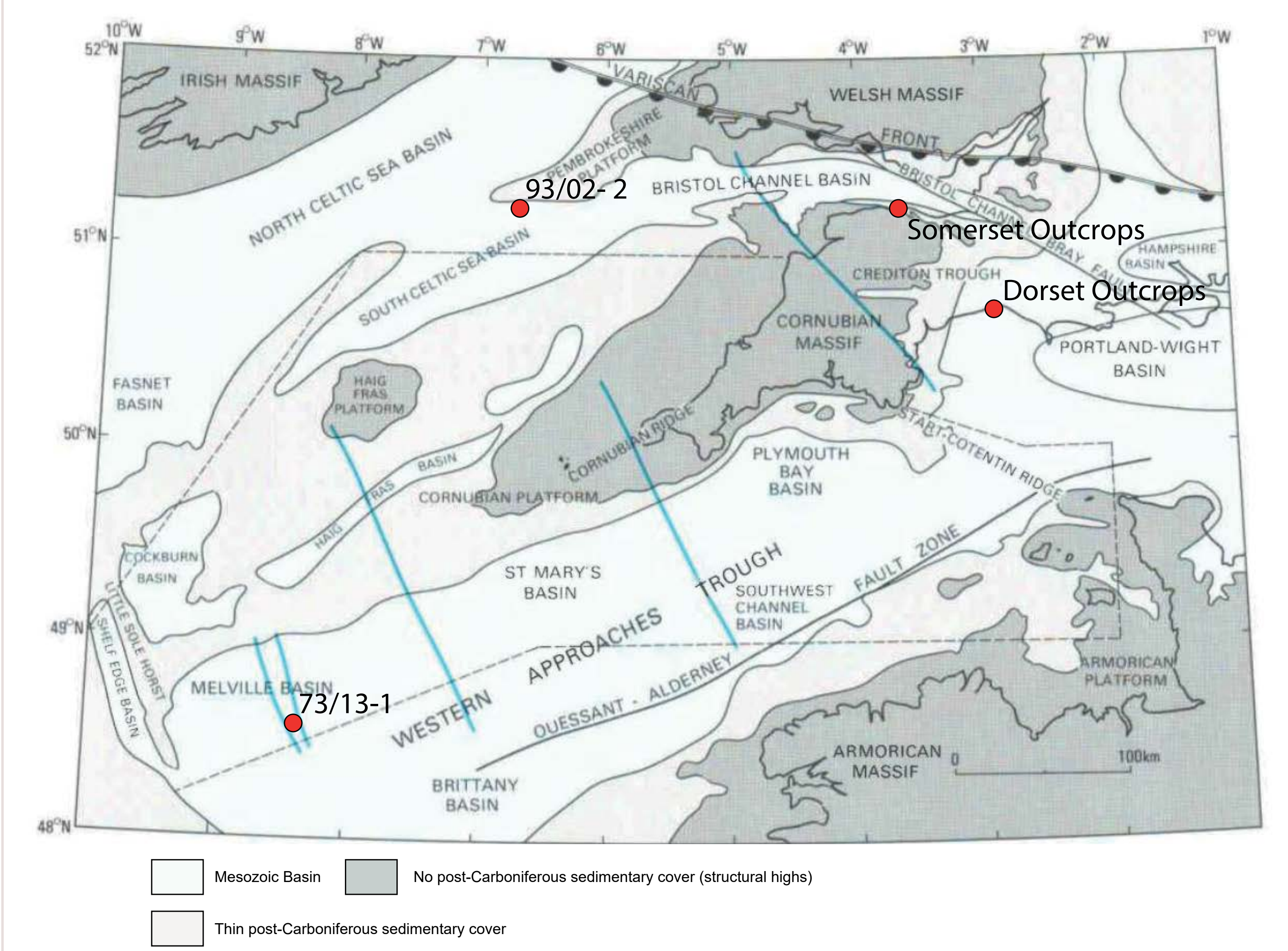
The Lower Jurassic onshore SW-England and Wales

Onshore Dorset and Somerset, the lower part of the Lias Group is known for its organic-richness and good source-rock prospectivity. As part of the HYPO-Lias project, the Blue Lias Fm. and (lower) Charmouth Mudstone Formation (i.e., the Shales with Beef Mb., Black Ven Marl Mb. and Stonebarrow Pyritic Mb., **Figure 3.1**) were extensively studied, in the coastal outcrops in Dorset. The study indicates that these compose rather homogeneous marine Type II-source rocks, deposited in an epeiric sea. Palynological patterns and visual organic-matter analyses indicate the persistance of anoxic surface-water conditions, leading to the dominance of specific hydrogen-rich organic-matter. Redox sensitive elemental analysis indicates predominant anoxic bottom water conditions. Terrestrial palynomorph associations reveal warm climatic conditions, in conjunction with strong monsoonal run-off patterns into this epeiric sea. In addition to the presence of diagenetic carbonates, dilution by both biogenic carbonate and detrital input posed the primary limiting factor on organic-richness. A predominantly anoxic water-mass was persistent during the Hettangian and Sinemurian. This led specific anoxygenic photosynthesizers to be a primary source of the hydrogen-rich organic matter. These strata represent the lateral source rock of the Wytch Farm Oil Field. Similar depositional conditions persist further to the north, as seen in the Somerset outcrops (e.g., Warrington et al., 1994), albeit there, the organic carbon content is consistently lower, due to a higher rate of detrital clay input (Ruhl et al., 2010). The same holds true for a record onshore Wales, from the extremely expanded Mochras Borehole (Van de Schootbrugge et al., 2005).

In general, the upper part of the Lias Gp. (Pliensbachian-Toarcian) in Dorset is not represented by source-rock facies. The Lower Pliensbachian Belemnite Marl Mb. of the Charmouth Mudstone Fm. is persistently dominated by carbonate and deposited in predominantly oxic settings (HYPO-Lias study, Weedon and Jenkyns, 2010). Overlying the Upper Pliensbachian to Lower Toarcian succession of the Dyrham Fm. and the condensed Beacon Limestone are deposited in an highly energetic and non-restricted setting. The Upper Toarcian Bridport Sandstone Fm. represents relatively expanded shoreface sandstones. The upper Lias Gp. thus in general reflects a transition to non-restricted settings with a progressive termination of tectonic quiescence in the region.



▲ **Figure 3.1: Summary of the lithostratigraphy used in the Wessex Basin. The facies are based on the Hypo-Lias study. The lithostratigraphy is after Cox et al. (1999).**



▲ **Figure 3.2: Map of the study area, including the major structural elements.** The locations of the two wells studied in detail as well as the Lower Jurassic oucrop sections in Dorset and Somerset are indicated. This map is after Evans et al. (1990) who simplifed it after Ziegler et al. (1987). The Western Approaches Through is the main basin axes, of which the St. Mary's and Plymouth Basins are part. The major structural highs in the area are the Armorican Massif in the southwest, Cornubian Massif separating the Celtic Sea Basin from the Western Approaches Through. The Welsh Massif forms the northernmost high in the area.

The Lower Jurassic offshore SW-England and Wales

A more regional understanding of the development of depositional patterns and linked to that, environmental conditions during the Lower Jurassic as a whole is largely lacking, especially in the offshore. A limited number of hydrocarbon exploration wells penetrate Lower Jurassic strata south, west and southwest of the Britain's South West Peninsula. These include the Quadrants 72, 73, 88, 93, and in wells offshore Dorset in Quadrants 97 and 98. Upper and Middle Jurassic deposits are largely lacking in the offshore due to uplift of the Western Approaches Trough and its peripheral basins (**Figure 3.2**). Middle Cretaceous strata therefore often overly Triassic or older strata. Whenever present, the Lower Jurassic is thin and erosionally truncated. In the Melville Basin (Quadrants 72 and 73), Jurassic sediments are restricted to two open synclines, which owe their preservation to salt withdrawal during the Late Jurassic.

In the vicinity of the Plymouth Bay Basin, a highly faulted sequence of Lower Jurassic sediments is present. Here, in Quadrant 88 good source-rock potential, akin to the Dorset outcrops have been recorded (Evans et al., 1990). Only in the South Celtic Sea Basin and in to the southern basins of the Western Approaches Trough (French offshore), thicker and more complete Lower Jurassic successions have been penetrated. The alternating limestone and shale facies is thought to be uniform, suggesting deposition in broard shallow epeiric sea. There is no formal lithostratigraphy for the Lower Jurassic as recognized in the offshore and hence the lithostratigraphic subdivision of the onshore is typically adopted (see **Figure 3.1**).

Tectonic setting

The basinal parts of the study area overly a basement that pre-dates the Variscan orogeny. The basement crops out on the Cornubian Ridge and the Armorican Massif (Figure 3.2) The former is composed of Devonian and Carboniferous rocks whereas the Armorican Massif to the south in North-West France and the Channel Islands is formed predominantly of Precambrian rocks. The Variscan collission between Gondwana and Laurasia that culminated in the Late Carboniferous produced two sets of major crustal discontinuities, north-east trending Variscan thrusts and north-north-west trending transfer faults. The Variscan orogeny ceased in the Early Permian, leaving an arid landscape with intermontane basins. By Late Permian to Early Triassic times, crustal rifting led to the formation of restricted basins containing thick continental red-bed sequences. The base of the Jurassic represents the onset of widespread marine deposition in the area. In the Melville Basin, gentle sagging leaves a relatively thin truncated Lower Jurassic preserved. The South Celtic Sea Basin, and its eastern continuation of the Bristol Channel Basin also formed along rejuvinated Variscan thrusts and represents a series of synclinal grabens,with a locally complete Lower Jurassic succession. Here, and also further south in the Brittany Basin, rapid fault-controlled subsidence resulted in thick Lower Jurassic successions.

By Middle Jurassic times, renewed crustal stress caused local uplift followed by extensive erosion during the Late Jurassic to Early Cretaceous. Opening of the north Atlantic led to the formation of local depocentres, in the southern parts of the Western Approaches Through (i.e., on the French side). The Early Cretaceous to Paleocene saw a more quiescent post-rifting regime and Alpine inversion through the Cenozoic (Evans et al., 1990).

Scope and objectives

Despite this limited number of well penetrations, we here evaluate the depositional conditions and resultant source-rock properties. We have analyzed cuttings materials from two wells; 73/13-1 in Melville Basin of the Western Approaches Through, and 93/02-2 in the South Celtic Sea Basin. We compare the results with well-logs from the abovementioned Quadrants and the detailed information that is available from onshore sections, along the Dorset Coast (Hypo-Lias Phase I), Somerset Coast (Ruhl et al., 2010; Bonis et al., 2010), the Mochras Borehole in Wales (Van de Schootbrugge et al., 2005). The overall aims are to (I) evaluate source-rock potential of the Lower Jurassic deposits and to (II) understand the regional depositional history across the area depicted in Figure 3.2.

3.2 Approach and methodology

Stratigraphic analysis

A first step towards reconstruction of the depositional history of the study area is to constrain the age-relationships between the wells. During the first stage of the HYPO-Lias project, a palyno- and isotope stratigraphic standard was constructed based on the coastal exposures in Dorset. The Triassic-Jurassic boundary can be straightforwardly identified using a series of marine and terrestrial palynomorph extinctions and a distinct number of carbon isotope excursions. However, the Hettangian, Sinemurian and Early Pliensbachian are relatively scarce of evident marker events. The carbon isotope variability during this interval is also minimal, and consequently with only material from cuttings available the latter are deemed purposeless. The Late Pliensbachian and Toarcian can be dated with much higher certainty.

Despite these uncertainties, we have palynologically analyzed material from the two wells (73/13-1 and 93/02-2) and integrated our findings with the initial biostratigraphic reports, that also constitute micropaleontological information to arrive at an approximate chronostratigraphic interpretation for these records. These interpretations are presented in the respective figure captions (Figure 3.3 and Figure 3.4). An important secondary objective of evaluating the palynological assemblages is to exclude the possibilty that the material, that is further interpreted in terms of source-rock characteristics is caved from overlying strata.

Palynological processing

The organic matter is extracted from the rock using standard laboratory processing procedures. During the first step, the sedimentary rock is crushed and treated with hydrochloric acid (30%) to digest the carbonate. After that, the mineral bonds of the silicates are destroyed by using hydrofluoric (35%) acid, thus releasing the acid-resistant organic matter. The organic residue is then concentrated by sieving over a 10 μm mesh. The organic matter particles larger than 10 μm are brought on a glass slide. Subsequently the palynological preparation is fixed by a permanent mounting medium (Norland Cement) and cured with UV-radiation and covered by a thin glass cover slip. The slide is studied using a transmitted light microscope with magnifications varying between 100 and 1000 microns. Up to 100 specimens were counted using the 40x objective. The samples were prepared by Malcolm Jones of Palynological Laboratory Services (PLS) in Wales.

Paleoclimate

During the first phase of the Hypo-Lias a synthesis of the climatic evolution of NW-Europe during the Early Jurassic was constructed, primarily by evaluating the terrestrial palynomorph assemblages in relation to independent paleoclimatic proxies such as $\delta^{18}O$-data. We consequently note two dominant palynology-based vegetation types with the *Classopollis*-dominated vegetation types characteristic for continental interior areas that are affected by warm, strong monsoonal environments and abundant *Perinopollenites* being ascribed to cooler conditions with a weaker seasonal monsoon.

Rock Eval and TOC-analyses

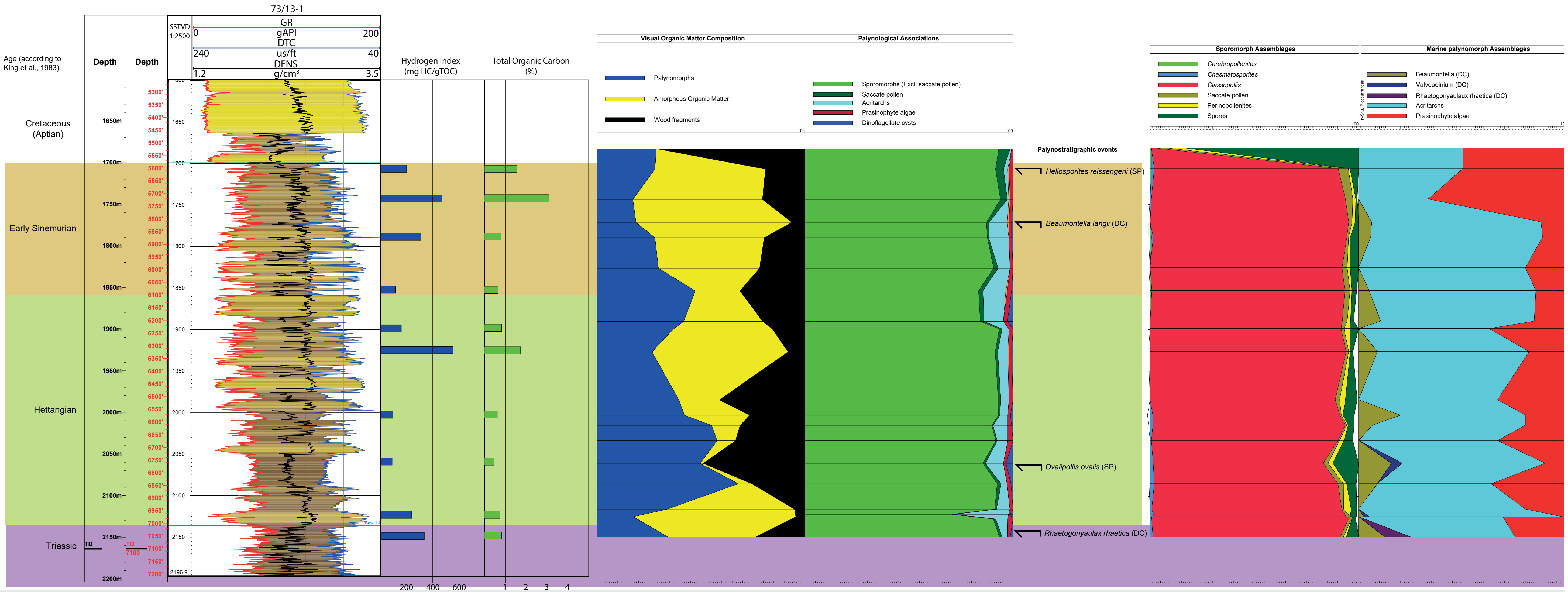
Rock Eval Pyrolysis analyses were performed by Geo-Lab in Garbsen, Germany.

During Rock-Eval pyrolysis ca. 100 mg of ground and homogenised sample is subject to a pyrolysis step followed by the complete oxidation of the residual sample. A FID detector measures the hydrocarbon released during pyrolysis, while CO_2 and CO are detected by infrared absorbance during both steps. In the here applied standard cycle for “whole rock” (IFP 2001), pyrolysis starts isothermally at 300°C for 3 minutes, after which the sample is heated to 650°C. The oxidation step starts isothermally at 400°C (3 min) and then heats up to 850°C. Organic carbon decomposition results in 4 main peaks: the S 1 peak (hydrocarbons released during the isothermal phase), the S2 peak (hydrocarbons produced between 300 and 650°C), the S3 peak (CO_2 from pyrolysis of OM up to 400°C), and the S4 peak (CO_2 released from residual OM below ca. 550°C during the oxidation step). Mineral carbon decomposition is recorded by the S3’ peak (pyrolysis-CO_2 released above 400°C), and the S5 peak (oxidation-CO_2 released above ca. 550°C).

These peaks are used to calculate the amount of total organic carbon (TOC) and the amount of mineral carbon (MINC). In addition, the so-called hydrogen index (HI = S2/TOC) and oxygen index (OI = S3/TOC) are calculated. The HI and OI indices are proportional to the H/C and O/C ratios of the organic matter, respectively, and can be used for OM classification in Van-Krevelen-like diagrams (Espitalie et al. 1977). The calibration standard used was the IFP-55000 (Institut Francais du Petrole; IFP 2001), a Jurassic marine sediment.

Petrophyiscal well panels

For this study eight wells from quadrant 73, 88, 93, 97 and 98 were used to construct a well-panel. Mainly the Gamma Ray (GR) and Sonic (DT) logs are used. The main aim is to evaluate trends in lithology, throughout time. The GR is scaled from 0 – 200 gAPI, the DT is scaled from 40 – 240 µS/ft. Well formation tops from the OGA and if applicable newly generated biostratigraphic data and data from reports is used. This is mentioned in the figure captions of the respective well-panels (Figure 3.6).



▲ **Figure 3.3: Rock Eval (HI and TOC), organic-matter and palynomorph association, biostratigraphic events and terrestrial and marine palynomorph association data from cuttings from Wells 73-13-1.** The log profile is indicated at the left of the Figure. The age age-derivations provided by initial biostratigraphic report (King et al., 1983) are in-line with our observations and give rise to the color scheme that is also adopted in the well section panels of this chapter. The organic-matter association data provide insight in the composition of the kerogen, whereas the other three graphs provide an indication of changes in the depositional setting and paleoclimate (see text below).

3.3 Results and interpretation

Well 73/13-1 (Melville Basin)

Stratigraphy

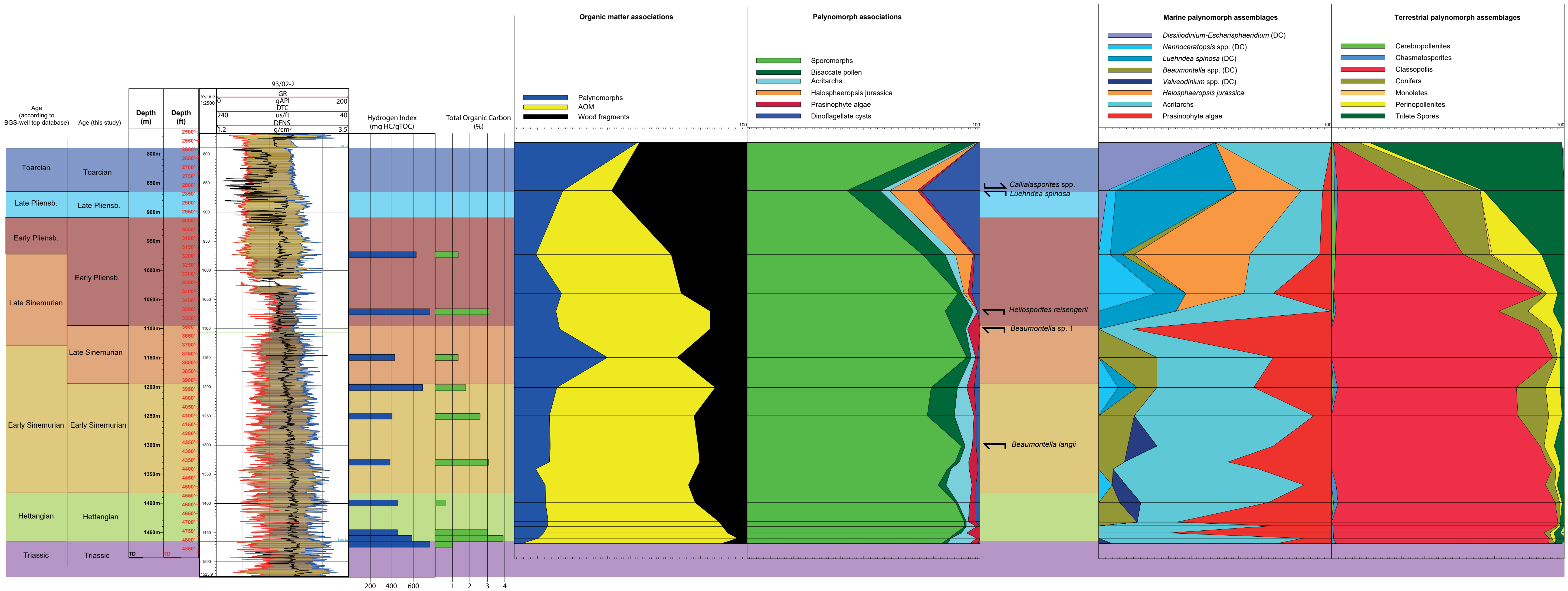
This well was drilled in the Melville Basin in 1983. The well terminates in Norian (Late Triassic) strata. It heralds a transition from continental deposits, a Latest Triassic carbonate bed to a succession of Hettangian to Early Sinemurian shales with carbonates (**Figure 3.3**). This lower Jurassic succession is recovered between 1700 and 2135 m (5577'-7005') depth and is overlain unconformably by Cretaceous (Aptian) strata. According to the initial biostratigraphic report (King et al., 1983), the age-assessment of the Lower Jurassic is based on the presence of the dinoflagellate cyst *Dapcodinium* (now *Beaumontella*) *langii* between 1900 m (6240') and 2154m (7070'). The highest occurrence of the sporomorph *Kraeuselisporites* (now *Heliosporites*) *reissengerii* at 1700 m (5577')indicates an Early Sinemurian age. We concur with this interpretation. We clearly recognize the extinction of the Rhaetian marker taxon *Rhaetogonyaulax rhaetica* at 2149 m (7050') depth. The extended consistent occurrences of the Triassic sporomorph *Ovalipollis ovalis* up to 2060 m (6758') depth are likely reworked. *Beaumontella langii* consistently ranges up to 1771 m. This taxon ranges up to the Late Sinemurian, as does the sporomorph *H. reissengerii*. However the absence of the dinoflagellate cyst Liasidium variabile, which has an abundance optimum in the Late Sinemurian, suggests that the top of the Lower Jurassic in Well 73/13-1 is still of Early Sinemurian age. The absence of conspicuous younger or older elements in the Lower Jurassic succession indicates that the organic-matter is of a predominant autochtonous origin.

Note that Well 73/1-1A recovered a succession of apparently similar age and thickness (**Figure 3.5**). A substantially thinner, ~100 m thick Hettangian succession overlies Rhaetian deposits in well 72/10-1A (Bennett et al., 1985). The section here is erosionally truncated.

Organic matter composition in relation to climate and environment

The visual organic-matter analyses indicate substantial fluctuations in the proportion of palynomorphs (predominantly Classopollis pollen grains), wood-fragments and Amorphous Organic Matter (AOM). The latter is considered characteristic for marine source-rocks. AOM is considered indicative of hydrogen-rich organic matter, which in turn is the consequence of enhanced marine, possibly anoxygenic productivity and enhanced preservation (Calvert and Pedersen, 1993; Pacton et al., 2011).

The TOCs are relatively low (1-3 weight %), although a clear correspondence between elevated Hydrogen Index (HI) values (400-500 g HC/gTOC) and the abundant AOM is observed (Figure 3.3). The palynomorph assemblages are dominated by *Classopollis* pollen, indicating the persistence of warm, monsoonal climate mode and substantial input of terrestrial organic-matter. Also in the intervals with abundant AOM, *Classopollis* is dominating the palynological assemblages. Consequently, marine palynomorphs are scarce. Small chorate acritarchs like *Michrystridium* and prasinophyte algae are dominant. The general scarcity of dinoflagellates is ascribed to predominant anoxic surface-water conditions, with the AOM being provided by anoxygenic microbial communities. We can not test this hypothesis directly, but is seems that anoxia have persisted throughout the Hettangian and Sinemurian at the locality of well 73/13-1. The substantial rates at which terrestrial and detrital material were supplied to the depocenter at this locality, prevented the organic-matter from accumulating in high concentrations and from developing into an hydrogen-rich and potentially excellent Type II source rock. In addition, the overall low TOC-values are also affected by the high concentrations of carbonate in the succession. Hence, it seems that the Lower Jurassic sediments in the Melville Basin have a poor to moderate source-rock potential. The remainder of the Lower Jurassic has erosionally been truncated during Late Jurassic to Cretaceous times. As a consequence, it seems unlikely that the potentially prolific source rocks of Sinemurian-Toarcian age that were eroded, had to chance to mature and generate hydrocarbons.



▲ Figure 3.4: Rock Eval (HI and TOC), organic-matter and palynomorph association, biostratigraphic events and terrestrial and marine palynomorph association data from cuttings from Wells 93/02-2. The log profile is indicated at the left of the Figure. The age age-derivations provided by initial biostratigraphic report (leftmost) and revised according to the findings of this study (2nd from right). The age color scheme is adopted in the well section panels of this chapter. The organic-matter association data provide insight in the composition of the kerogen, whereas the other three graphs provide an indication of changes in the depositional setting and paleoclimate (see text below).

Well 93/02-2 (South Celtic Sea Basin)

Stratigraphy

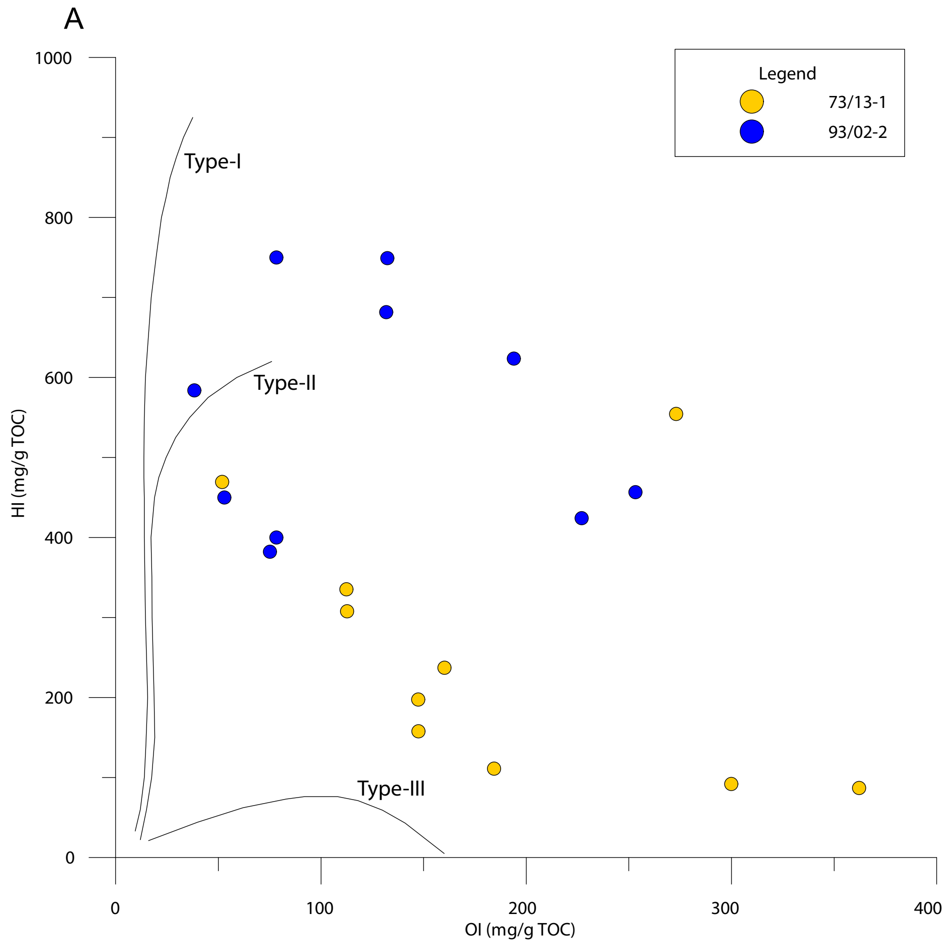
This well was drilled 1986 in the South Celtic Sea Basin, an east-northeast trending synclinal structure (Van Hoorn, 1987). Locally, there is a fairly thick Lower Jurassic sequence. In well 93/02-2 this sequence inferred to be about 690 m (2263') thick, recovered between 780 and 1470 m (2560'-4822') depth (Figure 3.4). According to the initial age-model for the wells, as derived from the well completion report, lowermost Jurassic Hettangian deposits overly the characteristic Uppermost Triassic carbonates beds (the White Lias). Successively, a sequence of shales and carbonates were deposited, supossedly all of Sinemurian age. A remarkable increase in Gammalog intensity, likely signifying a series of more organic-rich shales is recorded between 1040 and 1100 m (3400-3600') depth. Based on the palynological associations we have revised the stratigraphic interpretation for this interval. The shale interval between 1040 and 1100 m (3400' and 3600') depth is most likely of Early Pliensbachian age, as reflected by the extinction of *Heliosporites reissengerii* and *Beaumontella* sp. 1 (see HYPO-Lias study). Remarkably, this interval thus coincides with the dysoxic Pyritous Shale Mb. of the Redcar Mudstone Fm. in Yorkshire.

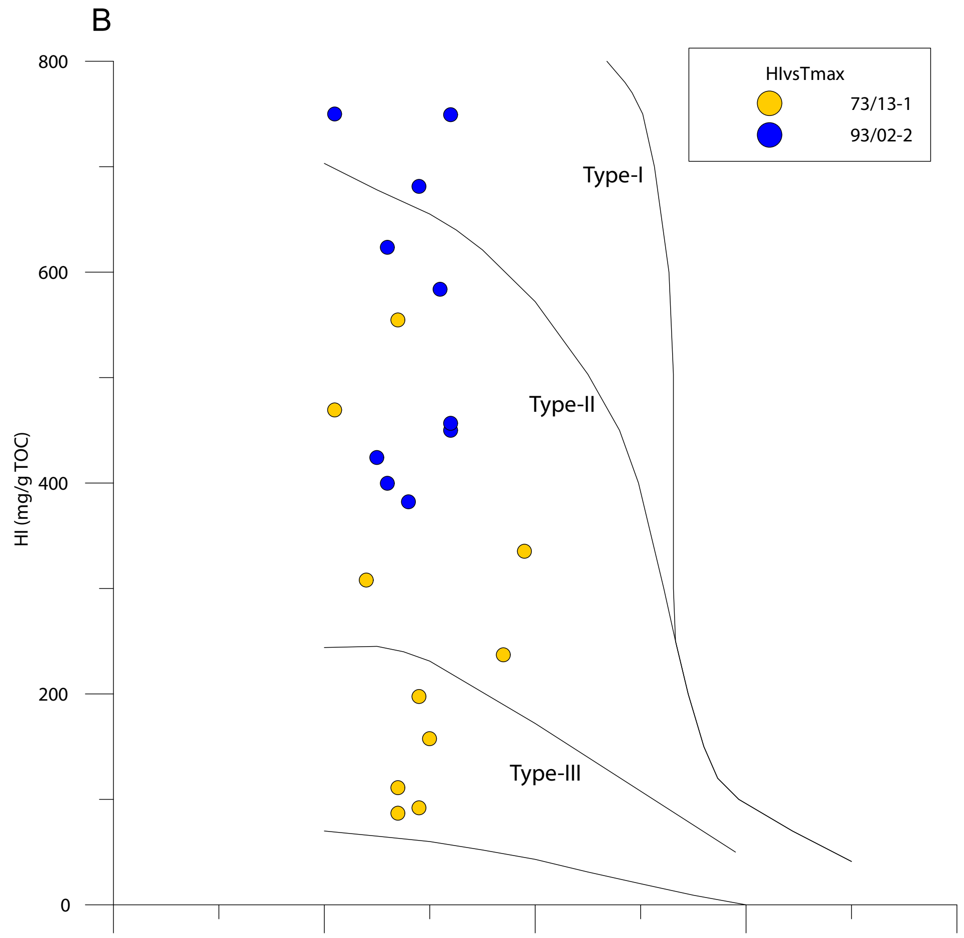
Successively, the sequence which spans the remainder of the Pliensbachian and Toarcian becomes more carbonate-rich, owing to the decrease in gammalog and increase in sonic velocity. The appearance of *Halosphaeropsis liassicus* and the extinction of the dinoflagellate cyst *Luehndea spinosa* mark that the Early Toarcian OAE of the Exaratum Ammonite Subzone is located at approximately 860 m (2850') depth, in a non-shaly source rock log facies.

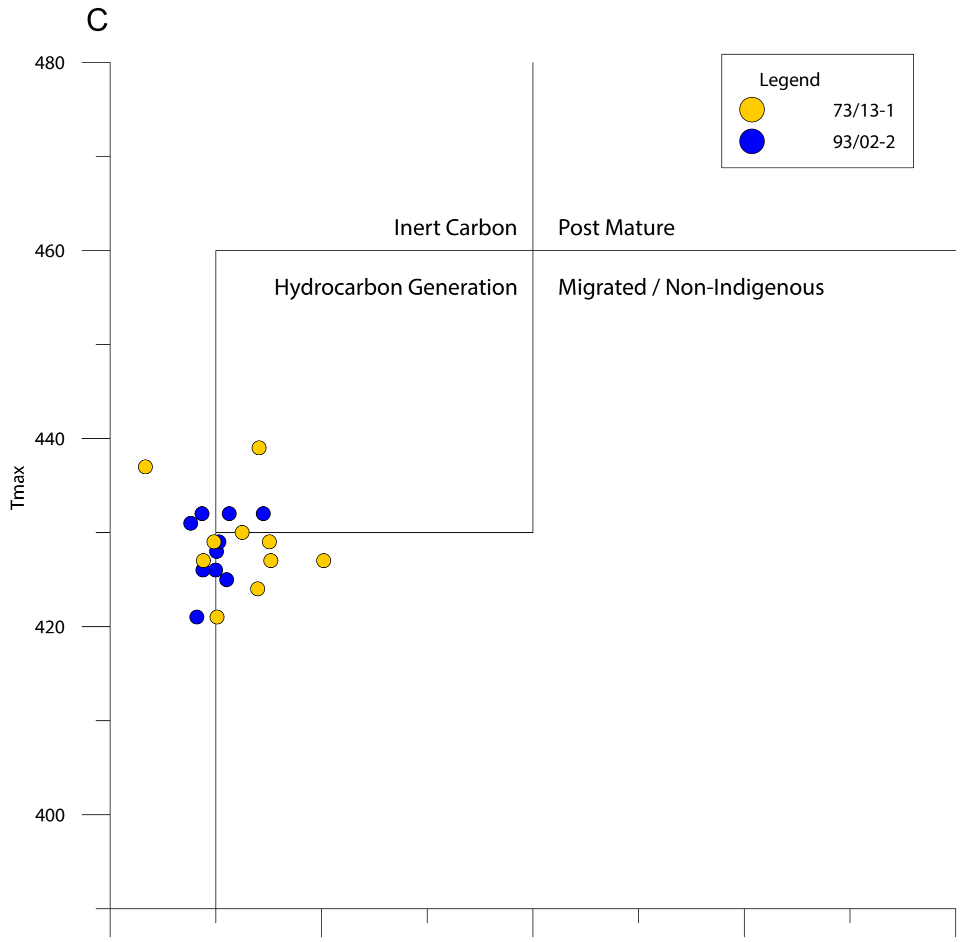
Organic matter composition in relation to climate and environment

The Hettangian-Sinemurian part of the succession is characterized by organic matter associations that are dominated by AOM. Terrestrial palynomorphs are dominant in the palynological associations. The marine palynological assemblages are dominated by acritarchs and prasinophyte algae, with only minor occurrences dinoflagellates of the genus *Beaumontella*. This signifies predominant anoxic surface-water conditions. Terrestrial palynomorph assemblages are dominated by *Classopollis*, reflecting a warm monsoonal climate. In concordance with the onset of more carbonaceous facies at 1040 m (3410'), above the presumed Lower Pliensbachian shale-interval mentioned above, we note an increase in the abundance of organic-walled dinoflagellate cysts at the expense of acritarchs and prasinophyte algae, signifying a increase in the degree of water column oxygenation. A similar observation is made in Yorkshire, but substantially later, by Late Pliensbachian times (HYPO-Lias report). This level also marks a major change in terrestrial vegetation composition, with an increase of *Perinopollenites* and trilete spores at the expense of *Classopollis* spp., signifying a cooler, equitable continental climate mode. The Toarcian OAE is likely positioned at about 860 m (2850') depth. According to the marine palynological, which consitute ample in-situ dinoflagellate cysts, anoxia were not very persistent, as is seen in the Southern North Sea Basin. Also the organic-matter associations are dominated by wood-fragments and no longer by AOM by this time. The T-OAE does not represent a good source-rock in the South Celtic basin.

The contrary is true for the underlying Hettangian to Early Pliensbachian succession of about 400 m (1300') thickness. The HI consistently exceeds 400 mg HC/ g TOC) and the TOC fluctuates between 2 and 4%, thus providing a moderate to good Type II source rock. The maturity of the section is within the early oil window according to the Tmax values (see Figure 3.6).The high HI is a common shared factor with coeval outcrops in Dorset and Somerset, albeit particularly the former has substantially higher TOCs.
This is likely due to the more expanded nature of the Celtic Sea Basin and Somerset outcrops compared to the more condensed Dorset outcrops.



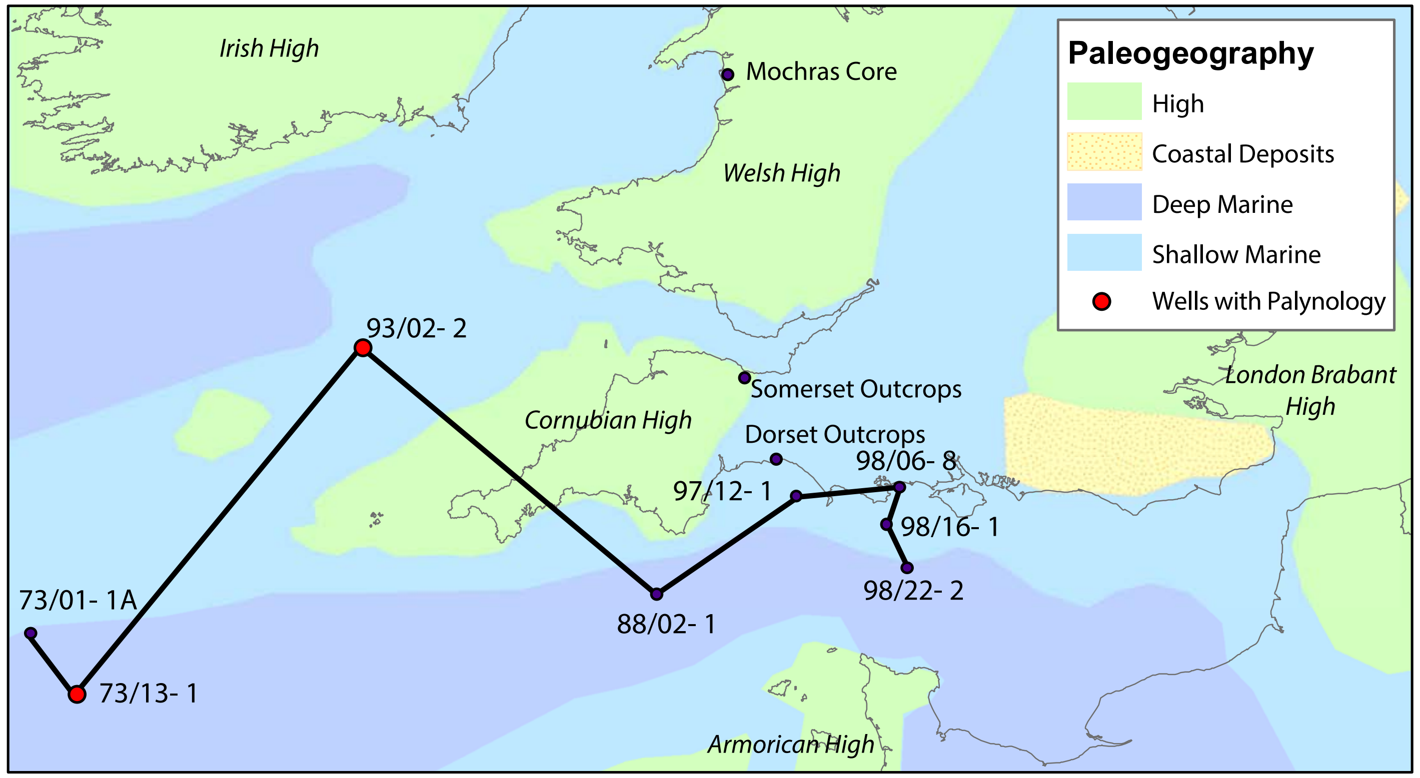




◄ ▲ Figure 3.5: Rock-Eval results from the Western Approaches area from well 73/13-1 from the Melville Basin and from Well 93/02-2 in the South Celtic Sea Basin. The former covers the Hettangian and Sinemurian, due to a major unconformity at the top of the section. The latter covers a complete Lower Jurassic section. Rock Eval data were generated to evalute the source-rock potential of the areas. The Pseudo-Van Krevelen Diagram (**Figure 3.5a**) shows that the samples from well 93/02-2 in general have Hydrogen Index values (HI) of more than 400 mg/g TOC which equals to Type II to Type II/III. The samples from well 73/13-1 show mainly lower HI values which relate to more Type III organic matter. Several samples from both wells show very high Oxygen Index values (OI). In some cases this can be related to insufficient sample material for the analysis, in other cases very high OI values can be linked to very low TOC values (< 1%).
The measured Tmax of both wells increases with depth as can be expected. Overall the maturity of the samples is low, Tmax values range from 420 to 432 in well 93/02-2 and from 420 to 439 in well 73/13-1 which can be classified as immature to early oil maturity in both cases (**Figures 3.5b&c**).

St. Mary's and Plymouth Basin

To the east of the Melville Basin, in the St. Mary's and Plymouth Basin, similar Lower Jurassic sediments were likely once deposited but subsequently eroded. An exception forms well 88/02-1 which according to its log-pattern resembles wells from closer to the Dorset outcrops, with a characteristic Blue Lias Fm. and Charmouth Mudstone Fm. facies. Here, the lower Jurassic is about 650 m (2130') thick. According to Evans et al. (1981), these rocks have a moderate to good source rock potential. The presence of fibrous calcite in the lower 35 m suggests that fluid expulsion occurred. Hence, the succession from this area seems to more closely resemble those found in the Bristol Channel Basin and the Wessex Basin. Remarkably, there appears to be a more shaly high gamma, low velocity interval of potential Early Toarcian age (at about 220 m depth,). Hence, this may reflect an expression of the T-OAE in organic-rich shale facies.

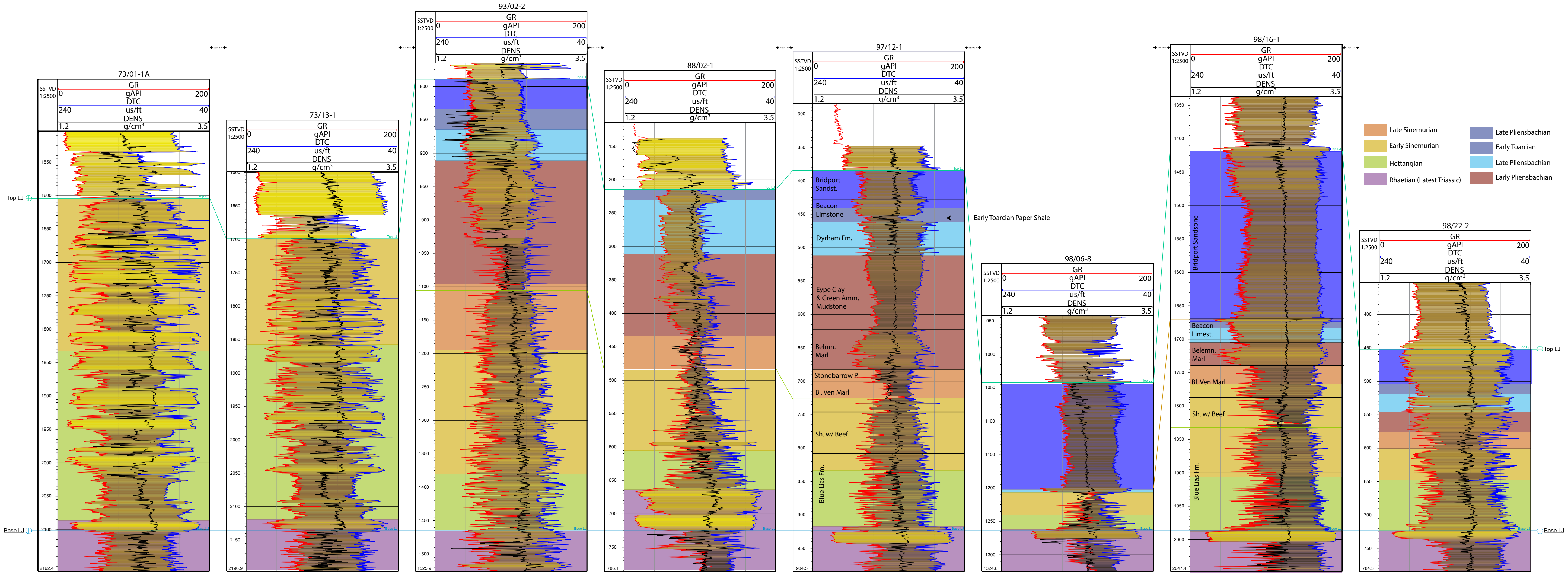


◄ ▼ Figure 3.6: Well-log panels across the transect depicted in the map at the left, using gamma-, sonic and density logs). The colored shading indicate the inferred ages. For wells 73/13-1 and 93/02-2 these are based on the current studies. For well 97/12-1 these are based on the lithostratigraphic subdivision and the observations of Ainsworth and Riley (2010). Note that wells 73/13-1 and 73/01-1A are stratigraphically confined to the Hettangian and Early Sinemurian. The Early Toarcian paper shale in Well 97/12-1 likely represents a local potential source rock related to the T-OAE. This is not recorded in any of the other wells.

Wells in Quadrants 97 and 98

Well 97/12-1 is located slightly offshore southwest of the Wessex Basin outcrops in Dorset. Based on the log-pattern a cl and available biostratigraphic information (Ainsworth and Riley, 2010) a clear correlation to the lithostratigraphic units recognized in those outcrops can be established (Figure 3.6). In Well 98/16-1 a similar succession is recorded. The Lower Liassic Blue Lias Fm. and the organic-rich members of the Charmouth Mudstone Fm. (Shales with Beef, Black Ven Marl and the Stonebarrow Pyritic Mbs.) are collectively twice as thick as in the outcrops, about 200 m (656'). The overlying more carbonaceous and/or sandy succession is also stratigraphically complete. An exception to the picture that emerges from the Dorset outcrops, is the presence of an approximately 10 m (30') interval of so-called 'paper shales' at about 450 m in Well 97/12-1 (between 1500', see Ainsworth and Riley, 2010). This organic-rich unit corresponds to the Toarcian OAE and is not recognized in the outcrops and/or nearby wells, in which the T-OAE is part of the condensed

Beacon Limestone Fm.



3.4 Discussion and conclusions

In the Melville Basin only sediments corresponding to the Hettangian-Sinemurian Blue Lias Fm. are preserved (**Figure 3.6**) . Elsewhere in the region, the most prolific source rocks are of Early to Late Sinemurian age, corresponding to the onshore Shales with Beef Mb. and the Black Ven Marl Mb. The absence of these rocks in the Melville Basin is due to Late Jurassic to Early Cretaceous uplift. Hence, it seems unlikely that these more prolific Sinemurian strata reached burial depths accounting for maturation into the oil window, between the time of deposition and time of erosion. Therefore, we conclude that the Melville Basin was unlikely to have experienced charging from Lower Jurassic stata.

Excellent Hettangian and Sinemurian hydrogen-rich source-rocks are deposited in the southern end of the Wessex Basin, as manifested in the Dorset outcrops near Lyme Regis and Charmouth. Particularly the Blue Lias Fm. and the lowermost two members of the Charmouth Mudstone Fm. (Shales with Beef Mb. and the Black Ven Marl Mb.) provide TOCs of up to 15% TOC and HIs between 500 and 600 mgHC/gTOC over a thickness of about 100 m. Based on their log signature, wells to the south and southwest (Quadrant 97 and 98), contain a similar Hettangian and Sinemurian succession, equating to a maximum thickness of about 200 m in well 97/12-1 (**Figure 3.6**). Albeit only marginally mature at outcrop, there is ample evidence for source rock maturation having occurred prior to tectonic inversion in the Tertiary (Underhill and Stoneley, 1998). The fact that these strata provide such excellent source-rocks, is due to the restricted, anoxic basinal setting in conjunction with a relatively condensed sedimentary nature.

Good to moderate Sinemurian source-rocks are recorded in the South Celtic Sea (Quadrant 93), in the Plymouth Basin (Quadrant 88). Similar to what is known from the Mochras Borehole in Wales and the outcrops in Somerset (Ruhl et al., 2011), the sedimentary thicknesses in these basins are substantially more expanded than in the Dorset area, equating to about 600-800 m thickness. Palynological records from Mochras (Van de Schootbrugge et al., 2005), well 93/02-2 (this study) and Somerset (Bonis et al., 2010) indicate persistent anoxic and restricted conditions throughout the Hettangian-Sinemurian. In well 93/02-2 we also found indications for an Early Pliensbachian organic-rich interval, much akin to what is seen Yorkshire (The Pyritous Shale Mb. of the Redcar Mudstone Fm.) and in the Southern North Sea (see HYPO-Lias study). The overall lower TOCs are ascribed to the expanded nature of these sediments. Tmax data from Well 93/02-02 suggest predominantly immature organic-carbon (**Figure 3.5**), whereas the lowermost two samples from well 73/13-1 may reach the early oil window.

The Toarcian in the study area does not pose an excellent source-rock in the study area. Palynological data from Mochras and Well 93/02-02 indicate a transient shift towards anoxic surface water conditions. Log patterns do not reveal a striking organic-rich shale interval as is seen in the Southern North Sea Basin. Likewise, in the Mochras borehole, the T-OAE is part of a very expanded succession due to synsedimentary fault activity. Here TOCs exceeding 1% are not recorded, which may be a consequence of the high detrital input.

The T-OAE may however provide a moderate quality source rock in South Celtic Sea Basin. In the offshore of the Wessex Basin in Well 97/12-1 an organic-rich shale unit corresponding to the T-OAE is recorded. Due to absence of a similar pattern in the nearby outcrops and other wells, this is considered a local phenomenon. In other wells from the study area, including the the Toarcian OAE is part of a condensed sedimentary facies (Beacon Limstone Fm.).

Conclusions

Conclusions

1. The Lower Jurassic in the Melville Basin does not provide excellent source-rocks. High carbonate content and/or detrital input leaves TOCs below 2%. Relatively low HI-values (<300 mgHC/gTOC) and palynological patterns indicate a dominant contribution of terrestrial organic-material. However, based on the results from the broader area, the best source rock potential is expetected for the Sinemurian and Lower Pliensbachian. These rocks are no longer present as they were eroded in the Late Jurassic to Early Cretaceous, likely before they could reach sufficient burial depth for hydrocarbon generation.

2. In the South Celtic Sea Basin, the St. Mary Basin and the Plymouth Basin, good-moderate Hettangian-Sinemurian source were deposited. In the South Celtic Sea, these seem to be immature.These strata were deposited under anoxic conditions and primarily componse marine, possibly anoxygenic microbial organic-matter. Due to their expanded nature, TOCs are not expected be very high, unlike observed in the Dorset Outcrops and offshore Dorset in Quadrants 97 and 98.

3. Overall the T-OAE does not seem to provide such an excellent source rock as is observed in the Southern North Sea Basin. It may however locally provide a relatively thin organic-rich shale.

Cross-section through ammonite in Blue Lias Fm., Somerset

04

Summary and conclusions

4. SUMMARY AND CONCLUSIONS

This addendum to the Hypo-Lias Project focused on two central aspects. The topics are shortly introduced and the main findings are summarized below. The insights from these two research topcis allow for a paleogeographic synthesis.

The T-OAE in the East Shetland Platform area

The first topic addressed the stratigraphic position of the Toarcian Oceanic Anoxic (T-OAE) in relation to sand (Cook) and shale (Drake) facies in the UKs East Shetland Platform Area. Via establishing stratigraphic correlations using stable carbon isotopes and palynostratigraphy, the relevance of the T-OAE as a potential phase of source rock deposition is discussed. By establishing understanding of the timing of depositional patterns in this key region with respect to its proximity to the Viking Strait, the paleogeographic evolution and influence on the Toarcian source-rock system in the Southern North Sea was also evaluated.

The T-OAE was successfully traced through isotope and palynostratigraphy through the study area. The T-OAE is consistently positioned within the Upper Cook Fm. (Cook-IV unit). Consequently, the T-OAE does not correspond to a conspicuous shale facies in any of the wells. Based on the palynological assemblages, the T-OAE is, in even in the high-accumulation dynamic setting of the Cook Fm., associated with anoxic depositional conditions. This led organic-material to be rich in hydrogen, constituting a Type-II kerogen. TOCs remain relatively low however. Therefore, we do not consider the T-OAE to represent promising source rocks in the East Shetland Platform. Above the T-OAE, we note a conspicuous shale interval, part of the overall finer-grained Drake Fm. Biogeographic patterns of dinoflagellate cysts, indicate that this unit is accompanied by an introduction of Arctic/Boreal water-masses, In Yorkshire (UK) and the Netherlands this introduction of taxa corresponds to the late Early Toarcian (Bifrons Ammonite Subzone), where it is accompanied by a demise in TOC-values. Hence, the establishment of a boreal connection through the Viking Strait by late Early Toarcian times seems to have ended the restricted anoxic settings that led to good source rock formation in the Southern North Sea Basin by introducing cooler, well-oxygenated water-masses into the hitherto restricted basin.

Source rock potential of the Western Approaches area

In order to evaluate the source-rock potential of the greater Western Approaches area, material from two wells was analyzed for rock eval characteristics, organic-matter associations and palynomorph assemblages, also with the aim of refining biostratigraphic constraints. A further regional evaluation of well-log patterns aimed for a better understanding of those depositional characteristics promoting source-rock deposition southwest of the British Mainland.

The results indicate that the Lower Jurassic in the Melville Basin, which only preserves the oldest two Stages (Hettangian and Sinemurian) of the Early Jurassic, does not provide excellent source-rocks. High carbonate content and/or detrital input leaves TOCs below 2%. Relatively low HI-values (<300 mgHC/gTOC) and palynological patterns indicate a dominant contribution of terrestrial organic-material. The influence of terrigeneous material from the adjacent Armorican and Cornubian Massifs was greater than what might intuitively be expected. Based on the results from the region, the best source rock potential might expected in Sinemurian and Lower Pliensbachian strata. These rocks are no longer present in Melville basin, as they were eroded in the Late Jurassic to Early Cretaceous, before they could reach sufficient burial depth for hydrocarbon generation. In the South Celtic Sea Basin, the St. Mary Basin and the Plymouth Basin, good to moderate Hettangian-Sinemurian source rocks were deposited. In the South Celtic Sea, these seem to be immature. These strata were deposited under anoxic conditions and primarily compose marine, anoxygenically produced microbial organic-matter. Due to their expanded nature, TOCs are not expected be very high, in contrast to what is observed in the Dorset Outcrops and offshore Dorset in Quadrants 97 and 98. The T-OAE does not seem to provide such an excellent source rock as is observed in the Southern North Sea Basin. It may however locally provide a relatively thin organic-rich shale as is evident in Well 97/12-1.

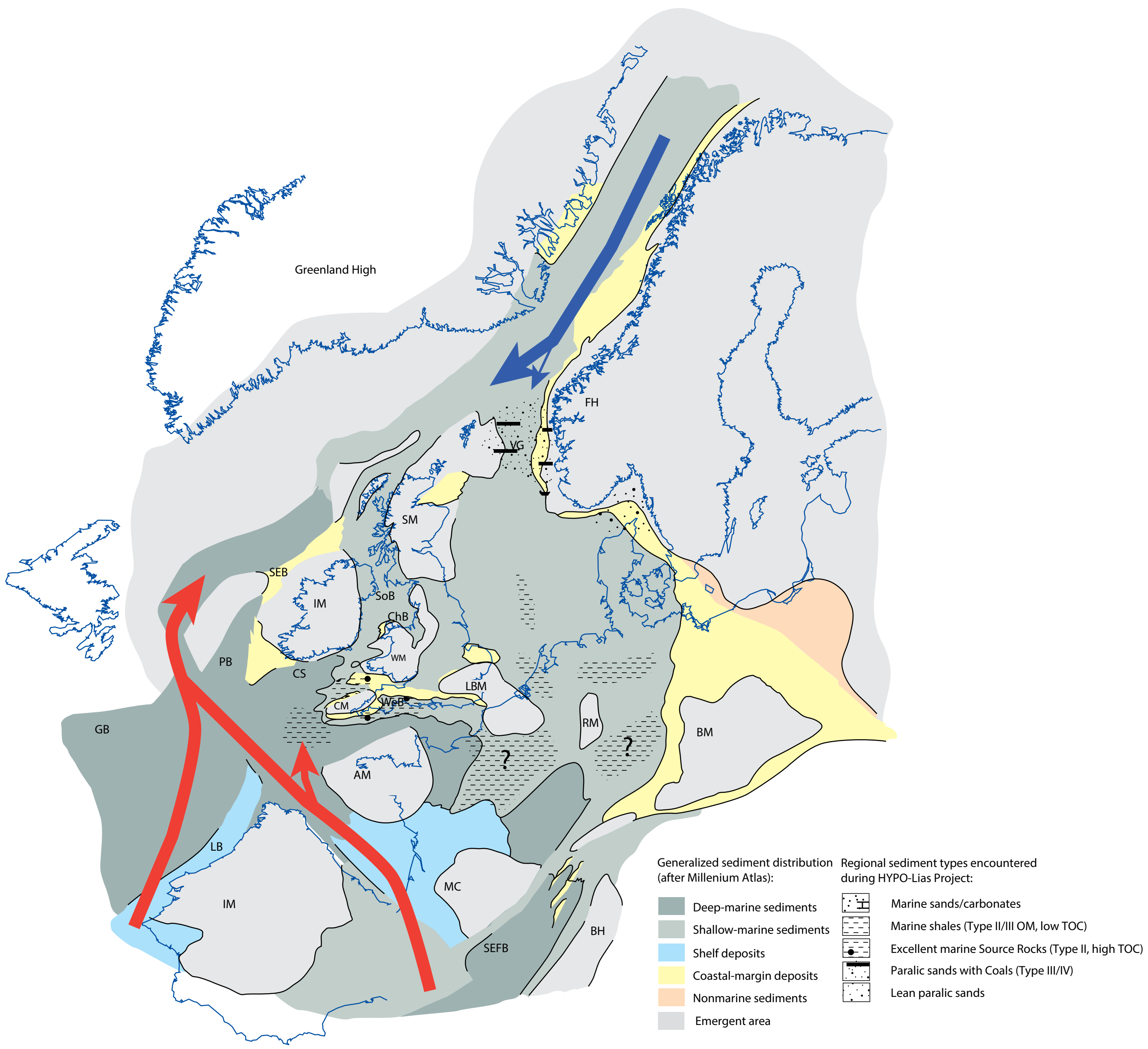
Paleogeographic synthesis

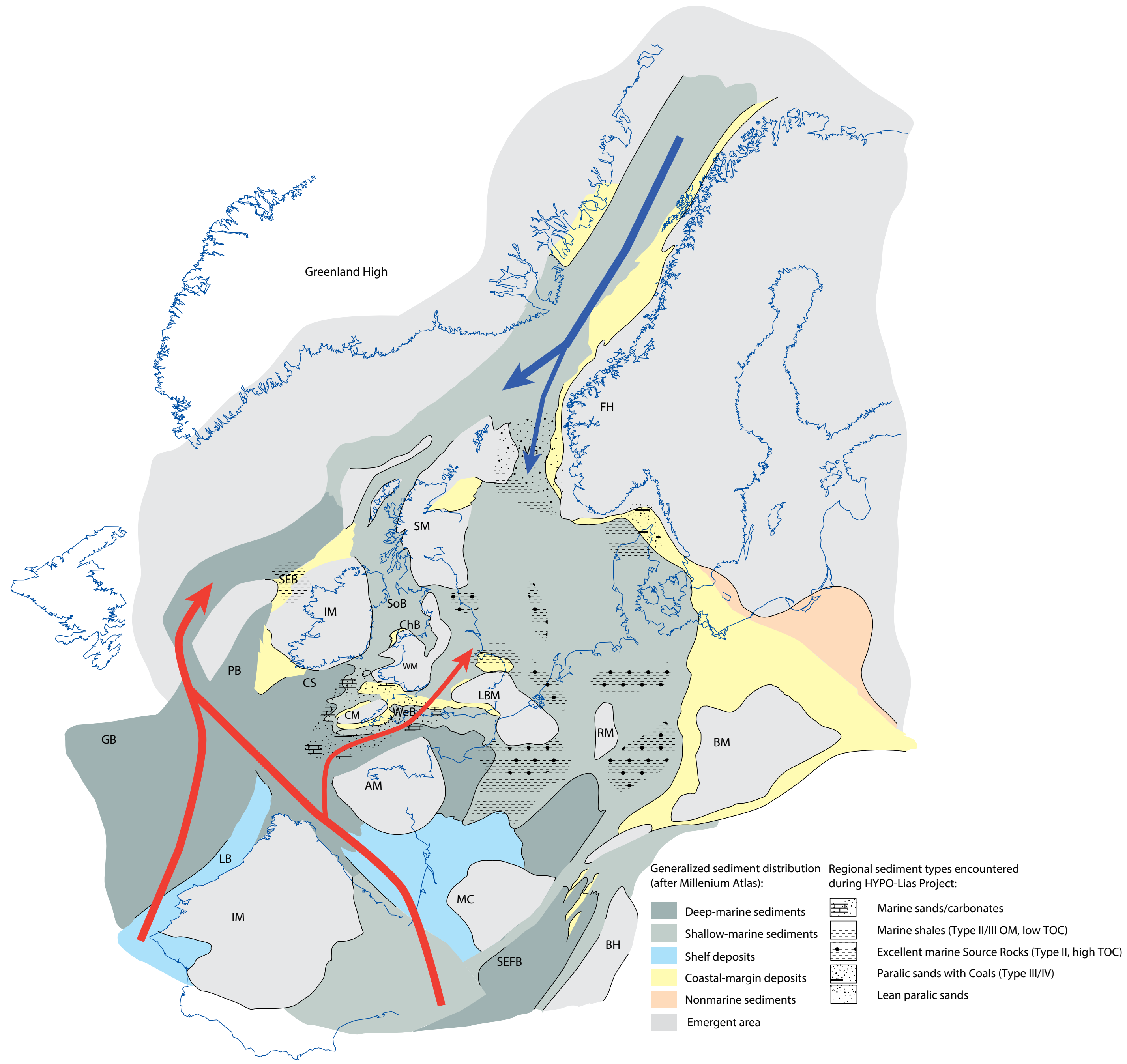
Whereas the first phase of the HYPO-Lias focused primarily on the North Sea Basin, the extension of spatial coverage presented in this report now allows for the evaluation of depositional and paleogeographic trends in a geographically more widespread area. By also including the information now available from a number of recent publications, two conceptual paleogeographic maps were constructed for the Hettangian-Sinemurian and Early Toarcian situations (**Figure 4.1** and **Figure 4.2**).

In the Hettangian and Sinemurian, the northern conduit through the Viking Strait was essentially closed for marine troughflow as indicated by widespread deposition of the paralic Statfjord Group in the Viking Graben area and across the East Shetland Platform (**Figure 4.1**). There are some coal layers in these strata, that may provide a potential source rock for gas. Cooler and better oxygenated water masses likely flowed into the now opening proto-Atlantic further to the east, bypassing the shallow, restricted epicontinental Southern North Sea Basin. Climatic conditions in the Hettangian and Sinemurian were generally very warm, owing to high atmospheric CO2-concentrations due to activity of the Central Atlantic Magmatic Province (CAMP). As part of the first phase of the HYPO-Lias project, we have noted that vegetation patterns confirm this hypothesis, also suggesting strong seasonally-focused monsoonal run-off patterns into the epeiric seas. Albeit there may have been some local organic-enrichment, no conspicuous Hettangian-Sinemurian source rocks were identified in Southern Norway, Denmark, the Netherlands nor NW-Germany. This is ascribed to a general high degree of detrital input, diluting organic-matter accumulation, despite a predominantly anoxic epeiric basin setting. In contrast, exposures from southwest England (comprising the Blue Lias Fm. and Charmouth Mudstone Fm.) compose excellent marine source rocks, deposited under predominant anoxic surface-water conditions. Similar successions are found offshore Dorset in Quadrants 97 and 98. The current study shows however that in the Melville Basin, in the western edge of Western Approaches Through, coeval strata do not represent such excellent source-rock potential. A substantial flux of terrigeneous material prevents the accumulation of hydrogen-rich organic-matter. Based on palynological assemblages, persistent anoxic conditions are not to be invoked. In the South Celtic Sea Basin sediment accumulation rates were also higher compared to Dorset and thus susceptible to dilution of organic-matter accumulation. In contrast, environmental conditions were clearly anoxic, explaining the abundance of hydrogen-rich organic carbon in well 93/02-2. The apparent difference in oxygenation between the Melville Basin and the other basins of the southwest UK, may be ascribed to the potentially strong influence of a southerly sourced Tethyan current, providing well-oxygenated Tethys waters (**Figure 4.1**, see also Dera et al., 2011). Possibly, this current system was blocked from reaching the eastern areas of the Western Approaches Through by the Armorican Massif.

Since this study did not focus specifically on the Pliensbachian, we were not able to conceptualize the paleogeographic evolution of the study area. The next interval for which we now have sufficient information is the Early Toarcian (**Figure 4.2**). Already during the Late Pliensbachian, eustatic sea-level rose leading to flooding of the Viking Strait to establish persistent shallow marine depositional environments, as reflected by the deposition of the Burton and Cook Fm. heterolithics and sandstones. In Southwest England, sedimentary successions become progressively condensed, which is a convolution of progressive rifting across the Western Approaches region and intensification of Tethyan-derived ocean currents. As the Viking Strait was still closed to deeper water throughflow, the Southern North Sea Basin remained restricted. The carbon cycle perturbation associated with the T-OAE, led to a transient intensification of the hydrological cycle, causing anoxic conditions in the restricted Southern North Sea Basin (Germany, Netherlands and Yorkshire) and the consequent accumulation of anoxygenically produced hydrogen-rich organic-carbon, constituting the excellent source rocks of the Lower Toarcian. During the first phase of Hypo-Lias we have noted that in the East Midlands Shelf area, which lies in front of the marine connection across the British mainland, the Toarcian apparently did not evolve into a source-rock facies. This may be ascribed to the introduction of oxygenated waters from the Wessex Basin area across this conduit. The T-OAE perturbation led to the deposition of moderate to good source-rocks in the Slyne Basin of Ireland (Silva et al., 2017).

The Early Toarcian restricted regime in the Southern North Sea appears to be rather abruptly terminated by late Early Toarcian times. Results from the East Shetland Platform study have revealed that the transition to deeper-water shale facies of the Drake Fm. is accompanied by the incursion of boreal dinoflagellate taxa. Hence, it seems that the restricted regime of the Southern North Sea Basin was terminated due introduction of cool and well-oxygenated boreal water-masses, which is ascribed to a combination of deepening of the Viking Strait conduit and progressively rising eustatic sea-level across the Toarcian. This reorganisation is widely noted in facies change in the Southern North Sea Basin, and a drastic demise in TOC-values.





▲ **Figure 4.1: Schematic map of depositional patterns during the Hettangian and Sinemurian.** The base-map is taken from Evans et al. (2003). During these times, a northern connection between the Boreal Seas and the Southern North Sea was closed. Paralic Statfjord Group and Lower Dunlin Group deposits may contain some coals in the Viking Graben and East Shetland Platform Areas. The Southern North Sea became restricted. Substantial source-rock accummulations are not expected as sedimentary accummulation rates seemed to outpace organci-matter supply. In the Wessex Basin of Dorset and Somerset and the South Celtic Sea Basin this seems to have been different. Good marine source-rocks are recorded here, deposited under predominant anoxic settings. In the Melville Basin of the western part of the Western Approaches Through, such anoxic settings are not clearly developed, nor are good marine source rocks. This is ascribed to a substantial Tethyan influence from the south.

▲ **Figure 4.2: Schematic map of depositional patterns during the Early Toarcian (Falciferum Ammonite Zone).** The base-map is taken from Evans et al. (2003). During these times, the northern connection between the Boreal Seas and the Southern North Sea started to become deeper, as manifested by the cyclic deposition of Cook sandstones and Burton and Drake shales. During the T-OAE, conditions became anoxic on the southern edges of the East Shetland Platform area, causing hydrogen rich organic matter to be deposited. However, no elevated TOCs are observed. The remainder of the Southern North Sea Basin is characterized by strongly anoxic and/or euxinic conditions during the T-OAE. This led to the deposition of excellent Type-II source rocks in Germany and the Netherlands and Northern France. An exception is observed on the East Midlands Shelf area of the western part of the Southern North Sea. This is ascribed to the introduction of oxygenated waters across the British Landmass from the southwest. Further to northeast, in Denmark and Southern Norway, clastic input is substantially higher, due to the systems coming from the Baltic landmass, and consequently marine sediments of the Fjerritslev Fm. are diluted in terms of organic-carbon. Paralic deposits in the Farsund Basin are dominated by brackish-water green alga *Botryococcus*, providing a moderate source-rock. In contrast to the Southern North Sea Basin, the more Atlantic/Tethyan influenced Wessex Basin and Western Approaches region are not characterized by good source-rock prospectivity. The post-Pliensbachian succession here is typically strongly condensed and deposited under oxic conditions. In the Mochras Core of Wales, the Toarcian succession is strongly expanded due to synsedimentary faulting. Here, TOCs also remain relatively low. Some localized exceptions are recorded. A good-moderate source-rock has been observed in the Slyne Basin of Ireland and locally in Well 97/12-1. The restricted regime that caused the excellent source-rocks of the Southern North Sea Basin is terminated in the late early Toarcian due to introduction of cool, oxygenated water masses from the Boreal seas.

5. REFERENCES

Ainsworth, N. R., & Riley, L. A., 2010. Triassic to Middle Jurassic stratigraphy of the Kerr McGee 97/12-1 exploration well, offshore southern England. *Marine and Petroleum Geology*, 27(4), 853-884.

Bonis, N. R., Ruhl, M., & Kürschner, W. M., 2010. Climate change driven black shale deposition during the end-Triassic in the western Tethys. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 290, 151-159.

Calvert, S. E., & Pedersen, T. F., 1993. Geochemistry of recent oxic and anoxic marine sediments: implications for the geological record. *Marine Geology,* 113(1-2), 67-88.

Charnock, M.A., Kristiansen, I.L., Ryseth, A. and Fenton, J.P.G., 2001: Sequence stratigraphy of the Lower Jurassic Dunlin Group, northern North Sea. In: Sedimentary Environments Offshore Norway – Palaeozoic to Recent (Eds. O.J. Martinsen and T. Dreyer,). *Norw. Petrol. Soc. Spec. Publ*., 10, 145–174.

Churchill, J. M., Poole, M. T., Skarpeid, S. S., & Wakefield, M. I. (2016). Stratigraphic architecture of the Knarr Field, Norwegian North Sea: sedimentology and biostratigraphy of an evolving tide-to wave-dominated shoreline system. *Geological Society, London, Special Publications*, 444(1), 35-58.

Coward, M.P., Dewey, J., Hempton, M., Holroyd, J., 2003. Tectonic Evolution. *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea*, 17–33.

Cox, B.M., Sumbler, M.G., Ivimey-Cook, H.C., 1999. A formational framework for the Lower Jurassic of England and Wales (onshore area). Keyworth, Nottingham, *British Geological Survey*, 1–25.

Dera, G., Neige, P., Dommergues, J. L., & Brayard, A., 2011. Ammonite paleobiogeography during the Pliensbachian–Toarcian crisis (Early Jurassic) reflecting paleoclimate, eustasy, and extinctions. *Global and Planetary Change,* 78(3), 92-105.

Doornenbal, J.C., Stevenson, A.G., 2010. Petroleum Geological Atlas of the Southern Permian Basin area. E*AGE Publications, Houten, NL* pp. 342.

Espitalié, J., Laporte, J.L., Madec, M., Marquis, F., Leplat, P., Paulet, J., Boutefeu, A., 1977. Methode rapide de characterisation des roches meres, de leur potential petrolier et de leur degre d'evolution. *Rev. Inst. Fr. Petr.* 32, 23–42.

Evans, C.D.R., 1990. The Geology of the Western English Channel and its Western Approaches. United Kingdom Offshore Regional Report. HMSO for the British Geological Survey, London, 94 pp.*Western Approaches. United Kingdom Offshore Regional Report*, British Geological Survey; HMSO, London (93 pp).

Evans, D. (Ed.), 2003. The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea *[a Project of the Geological Society of London, the Geological Survey of Denmark and Greenland and the Norwegian Petroleum Society]*.

Gradstein, F. M., Ogg, J. G., Schmitz, M., & Ogg, G. (Eds.), 2012. *The geologic time scale 2012 2-volume set*. Elsevier, Amsterdam, NL.

Hesselbo, S. P., Gröcke, D. R., Jenkyns, H. C., Bjerrum, C. J., Farrimond, P., Bell, H. S. M., & Green, O. R., 2000. Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. *Nature* 406, 392-395.

Hesselbo, S. P., Jenkyns, H. C., Duarte, L. V., & Oliveira, L. C., 2007. Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal). *Earth and Planetary Science Letters* 253, 455-470.

Van Hoorn, B. (1987). Structural evolution, timing and tectonic style of the Sole Pit inversion. *Tectonophysics*, 137(1-4), 239259270-254268284.

Husmo, T., Hamar, G. P., Høiland, O., Johannessen, E. P., Rømuld, A., Spencer, A. M., & Titterton, R., 2003. Lower and Middle Jurassic. *The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea. Geological Society, London*, 129-155.

Jenkyns, H. C.,1988. The early Toarcian (Jurassic) anoxic event; stratigraphic, sedimentary and geochemical evidence. *American Journal of Science* 288, 101-151.

Jiménez, A. P., De Cisneros, C. J., Rivas, P., & Vera, J. A. 1996. The Early Toarcian anoxic event in the westernmost Tethys (Subbetic): paleogeographic and paleobiogeographic significance. *The Journal of Geology*, 399-416.

Kemp, D. B., Coe, A. L., Cohen, A. S., & Schwark, L., 2005. Astronomical pacing of methane release in the Early Jurassic period. *Nature* 437, 396-399.

King, C., Rasul, S., Bailey, H., Drummond, M., Jutson, D. and Jacovides, J., 1983 .Well 73-13-1 *Paleoservices Report*.

Korte, C., & Hesselbo, S. P., 2011. Shallow marine carbon and oxygen isotope and elemental records indicate icehouse-greenhouse cycles during the Early Jurassic. *Paleoceanography* 26.

Littler, K, Hesselbo, S. and Jenkyns, J., 2010. A carbon-isotope perturbation at the Pliensbachian–Toarcian boundary: Evidence from the Lias Group, NE England. *Geological Magazine* 147, 181-192.

Marjanac, T., Steel, R.J., 1997. Dunlin Group sequence stratigraphy in the northern North Sea, a model for Cook Sandstone deposition. *Bulletin of American Association of Petroleum Geologists* 81, 276-292.

McElwain, J. C., Wade-Murphy, J., & Hesselbo, S. P., 2005. Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals. *Nature*, 435, 479.

Montero-Serrano, J. C., Föllmi, K. B., Adatte, T., Spangenberg, J. E., Tribovillard, N., Fantasia, A., & Suan, G., 2015: Continental weathering and redox conditions during the early Toarcian Oceanic Anoxic Event in the northwestern Tethys: Insight from the Posidonia Shale section in the Swiss Jura Mountains. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 429, 83-99.

Pacton, M., Gorin, G. E., & Vasconcelos, C., 2011. Amorphous organic matter—Experimental data on formation and the role of microbes. *Review of Palaeobotany and Palynology* 166,

Page, K. N., 2003. The Lower Jurassic of Europe: its subdivision and correlation. *Geological Survey of Denmark and Greenland Bulletin* 1, 23-59.

Palliani, R. B., & Riding, J. B. 2003. Biostratigraphy, provincialism and evolution of European Early Jurassic (Pliensbachian to Early Toarcian) dinoflagellate cysts. *Palynology 27*, 179-214.

Riding, J. B., 1984. A palynological investigation of Toarcian to early Aalenian strata from the Blea Wyke area, Ravenscar, North Yorkshire. *Proceedings of the Yorkshire Geological and Polytechnic Society*, 45, 109-122.

Röhl, H. J., Schmid-Röhl, A., Oschmann, W., Frimmel, A., & Schwark, L. 2001. The Posidonia Shale (Lower Toarcian) of SW-Germany: an oxygen-depleted ecosystem controlled by sea level and palaeoclimate. *Palaeogeography*, Palaeoclimatology, Palaeoecology, 165(1), 27-52.

Ruhl, M., Deenen, M. H. L., Abels, H. A., Bonis, N. R., Krijgsman, W., & Kürschner, W. M., 2010. Astronomical constraints on the duration of the early Jurassic Hettangian stage and recovery rates following the end-Triassic mass extinction (St Audrie's Bay/East Quantoxhead, UK). *Earth and Planetary Science Letters* 295, 262-276.

Ruhl, M., Hesselbo, S. P., Hinnov, L., Jenkyns, H. C., Xu, W., Riding, J. B. and Leng, M. J., 2016. Astronomical constraints on the duration of the Early Jurassic Pliensbachian Stage and global climatic fluctuations. *Earth and Planetary Science Letters* 455, 149-165.

Van de Schootbrugge, B., et al., 2005. Early Jurassic climate change and the radiation of organic-walled phytoplankton in the Tethys Ocean. *Paleobiology* 31, 73-97.

Van de Schootbrugge, B., Quan, T. M., Lindström, S., Püttmann, W., Heunisch, C., Pross, J. and Rosenthal, Y., 2009. Floral changes across the Triassic/Jurassic boundary linked to flood basalt volcanism. *Nature Geoscience* 2, 589-594.

Silva, R. L., Carlisle, C. M., & Wach, G., 2017.. A new TOC, Rock-Eval, and carbon isotope record of Lower Jurassic source rocks from the Slyne Basin, offshore Ireland. *Marine and Petroleum Geology 2017*.

Suan, G., Schootbrugge, B., Adatte, T., Fiebig, J., & Oschmann, W., 2015. Calibrating the magnitude of the Toarcian carbon cycle perturbation. *Paleoceanography*, 30, 495-509.

Underhill, J. R., & Stoneley, R., 1998.. Introduction to the development, evolution and petroleum geology of the Wessex Basin. *Geological Society, London, Special Publications,* 133(1), 1-18.

Zakharov, V. A., Shurygin, B. N., Il'ina, V. I., & Nikitenko, B. L., 2006. Pliensbachian-Toarcian biotic turnover in north Siberia and the Arctic region. *Stratigraphy and Geological Correlation*, 14(4), 399-417.

For more information and questions, please contact:

Friso Veenstra
✉ friso.veenstra@tno.nl
✆ +31 (0) 88 866 53 55

innovation for life

TNO APPLIED GEOSCIENCES | PRINCETONLAAN 6 | POSTBUS 80015 | 3508 TA UTRECHT |