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Greater North Atlantic Liassic Petroleum System Synthesis

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INTRODUCTION

In the absence of definitive, direct evidence for a Lias (i.e. Lower Jurassic) petroleum system offshore Nova Scotia, information is required on source rock analogs around the greater North Atlantic region. It is important to document which areas were favorable for the accumulation of organic rich sediments across the various stages of the Lias, and consider how local and global earth system controls facilitated that process. This knowledge can subsequently be employed for improved paleogeographic mapping, source rock prediction and thereby an objective assessment on the likelihood of Lower Jurassic source rock presence in the Nova Scotian deepwater area.

The Jurassic is one of the most important geological periods when it comes to source rock deposition. As Klemme and Ulmishek (1991) demonstrated, a large proportion of discovered hydrocarbons are derived from Jurassic age source rocks. However, the effectiveness of Upper Jurassic petroleum systems dwarfs that of other Jurassic sequences, notably the Lias. It is conceivable that the significance of the Lower Jurassic has been underestimated due to the dominance of Kimmeridgian and Tithonian age source rocks.

Objectives

The primary aim of this study is to synthesize information on organic rich sediments, as well as any associated known hydrocarbon occurrences, of Lias age in key Mesozoic basins. Consideration has also been given to known Lias age petroleum systems to assess if there any geochemical characteristics which are diagnostic for hydrocarbons of this age.

Background

The Lias is the geological epoch which immediately follows the initial break-up of Pangea, with the initial opening of the Atlantic, reflected by the evolving paleogeography (Figure 1). The Central Atlantic Magmatic Province (CAMP) is one of the biggest large igneous provinces (LIP) known in the geological record, with the main phase of igneous activating being around 201 Ma and lasting ca. one million years (Rainbird and Ernst, 2001).

Radiating dyke swarms in North America, Africa and South America indicate an initial central plume location, and thereby center of original Pangea break-up, centered between central Florida and Senegal (Ernst and Buchan, 1997). However, igneous activity and development of rift basins spread out for thousands of kilometers along the triple point vectors diverging from this location, including along the proto-North Atlantic margins. Outgassing from the igneous activity was associated with significant changes in atmospheric chemistry, which led to a major global mass extinction (Marzoli et al., 1999).

A further large igneous province developed at the end of the Pliensbachian associated with the initial breakup of Gondwana, with the Karoo-Ferrar LIP (Courtillot and Renne, 2003). The Karoo volcanics date very closely to the isotope excursions noted at the start of the Toarcian (Hermoso et al., 2011), with this association being a major focus of academic research.

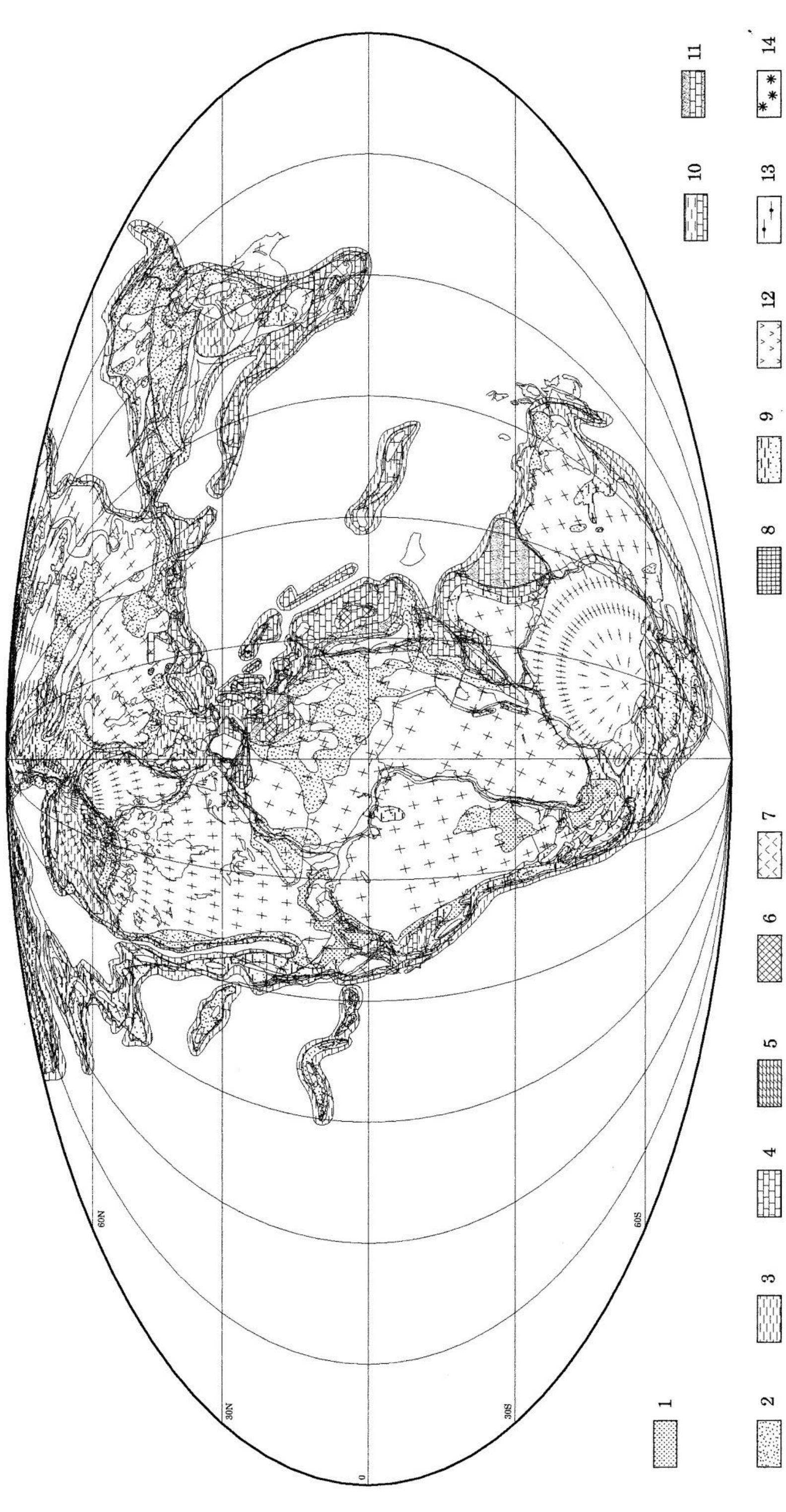

Fig. 16. Lithofacies of Sinemurian–Toarcian — Early–Middle Jurassic, tentative age range 205–176 Ma, mapped on the 195 Ma plate tectonic reconstruction. 1, coarse-grained clastic undifferentiated; 2, sandstone/siltstone; 3, shale, clay, mudstone; 4, limestone; 5, dolomite; 6, evaporites, undifferentiated; 7, anhydrite and gypsum; 8, salt; 9, mixed sandstone/shale; 10, mixed carbonate/shale; 11, mixed carbonate/sandstone; 12, volcanics/igneous undifferentiated; 13, organic-rich deposits; 14, active volcanoes, undifferentiated.

Figure 1: Sinemurian/Pliensbachian paleogeography and distribution of depositional environments (from Golonka and Ford, 2000).

Stratigraphy

Global sea level rose progressively through the Lias, from the Phanerozoic low levels which were typical during the Triassic, reflecting the initial breakup of Pangea (Figure 2; Haq, 2017). But significant divergences from the overall trend did occur, and some basins were subject to regional effects, which led to a local disconnect between relative sea level and global eustatic trends.

In this study, the standard chronostratigraphic assignment scheme adopted by the International Commission on Stratigraphy for the Jurassic Period is used, as documented in Ogg and Hinnov (2012), as used by Haq (2017) in Figure 2.

Compilation

If we are to effectively appraise the likelihood of source rock deposition in the Nova Scotia area of interest during the Lias, it is necessary to compile direct evidence for such source rocks in basins around the North Atlantic. The following two questions are key:

- At which times where conditions favorable for source rock deposition in each of the pertinent analog basins?
- And if source rocks of a certain age are present in one basin but not another nearby, what are the non-source lithologies in the latter?

Lias age source rock units may occur in Sinemurian, Pliensbachian and/or Toarcian age strata. But source rocks are not deposited for each of these ages in all of the basins. It is important to also record the nature of non-source lithologies, and thereby assess depositional environment conditions in locations when/where organic rich sedimentation was not favorable. Only in this way can a broad picture be developed of the North Atlantic environmental framework for Lias source rock deposition.

Petroleum System Characteristics

It is also necessary to establish the key criteria for recognition of hydrocarbons derived from a Lias age source rock. This is essential for testing potential Lias age fluids in oil and seeps (legacy and potential future data) in the Nova Scotia area of interest.

We need to establish what Lias petroleum systems look like, in terms of:

- Fluid properties
- Molecular Markers
- Isotopic Characteristics

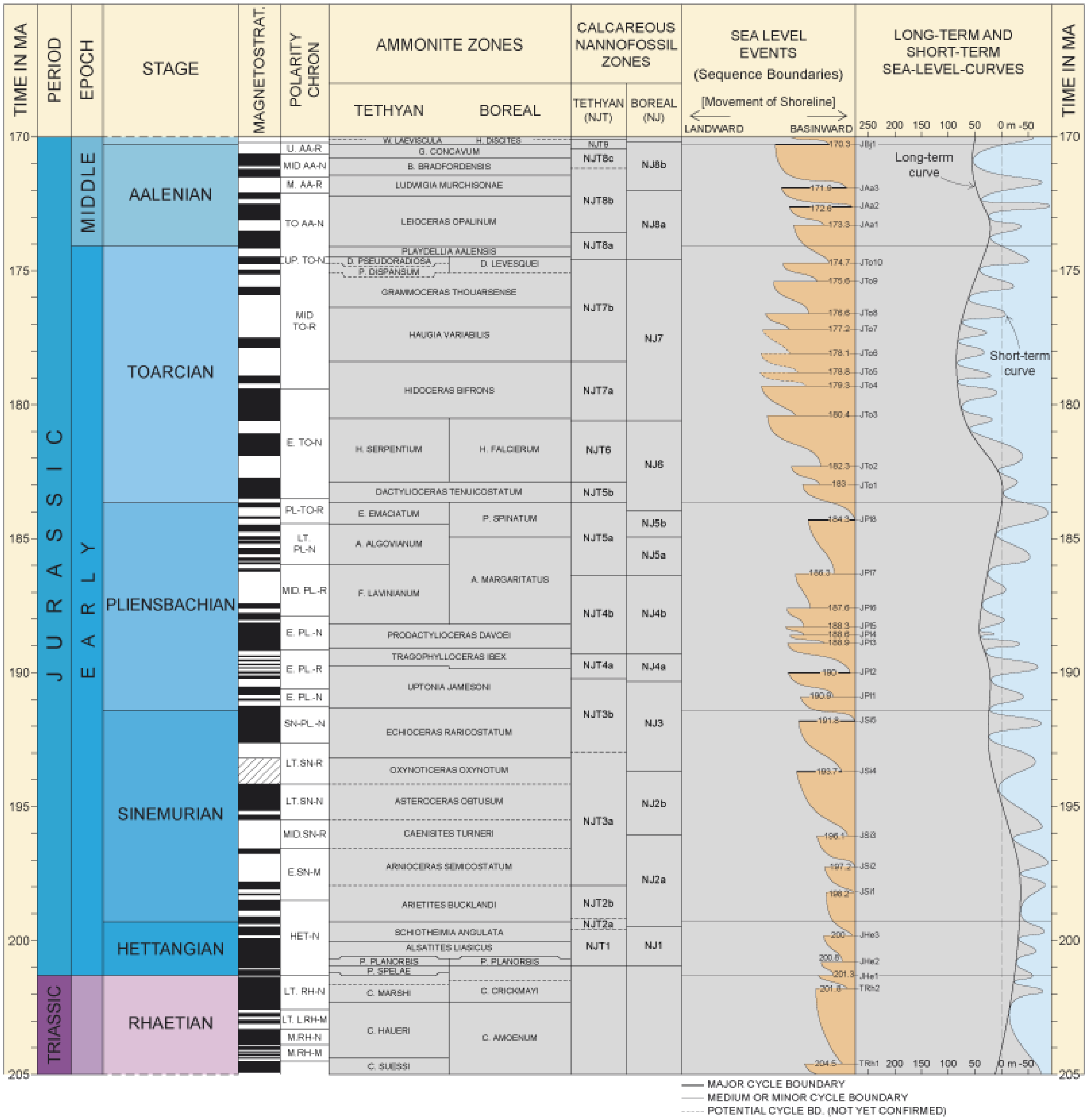

Figure 2. Lower Jurassic chronostratigraphy, including major global eustatic cycles (from Haq, 2017).

COMPILATION

Arctic

A comprehensive synthesis of known petroleum systems and stratigraphy of the Arctic is published by Spencer et al. (2011). Lias sequences are widespread across this region, but some sections are missing in a few basins, or dominated by coarse clastics (Figure 3).

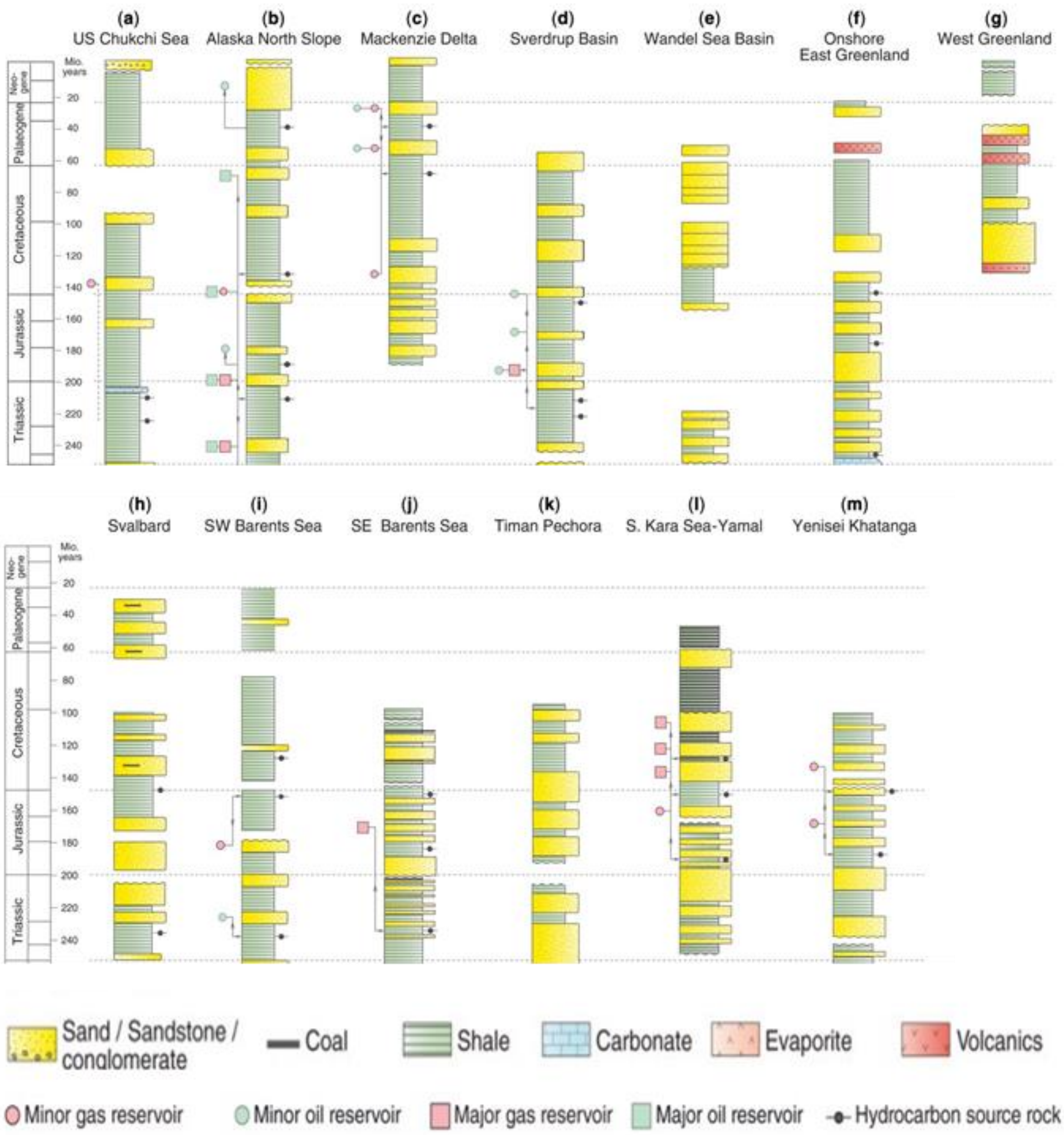

Figure 3. Compilation of Mesozoic sedimentary sequences from around the Arctic known petroleum system elements (from Spencer et al., 2011). Lias deposition is widespread across this interval, with known source rocks present in several basins.

Chukchi

Across the Chukchi Basin, the Jurassic is essentially absent. Stratigraphy and geochemical data for the offshore exploration wells drilled in this area is documented by Homza and Bergman (2019). In the wells shown, Lower Cretaceous sands of the Kuparak Formation generally rest on Triassic (Shublik Formation) or older sequences.

North Slope

The Jurassic sequence in the North Slope Basin is comprised solely of the Kingak Shale. Towards the northeast quadrant of the basin, it may be largely removed by the Lower Cretaceous Uncomformity (Housenecht and Bird, 2004). As shown in Figure 4, the Kingak is subdivided in to two intervals: K1 (Lower Kingak) and the K2 (Upper Kingak). The Lower Kingak corresponds to the Lias, ranging in age from the Hettangian to the Toarcian, resting conformably on the Triassic Shublik and Sag River Formations below. The Upper Kingak ranges in age from the Oxfordian to the Kimmeridgian. Much of the Middle Jurassic and uppermost Jurassic is missing across the basin (*ibid*).

Detailed, high resolution chronostratigraphic information is not readily available in the public domain for the Kingak Shale. However, documented geochemical information indicates the most organic rich section of the Kingak is the lowermost part of the Lower Kingak (Masterson et al. 2019). This probably relates to Sinemurian or Pliensbachian age source horizons, rather than the Toarcian. In the Kalubik #1 well, an organic rich interval is present within the Kingak Shale at 2,400m, spanning ca. 10m with an average TOC of ~4% and HI of 300 (Figure 4; *ibid*). This interval is possibly of oil window maturity, given the depth, thus the original HI may have been higher.

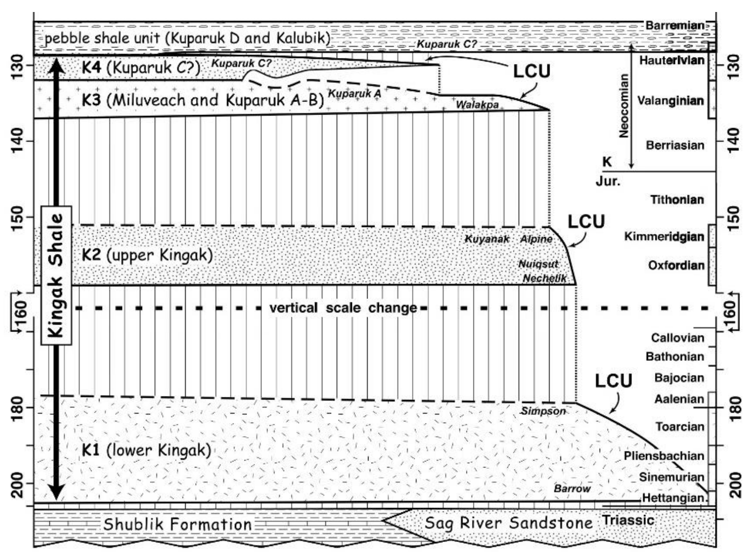

Figure 4. Inferred chronostratigraphic correlation of the Kingak Shale Formation in the NPRA, Alaska (from Housenecht and Bird, 2004). Kingak is divided in to Lower (K1) and Upper (K2) units, with K1 corresponding to the Lias. The Middle and uppermost Jurassic sequences are absent.

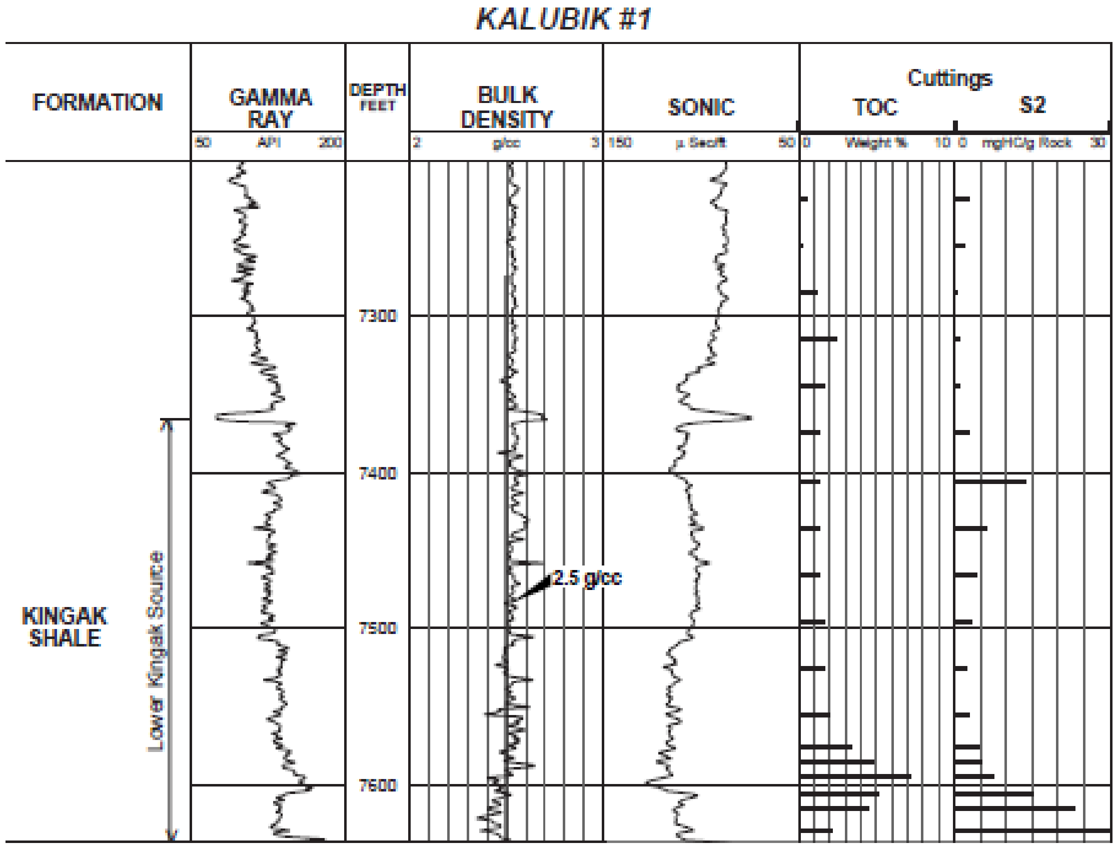

Figure 5. Organic geochemical data on the Lower Kingak (L1) unit from the Kalubik #1 well, Alaska (from Masterson et al. XXXX). Organic rich section is present in the lower most section, though precise stratigraphy is not known.

Sverdrup

The Lias in the Sverdrup comprises a shallow shelf setting, with occasional influxes of deltaic sands. Mudstones are mostly deposited under oxic conditions with varying amounts of siderite and glauconite (Rismyhr et al., 2018).

Svarlbard

Like the sequence found in Sverdrup, the Lias in Svarlbard comprises proximal sediments, with coarse clastics interspersed by oxic prodelta shales, deposited under brackish conditions (Nagy et al. 2011).

E Greenland

The Kap Stewart Formation is a lacustrine sequence found in the Jameson Land Basin (East Greenland), which ranges in age from the Rhaetian to the Sinemurian, overlain by shallow marine sediments of the Pliensbachian Neill Klinter Formation (Dam and Christiansen, 1990). The Kap Stewart comprises classic lacustrine cyclic sedimentation, related to multiple cycles of lake evolution, with organic rich intervals containing up to 10% organic carbon, and Type-II organic matter (HI ~600; *ibid*).

Barents Sea

Promixal, prodelta shales of the Nordmela Formation account for much of the Lias sequence in the Barents Sea Basin, which ranges in age from the Sinemurian to the Late Pliensbachian / Toarcian (Smelror, 1994). Although most of this interval comprises gas prone, Type-III kerogen, Lerch (2016) shows data which indicates solid Type-II kerogen potential (HI ~600) for at least some samples from the Nordmela. The precise age of these specific samples is not reported.

West Siberia

The main source rock in the West Siberian basin is the Upper Jurassic Bazhenov Formation, but source rocks are also reported in the Middle Jurassic (Tyumen) and the Lower Jurassic (Togur; Schenk, 2008). The Lias sequence comprises mostly oxic shales, with occasional sand units (*ibid*). Deposition of the Lias was initially only in the northern part of the basin, but sedimentation progressively spread south. Thus, much of the Hettangian and some of the Sinemurian is not present across much of the basin (ibid). Geochemical data indicates that an organic rich interval is found in the Pliensbachian, with TOC values of up to 10% and HI values ca. 400 (Kontorovich et al., 1997).

East Siberia

Cross-sections published by Nikitenko et al. (2008) indicate reasonably complete Lias sections around the Siberian Arctic, with Toarcian bituminous shales present in some of the major basins (Figure 6). Lias source rocks are reported for the Kara Sea, Yamal and Yenisei Khatanga basins (Spencer et al. 2011).

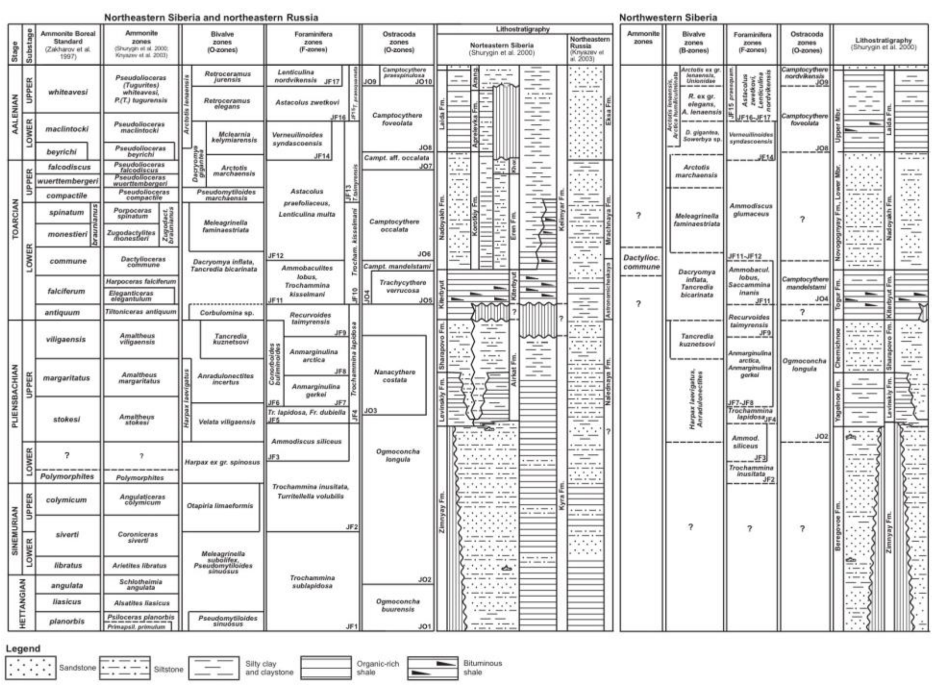

Figure 6. Stratigraphy of Lower Jurassic sediments in West and East Siberian basins (from Nikitenko et al., 2008), showing reported occurrences of Toarcian bituminous shales.

Western Europe

Sweden

A limited Lias succession in southern Sweden comprises proximal, fluvial dominated fine-grained shales with multiple sandstone intervals, ranging in age from the lowermost Hettangian to the Lower Sinemurian. The Quaternary sits directly above this interval.

Denmark

Onshore Denmark bears similarities to the section in southern Sweden, though more of the sequence is present. The Lias is dominated by non-source proximal shales, with some coarser units (Surlyk et al. 1993). The Hettangian-Sinemurian paleogeography illustrates the regional facies distribution, with clastic, deltaic sources sitting to the east (Figure 7a). A regional cross-section shows that this facies pattern varied during the Lias, with the clastic dominated section pushing westwards during the Pliensbachian (Figure 7b).

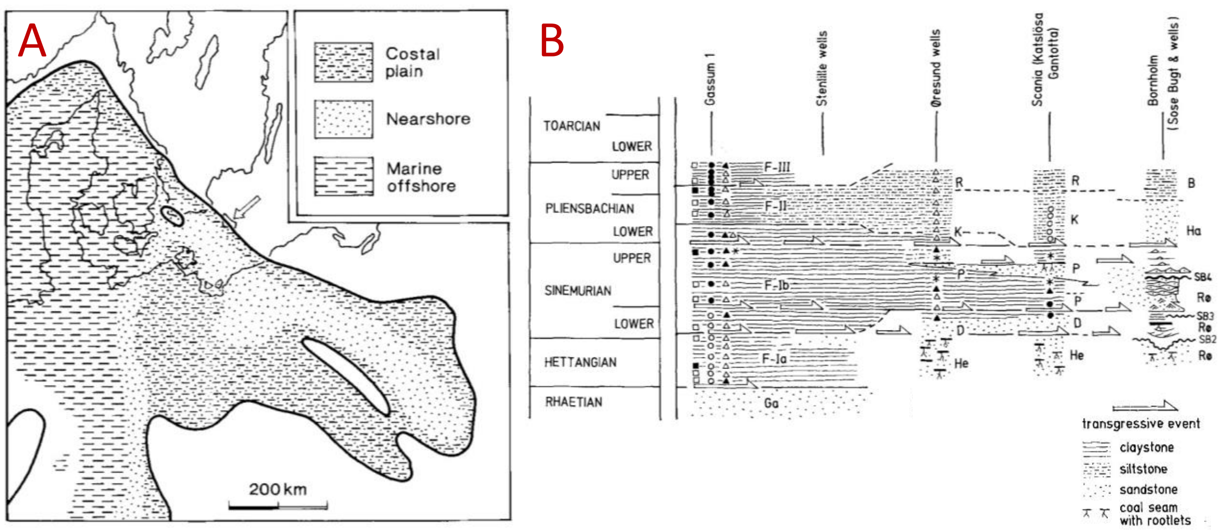

Figure 7. Distribution of Lias sediments in the greater Baltic region, illustrating the basinward shift of coarse clastic deposition during the Pliensbachian (from Surlyk et al., 1993).

Lower Saxony Basin

Data is plentiful on the Toarcian of the Lower Saxony Basin, corresponding to the Posidonia Shale Formation. Song et al. (2017) shows data for several wells across Germany and the Netherlands, with TOC values generally well in excess of 5%. Much less information is readily available on the older Lias units, which correspond to the Aalburg Formation. A cross-section shown by Song et al. (2017) indicates a predominantly shaley sequence for this unit across western areas.

West Netherlands Basin

Published information on the Lias sequence of the West Netherlands Basin is limited. As with the Lower Saxony Basin, the Lower Toarcian Posidonia Shale Formation is recognized as the most organic rich zone, and is the reputed source for the oil and gas accumulations in this area (Racero-Baena and Drake 1996).

Below the Posidonia, the Aalburg Formation comprised a shale sequence ranging in age from the Hettangian to the Pliensbachian (Balen et al. 1999). Organic data on this interval is sparse, but Gasparik et al. (2012) report data on two Aalburg Formation samples, one with a TOC content of 5% and an HI of 493.

Paris Basin

The organic rich shale of the Lower Toarcian in the Paris Basin is one of the most well characterized source rock sections in the geochemical literature. Given the location of the IFP research center within this region, it is inevitable that this basin attracted considerable scrutiny. Bessereau et al. (1995) discuss the association of source potential in the Lias sequence of the Paris Basin with sequence stratigraphic variance. Maximum flooding surfaces are associated with relatively organic rich intervals in the Hettangian, Sinemurian, Pliensbachian and Toarcian (Figure 8). The intervals in the Sinemurian and the Pliensbachian are of sufficient richness and thickness to be considered as source rocks across much of the basin, however, the MFS within the Toarcian section, corresponding to the Schistes Carton, is the most organic rich interval across the Lias of the Paris Basin (e.g. Figure 9; Huc 1988).

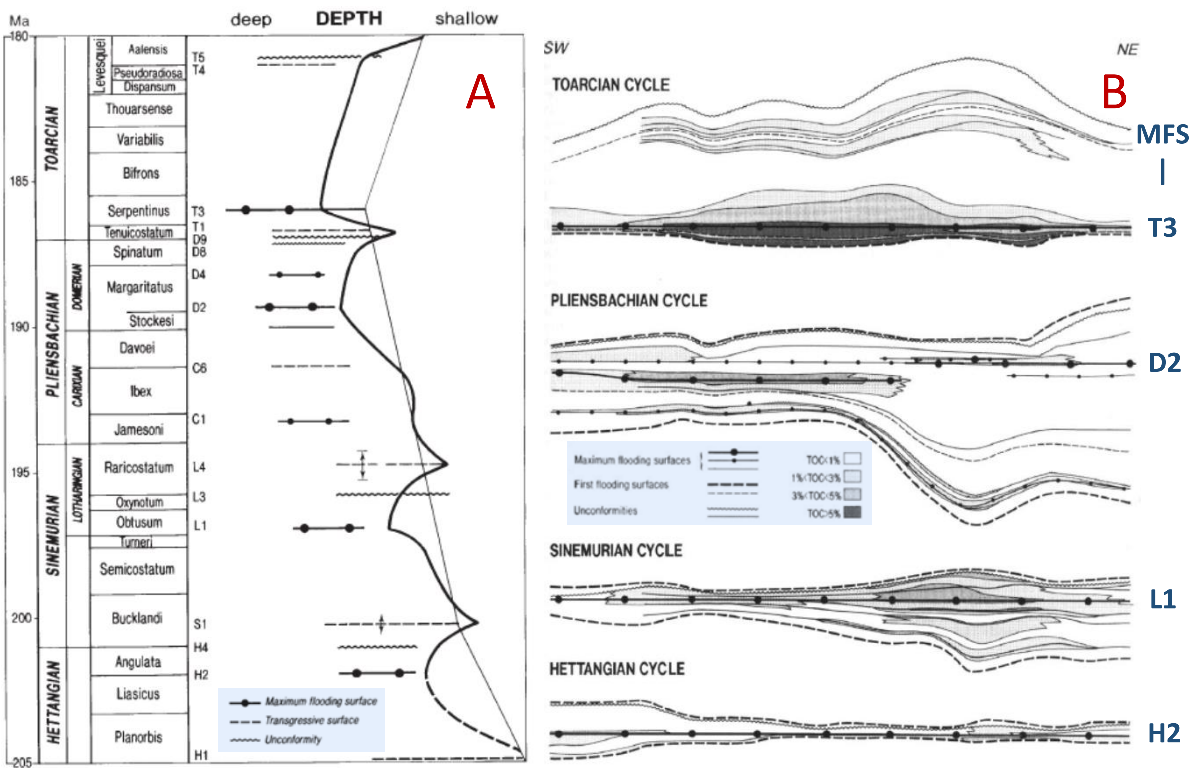

Figure 8. Correspondence of relatively sea level variance (A) with organic enrichment (B) during the Lias in the Paris Basin. Zones of high organic content correspond with maximum flooding surfaces (MFS), with source rock richness increasing progressively through the Lias (from Besserau et al., 1995).

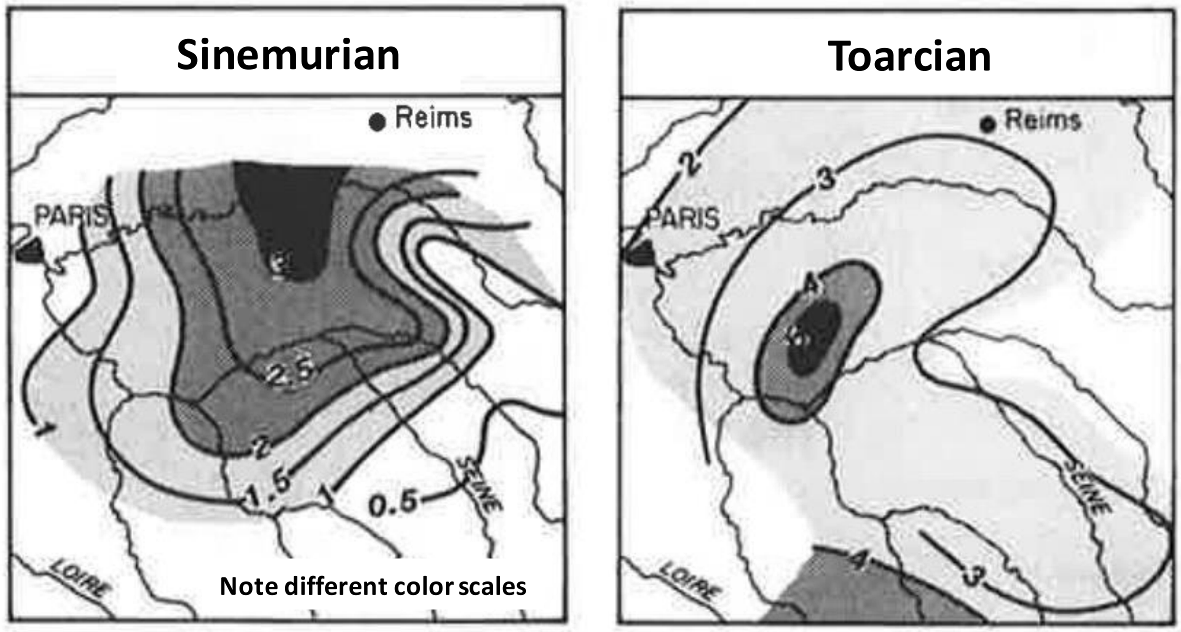

Figure 9. Comparison of the areal distribution of organic enrichment in the Paris Basin between source rock intervals of Sinemurian and Toarcian age (from Huc, 1988).

North Sea

Though is undoubtedly a considerable volume of data on the Lias across the North Sea, much of this is restricted to proprietary industry datasets. The Lias is absent across much of this basin due to erosion. In basinal areas where thicker sequences of the Jurassic were deposited and which have undergone lower amounts of uplift, it is probable that thick sequences of the Lias are preserved. The Statfjord Formation comprises proximal fine-grained clastic deposits of Hettangian to Sinemurian age, while the Sinemurian to Toarcian Dunlin Formation consists of shallow marine shales and siltstones with occasional, thin sandstones (Goff, 1983).

Morton (1993) suggests in some figures that source rocks may be present East of Shetland and in the North Viking Graben, of Sinemurian and Toarcian age. Additional work is needed to verify this observation.

In the southern North Sea, a complete Lias section is present in some areas, for instance the Danish Basin. A stratigraphic column shown by Surlyk and Ineson (2003) indicates a complete, shale dominated section from Hettangian through Toarcian age, with source intervals present in the Pliensbachian and the Toarcian. However, no direct data has yet been found to corroborate these indications, or help specify the accurate chronostratigraphic assignment of any organic rich horizons.

Onshore UK: Cleveland and Wessex Basins

The Lias is widely exposed at outcrop (Figure 10), and well characterized from numerous boreholes, across a wide swath of southern Great Britain. It is apocryphally reported that the term ‘Lias’ originated from slang used by quarrymen in the region in reference to this geological unit, who referred to it as ‘layers’ but spoken in thick, English West Country accent. A large volume of basic rock property data has been compiled on the Lias by the British Geological Survey, as this unit is the most significant cause of landslips in the United Kingdom (Hobbs et al., 2012).

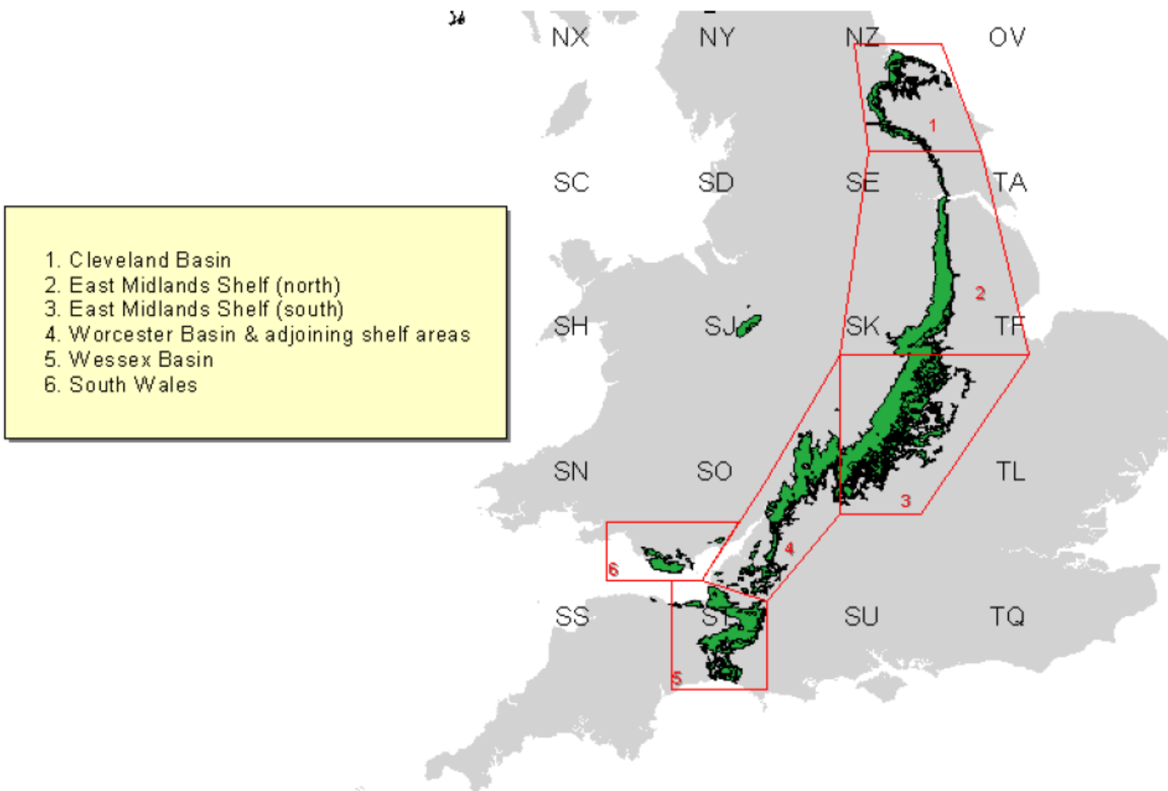

Figure 10. Map of England and Wales showing the surface outcrop of Lias age sediments (from Hobbs et al., 2012)

Key Locations:

North Yorkshire Coast

Several locations along the Yorkshire coast afford exposures of the Lias. The most well known organic rich horizon in this area is the Jet Rock, corresponding to the Falciferum exaratum zone of the Toarcian. In this interval, TOC values are generally above 5% and can range over 15% (McArthur et al. 2008). The maturity of this section is ca. 0.6 VR, close to the onset of generation. Typical hydrogen index values of the Jet Rock are ca. 600, indicating Type-II kerogen. Information on the older Lias units is limited compared to that of the Toarcian.

The Pliensbachian is more oxic, with the Upper Pliensbachian corresponding to the Cleveland Ironstone Formation. Beneath this unit, modest organic enrichment is noted in the Lower Pliensbachian age Pyritous Shale Member of the Redcar Mudstone Formation, with non-source fine grained Sinemurian sediments preserved further below. Thus, it appears that the only significantly organic rich zone within the Yorkshire Lias is restricted to the Toarcian Jet Rock.

Mochras Borehole

This well was drilled as a stratigraphic test on the Lleyn Peninsular in North Wales. It comprises a thick Lias section, with fine grained sediments ranging in age from the Hettangian through the Sinemurian. However, the organic carbon content of these sequence is low throughout. The global isotope reversals during this time period are recorded at this location, hence there is a wealth of data on this important stratigraphical control point (e.g. Xu et al., 2018).

St. Audries Bay / East Quantoxhead

The lowermost Lias is well exposed along the Somerset coast, e.g. St. Audries Bay, near the community of Kilve. This location is now the Global Stratotype for the Hettangian-Sinemurian Boundary (Bloos and Page, 2002). Several studies have reported on the sedimentology and geochemistry of these sequences (i.e. Ruhl et al. 2010; Husing et al., 2014 and Xu et al. 2016). Sections with good organic carbon contents are found in both the Hettangian and Sinemurian, each comprising decent net source rock with thicknesses of ca. 30m (Figure 11). Information is not included in these studies on the Pliensbachian or the Toarcian in this area.

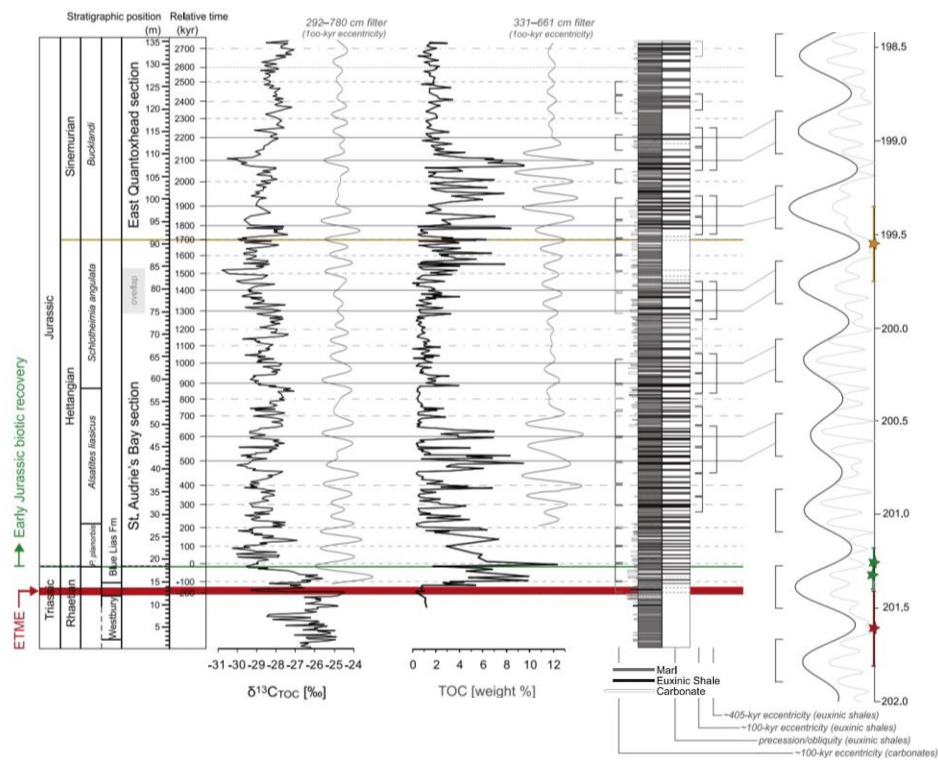

Figure 11. Distribution of organic carbon in Hettangian and Sinemurian sediments along the North Somerset coast (UK), St. Audrie's Bay and East Quantoxhead (from Husing et al., 2014).

Gloucestershire

A complete section of the Lower Lias is present in multiple outcrops around the southern Severn Valley. A sequence comprising calcareous mudstones, marls and limestones ranges from Hettangian to Lower Pliensbachian in age (Simms 2007). No information is available on the organic richness of these sections.

Central Dorset

A borehole drilled at Winterbourne Kingston records some Lower Jurassic sediments (Rhys et al. 1981), with the notable occurrence of a thin Toarcian organic rich interval. Jenkyns et al. (2001) document TOC variance through a portion of this borehole, which indicates a 1m thick interval in the Lower Toarcian, with TOC values of up to 4% (Figure 12). This contrasts with Toarcian sequences elsewhere in Western Europe, where much thicker organic rich intervals are well documented.

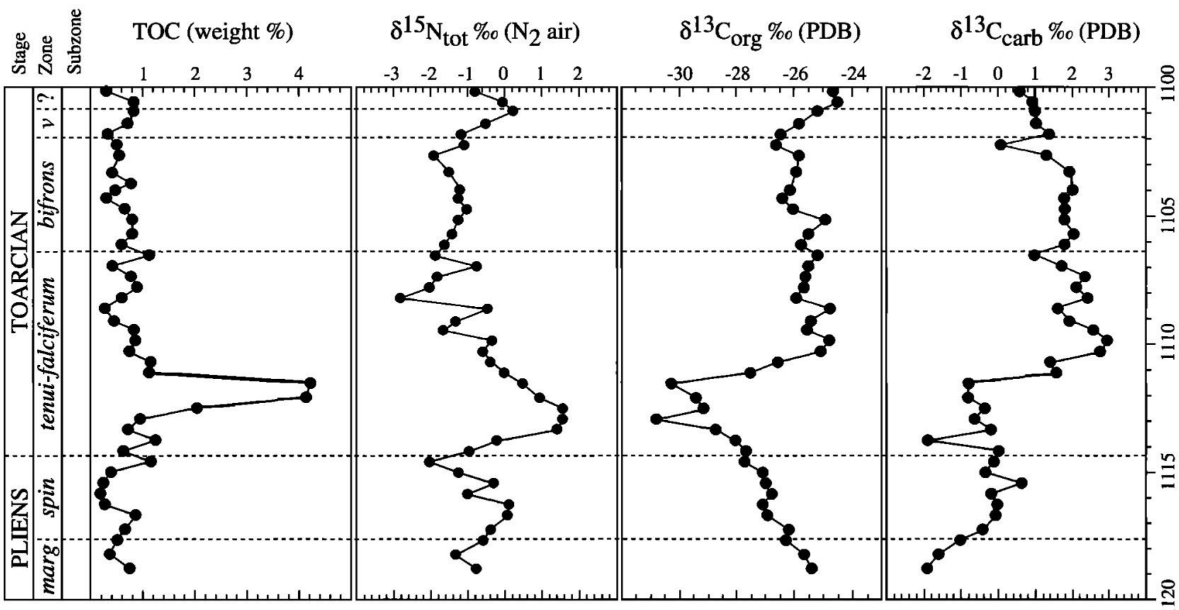

Figure 12. Evidence for a thin Toarcian source rock onshore in the Wessex Basin (from Jenkyns et al., 2001).

UK Northwest Continental Shelf

Across much of the continental shelf around the northwest of Great Britain, the Lias is completely absent in most of the wells which have been drilled (Hitchen and Stoker 1993), including proximal to the Rockall Trough. However, these wells have been drilled either directly on, or adjacent to, basin high positions. Thus, it is possible that Lias sections have been preserved in the basin depocenters.

Hebrides Basin

Lias age sediments are well exposed at numerous locations around the Hebrides Basin. In some instances, key exposures of fine-grained sediments are proximal to the large central intrusions, which have significantly indurated these strata preventing a reasonable assessment of their organic content. Fine grained sediments comprise the Hettangian and Sinemurian sequences with significant organic richness in the Pabba Shales (Sinemurian). The Pliensbachian comprises more detrital, coarse grained sediments, reflecting low stand sequence conditions, possibly resulting from regional uplift. The start of the Toarcian is marked by transgressive conditions, with the deposition of the Toarcian age Portree Shale Formation. This sequence has a significant organic carbon content. Geochemical data is scarce on this unit however, as it proved a preferred horizon for regional dolerite sill intrusion (Bishop, 1992).

Irish Sea

Across much of the Irish Sea, both in the Eastern Irish Sea and Central Irish Sea Basins, a similar pattern of substantial regional erosion is evident. It has been suggested on the basis of regional seismic that thick Lias deposits, up to 2,500m thick, may be present in some of the basin centers (Newman, 1999). In the 42/21-1 well (Central Irish Sea), a Toarcian sequence has been reported with TOC values up to 3% and HI values of 525 (Corcoran and Clayton, 1999)

Slyne Trough

This basin is located off the west coast of Ireland, and has been penetrated by several exploration wells. The geochemistry of one of these wells has been documented by Silva et al. (2017). The Lower Sinemurian consists of oxic mudstones, which pass up into a sandstone dominated section that extends up through the Pliensbachian. This reflects the situation in the Hebrides and Cleveland basins, where coarser grained lithologies comprise the Pliensbachian, especially the younger units. A return to mudstone deposition marks the start of the Toarcian, and this exhibits decent organic carbon contents. In the lower Toarcian, correlated to the Portree Shale Formation, TOC values in excess of 4% are reported, with an organic rich interval of ca. 20m (Figure 13).

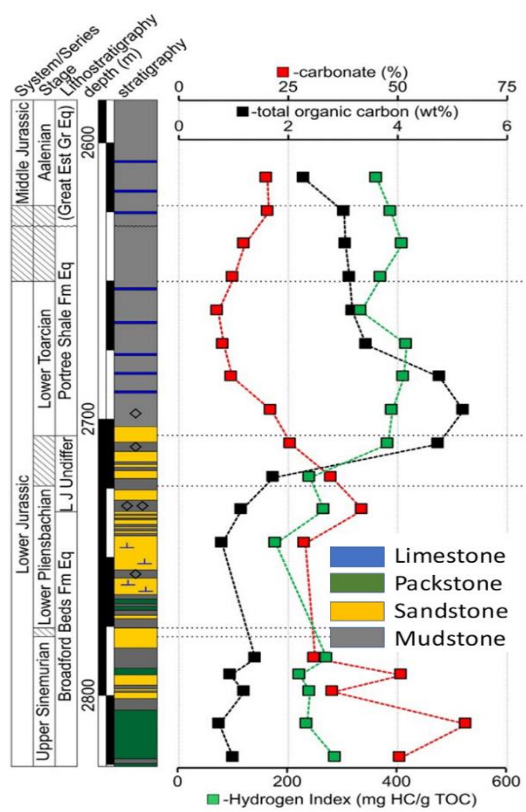

Figure 13. Lias sediments in the Slyne Trough showing source quality in the Lower Toarcian (from Silva et al., 2017).

Western Approaches

Several wells have been drilled in basinal areas offshore the Amorican Massif, off the coast of northwest France. To date, no commercial discoveries have been reported. However, the well data records think Lias sequences in some of the wells, with black shales in the Hettangian to Pliensbachian sequence (Deronzier et al., 1994). Organic contents are low, typically around 1%, but due to the high maturity of this section, original carbon contents may have been higher (*ibid*).

Mediterranean

There are numerous examples of Lias sedimentation around the margins of the Mediterranean which record Tethyan realm deposition. The following represents a few notable examples.

Italy

The Lombardy Basin contains a limestone sequence dating from the Triassic through the Sinemurian. Carbonate pelagic sedimentation continued from Pliensbachian time onwards, including the deposition of red nodular limestones during the late Pliensbachian (Jenkyns et al., 1985). A thin organic rich shale is found across much of this region, corresponding to the Falciferum zone of the Toarcian (Farrimond et al. 1989).

Adriatic

Campana et al. (2017) reports organic geochemical data on Lias sediments in several wells drilled in the Central Adriatic. This data shows modest source potential in the Toarcian, with good source potential in the Sinemurian (Figure 14).

Greece

Like Italy, the lower Lias found in the basins of Western Greece consists mostly of limestones, with water depth progressively increasing through the Toarcian. Organic rich, calcareous shale deposition commences at the start of the Toarcian and continues through much of the subsequent Jurassic (Karakitsios and Rigakis, 2007).

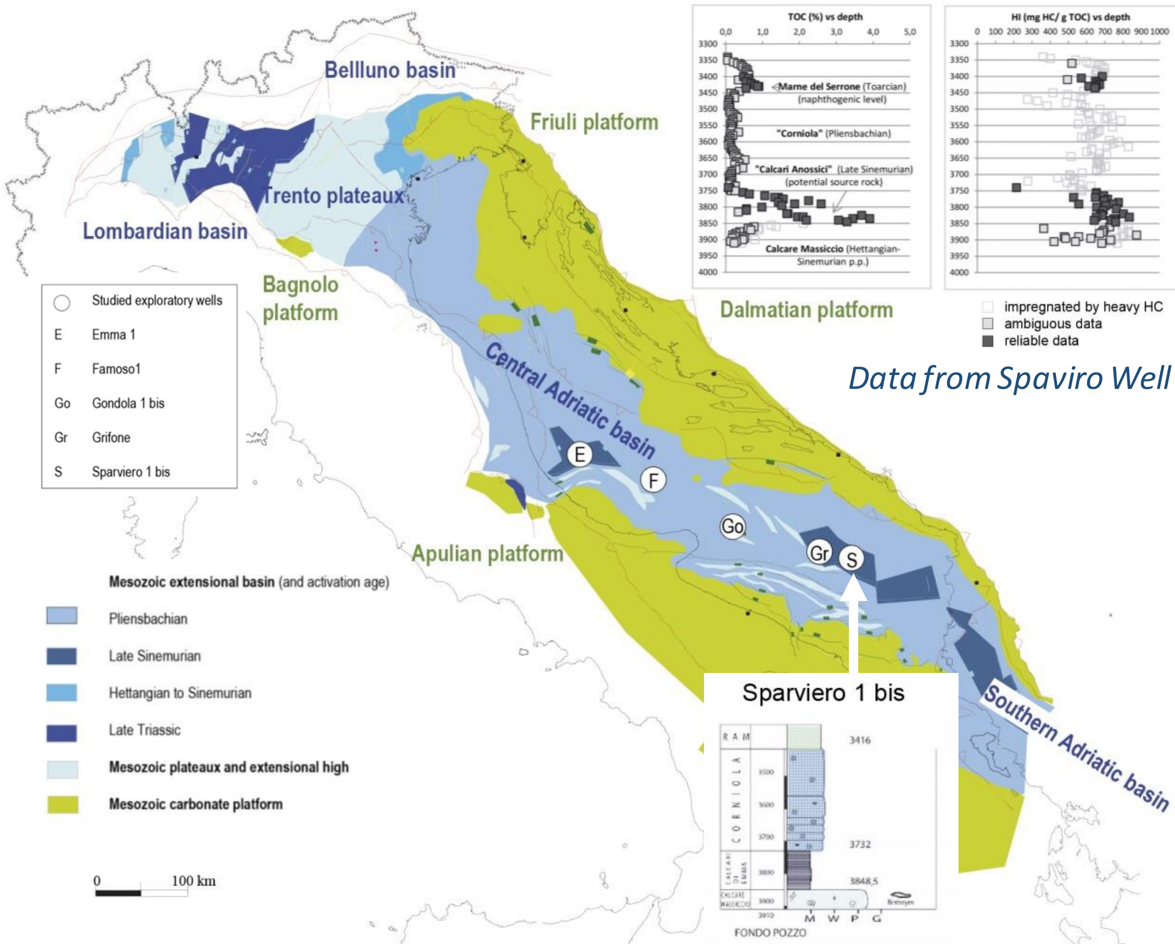

Figure 14. Example source rock data from Lias sediments in the Adriatic, showing significant organic content in the Sinemurian (from Campana et al., 2017).

Iberia

The Iberian peninsula was located at the western edge of the Tethyan realm during the Lias (Figure 15). Approximately, 50% of the terrane was emergent to varying degrees during this period. Towards the east, the Lias succession is comprised primarily of platform carbonates, with little or no fine grained sedimentation. But quality source rocks were deposited around the northern and western margins at various times. Significant sections are missing in many of the basins (Aurell et al. 2003), indicating periods of uplift in the Middle and Upper Jurassic.

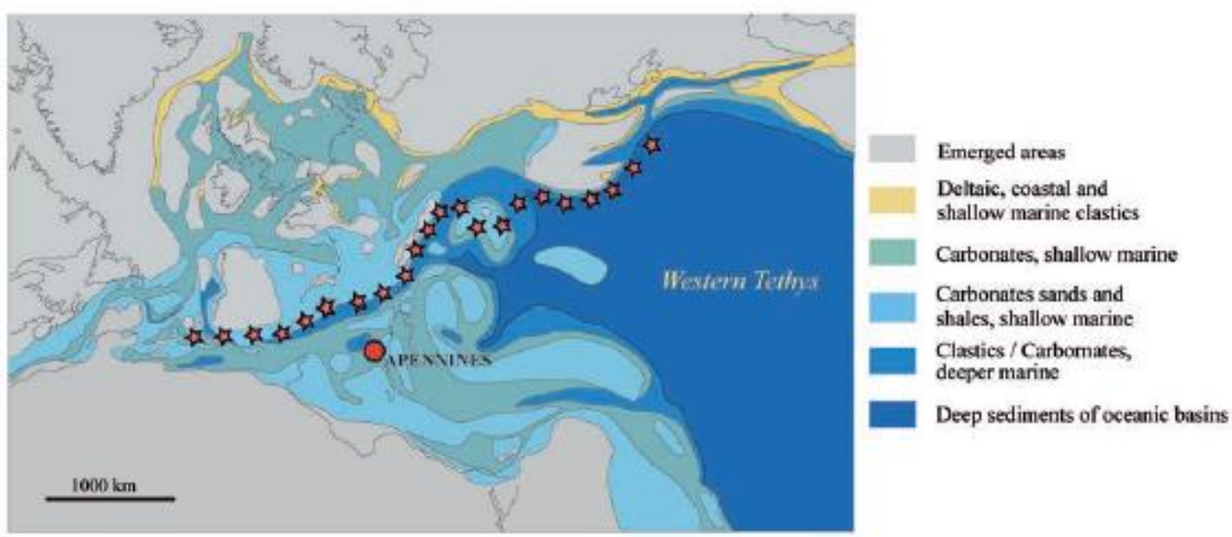

Figure 15. Sinemurian/Pliensbachian paleogeography of Europe showing the position of the Iberian Peninsula at the western most margin of the Tethyan realm (from Meister and Blau, 2014).

Asturian Basin

Pliensbachian marls, with TOC values of generally 2 to 3% and as high as 8% (Figure 16; Gomez et al., 2016). Organic contents fall to less than 1% during the Toarcian (ibid).

Basque-Cantabrian Basin

Deposition of the Lias began with dolomites and evaporites deposited under shallow marine conditions, with shelf carbonates deposited during the Sinemurian (Beroiz and Permanyer, 2011). Marl deposition followed during the Pliensbachian, as water levels deepened, with serval intervals of organic rich shales (see Figure 16). Oil accumulations in this basin type to these Pliensbachian marls (ibid).

Lusitanian Basin

The Lias sequence of the Lusitanian Basin is dominantly calcareous, varying both spatially and temporally in facies (Figure 17; Duarte et al. 2012). Marls and black shales are common. The most organic rich intervals occur in the Upper Sinemurian (Oxynotum / Rariocostatum) and the Upper Pliensbachian (Margaritatus), as shown in Figure 18 (Duarte et al. 2010). The Toarcian is non-source.

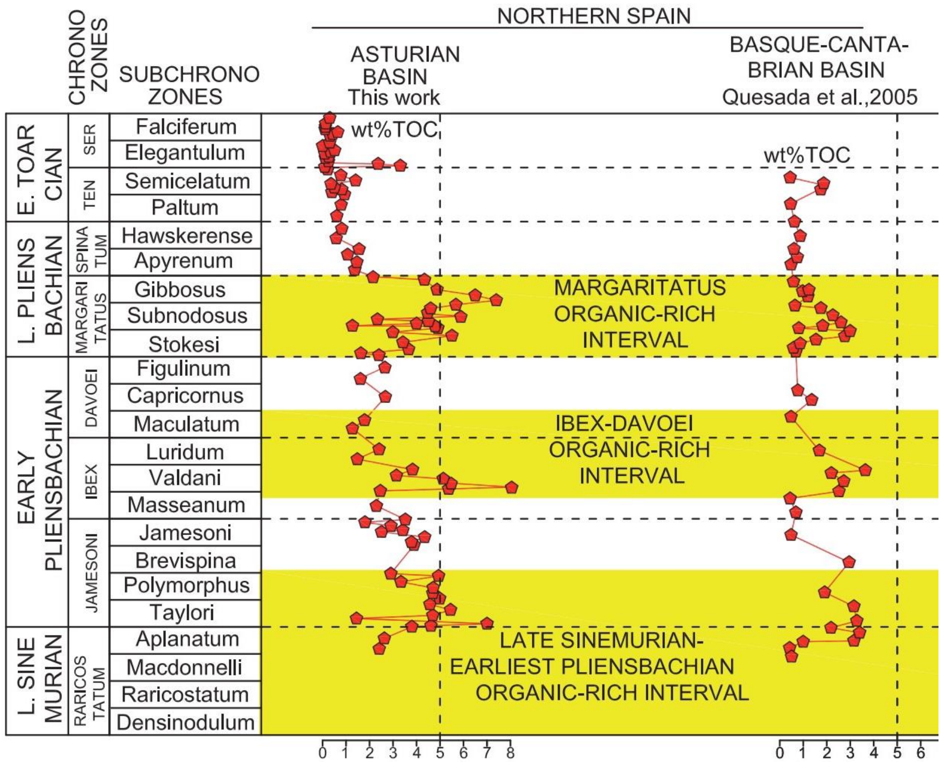

Figure 16. Distribution of organic carbon in the Asturian and Basque-Cantabrian Basins, northern Spain (from Gomez et al., 2012).

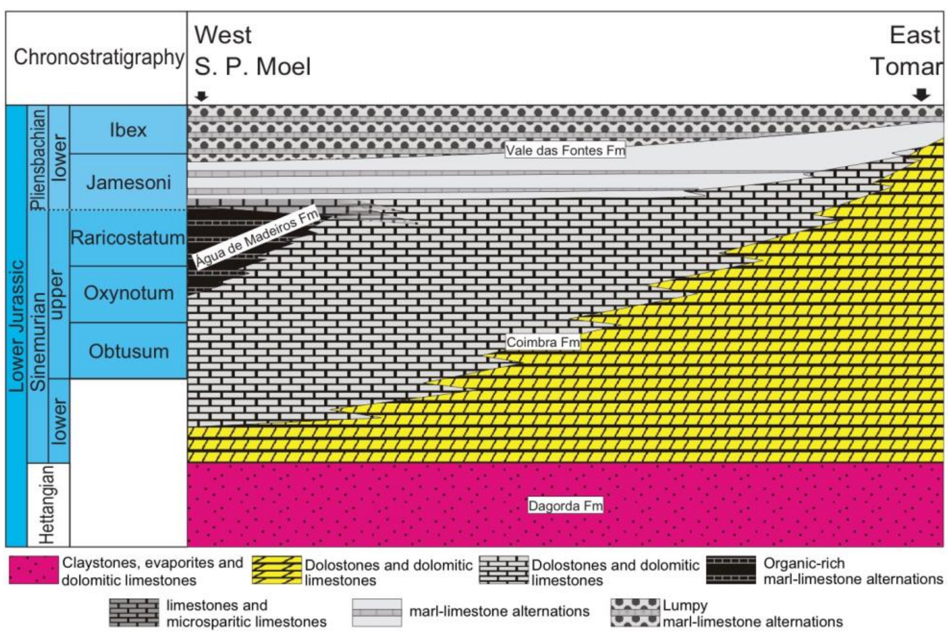

Figure 17. Variation in Lias lithofacies in the Lusitanian through time and across the basin (from Duarte et al., 2012).

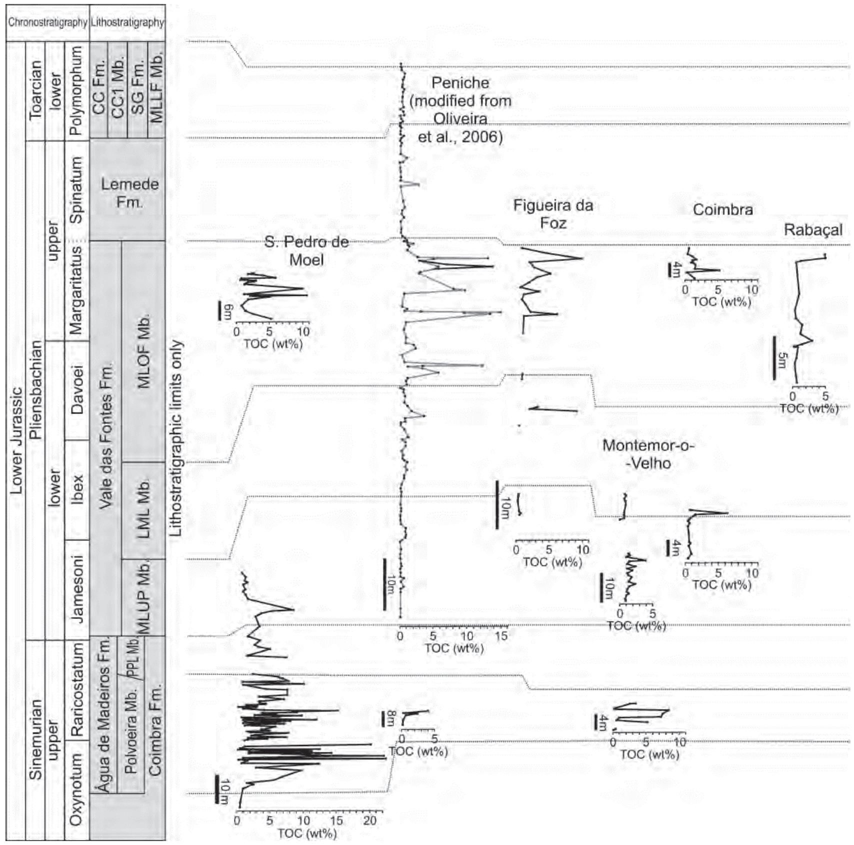

Figure 18. Organic rich horizons in Lias locations across the Lusitanian Basin (from Duarte et al., 2010). Upper Sinemurian and Upper Pliensbachian have highest levels of organic enrichment.

Northwest Africa

As shown in Figure 15, the northwest corner of the African craton separates the westernmost Tethyan realm from the proto-Atlantic. Thus, locations which are in close proximity may have experienced quite different conditions during the Lias. In Morocco, sites to the east of the Atlas mountains correspond closely to sites in the Tethyan realm. Conversely, those locations in the west are most similar to other sections around the Atlantic. Careful consideration of paleogeography is important when considering the relevance of these sites as potential Scotian Shelf analogs.

Atlas Rift Basin

The second phase of extension in this basin during the Lias led to the deposition of a similar sedimentary succession as that seen in the Lusitanian basin: a predominantly carbonate succession, with intercalcations of limestone units and marls (Sachse, 2012). This basin is situated on the far western reaches of the Tethyan realm. In the Ait Moussa area, the Pliensbachian includes fine-grained lithologies of moderate source potential, with TOC values above 2% and Type-II organic matter (Sachse et al., 2012).

Offshore Morocco

Lower Jurassic sediments have been encountered in a number of wells drilled off the coast of Morocco. One of the most complete examples is recorded by the MZ-1 well, drilled by Freeport McMoRan in 2015 within the Mazagan concession. It is a deepwater well, spud in 2,176m water depth and with a TD of ~6,500m subsea. The Lias ranges in depth from 3,300m to 3,900m below mudline (Weston Stratigraphic Ltd., unpubl.). Organic carbon contents are generally low throughout the Lias (Fowler, unpubl.). Even given the relatively high maturity likely for this section, from ~1.0 to ~1.5? VR, source presence is unlikely. The section comprises primarily calcareous mudstones, with some limestones around the late Sinemurian – early Pliensbachian boundary.

Sengal Basin

Onshore data and coastal offshore drilling indicate a condensed Jurassic section in this basin, with proximal sediments, devoid of significant source rocks (Brownfield and Charpentier, 2003). However, seismic shows that the Jurassic expands substantially offshore, potentially reaching up to 3km in thickness (Figure 19). The Lower Jurassic is mostly likely to comprise limestone with occasional shale and evaporites towards the base (*ibid*).

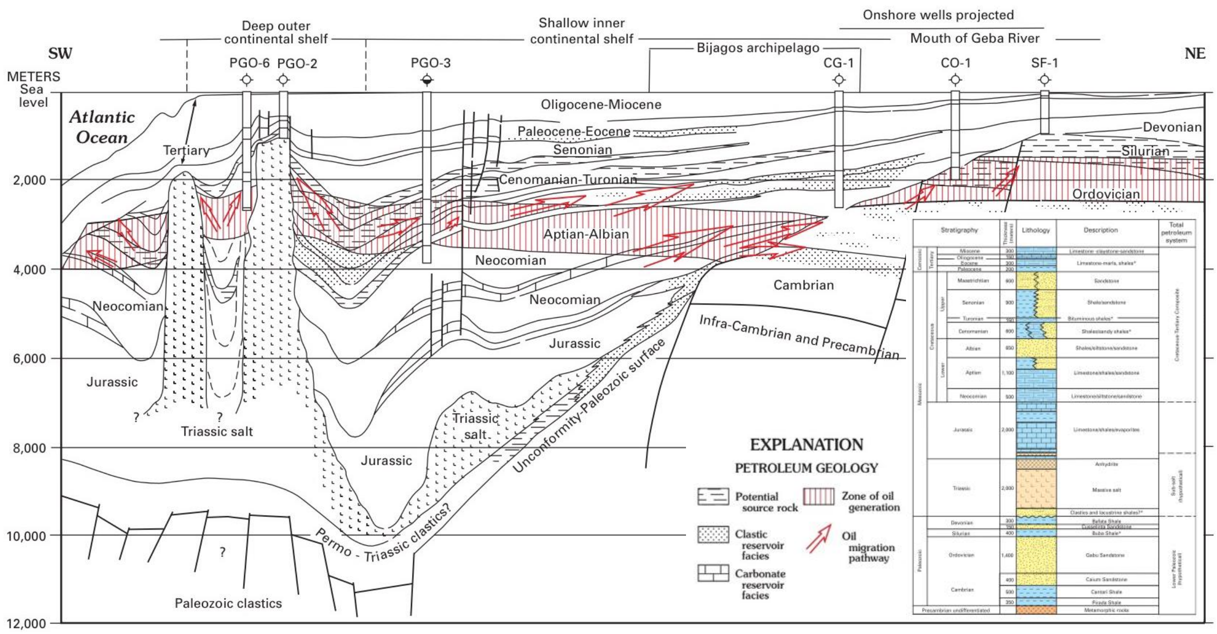

Figure 19. Composition of the Jurassic section in the Senegal Basin, with a cross-section showing an increase in thickness offshore, based on seismic interpretation (from Brownfield and Charpentier, 2003).

North America Atlantic

Data on Lias sequences on the North American side of the Atlantic is mostly confined to the limited offshore wells which penetrated the Lower Jurassic section. Several rift basins are present along the eastern seaboard of the United States, with sedimentary sections dating from the Triassic through the middle Jurassic. However, these are wholly lacustrine and have not been considered in this review.

Grand Banks

The Lias section in the Jeanne D'Arc basin comprises rift and syn-rift sediments (Figure 20). The Argo Formation, consisting of evaporites including thick salt, is dated to the Hettangian. Above this, dolomite and limestone sequences of the Iroquois Formation comprise the Sinemurian sequence. Shales and limestones of the Downing Formation span the Pliensbachian to the Bathonian.

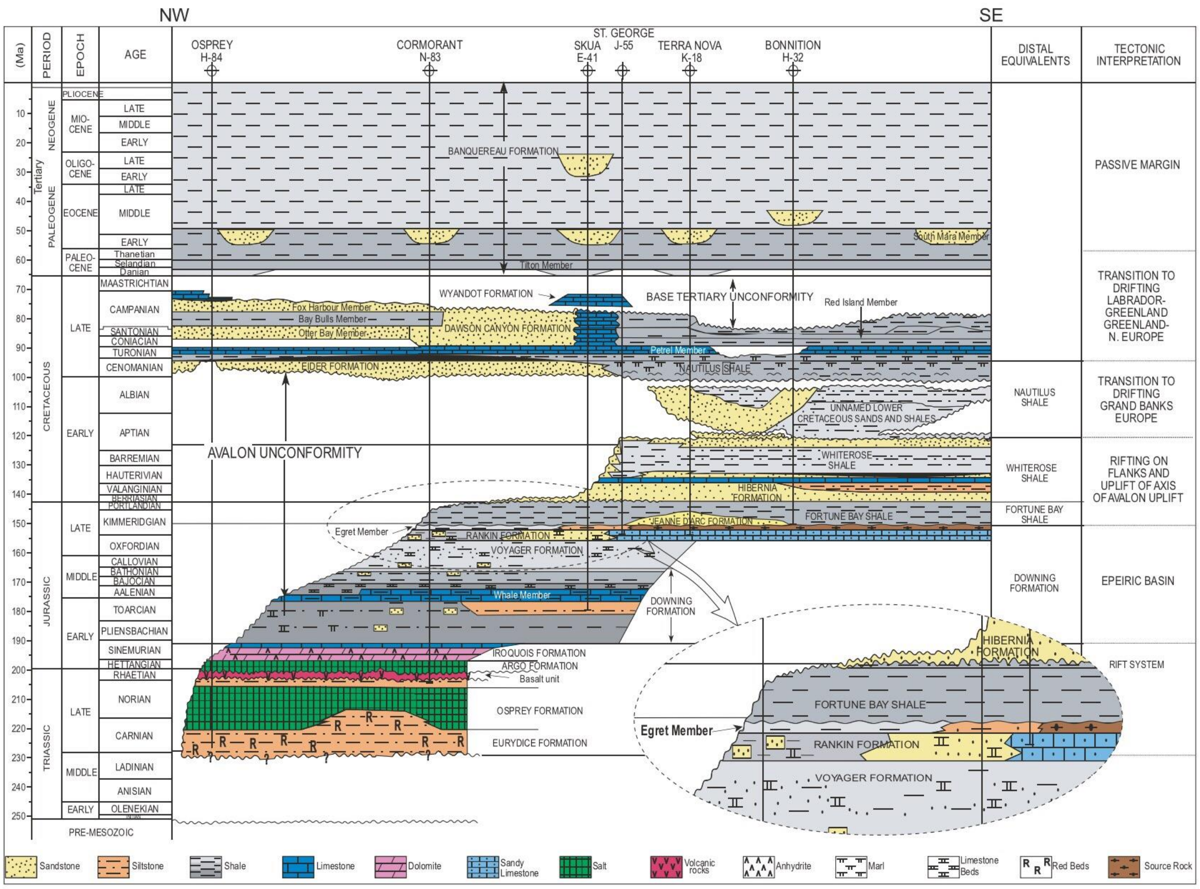

Figure 20. Stratigraphy of the Grand Banks (from Wielen et al., 2006)

Orphan Basin

Little public information is available on the deeper Jurassic sequences in this basin. One of the deepest wells, Great Barrasway F-66, was completed in the Rankin Formation (Gouiza et al., 2017). Thus, there is no readily available direct information on the pre-Callovian section.

Scotian Basin

Direct evidence on Lias sediments from the Scotian Basin is rare. Some early wells originally misinterpreted Middle Jurassic sequences as being Lias (e.g. Mohican I-100), but subsequent drilling results and improved chronostratigraphic appraisal have led to those observations being discounted.

US Eastern Seaboard

As with the Canadian basins on the eastern seaboard, the Lias remains largely unpenetrated in the exploration wells which have been drilled offshore to date (e.g. Prather, 1991). Several COST (Continental Offshore Stratigraphic Test) wells were drilled ca. 1980 along this margin. The only well originally recognized as including Lias age strata is the G-2 well drilled on Georges Bank (Poag and Schlee, 1984). However, this well was stratigraphically correlated with Shell's Mohican I-100 well on the Scotian Shelf (Scholle and Wenkam, 1982). Given that it is now understood that the Mohican well was actually completed in the Middle Jurassic, the COST G-2 biostratigraphic assignments need to be revisited before the significance of these observations can be properly assessed. The strata originally reported as being of Lias age generally have low organic carbon contents (i.e. <0.5% TOC), but are very high maturity (1.0-3.0% VR; Amato et al., 1980).

PETROLEUM SYSTEM CHARACTERISTICS

Several significant petroleum systems sourced from Lias age strata are known from around the world. Though published data on oil chemistries is typically hard to find in the public domain, sufficient information is available to afford some insights into common characteristics. Any distinctive properties of Lias age oils can be used to test potential fluid contributions to known accumulations offshore Nova Scotia, as well as future seafloor seep samples.

Basins with Lias Oil Accumulations

Oil geochemistry data, believed to have been generated from Lias age source rocks, has been compiled for the following basins (key characteristics summarized in Table 1):

- North Slope, Alaska
- Neuquen Basin
- Basque-Cantabrian Basin
- Lusitanian Basin
- Paris Basin
- Lower Saxony Basin
- Wessex Basin

North Slope, Alaska

The Lias age Kingak Shale Formation is recognized as an important source rock in this basin (Seifert et al., 1980; Premuzic et al.. 1986), with fields such as Alpine and Kaverak Point suggested as being sole sourced from the Lower Jurassic (Masterson, 2001). The Upper Jurassic is not a source rock in this region. The Lias oils have both light carbon (~ -31.4‰) and sulfur isotopes (~ -10‰; Premuzic et al., 1986).

Neuquen Basin, Argentina

Most of the hydrocarbons in this basin are sourced from the Upper Jurassic Vaca Muerte Formation, but some oils are found which are believed to be derived from the Lias age Los Molles Formation (Zumberge, 1993). The Lias sourced oils are located in the eastern portion of the basin, corresponding to the Rio Negro Norte Block. Zumberge (1993) used Principal Components Analysis (PCA) to distinguish the Los Molles (Lias) and Vaca Muerte (Tithonian) sourced oils. One of the most distinctive parameters reported is the carbon isotopic composition of the saturate and aromatic fractions, with the Lias oils being significantly lighter (d13C ~ -32 to -30‰).

Basque-Cantabrian Basin, Spain

Black shales of Pliensbachian age are the source of much of the oil in this basin (Beroiz and Permanyer, 2011). The only commercial accumulation is the Ayoluengo Field, discovered in 1964 and in continuous production until 2017 (largest field onshore Spain). These fluids are quite variable in oil gravity and sulfur content, this variability being primarily maturity related. Notably, the carbon isotopes of these oils are relatively light, similar to the compositions noted in the Neuquen Basin for example.

Lusitanian Basin

Numerous small oil fields are found in the Lusitanian Basin which are sourced from units in both the Lower and Middle Jurassic. The accumulations are mostly small, with little public domain information available on the reservoired oils.

Paris Basin

The first discovery in the Paris Basin was in 1958, but serious exploration interest only began around 1983 following the discovery of the large Chaunoy Field (Craig et al., 2018). Original reserves are relatively low, with conventional STOIIP of less than 300 million barrels (Ganley, 2008). The other most significant field is at Villeperdue, which contains a low sulfur, light oil (Peters et al., 2005).

Lower Saxony Basin

This basin is one of the oldest producing petroleum provinces in the world, with production dating from 1864, and has been Germany's dominant region of domestic oil production (Bruns et al., 2013). Multiple sources have contributed to the reservoired hydrocarbons, including the Zechstein (Permian), Wealden (Cretaceous) as well as the Posidonia (Toarcian). Typical Toarcian sourced oils are medium gravity with moderate sulfur contents, and relatively light carbon isotope compositions (Kockel et al., 1994).

Wessex Basin

The Wytch Farm oil field is the largest onshore hydrocarbon accumulation in Western Europe. Discovered by BP, it is still in production being operated by Perenco. The oil is a very low sulfur, light oil. Despite relatively shallow reservoir depths, which are below 80°C, the oils do not appear to be biodegraded. Wilhelms et al. (2001) attribute this phenomenon to the process of 'paleopasteurization.' The hydrocarbons are sourced from the Lias.

Distinguishing Lias Oil Characteristics

Though the number of available examples is limited, there appear to be a couple of fluid properties which are common amongst the examples compiled. Firstly, most of the oils are relatively light, generally with low sulfur contents. This is somewhat surprising given how many of the Lias source intervals are relatively carbonate rich.

The most notable common feature of these oils is the relatively light carbon isotopic compositions. Most of the Lias sourced oils have $\delta^{13}C$ values of around -30‰. This is significantly lighter than the typical values for Upper Jurassic sourced oils in the Scotian and Jeanne D'Arc basins which are both around -25.6‰ (Chung et al., 1992). Based on unpublished data from offshore Nova Scotia, no oils have yet been reported which have carbon isotopes as light as -30‰ (Fowler, pers com.). Thus, this might prove a useful tool for recognizing Lias charge in future oil and seep analyses. The sulfur isotopes may also be useful, if the very light values noted for the Kingak sourced oils in Alaska reflect a global control as does carbon.

Basin	Field	Reservoir	Oil Gravity	Oil % S	Oil $\delta^{13}C$		Data Source
			° API		Saturate	Aromatic	
North Slope	Alpine	Kingak Fm.	36 - 39	< 0.30	-30.7	-30	Masterson (2001)
Neuquen	Estancia Vieja	Lajas Fm.	21 - 23	~ 0.45	-31.5	-30.5	Zumberge (1993)
	Puesto Flores	- ? -	23.1	0.04	-33.9	-32.8	
Basque	Ayoluengo	Purbeck	24 - 37	-	-30.1	-29.4	Beroiz and Permanyer (2011)
Lusitanian	Northern Sector	Lias	-	-	-28.9		Brito et al. (2017)
Paris	Ville Perdue	Callovian Oolite	38.3	0.25	-30.4	-29.4	Peters et al. (2005)
Lower Saxony	Multiple	Various Mesozoic	25.7	0.75	-	~ -29.0	Kockel et al. (1994)
Wessex	Wytch Farm	Bridport Sands	40.2	0.12	-30		Perenco (2018); Burwood et al. (1991)

Table 1. Compilation of basic oil properties for Lias sourced oils from around the world.

DISCUSSION

It is evident from this review that organic richness occurs in every stage of the Lias. It is often assumed by exploration geologists that the Toarcian is the most important period in the Lower Jurassic for source rock deposition. This is clearly not the case.

Stratigraphic Synthesis

Simplified sedimentary sequences for the locations described in this report are shown in Figure 21. High level scrutiny of this graph reveals several intriguing features, as follows:

- The Toarcian section is absent in a significant number of locations
- Missing sections in the older Lias epochs is generally a continuation of the Toarcian removal
- The Pliensbachian comprises coarse clastics in a disproportionate number of locations, especially northwest Europe

These characteristics have important implications when it comes to understanding the spatial distribution of Lias source rocks.

Removal of Section

The locations with missing section, in particular with reference to the Toarcian, demonstrate that uplift and erosion is a major control on source rock presence. This is a first order control on source occurrence and distribution. Understanding which processes control uplift and where this is a critical risk for Lias age sequences should obviously be a central topic for future studies. Thermal doming under the North Sea during the late Toarcian and the Aalenian, as described by Underhill and Partington (1993), is probably responsible for the some of the examples in this study.

Non-Source Deposition

In many locations, sedimentary sections are present, but comprise coarse clastic, or organic lean shales or carbonates. In many cases, this is due to shallow water depths and/or proximity to major clastic sources. During the Pliensbachian, as mentioned above, many locations have dominantly sandy lithologies. This may well be uplift related. An intriguing example is the Hebrides Basin, off the northwest coast Scotland, where a Hettangian/Sinemurian shale section gives way to coarse clastics during the Pliensbachian, but returns to shale deposition at the start of the Toarcian. It seems unlikely that this uplift is related to the North Sea doming which initiates later, towards the end of the Toarcian. Understanding how varying basin dynamics interrelates with global eustatic trends is needed to finesse a prediction methodology to account for such situations.

Several locations are close to paleo terrigenous clastic sources, and these display characteristic proximal sedimentary characteristics, i.e. prodelta shales interbedded with thick sands, and in some instances, occasional thin coals. Some of the locations in Scandinavia, Sverdrup and Svalbard are typical examples. The Barents Sea is similar, but it is reported that organic rich shales do occur with the Nordmela Formation. Thus, source rocks might occasionally occur in such settings, but this is certainly high risk.

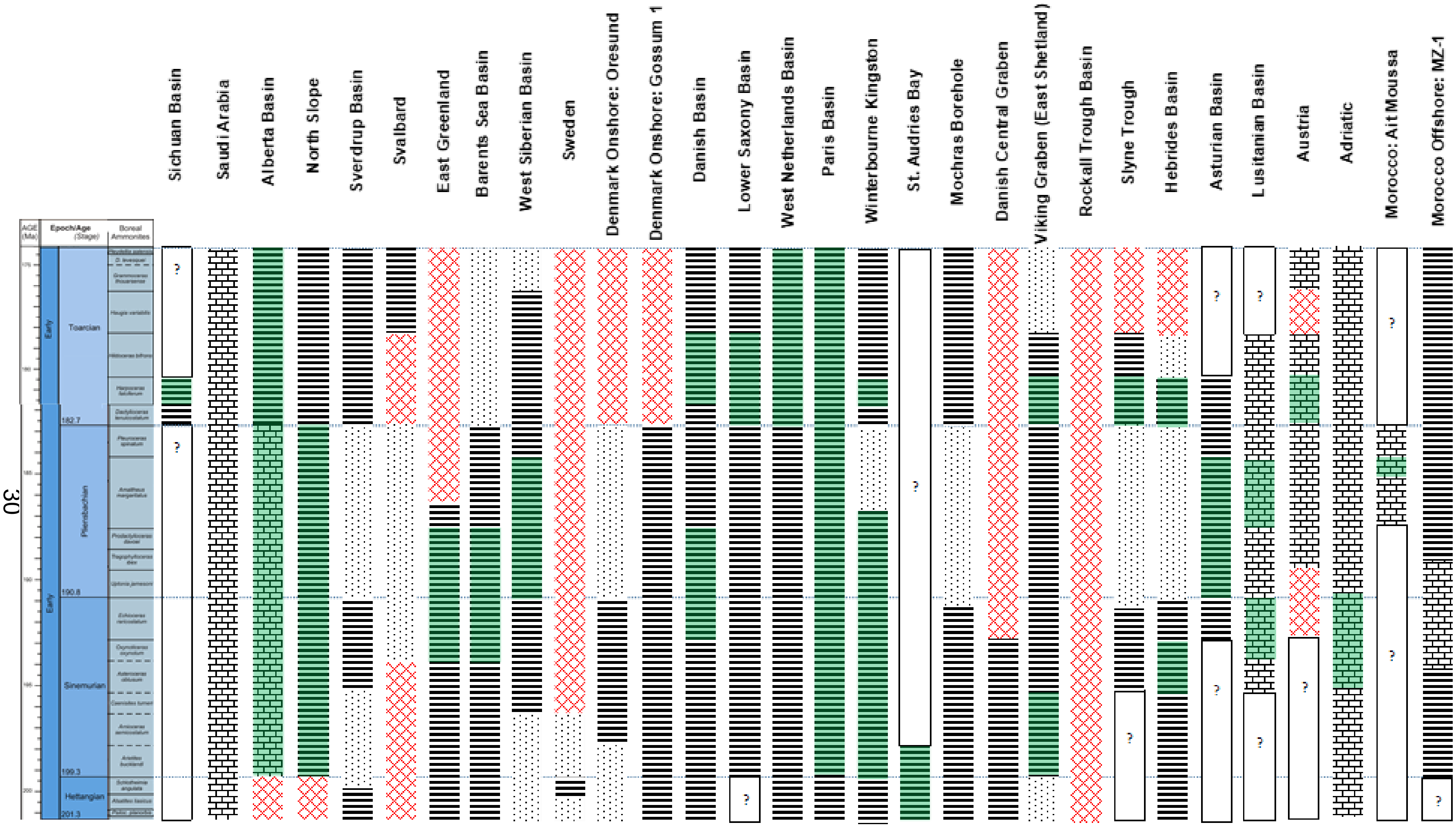

Figure 21. Synthesis of major Lias sections summarized in this study. Zones of organic enrichment highlighted in green. Lithologies for shale, sandstone and limestone shaded with standard symbologies.

Spatial Distribution of Source Rocks

Figure 22 shows the distribution of significant organic rich intervals across the greater North Atlantic region, plotted on a 195 Ma paleogeographic map (Scotese, 2014). Though data density is limited, some notable characteristics are evident.

Little information is available for the Hettangian, but scattered examples of the Sinemurian are found across much of the region. However, location density is too sparse to draw any significant conclusions. The Pliensbachian follows an arc which coincides for the most part with the eastern margin of the Atlantic (probably reflecting data availability rather than a mechanistic preference for the eastern margin over the west). Conversely, the Toarcian forms a belt at a right angle to the Atlantic, paralleling the midline of the Tethys.

Are these observations significant, or is this just happenstance co-incidence of a limited data set? Hopefully, additional data in the future may help clarify this.

But assuming this is real, it hints at possible major megaregional controls. The distribution of the Pliensbachian suggests that this source rock was deposited in association with basin conditions primarily responding to the Atlantic rifting. Conversely, the Toarcian source rocks may have been related to Tethyan basin processes. Applicable basin processes to consider include uplift/subsidence, upwelling, inflow of nutrient / low oxygen waters, and restriction. But until more information is forthcoming, these suggestions are highly speculative.

Future Work

Key regions to investigate further, in order to better understand these source rock spatial differences, are (1) Iberia and (2) Southern England (i.e. Wessex Basin). In the Iberian basins, decent thicknesses of Pliensbachian organic rich sediments are overlain by shallow-water, non-source Toarcian lithologies. Similarly, in the Wessex Basin, optimal Sinemurian and Pliensbachian source rocks are overlain by a condensed Toarcian section, but with a very thin organic rich interval. What basin processes control original organic content of deposited sediments and accommodation space in these locations?

Understanding regional uplift patterns, and how those relate to the Scotian Basin will require a robust characterization of basin dynamics. Important considerations are where deep igneous activity, e.g. mantle plumes, are having an effect and their timing. Changes to the rate of seafloor spreading may also be part of this story.

Finally, additional work is needed to consider non-source, thick shale sections, which may or may not be proximal to terrigenous point sources. One example is the Mochras borehole in northwest Wales. This core contains a full Lias sequence spanning from the end Triassic through the end of the Toarcian. It includes over 250m of Toarcian fine grained sediments which are typically ~1% TOC and with HI values of ~200. Is this dilution or poor preservation due to oxygenation?

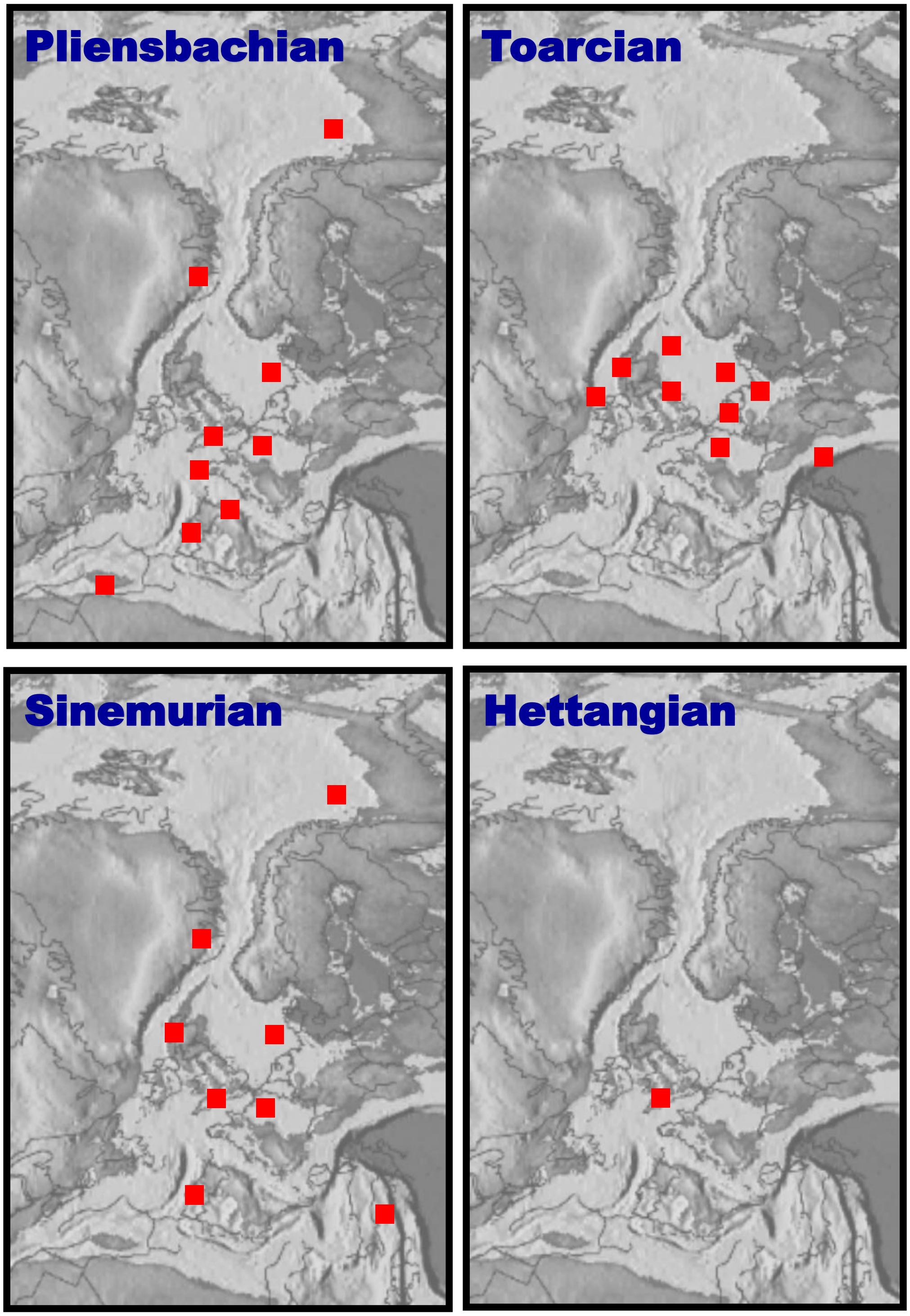

Figure 22. Distribution of significant organic rich sequences across the greater North Atlantic region, broken out by epoch. Locations per Figure . Lias (195 Ma) paleomap from Scotese (2014).

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