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Stratigraphical palynology of the Middle to Late Triassic successions of the Central North Sea

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Abstract:
Historically the continental Triassic successions of the Central North Sea (CNS) have proven difficult to correlate in part due to the poor palynomorph recovery associated with these sedimentary rocks. The existing framework for correlation is lithostratigraphical and whilst this has proven effective in United Kingdom Continental Shelf (UKCS) Quad 30 where the mudstone members are well defined, elsewhere in the basin it is more problematic with confident identification of stratigraphic units becoming more difficult. Samples from 32 wells within UKCS Quads 22, 29 & 30 and Norwegian Quads 7, 15 &16 underwent palynological analysis in which a processing method was utilized that was designed to concentrate palynomorph recovery from Triassic strata.

The results of this analysis allowed the proposal of a new zonal scheme consisting of 8 biozones. These biozones can then be used to correlate the Triassic successions of the CNS, helping provide both clarity and age constraint on previously disputed stratigraphic units, particularly the J-members of the Skagerrak Formation. Within the correlation framework outlined here the Julius Mudstone Member is shown to be a productive horizon for palynomorph recovery, representing a widespread swamp environment. Here its lateral extent is defined which is an important consideration when correlating the Triassic stratigraphy of the CNS given that this member can compartmentalize potential reservoirs contained within these successions. The stratigraphical palynology outlined here also allows clarity on the J-member equivalence of some of the informal units previously described within Triassic successions of the CNS including the Marnock shale and Heron shale.

In recent years there has been renewed interest in the High-Pressure High Temperature (HPHT) hydrocarbon reservoirs contained within the Triassic successions of the Central North Sea (CNS), with these reservoirs becoming more attractive production targets (McKie & Audretsch, 2005). However, hydrocarbon extraction in the past has been hindered by a lack of knowledge regarding stratigraphy at a basinal, sub-basinal and field scale (e.g. Goldsmith et al., 1995).

The continental environment of the Triassic successions of the CNS restricts biostratigraphic control to terrestrial palynology; specifically spores, pollen and algae. Palynology has been routinely used within the petroleum industry as a tool to aid stratigraphical and environmental analysis, however previous palynological analysis of Triassic sedimentary rocks within the CNS has been limited by poor recovery due to a combination of the use of Polycrystalline Diamond Compact (PDC) drill bits, oil-based muds, poor palynomorph preservation and the heavily oxidised nature of Triassic sediments (Goldsmith et al., 1995). To date very little palynology data has been published from the CNS, with Goldsmith et al. (1995, 2003) and Mouritzen et al. (2017) largely the only authors to have published on palynomorph content from the Skagerrak Formation in any detail. Additional unpublished work has been performed looking at the sedimentological controls on palynomorph preservation from the Skagerrak Formation (Farris, 1999), however this latter work is restricted to cored intervals. Whilst there is a limited amount of published palynological data available for the CNS, extensive palynological research exists in adjacent regions including the Barents Sea (Mangerud & Rømuld, 1991; Vigran et al., 1998; Paterson & Mangerud, 2015, 2017, 2019; Vigran et al., 2014) and North West Europe (Geiger & Hopping 1968; Herngreen, 2005; Kürschner & Herngreen, 2010; Lindström et al., 2009, 2017; Orlowska-Zwolinska; 1984). It is the understanding of palynofloral trends in these adjacent regions that help provide constraint for the palynofloral trends observed in the CNS, particularly as there is little independent macrofaunal or chronostratigraphic age control for the CNS.

By utilizing a refined laboratory processing method, this study aims to concentrate palynomorph assemblages from the Triassic successions of CNS to allow for an improved and enhanced regional understanding of this area.

Geological setting:

Within the Central Graben area, the Triassic successions of the North Sea can be divided into two; the Early Triassic Smith Bank Formation and the Middle-Late Triassic Skagerrak Formation. The Smith Bank Formation is thought to represent a predominantly distal aeolian environment and consists of a monotonous sequence of brick red, silty claystones (Deegan and Scull, 1977) whilst the Skagerrak Formation is dominated primarily by fluvial deposits comprising a succession of alternating sandstone and mudstone members (Goldsmith et al., 1995; McKie, 2014). It is the sandstone members within the Skagerrak Formation that form important primary and secondary reservoirs and are of considerable commercial interest, however these reservoirs may be compartmentalized by the mudstone members that have the potential to act as baffles and seals making understanding their distribution important (e.g. McKie & Audretsch, 2005).

The Skagerrak Formation in the CNS is thought to represent the distal end of a terminal fluvial system developed within an endorheic basin with possible axial drainage to the south and sourced via lateral drainage systems derived from highlands in the UK and Fennoscandia (Mckie, 2014). The Skagerrak Formation has been sub-divided using the J-member system nomenclature developed by Goldsmith et al. (1995). Within the J-member system, 6 members were identified; 3 sandstone dominated members and 3 mudstone dominated members (Fig.1). The sandstone members were named after the ConocoPhillips fields from where they were first recognised and in ascending stratigaphical order these are the: Judy, Joanne and Josephine members. These sandstone members are interbedded with the Julius, Jonathan and Joshua mudstone members. The stratigraphy of these members is shown in figure 1. Due to Jurassic uplift and erosion the Josephine and Joshua members are rarely preserved. Additional to members described by Goldsmith et al. (1995), a number of other lithostratigraphical names have become established in the literature in the Triassic of the CNS including the Marnock Shale, The Heron Shale and the Bunter Sandstone (Mckie & Audretsch, 2005). The Marnock Shale is situated beneath the main sandstone reservoir within the Marnock Field, however there is still discussion as to the age of this shale and its equivalence to the J-members. The Heron Shale lies above the main sandstone reservoir in the Heron Field and as with the Marnock Shale its correlation to the J-members remains uncertain. The term Bunter Sandstone has been used to refer to sandstone successions thought to be correlative to the Smith Bank Formation and may be lateral equivalents of the Bunter Sandstone Formation described in the Southern North Sea (McKie, 2014).

Within the Triassic of the Central North Sea, halokinesis of the underlying Zechstein salt had a strong influence on Triassic deposition. Early Triassic syn-rift extension may have instigated the formation of a series of north-south oriented salt walls or ridges (Goldsmith et al., 2003) with differential sediment loading in the intervening depo-centres causing the development of synform 'sediment pods' (Hodgson et al., 1992) creating a "mini basin" topography across the Central North Sea. It is thought that the majority of the fill within these sediment pods comprises the Smith Bank Formation with the lower part of the Skagerrak Formation then being deposited by ephemeral sheet floods flowing over and between sediment pods with preservation potential greatest in the centre of subsiding pods (Mckie, 2014). The mid to upper Skagerrak Formation then most likely represents a more confined channelised depositional system (Hodgson et al., 1992).

Methods:

To maximise palynomorph recovery both a targeted sampling approach and a refined palynology processing technique was adopted. A summary of this technique is outlined below.

Targeted sampling:

To obtain better palynomorph yields care was taken to target finer grained intervals, as these are thought to be indicative of lower energy environments and thus more likely to yield better recovery. In core samples this was done by visually inspecting the core and identifying intervals of finer grained mudstone layers or in some instances targeting mudstone clasts from channel lags, as it was assumed due to the size and angular nature of these clasts they probably originated from an adjacent muddy floodplain or overbank deposits close to the channel. In cuttings samples finer grained intervals were identified using well log data to pick out intervals with both a consistently higher gamma ray value and a more pronounced cross over on the neutron density log. This combination of the gamma ray and neutron density logs was used as the high feldspathic content of the sandstones within the Skagerrak Formation gives it an anonymously higher gamma ray value than usually associated with sandstone packages (Goldsmith et al., 1995).

Palynology processing technique:

A variety of processing techniques have been outlined in the literature (Vidal, 1988; Grey, 1999; Traverse, 2007) and most involve Hydrofluoric acid digestion. Here a processing technique was developed that modified methods commonly used within industry to more effectively concentrate palynomorph content within Triassic samples of the CNS, particularly ditch cutting samples. Fundamentally this technique uses industrial strength detergent/degreasers in conjunction with conventional acid maceration steps to help clean up and concentrate structured organic material. Heavy liquid separation and swirling methods were then utilised to further concentrate palynomorphs from within the samples.

Approximately 15-20g of rock was used in each sample. Core samples were crushed using a pestle and mortar to increase the surface area of the sample to aid acid digestion and prior to crushing they were washed and scrubbed with a wire brush to try and remove any drilling contaminates that may be present. Cuttings also underwent this crushing process however beforehand they went through a solvent extraction process in which the cuttings were soaked in Dichloromethane solvent in order to remove any residue drilling fluid that may have coated them. This is important because if this drilling fluid is not properly removed then it will impede acid digestion and clog the pores of the sieve mesh preventing effective sieving of the samples after acid digestion.

To breakdown and demineralize the samples they were treated with cold Hydroflouric acid (HF) for 48 hours during which they were periodically agitated. Once HF digestion was complete, samples were neutralised with water through a series of dilution and decanting cycles, after which they were sieved using a 7µm nylon mesh. Each sample was then treated with 100ml of Hydrochloric acid (HCl) and heated for 20 minutes whilst being agitated via the use of a magnetic stirrer, after which they were once again sieved at 7µm. Following the HCl treatment a high concentrate industrial strength detergent/degreaser (ARCO cleaner) was then added to each sample which was then heated and agitated for a further 20 minutes before being sieved again.

Standard oxidation techniques were then applied to each sample in which cold Nitric acid (HNO_3) was added to each sample for 3 minutes before sieving. After oxidation the detergent treatment was repeated on each of the samples before they underwent heavy liquid separation using Sodium-Polytungstate (SPT) made to a specific gravity of 2.2. The organic residue extracted from each sample via heavy liquid separation was then swirled to separate the finer organic component from heavier organic debris. The finer organic component was then mounted onto a glass coverslip in a PVA solution which in turn was then glued to a glass slide using Petropoxy resin.

In order to gain a quantitative analysis of the palynomorph assemblages the first 250 specimens in each slide preparation were identified and counted. In samples with impoverished recovery where a 250 count was not possible then the entire slide was scanned and all palynomorphs present were counted. All Microscopy work was carried out on an Olympus BX51 microscope.

Results:

Palynomorph recovery:

A total of 344 samples were processed for palynological analysis across 32 wells (fig.2). Palynomorph recovery was variable and table 1 gives an overview of total palynomorph abundance from samples analysed across the study area. Palynomorph recovery was classified as either: abundant (total count = 200+), good (total count = 100 to 199), moderate (total count = 20 to 99), poor (total count = 10 to 19), very poor (total count = < 10) or barren (total count = 0). Any mention of palynomorph recovery hereafter is done so in the context of this classification system. Recovery was best from the J-ridge area of UKCS Quad 30, and was particularly good from two wells in the Judy Field; 30/07a-7 and 30/07a-9. The members encountered in these two wells have already been confidently identified (Goldsmith et al., 1995), so they were used as a “reference section” from which to develop a palynostratigraphic framework. This framework could then be used to correlate across the study area to wells where the member identification is more ambiguous, as well as allowing for subdivision of members.

Taxonomy:

Due to the highly variable level of preservation and heavily degraded nature of some of the recovered palynomorphs, a functional approach to taxonomy was utilized. In order to categorise some of the more degraded palynomorph specimens that could not be confidently assigned to a formal species or genus, a number of informal morpho-groups were also used. These groups describe palynomorphs that can be categorized by some basic morphological feature but the degraded level of preservation prevents any further identification, examples of these groups include; 'Saccates indeterminate' (palynomorph with a bisaccate outline), 'Pale spore' (trilete spore with a thin leavigate exine giving a pale to translucent appearance),' Spore indeterminate' (palynomorph with a visible trilete mark), 'Granulate sporomorph' (a structured palynomorph with a granulate texture) and 'Sporomorph indeterminate' (a structured palynomorph that lacks any defining morphological features).

Discussion:

Palynofloral events observed in the Judy Field "reference section":

Wells 30/07a-7 and 30/07a-9 are located approximately 5km apart and give a composite section from the lower Jonathan Member of the Skagerrak Formation through to the underlying Smith Bank Formation. The key palynofloral events from these two wells are shown in Figure 3.

30/07a-9

Well 30/07a-9 first penetrates the Skagerrak Formation in the lower part of the Jonathan Member at a drilled depth of 11,822ft (note all depths referred to hereafter are measured depths whilst drilling) where it is unconformably overlain by Cretaceous strata of the Valhall Formation. The well path then penetrates the Joanne, Julius and Judy members before reaching TD at 14,473ft in the upper part of the Judy Member. Two core runs were taken in the upper part of the Joanne Member between 12021ft and 12202ft with 180ft of recovered core. Thirty-two samples were analysed for palynology for this well in total; 6 core samples and 26 cutting samples. Some Paleogene palynomorphs were present in many of the cuttings samples due to contamination from the drilling mud and these specimens were isolated and excluded from the count data.

Jonathan Member (11822–11948ft)

Two cuttings samples were processed from the lower Jonathan Mudstone Member, the first at 11,850ft had very poor recovery with only a few degraded palynomorphs that could not be confidently identified. The second sample taken at 11,900ft had moderate palynomorph recovery with the presence of *Classopollis torosus* and *Limbosporites lundbladiae.*

Joanne Member (11948–13487ft)

Nineteen samples were analysed from this member; 13 cutting samples and 6 core samples. Palynomorph recovery was variable throughout this member, but intervals of good to abundant recovery were observed. *Classopollis torosus* and *Limbosporites lundbladiae* were recorded intermittently until their last downhole occurrence (first appearance datum) at 12,500ft. Within the cored interval an influx of *Araucariacites* spp. was recorded at 12040.2ft and several specimens of *Ovalipollis pseudoalatus* were recovered at 12102.1ft.

An interval of abundant recovery was recorded in the middle of the Joanne Sandstone Member at 12,880ft with an assemblage largely dominated by *Triadispora crassa*, *Triadispora* spp. and 'Saccates indet'. The first downhole occurrences (last appearance datum) of *Illinites kosankei* and *Retisulcites perforatus* were also recorded from this interval along with singular specimens of both *Protodiploxypinus doubingeri* and *P. sittleri*.

The lower part of the Joanne Sandstone Member is characterized by moderate to poor recovery with assemblages mainly dominated by gymnosperm pollen e.g. *Triadispora* spp. or more degraded palynomorphs such as 'Saccates indet' and 'Sporomorph indet'. Some spores were also recorded from this lower Joanne Member interval including *Aratrisporites* spp. and *Todisporites* spp. as well as a single specimen of *Densoisporites* spp. Recovery appeared to decline toward the basal part of the Joanne Member.

Julius Member (13487–13946ft)

Five cuttings samples were analysed from the Julius Member and were characterized by diverse assemblages with palynomorph recovery ranging from good to abundant. The interval between 13650ft to 13800ft yielded the best recovery from this member. The first common downhole occurrences of *Protodiploxypinus doubingeri* and *P. sittleri* were observed towards the upper boundary of the Julius Member. *Protodiploxypinus decus* was also found in this interval.

An increase in spore abundance and diversity was observed in the Julius Member, most notably a large influx of *Porcellispora longdonensis* as well as increases in *Cyclotriletes* spp. – *large, Todisporites* spp. and 'Pale spores'. Gymnosperm pollen were still common throughout this member including *Triadispora crassa, T. staplini, Triadispora* spp., *Spheripollenites* spp. and *Inaperturopollenites* spp.. The presence of *Retisulcites perforatus* was also noted to occur constantly, albeit in low numbers and an influx of *Triadispora crassa* was observed at 13800ft. The first downhole occurrence of *Jerseyiaspora punctispinosa* was recorded at the basal part of the Julius Member at 13,900ft.

Judy Member (13946–14473ft)

Only the upper part of the Judy Member is present in this well and six samples were analysed from this interval. All but one sample yielded good to abundant recovery with diverse palynomorph assemblages recorded. The one sample that did have reduced recovery was from the upper most part of this interval. Gymnosperm pollen remained a significant component of the assemblages from all these samples, with *Triadispora* and *Protodiploxypinus* taxa common throughout. Increases in *Protodiploxypinus fastidiosus, Striatoabietes* spp. and "Striate Saccate spp". were also recorded. Spore taxa were still common with increases in *Todisporites* spp., *Densoisporites* spp. and *Calamospora* spp. An acme of *Aratrisporites scabratus* and *Aratrisporites* spp. was observed between 14180ft and 14270ft. *Plaesiodictyon mosellanum* algae was also recorded consistently through the Judy Member section of this well albeit in low numbers.

30/07a-7

Well 30/07a-7 first penetrates the Skagerrak Formation in the Julius Member at 11,119ft where similar to well 30/07a-9 it is unconformably overlain by Cretaceous strata of the Valhall Formation. The well path then penetrates the Judy Member, Marnock Shale and Bunter sandstone before reaching TD in the Smith Bank Formation at 13,500ft. Three core runs were taken in the upper part of the Judy Member between 11289ft and 11553.3ft with 205ft of core recovered. Thirty-eight samples were analysed for palynology in this well; 20 core samples and 18 cutting samples. As with well 30/09a-9 some Paleogene contamination was present in the cuttings samples.

Julius Member (11119–11286ft)

Three cuttings samples were processed from the Julius Member and all had abundant recovery. The palynomorph assemblages recorded were very similar to those recorded from the Julius Member samples in well 30/07a-9, particularly with the acme of *Porcellispora longdonensis*.

Judy Member (11286–12533ft)

Twenty-nine samples were analysed from the Judy Member; 20 core and 9 cuttings samples. The upper part of the Judy Member from 11292.5–11700ft was most productive with the majority of samples yielding diverse and abundant assemblages. The 20 core samples were taken between 11292.5 and 11551.7ft with sample spacing ranging from 3.6ft to 18.8ft depending on targeted lithologies but averaging approximately 10ft. this resulted in a reasonably high resolution palynological analysis of the cored interval. From the 20 core samples; 12 had good to abundant recovery; 2 had moderate recovery and 5 yielded very poor recovery.

The first downhole occurrence of *Jerseyiaspora punctispinosa* was recorded at 11292.5ft, which differed slightly from well 30/07a-9 where it was recorded in the basal part of the Julius Member. However, this might be a function of sampling as the Julius/Judy Member boundary in this well is 11286ft but due to the limited quantity of cuttings material available it was not possible to sample below 11240ft, so it is possible that *J. punctispinosa* is present in the un-sampled basal Julius interval. Similar to well 30/07a-9 increases in *Todisporites* spp., *Densoisporites* spp. and *Calamospora* spp. were observed in the upper part of the Judy

Member, along with an acme of *Aratrisporites scabratus*. There were two distinct influxes of *A. scabratus* within this well; one at 11326.5ft and another between 11464.3-11470ft as opposed to the one more general influx observed in well 30/07a-9. This may be a function sample type as the two influxes observed in well 30/07a-7 were recorded from core and the acme from well 30/07a-9 recorded from cuttings. Cuttings potentially blur distinct influxes into a more general acme.

Similar to well 30/07a-9 gymnosperm pollen still made up a significant component of the assemblages with *Triadispora* and *Protodiploxypinus* taxa common throughout. An increase in *Protodiploxypinus fastidiosus* was also recorded. A few specimens of *Retisulcites perforatus* were found from a number of core samples from the upper part of the Judy Member. As with well 30/07a-9, the alga *Plaesiodictyon mosellanum* was recorded in the upper part of the Judy Member, however, whilst it had been observed in low numbers in well 30/07a-9 here it was much more abundant with 4 distinct influxes (at 11292.5ft, 11347.6-11362.6ft, 11477.1ft and 11528ft). "Striate bissacate spp." were also more common in this well than in well 30/07a-9, with 3 distant influxes observed at 11311.8-11314.7ft, 11347.6ft and 11486.6ft respectively.

An influx of *Protodiploxypinus doubingeri*, *P. sittleri* and *Protodiploxypinus* spp. was observed at 11600ft. Below 11700ft palynomorph recovery declines with most samples having poor or very poor recovery until 12370ft where an interval of good recovery was observed, however diversity was low in this interval and the preservation of palynomorphs was poor consisting of mostly degraded forms such as "Saccates indet" or "Sporomorph indet".

Marnock Shale (12533–12650ft)

This interval was thought to represent a UKCS Quad 30 lateral equivalent of the Marnock Shale defined in UKCS Quad 22 (Goldsmith et al., 1995; McKie & Audretsch, 2005; Mouritzen et al., 2017). One sample underwent palynological analysis from this interval from which 9 in-situ Triassic palynomorphs were recovered however these were mostly degraded specimens. This unit was primary identified on log character.

Bunter Sandstone (12650–12893ft)

This interval was thought to represent a UKCS Quad 30 lateral equivalent of the Bunter Sandstone identified Quad 22 below the Marnock shale. (McKie & Audretsch, 2005). Two samples from this unit underwent palynological analysis; one was barren of in situ Triassic palynomorphs whilst the other contained one heavily degraded "sporomorph indet." As with the Marnock shale this unit was identified on log response. Within UKCS Quad 22 this unit is better developed whilst here it thought to represent a more distal lateral equivalent.

Smith Bank Formation (12893-13550ft)

Three samples were analysed from the Smith Bank Formation and recovery was very poor to barren. Two samples were barren of Triassic palynomorphs, whilst one "bissacate indet." was recovered from other.

Palynofloral zones:

Using the key palynomorph events observed in wells 30/07a-9 and 30/07a-7 (Fig. 3) a zonation scheme of palynofloral events was constructed with eight identifiable biozones that could then be used to correlate over the study area (Fig.4). A selection of the key taxa that define these biozones are illustrated in Plate 1. These biozones are restricted to the Skagerrak Formation as the impoverished palynomorph recovery observed within the Marnock shale, Bunter Sandstone and Smith Bank Formation, prevented the identification of any useful palynofloral events.

***Classopollis* zone (CP):**

Age: Norian or younger

Description: This zone is defined by the presence of *Classopollis torosus.* The upper boundary of this zone is difficult to identify due to the combination of reduced recovery associated with the Jonathan Member and from the stratigraphy missing as a result of Post-Triassic uplift and erosion. The lower boundary of this zone is identified by the last downhole occurrence of *Classopollis torosus*. *Limbosporites lundbladiae* was common from the Judy Field "reference section" in this zone but it was rarely encountered elsewhere. An influx of *Araucariacites* spp. along with the occurrence of *Ovalipollis pseudoalatus* was also observed in association with this zone from the "reference section". This zone spans from Jonathan Member to the upper part of the Joanne Member.

Remarks: *Classopollis torosus* is often documented as having a last down hole occurrence at the base of the Norian stage (Warrington 1984; Goldsmith et al., 1995; Crilli, 2010), and is known to be common in the Norian from the Barents Sea where it has been calibrated against early Norian ammonoid fauna (Paterson & Mangerud, 2019). *Limbosporites lundbladiae* is described as being characteristic of Rhaetian aged sediments from North West Europe (Herngreen, 2005; Crilli, 2010; Kürschner & Herngreen 2010) but has been found in Norian aged sediments from the Barents Sea (Vigran et al., 2014). The presence of *C. torosus* constrains the age of this biozone as Norian or younger, whilst the presence of *L. lunbladiae* could be suggestive of the Rheatian.

The genus *Araucariacites* has previously been found to be common in the Late Triassic (Carnian or younger) from the Barents Sea (Hochuli & Vigran, 2010) and *Ovalipollis pseudoalatus* has a known stratigraphical range from the Ladinian to the Rhaetian (Goldsmith et al., 2003; Herngreen, 2005), so both these taxa would be consistent with the Norian or younger age proposed for this interval.

***Retisulcites* zone (RSt):**

Age: Ladinian

Description: The upper boundary of this zone is defined by the first downhole occurrence of *Retisulcites perforatus*. Within the "reference section" the first downhole occurrence of *Illinites kosankei* and an influx of bisaccates including; *Triadispora crassa*, *Triadispora.* spp. and *"*Saccates indet*"* were associated with this zone. Singular specimens of both *Protodiploxypinus doubingeri* and *P. sittleri* were also observed within this zone from well 30/07a-9. This zone spans an interval within the middle part of the Joanne Member. Within the "reference section" this zone was recorded in only one sample. Across the study area this zone was only confidently identified in two wells (30/07a-7 and 30/12b-2), and tentatively identified in another (22/29-2), so a degree of caution is needed when correlating this biozone.

Remarks: *Illinites kosankei* is thought to range from the Anisian to the mid-Carnian (Goldsmith et al., 1995) and *Retisulcites perforatus* is thought to be restricted to the Ladinian (Warrington, 1984; Goldsmith et al., 2003), such that the latter constrains this zone as being attributable to the Ladinian. However, whilst *R. perforatus* is thought to be restricted to the Ladininan in the CNS (Goldsmith et al. 2003) and is most often associated with sediments considered to be Ladinian in age from NW Europe (Herngreen, 2005), the morphotype was first described by Madler (1964) from the lower Keuper of the South Permian Basin, which represents Ladinian to Carnian aged sediments (Kürschner et al., 2010). This species has also been recorded from Carnian or younger aged sediments by some authors (Morbey & Dunay, 1978; Embry & Suneby, 1994), and within the Barents Sea it has a described range from the Julian substage of the Carnian to the Illyrian substage of the Anisian (Paterson & Mangerud, 2019). So, whilst the first downhole occurrence of *R. perforatus* within this biozone may represent the top Ladinian in the CNS, it could also potentially represent a low resolution Ladinian to Carnian interval. However, this biozone is no younger than mid-Carnian based of the first downhole occurrence of *I. kosankei* (Goldsmith et al. 1995). Interestingly, a few specimens of *R. perforatus* were found from a number of core samples from the upper part of the Judy Member which is thought to be Anisian in age (Goldsmith et al., 1995; Archer et al., 2010; Mouritzen et al., 2017). So, whilst Goldsmith et al. (2003) recorded this species as ranging from the top Ladinian to the base Ladinian in the CNS, within the dataset presented here the last downhole occurrence of *R. perforatus* seems to be more consistent with the upper part of the Anisian.

***Protodiploxypinus* zone (PDt):**

Age: Ladinian

Description: The upper boundary of this zone is identified by the first common downhole occurrence of *Protodiploxypinus doubingeri* and *P. sittleri*. *Protodiploxypinus decus* is found in association with this zone and *Triadispora* forms are common including *T. crassa* and *T. staplini*. *Retisulcites perforatus* is also found within this zone. The upper boundary of this zone typically coincides with the upper boundary of the Julius Member and lower boundary is identified by the top of the underlying *Porcellispora zone* (PCi).

Remarks: *Protodiploxypinus doubingeri* and *P. sittleri* are thought to have a first downhole occurrence in the Fassanian sub-stage of the Ladinian in the CNS (Goldsmith et al., 1995), and *P. decus* is considered to have a last downhole occurrence at the Anisian/Ladinian boundary (Goldsmith et al. 2003). Whilst last downhole occurrence events have to be used with caution in cuttings samples, the consistent appearance of *P. decus* within this zone in conjunction with the common appearance of *P. doubingeri* and *P. sittleri* would constrain the age for this interval to early Ladinian. Singular specimens of both *P. doubingeri* and *P. sittleri* were observed in the above Retisulcites (RSt) biozone in well 30/07a-9, however it is thought that those specimens may be reworked. It is worth noting that in the Barents Sea, *P. decus* is considered to have a different range than that suggested by Goldsmith et al. (2003) for the CNS. Within the Barents Sea, *P. decus* is described as having a first downhole occurrence at the top of the Anisian (Vigran et al., 2014), however this has been questioned by some authors (Paterson & Mangerud, 2019), who have observed it in younger sediments from this region. *P. decus* has also been recorded from Keuper sediments from the Polish Carpathian Foreland which are believed to be Carnian in age (Pautsch, 1973).

***Porcellispora* zone (PCi):**

Age: Ladinian

Description: The upper boundary of this zone is identified by a significant influx of *Porcellispora longdonensis*. As with the PDt biozone *Protodiploxypinus doubingeri*, *P. sittleri* and *Triadispora* forms are still common and *P. decus* and *Retisulcites perforatus* are still present. An increase in *Spheripollenites* spp., *Inaperturopollenites* spp. and "*Cyclotriletes* spp. – *large"* is also associated with this zone. The lower boundary of this zone is defined by either the upper boundary of the underlying zone or an interval of reduced recovery.

Remarks: *Porcellispora longdonensis* is long ranging within the Triassic, and in NW Europe it has been observed from the Ladinian to the Rhaetian (Herngreen, 2005). The influx that defines this zone appears to be a correlatable across a number of wells in the CNS and as such is a useful palynofloral event, however its lateral extent is most likely controlled by facies. The age of this zone is similar to that of the PDt biozone.

***Jerseyiaspora* zone (JSp):**

Age: Anisian

Description: The upper boundary of this zone is identified by the first downhole occurrence of *Jerseyiaspora punctispinosa*. The upper boundary usually coincides with either the basal part of the Julius Member or the upper part of the Judy Member. The lower boundary of this zone is marked by the upper boundary of the underlying zone.

Remarks: Within the CNS *Jerseyiaspora punctispinosa* has a first downhole occurrence in the Anisian (Goldsmith et al., 2003; Mouritzen et al., 2017), which would suggest an Anisian age for this biozone. In the Barents Sea, *J. punctispinosa* is thought to range from the Spathian sub stage of the Olenekian to the late Anisian, with Its late Anisian occurrences independently dated through geochemical Re-Os analysis (Vigran et al., 2014).

***Aratrisporites* zone (ASi):**

Age: Anisian

Description: The upper boundary of this biozone is identified by an influx of *Aratrisporites scabratus* and *Aratrisporites* spp. and occurs in the upper part of the Judy Member. As with the JSp biozone *Jerseyiaspora punctispinosa* is still present. An increase in *Protodiploxypinus fastidiosus*, *Densoisporites* spp., *Todisporites* spp., *Calamospora* spp., *"*Striate saccate spp.*"* and *Plaesiodictyon mosellanum* are also associated with this biozone. Within some intervals *"*Striate saccate spp.*"* and *P. mosellanum* can become very abundant. The lower boundary of this zone is identified by either the upper boundary of the underlying zone or an interval of reduced recovery.

Remarks: *Aratrisporites scabratus* was first described by Klaus (1960) from the Carnian of the Eastern Alps. Within in the CNS this taxa is known to range from the Norian to the Olenekian (Goldsmith et al. 1995), so offers little age constraint. However, the influx that defines this zone seems to be correlatable across parts of the CNS in the upper part of the Judy Member, and as such is deemed a useful palynofloral event. Common *Aratrisporites spp.* has also been observed in Anisian sediments from the Barents Sea (Paterson & Mangerud, 2019). *Plaesiodictyon mosellanum* also has a broad range within Triassic successions with occurrences from the Norian to the Anisian (Goldsmith et al. 1995; Lindström 2009). Vigran (2014) observed *P. mosellanum* to be a common in some areas of the Barrents Sea during the Anisian, whilst Baranyi et al. (2019) observed an influx in the Carnian aged Arden sandstone Formation of the Mercia Mudstone Group from onshore UK. The abundance of *P. mosellanum* in this zone from well 30/07-7 most likely represents a well-developed fluvial-lacustrine environment at that locality.

***Protodiploxypinus* influx zone (PDi):**

Age: Anisian

Description: The upper boundary of this Biozone is identified by an influx of *Protodiploxypinus doubingeri*, *P. sittleri* and *P.* spp. The lower boundary is identified by an interval of impoverished recovery.

Remarks: In NW Europe, Kürschner & Herngreen (2010) observed common *Protodiploxypinus doubingeri* from the upper most Röt to the lower middle Muschelkalk successions which are believed to be Anisian in age (Aegean to earliest Illyrian). The increase of *Protodiploxypinus* taxa observed in this zone could possibly be correlatable to that event. It should be noted that this biozone was only identified in two wells; 30/07a-9 and 29/05b-F3Z. However, where this biozone was identified, the dominance of *Protodiploxypinus* taxa differentiated it from the overlying ASi biozone.

Degraded zone (DG):

Age Anisian or older

Description: The upper boundary of this Biozone is identified by an influx of degraded palynomorphs such as “Saccates indet” or “Sporomorph indet. The lower boundary of this zone is identified by a return to impoverished recovery.

Remarks: This biozone is not age diagnostic but it typically coincides with the basal part of the Judy Member and characterises an interval of improved recovery after a section of impoverished recovery, and as such it is a useful palynofloral event. Preservation within this zone is poor with low diversity generally dominated by degraded gymnosperm pollen or seed fern pollen.

Comparison of palynofloral zones with previous work:

Figure 5 shows the biozones defined here for the CNS alongside zonation schemes previously published for the Barents Sea (Paterson & Mangerud, 2019) and NW Europe (Kürschner & Herngreen, 2010). Due to the intermittent palynomorph recovery in the CNS, some of the biozones defined here are discontinuous. Comparisons of the zonation schemes from the Barents Sea and NW Europe to the biozones here show that there are some common taxa (e.g *Classopollis torrosus*, *Protodiploxypinus doubing*erii), however a number of taxa from the Barents Sea and NW Europe were not recorded within the CNS. This may be a result of the more marine influenced successions from the Barents Sea and NW Europe representing a wetter environment with better preservation potential than that of the CNS, which is thought to represent an endorheic fluvial system (McKie, 2014).

The biozones proposed here indicate attribution of Judy Member strata to the Anisian or older (Fig.4). The Julius Member is attributable to the uppermost Anisian and lower part of the Ladinian stages. The Joanne Member is attributable to the middle and upper Ladinian, the Carnian and part of the Norian. The Jonathan Member is attributable to the Norian or younger. The Josephine and Joshua members are rarely preserved and where they are, age diagnostic palynomorphs are typically absent which makes assigning an age to them difficult. However, they are regarded here as being attributable to the Norian and Rhaetian. This stratigraphy differs from those proposed previously (Fig. 6), particularly from that of Goldsmith et al., (2003) where the upper boundary of the Joanne Member was regarded as being coincidental with the Carnian/Norian stage boundary. From the palynology zonation presented here it is clear that stage boundaries do not necessary coincide with lithostratigraphical boundaries (Fig.6).

Biostratigraphic Correlation:
Correlation across Quadrant 30:

Eight wells were processed in total from the J ridge area of Quad 30. The lithostratigraphy in most of these wells has already been established. However, using the biozones defined from the Judy Field it is possible to correlate at a resolution higher than that of lithostratigraphic members, and whilst overall recovery was generally lower outside of the Judy Field it was still possible to identify a number of the biozones (Fig.7).

The correlation in figure 7 shows the Julius Member was a productive horizon for palynomorph recovery which is correlative across the J ridge area of Quad 30 and indicative of the earlier part of the Ladinian. Across this member the PDt and PCi biozones are easily identifiable in the Kessog, Jade and Judy Fields, although in well 30/07a-7 from the Judy Field the PDt biozone is not preserved. Within the Halley Field only the PCi biozone was identified in well 30/12b-2, and in well 30/12b-3 palynomorph recovery was very poor with neither the PDt or PCi biozones identifiable.

Abundant palynomorph recovery was recorded from the upper part of the Judy Member in the Jade Field in well 30/02c-J5 with the ASi biozone confidently identified. However, in this well it was not possible to identify the JSp biozone as the first downhole occurrence of *Jerseyiaspora punctispinosa* coincided with the *Aratrisporites* spp. influx suggesting the JSp biozone is absent although this could be an artefact of sampling resolution. Below the ASi biozone there was no significant influx of *Protodiploxypinus* taxa observed preventing the positive identification of the PDi biozone. The DG biozone was also not identified in this well. However, the full Judy Member was not penetrated such that the well path may have reached TD prior to encountering this biozone. In the wells from the Kessog and Halley Fields; samples from the Judy Member were either barren or had very poor palynomorph recovery. A possible Quad 30 Marnock Shale package and Bunter Sandstone equivalent was identified in well 30/07a-7 from the Judy Field based on log response, but these units were not identified in any other of the Quad 30 wells analysed. Within the Halley Field wells; 30/12b-2 and 30/12b-3 the Judy Member appears to sit directly on top of the Smith Bank Formation and in well 30/07a-7 the Bunter Sandstone interval is not as well developed as in Quad 22, and most likely represents a distal equivalent which does not reach the Halley Field.

Outside of the Judy Field palynomorph recovery within the Joanne Member was largely poor. The CP biozone was identified in the 30/01c-5a Kessog well based on the presence of *Classopollis torosus* and the CP biozone was also tentatively identified in well 30/02c-4 from the Jade Field based on one possible specimen of *Limbosporites lundbladiae* which was recorded from a core sample. In the Halley Field an Interval of good recovery was recorded from the upper part of the Joanne Member in well 30/12b-2. The assemblage from this interval was generally dominated by gymnosperm pollen including *Triadispora* taxa and degraded bisaccates but the RSt biozone was identified based on the presence of *Retisulcites perforatus* and *Illinites kosankei*.

The observation that in well 30/12b-2 a Ladinian aged interval occurs in the upper part of the Joanne Member penetration for that well would indicate either: an unconformity with non-deposition during the Carnian to Norian Joanne section, or the presence of an erosional surface between the upper Joanne and Jonathan members. The latter was observed locally in the Jasmine Field (Archer et al., 2010). An erosional surface between the Jonathan and the Joanne members would help explain thickness differences between the Joanne Member in well 30/12b-2 (705ft) and the Joanne Member in 30/07a-9 (1539ft). Although these are measured drilling thickness (MBRT) and may not necessarily represent the true stratigraphic thickness, it still does suggest that at least some of the upper Joanne Member in the 30/12b-2 is missing. This may also be the case in the neighbouring 30/12b-3 well, which also appears to have a thin Joanne Member succession although this well lacks any good age constraint due to very impoverished palynomorph recovery. Despite the absence of biostratigraphical evidence, well 30/12b-3 was used by Goldsmith et al. (1995) as the type section for the typical log response of the Skagerrak Formation as it is thought to contain all six members within the Skagerrak Formation.

The Jonathan Member, with the exception of well 30/07a-9, yielded poor to barren palynomorph assemblages and generally contained degraded palynomorphs in all analysed samples. Only the well 30/01c-5a from the Kessog Field was thought to contain a complete Jonathan Member sequence. The Josephine Member was only present in wells 30/12b-3, 30/01c-5a and possibly well 30/13a-9. In well 30/01c-5a it was not possible to sample the Josephine interval and in wells 30/12b-3 and 30/13a-9 it yielded very poor to barren assemblages which similar to the underlying Jonathan Member, contained degraded palynomorphs.

Well 30/13a-9 had a complex well path that is thought to have penetrated the Josephine and Jonathan members before re-penetrating the Josephine Member, after which it went straight into the Judy Member reaching TD in the Smith Bank Formation. All samples analysed from this yielded very poor to barren palynomorph abundances from which only degraded or taxa with a long stratigraphical range were recovered preventing any meaningful age constraint and correlation.

Correlation across Quad 22:

Correlation across Quad 22 is more difficult than across Quad 30, primarily because the mudstone members are either poorly developed or not present, making sandstone member separation problematic, particularly as the J-member nomenclature system is a lithostratigraphic correlation scheme. Palynomorph recovery decreased in Quad 22 compared to Quad 30 (Table 1) and as a consequence of the reduced level of recovery, biozones were more difficult to define. However, even in wells with impoverished recovery, some useful palynomorph observations could be made that offered age constraints and facilitated correlation across Quad 22 (Fig. 8) helping to resolve uncertainties present in the literature associated with Triassic successions in this area (e.g. determining how some of the informal nomenclature in this region such as the Marnock Shale and Heron Shale relate to the J-member nomenclature) (Goldsmith et al., 1995; Mckie & Audretsch, 2005).

Within Quad 22 the Julius Member was poorly developed in comparison to Quad 30. The Julius Member could be confidently identified in well 22/29-1ST from the Seagull Field with the presence of the PCi biozone. Further north of this well, palynomorph recovery from the Julius Member is largely very poor and the Julius Member was correlated across based on log character and lithology with these intervals being constrained by palynoflora events from the over and underlying sand members. A core sample from the Julius Member interval of well 22/24a-5Z (Marnock Field) however, did contain large quantities of heavily oxidised structured organic material but was largely devoid of palynomorphs. This may possibly indicate an oxidised floodplain environment, such that the Julius Member here represents a different environment to the diverse assemblages recorded in Quad 30. A similar correlation of the Julius Member across Quad 22 has been proposed by Mouritzen et al., (2017) with the Julius being identified on the basis of a change in the apatite roundness index (ARI) from heavy mineral analysis.

Figure 8 shows that the CP biozone could be identified in core from the upper part of several wells across Quad 22 from the Fiddich, Marnock, Skua, Culzean and Egret Fields, based on the presence of *Classopollis torosus*. This allows these intervals to be identified as a Joanne Member equivalent. The CP biozone was also tentatively identified in the Heron Field within well 22/30a-6, in the shale package in the upper part of the Triassic succession. This shale package is often referred to as the Heron Shale and there is some discussion as to whether the Heron Shale is a Jonathan or Julius member equivalent (McKie et al., 2005; Mouritzen et al., 2017). The CP biozone in well 22/30a-6 was not identified based on the presence of *Classopollis torosus* but instead on an influx of *Callialaspoirtes* spp. and *Araucariacites* spp. observed from a core sample. *Callialasporites* and *Araucariacites* are thought to be associated with each other and have been found in conjunction with the same parent plant: *Brachyphyllum mamillare* (an Araucariaceae conifer) from outcrop studies (Van Konijnenburg-van Cittert, 1971). The influx of *Callialaspoirtes* spp. and *Araucariacites* spp. observed in well 22/30a-6 is most likely correlatable with the influx of *Araucariacites* spp. observed in the CP biozone from well 30/07a-9. This would support the assessment by Mouritzen et al., (2017) that the Heron Shale is equivalent to the Jonathan Member. Although it must be noted that the influx observed within 30/07a-9 was recorded in the uppermost Joanne Member whilst in 22/30a-6 it is associated with the lowermost Jonathan Member, however this discrepancy may be a result of sampling resolution and preservation.

Across Quad 22, palynomorph recovery from the Judy Member was generally poor. The diverse assemblages seen in the upper part of the Judy Member in Quad 30 were mostly absent in Quad 22. Within well 22/29-1ST from the Seagull Field, an interval of moderate recovery was observed in the upper part of the Judy Member from which the ASi biozone was identified. The JSp biozone could also be identified in the well 22/25a-9Z from Culzean Field based on the presence of *Jerseyiaspora punctispinosa*. The identification of the JSp biozone in well 22/25a-9Z in conjunction with the CP and possible RSt biozones identified in well 22/25a-10 allowed for the correlation of the Joanne, Julius and Judy members across the Culzean Field.

In the lower part of the Judy Member the DG biozone was identified in wells; 22/24b-5Z (Marnock Field), 22/24b-9 (Skua Field) and 22/25a-9Z (Culzean Field). Within the Marnock Field this interval was above the shale package commonly referred to as the Marnock Shale. This shows the Marnock Shale is not a Julius equivalent as suggested by some authors

(Goldsmith et al., 1995), but instead either a lowermost Skagerrak shale or a Smith Bank equivalent.

Mouritzen et al. (2017) correlated the Marnock shale into the adjacent Skua and Culzean Fields using heavy mineral zones, and here it is also extended into the Seagull Field and well 22/12a-1 through log association. Within well 22/12a-1 the Marnock Shale interval is thinner suggesting a pinch out to the north. Following the convention set out by McKie et al., (2005) here the sandstone package beneath the Marnock Shale were assigned to the Bunter Sandstone. Samples analysed from both the Marnock Shale and the Bunter Sandstone all yielded poor or very poor palynomorph recovery and as a consequence, defining the Marnock Shale and Bunter Sandstone as either a Skagerrak or Smith Bank equivalent is problematical. The most likely interpretation is that the Marnock Shale represents the upper part of the Smith Bank Formation with the Bunter sandstone representing an early Triassic sandstone package that is largely restricted to Quad 22, with the exception of a possible distal lateral equivalent in well 30/07a-7 from Quad 30.

Within well 22/24b-9 from the Skua Field the identification of both the CP and DG biozones in the sandstone package above the Marnock Shale suggests that this package represents both a Joanne Member equivalent and a Judy Member equivalent with an erosional surface between the two. This is in contrast to the interpretation by Mourtizen et al., (2017) who identified this whole sand package as a Judy Member equivalent based on higher ARI values that are more associated with the Judy Member. However, the presence of and erosional surface between the Judy Member and Joanne Member could result in reworking of Judy Member apatite's into the Joanne Member equivalent of this well distorting the ARI values.

Correlation of the members through the well 22/29-2+2Z from the Seagull Field was problematic. A possible RSt biozone was identified from a core sample in the upper part of the Triassic succession suggesting a Joanne Member equivalent. The Marnock Shale and Bunter Sandstone were identified in the lower section of this well from log association. Palynomorph analysis from the cutting samples in this well was hindered by heavy contamination from the overlying Pentland Formation, and analysis from the cored intervals contained poorly preserved palynomorphs difficult to identify. As a consequence, separating the Joanne and Judy members is difficult especially as no obvious Julius Member can be identified. If the Julius Member is present in well 22/292+2Z it is more poorly developed than in the adjacent well 22/29-1ST, however well 22/29-1ST is drilled off structure within the Seagull field and tectonic halokinesis may be a factor when correlating 22/29-1ST with 22/29/2+2Z.

Correlation across Quad 29:

Five wells were sampled across Quad 29 and with the exception of the Franklin 29/05b-F3Z well, impoverished in-situ Triassic palynomorph recovery made the correlation of the wells analysed from this quad difficult (Fig. 9). Within well 29/05b-F3Z from the Franklin Field good to abundant palynomorph recovery was recorded for some intervals of the Julius and Judy members allowing confident identification of the PCi, PDi and DG biozones. It was not possible to identify the JSp and ASi biozones in this well as neither *Jerseyiaspora punctispinosa* nor an influx or *Aratrisporites scabratus* were observed.

No palynomorph based correlation could be made through the Puffin Field wells 29/10-3Z and 29/05a-7 and the Corfe prospect well 29/03b-9 as all these wells yielded very poor recovery of in-situ palynomorphs. Cutting samples from the Puffin Field wells contained large quantities of Jurassic contamination from the overlying strata and cutting samples from 29/03b-9 had been drilled using a PDC drill bit which resulted in poor sample quality for palynological analysis. The Smith Bank Formation was picked in these wells using wireline logs, however the overlying Skagerrak Formation was not sub divided. Within well 29/08a-3 from the Acorn Field the DG biozone was identified in a core sample identifying a Judy Member equivalent for the sand package in the upper part of the Triassic succession in this well and the Smith Bank Formation was then identified below this from well logs.

Correlation of Norwegian sector:

As with the UKCS Quad 29, impoverished in situ Triassic palynomorph recovery made the correlation of the wells analysed from the Norwegian sector difficult (Fig. 10).

Palynomorph recovery from the three wells sampled in Norwegian Quads 15 and 16 (15/9-15, 16/7-4 and 16/7-7s) ranged from poor to barren. These wells are situated in more northerly locations than any of the other wells sampled and the Triassic successions within these wells appeared to have a coarser grain size with few finer grained mudstone intervals. In an attempt to maximise recovery mud clast(s) from intervals of channel lag facies identified with the cored intervals were preferentially sampled as it was assumed these mud clasts likely originated from floodplain environments close to the channel. However, despite these efforts palynomorph recovery was still impoverished. A possible specimen of cf. *Quadreculina anellaeformis* was recovered in the upper part of well 16/7-7S, however it was heavily degraded but if this tentative identification is correct it would suggest an age of Norian or younger (Goldsmith et al., 1995) and indicate either a Joanne or Jonathan Member lateral equivalence. Beyond this, no further separation of the Skagerrak Formation from these wells could be determined

From Norwegian Quad 7 the CP biozone was identified in the cored section of well 7/11-6 based on the presence of *Classopollis torosus* identifying the upper sandstone package in this well as a Joanne Member equivalent. No cuttings samples were analysed from this well but the Julius and Judy members were separated using well log data.

Within well 7/8-4 intervals of abundant palynomorph recovery were recorded from the cored section in the upper most part of the well which was identified as representing the PDt biozone constrained by the presence of *Protodiploxypinus doubingeri*, *P. sittleri* and *P. decus*. Towards the base of the cored interval a large influx of *Callialasporites* spp. was observed along with a smaller influx of *Araucariacites* spp.. As mentioned earlier these two species are known to have been found in association with each other (Van Konijnenburg-van Cittert, 1971) and are probably part of the same plexus. Within the Judy Field reference section an influx of these two species was observed in association with the CP biozone, however here it occurs within the PDt biozone. These two taxa are not age diagnostic within the Triassic, although *Araucariacites* spp. is known to be more common in the Late Triassic. As the CP biozone and upper Joanne is absent in this well it is unknown whether another influx another of *Callialasporites* spp. and *Araucariacites* spp. associated with the CP biozone would be observed in this well.

An interesting observation from well 7/8-4 is that whilst in the UKCS Quads the PDt biozone coincides with the Julius Member, here it is first identified in the very thin sandstone package that sits directly above the mudstone package in the upper part of this well but does extend down into the mudstone package. This mudstone package was identified as the Julius Member and the thin sandstone package above as the basal Joanne Member. The observation that the PDt zone was identified in the basal Joanne Member in Norway but is restricted to the Julius Member in the UKCS suggests the lithostratigraphic members may be diachronous. This observation can be taken to support the suggestion by McKie (2014) that sediment supply came from Fennoscandia during Joanne Member times and that during the upper part of the PDt biozone; the Julius Member package is being deposited within the UKCS, whilst in Norwegian Quad 7 deposition of the lowermost Joanne Member package is starting to prograde into the basin possibly sourced from Fennoscandia. Unfortunately, the cuttings for this well were not available for sampling restricting analysis to the cored interval. Based on gamma log response, the sand package beneath the Julius has been attributed to the Judy Member, with the lowermost part of the well thought to be Smith Bank Formation.

In wells 7/11-8 and 7/7-1 it was not possible to identify any of the biozones as palynomorph recovery was mostly poor to very poor throughout. The core samples from both wells yielded only a few heavily degraded palynomorphs whilst the cuttings samples were heavily contaminated with both Jurassic and Cretaceous palynomorphs from overlying strata or with Paleogene palynomorphs presumably derived from drilling fluids. From log character the 7/7-1 well was thought to represent the lower part of the Judy Member and the Smith Bank Formation. A slight increase in palynomorph recovery was observed between in the mud package observed in the middle part well 7/11-8 with some samples yielding moderate recovery, however palynomorphs from this interval were either taxa ranged throughout the Triassic or degraded forms. This increase may represent the Julius Member although none of the characteristic Julius taxa could be confidently identified. By association the overlying sandstone package in well 7/11-8 was assigned to the Joanne Member, and the underlying-sand package assigned to the Judy Member. However, the reduced palynomorph recovery from both the 7/11-8 and 7/7-1 wells makes correlation of these wells tentative.

Julius Member distribution and thickness:

The Julius Member yielded moderate to abundant recovery in a number of wells and is a useful correlation marker for the lower part of the Ladinian when present. The distribution and thickness of the member is variable (Figs. 11 & 12). It should be noted that thickness data presented here are derived from measured thicknesses encountered whilst drilling and are not the true vertical thickness, thus do not take into account bed dip or well path deviation. However, in the absence of any high-resolution seismic data or detailed dipmeter logs the measured thickness still serves as a useful proxy for thickness, particularly as most sampled wells had a vertical or near vertical well path. A north-south correlation panel (Fig. 12) shows the Julius Member to be well developed within the Judy, Jade and Kessog Fields from the J-ridge of Quadrant 30 but in the Halley Field to the south the Julius thins to less than a third of the thickness in these fields. A similar trend can be seen to the north of the J-ridge area where the Julius Member thins towards the Franklin, Seagull and Culzean Fields. The member does not appear to extend any further north than the Fiddich Field and within this area it is only around 60ft thick and is identified using well log data as palynomorph recovery was very poor. Figure 11 depicts the distribution and thickness of Julius Member across the CNS. For accuracy the contours are constrained by well log data giving the member an apparent elongate distribution, whilst in reality it may extend further to the east and west, however the lack of Triassic well penetration limits further extrapolation. The absence of Julius Member penetrations between the UCKS Quadrant 22 and the Norwegian sector makes correlation of the member between these areas difficult. The Julius Member in Norwegian wells; 7/8-4 and 7/11-8 is much thicker than its lateral equivalents in UKCS Quad 22. This could either be a function of salt-related tectonics creating more accommodation space in this area or it is possible that the Julius Member represents a separate discrete mudstone package in this area. Within the UKCS the Julius Member appears to be thickest around the Judy Field suggesting a potential depo-centre in this area. When relating palynomorph recovery to Julius Member thickness; the wells with the best palynomorph recovery were in the Judy, Jade and Franklin Fields where the Julius member is thickest, and palynomorph recovery diminished in the Halley, Seagull, Culzean and Marnock Fields where the Julius Member is thinner. The exception was the Kessog Field where the observed Julius thickness was 374ft (a similar thickness to the Jade and Judy Fields) however only a moderate level of palynomorph recovery was observed. This could be the result of a localised diagenetic control.

Paleo-Environmental reconstruction:

Figure 13 summarizes palynomorph abundances across the CNS at different time slices throughout the Skagerrak Formation. In all time slices depicted, the J-ridge area of Quad 30 generally yielded the best recovery but the composition of the palynofloral communities varied. This is consistent with the concept of an axial fluvial system fed by lateral drainage from the UK and Fennoscandia (McKie, 2014) with UKCS Quad 30 representing the terminal end of that system. Palynomorphs are naturally buoyant and when transported in a fluvial system behave as very fine grained sedimentary particles that would be flushed through the higher energy channelized regions and collected in lower energy, terminal splay environments.

In the lower part of the Judy Member (Fig.13a), the influx of degraded palynomorphs associated with the DG biozone are most prevalent in the J-ridge area of Quad 30 and the north eastern part of Quad 29. This influx may be the effect of the fluvial system bringing in material flushed in from the hinterland during lower Judy Member deposition. Palynomorph degradation would occur during transportation through abrasion in a high energy fluvial system. The marked influx of degraded palynomorphs in the lower part of the Judy member does however suggest enhanced water availability in the catchment compared to the underlying Smith Bank Formation and may indicate a change in climate within the source area such as an increase in precipitation.

Within the upper part of the Judy Member (Fig.13b), represented by the biozones Pdi, ASi and JSp, abundant and well preserved palynomorph recovery is observed within the J-ridge area. From well 30/07a-7 in the Judy Field an abundance of algal taxa (mostly *Plaesiodictyon mosellanum*) was observed indicating a fluvio-lacustrine environment (Goldsmith et al., 1995). This algal influx occurred in several discrete acmes. In-between some of these algal acmes, an influx of *Aratrisporites scabratus* was observed (Fig.4). The alternation of an algal influx and *Aratrisporites* influx is possibly suggestive of a cyclical setting switching between a lacustrine and wetland environment. *Aratrisporites* taxa has been found in the sporangia of a number of plants associated with the heterosporous lycopsid family Pleuromeiaceae (Balme, 1995), which are generally considered to favour coastal lagoon or mangrove-type habitats (Herngreen, 2005; Paterson & Mangerud, 2019). However, some of these plants were thought to be facultative halophytes (Retallack, 1974) and may thrive around an intermittent lacustrine setting in an endorheic basin. Common *Aratrisporites* taxa was also found just to the north of this in wells 30/07a-9, 30/02c-J5 and 22/29-1ST but without abundant algae. In Quad 29 to the west of the J-ridge area an area dominated by conifer pollen and other bissacate pollen was observed around the Franklin Field in well 29/05b-F3Z from the upper part of the Judy Member. Outside of these wells palynomorph recovery is predominately poor. These observations would suggest that during the upper part of the Judy Member a fluctuating lacustrine environment was present around well 30/07a-7 whilst immediately north of this a wetland environment existed which possibly extended as far as the Seagull Field in Quad 22. The influx of conifer and other bissacate pollen observed in the Franklin Field could be the result of some lateral drainage coming from the west bringing in material from upland areas. The poor palynomorph recovery observed in Quad 22 and Norwegian Quads 7, 15 and 16 may be because these areas represent higher energy fluvial environments where the majority of palynomorphs were transported further downstream. The area south of well 30/07a-7 possibly represents a drier playa lake type environment with reduced palynomorph recovery due to increased oxidation which may be associated with evaporitic environments.

Within the Julius Member (Fig. 13C), represented by the biozones PCi and PDt, a relatively widespread swamp environment developed that covered the J-ridge area of Quad 30, the Franklin Field of Quad 29 and the Seagull Field of Quad 22. Towards the fringes of this area palynomorph recovery declined and around the Culzean, Marnock and Fiddich area of Quad 22 palynomorph recovery was very poor or barren. This is perhaps because at the edges of the swamp the sediments are better drained and more oxidised and this in conjunction with the less established flora communities developed on the periphery of a swamp, would explain the poor palynomorph yields. In addition, this is also consistent with the presence of heavily oxidised structured organic material recovered from a core sample in the Julius interval of 22/24b-5Z. In Norwegian Quad 7, the observed influx of *Callialasporites* spp. and *Araucariacites* spp. within the uppermost Julius Member of well 7/8-4 may represent a dry lowland setting at this locality. These two taxa have previously been thought to indicate coastal environments, with the parent plants of these taxa (Araucariaceae conifers) adapted to survive long periods of drought and salt winds (Abbink et al. 2004). Whilst there is little evidence for coastal facies in the CNS, these plants would be well adapted to survive in a dry lowland setting.

The lower part of the Joanne Member (Fig.13D) is represented by the RSt biozone in the UKCS Quads however in Norwegian well 7/8-4 the lower most part of the Joanne Member is represented by the PDt biozone. Although it must be noted that only around 50ft of the Joanne Member is present in well 7/8-4 and it is thought to be a temporal equivalent of the UKCS Julius Member at which point the Joanne Member is beginning to prograde into the basin from Fennoscandia. Good to abundant palynomorph recovery was found in some intervals of the Joanne Member in the Judy and Halley Fields of Quad 30 with common gymnosperm bisaccate forms including *Triadispora* and *Illinites* taxa as well as common degraded saccates being recorded. This dominance of gymnosperm pollen in conjunction with the reduced number of spore taxa observed in comparison in the underlying Julius and upper Judy members suggests a relatively more arid environment with more upland input (Kustatscher et al., 2010). Within the Jade Field of Quad 30 and the Culzean and Seagull fields of Quad 22, intervals of moderate recovery are observed dominated by degraded "granulate sporomorphs". This likely indicates a more oxidised environmental setting than that prevalent in the Judy and Halley fields, representing relatively well drained floodplain environments in this area during these intervals.

In the upper part of the Joanne Member (Fig.13E) which is represented by the CP biozone, moderate recovery was recorded from intervals of the Marnock, Skua and Culzean Fields in Quad 22 and well 7/11-6 in Norway. These assemblages were generally dominated by gymnosperm pollen including *Classopollis torosus*, thought to represent xerophytic Cheirolepidiacaea conifers (Schrank, 2010), or degraded palynomorphs. This would indicate a relatively dry environmental setting. *C. torosus* is typically associated with halophytic coastal vegetation (Abbink et al. 200; Herngreen, 2005; Paterson & Mangerud, 2019), but the parent plant of this taxa could also be adapted to a dry lowland setting. Within the Judy Field, in well 30/07a-9 an interval of good palynomorph recovery was observed with common *Classopollis torosus* and *Limbosporites lundbladiae*. The latter is thought to have a lycopsid botanical affinity (Dehbozorgi et al., 2013) and suggests a possible wetland environment at this locality.

The Jonathan Member (Fig.13F) as with the upper part of the Joanne Member is represented by the CP biozone. Only eight of the thirty-two sampled wells contained the Jonathan Member and only two of these contained the full member. Most wells sampled had poor to barren palynomorph recovery. However, one interval of good palynomorph recovery was observed in well 22/30a-6 from the Heron Field which contained common *Callialasporites* spp. and *Araucariacites* spp. possibly suggestive of a drier lowland setting. Two intervals of moderate recovery were also observed from wells 30/07a-9 from the Judy Field and 22/25a-9Z from the Culzean Field. Well 30/07a-9 contained common *Classopollis torosus* and *Limbosporites lundbladiae* suggesting that a wetland environment prevailed in this area from the upper part of the Joanne Member to the lower part of the Jonathan Member, whilst well 22/25a-9Z was characterised by degraded palynomorphs possibly representing an oxidised floodplain environment

Palynomorph composition and distribution most likely responded to changes within the fluvial system which in turn was driven by climate fluctuations in the catchment area. The upper part of the Judy Member and the Julius Member (biozones Pdi, Asi, JSp, PCi and Pdt) appear to represent the wettest phase of the Skagerrak Formation with abundant spore taxa thought to represent wetland flora (Kustatscher et al., 2010) present in parts of Quad 30 and 22. In comparison, the Joanne and Jonathan members appear to have developed under a relatively drier climate with a reduction in spore taxa and an increase is gymnosperm pollen and degraded palynomorphs. This suggests that during the upper part of the Anisian and the lower part of the Ladinian there is a relative increase in precipitation in the catchment which increases discharge leading to the development of swamp/lacustrine environments in the basin particularly in the Quad 30 area. This is then followed by relative decrease in precipitation within the catchment area from the late Ladinian through the Carnian to mid Norian.

Carnian Pluvial Episode

In recent years there has been renewed interest in the concept of a mid-Carnian pluvial episode (CPE), and recently a number or papers have been published providing compelling evidence in favour of this concept (Archie & Gomez, 2018; Benton et al., 2018; Del Corso et al., 2018; Franz et al., 2018). Thought to have occurred around 232 Ma (Benton et al., 2018), the CPE is believed to have been triggered by volcanism associated with the Wrangellia large igneous province (Dal Corso et al., 2012). Within the South Permian basin and Tethys, both faunal turnover events (Simm & Ruffell, 1990), and a negative carbon isotope excursion (Del Corso et al., 2018) have been documented. Palynofloral trends across the CPE from western Tethys showed a change from pollen grains associated with xerophytic upland vegetation to a dominance of palynomorphs with hygrophytic associations attributable to Filicopsida (ferns), Lycopodiales, Equisetopsida (horsetails) and Cycadeoidales (Roghi et al., 2010). However, in this study there does not appear to be any clear expression of a mid-Carnian pluvial episode within the CNS.

Within the Triassic CNS successions; the Carnian stage is thought to be represented within the Joanne Member, however age constraints for this member can be poor. The best age constraint for the Carnian stage is in well 30/07a-9 from the Judy Field, where the Carnian stage which spans 8.5 Ma (Fig.7) is thought to be represented by only 380ft of sediment, whilst the underlying Ladinian stage, which spans 4.5 Ma, comprises 970ft of sediment. These thicknesses would give an average sedimentation rate of 13.6 mm/ky for the Carnian and 65.7 mm/ky for the Ladinian within this well. So, within the CNS not only is there no evidence for the CPE, there appears to be a reduced rate of deposition during the Carnian stage. If the Carnian does record a period of reduced sedimentation in comparison to the Ladinian, then an increase in finer grained material would be expected. However, the architecture of the Joanne Member is suggestive of channel dominated sediments (Farris, 1999; McKie & Audretsch, 2005; Archer et al., 2010; Grey et al., 2019).

An alternative possibility is that rather than the Carnian representing a period of reduced sedimentation, it is instead an incomplete section with missing stratigraphy within the Triassic successions of the CNS. Observations here suggest that within the Halley Field of Quad 30, the Carnian part of the Joanne Member is largely absent. Also, within Quad 22 the Norian section of the Joanne Member (represented by the CP biozone) is identified quite close to the interval identified as the Julius Member. Both these observations would be consistent with missing stratigraphy either through a period of non-deposition and/or erosion.

McKie (2014) suggested that during the CPE, exorheic drainage systems formed which diverted Fennoscandian sediments away from the CNS across the South Permian Basin towards Tethys; represented by incision of Stuttgart Formation Rivers flowing towards a lower marine base level. If true, this scenario could account for some of the missing Carnian sediments in the CNS, although it must be noted that the CPE is thought to have lasted 1.2 Ma and consisted of four to six phases (Ruffell et al., 2018), whilst the Carnian stage spans 8.5 Ma. If this scenario did occur, then sediment derived from Fennoscandia was most likely diverted away from the CNS for a longer time period than just the CPE. Also, if there was a prolonged period of non-deposition during the Carnian, it would most likely result in the development of periods of non-deposition potentially recorded by extensive palaeosol development, however to date, this has not been observed.

Rather than the Carnian being a period of non-deposition, an erosional unconformity may be present below the CP biozone. McKie (2014) has documented two regional unconformities within the Triassic successions of the CNS; the first being the Hardegsen which occurs at the top of the Bunter Sandstone, and the second being the Cimmerian 1 (C1) unconformity which occurs in the late Carnian within the Joanne Member. Both of these unconformities have been attributed to extensional pulses (Mckie, 2014) and the latter Cimmerian 1 unconformity would broadly coincide with the interval directly below the CP biozone. This unconformity would then mean much of the Carnian could have been removed through erosion. Figure 14 shows a correlation of wells from UKCS quads 22 and 30 where a potential regional upper Joanne Member unconformity can be identified.

The presence of an erosion surface below the CP biozone would also explain the anomalous stratigraphic relationships observed within well 22/24b-9 from the Skua Field. In this well, the upper part of the Joanne Member, expressed by the CP biozone, sits directly on the Judy Member (Fig. 8), with no Julius Member equivalent and a much thinner Judy Member in comparison to neighbouring wells. The Marnock and Skua Fields are located within the same intra-salt pod, and from seismic data the south of the pod closest to the Skua Field is grounded (McKie et al., 2010). If grounding occurred either prior to or synchronous with erosion surface development below the CP biozone, then it is likely that a larger stratigraphic interval within well 22/24b-9 would have been removed by erosion relative to other wells in the field due to the proximity of the well to the flank of the grounded pod. An important inference from this interpretation is that intra-Joanne salt movement had a significant impact on reservoir development.

The interpretation of well 22/29-2 and the side-track 2Z is interesting with regards to the presence of an unconformity in the upper part of the Joanne Member. In this well the RST biozone was tentatively identified in the uppermost part of the Triassic interval (Fig. 8). If identification of this biozone is accurate then it may suggest that erosion removed the Carnian sediments with the absence of overlying Norian to Rhaetian strata recording non-deposition or erosion due to the location of the well on a relative structural high. However, within this well there is no obvious Julius Member equivalent, despite the Julius Member being well developed in the adjacent well 22/29-1ST, although it must be noted that well 22/29-1ST is an exploration well drilled away from the Seagull Field and is situated closer to the Heron Field and located within the Heron pod. An alternative possibility is that within well 22/29-2+2Z a scenario similar to well 22/24b-9 occurred, with the pod containing the Seagull Field grounding either before or at the time of erosion surface development resulting in removal of older stratigraphy, with the upper part of the Joanne Member directly overlying the lower part of the Judy Member (depicted in figure 14 by the alternative red dotted line). For this interpretation to be correct, it would mean the identification of the Rst biozone is inaccurate, which is a possibility given the impoverished palynomorph recovery from this well, and the fact that this biozone was only tentatively identified based on the presence of one heavily degraded specimen of *Retisulcites perforatus*, which could also be derived from reworking of nearby Ladinian aged Joanne sediments. Due to the relatively widespread distribution of the Julius Member across Quads 30 and 22, the latter scenario is perhaps most likely.

The concept of a missing/reduced Carnian interval from parts of the CNS as a consequence of a regional unconformity below the CP biozone is interesting and would explain both the lack of any expression of a CPE, and why the Carnian is not easily identified in the biozones defined from this study. Within NW Europe, an influx of *Aulisporites astigmosus* is observed within the Carnian (Herngreen, 2005) and from the Mercia Mudstone Group from SW England Carnian sediments were characterized by the presence of *Camerosporites secatus* (Baranyi et al., 2019), however, neither of these species have been observed within the CNS. A missing/reduced Carnian interval across the CNS would also help to explain why the Judy and Joanne members have generally similar thicknesses despite deposition of the Joanne Member occurring over approximately twice the amount of time.

Conclusions:

By utilizing a refined palynology processing technique, it has been possible to enhance palynomorph recovery from some intervals within the continental Triassic successions of the CNS. Where palynomorphs are present the technique used here is effective at concentrating recovery, although some intervals do innately have poor recovery due to either the depositional environment having poor preservation potential or due to post-depositional diagenesis.

A new palynozonal scheme is proposed for the Skagerrak Formation in which eight biozones have been established that can be used for correlation across the basin on both the UK and Norwegian sectors. This has facilitated the identification of specific members particularly in areas that have previously been subject to discussion such as the Marnock Field in UKCS Quad 22. From these results it has been possible to ascertain that the Marnock Shale most likely represents a Smith Bank Formation equivalent and the Heron Shale is correlatable to the Jonathan Member of the Skagerrak Formation. This new zonation scheme also allows for correlation at a higher resolution than that of lithostratigraphic members, particularly in the J-ridge area of UKCS Quad 30. The Julius Member also appears to be correlatative horizon for the early Ladinian and its lateral extend can be mapped, which is important given its potential for compartmentalisation of the sandstone reservoirs within the Skagerrak Formation. Palynomorph abundance and distribution here is consistent with previously documented models that suggest that the Skagerrak Formation represents an axial fluvial system fed by lateral drainage from the UK and Fennoscandia with the CNS representing the distal end of that fluvial system. Climatic fluctuations in the catchment area strongly influenced depositional environments within the basin which ultimately controlled palynomorph diversity and recovery. Within the CNS there is little palynological evidence for the presence of the Carnian Pluvial Episode, however this may be the result of a missing/reduced Carnian interval in the CNS due to the development of a regional upper Joanne unconformity.

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Figure captions

Figure 1: Summary of the CNS Triassic stratigraphy. Modified after Goldsmith et al., 2003.

Figure 2: a map showing the location of wells sampled for palynological analysis across the CNS. Well locations are labelled with both well name and field where applicable.

Figure 3: Palynomorph abundance charts showing key palynofloral events for Judy Field reference section; A) 30/07a-7, B) 30/07a-9, C) map showing the proximity of the two wells in the Judy Field (UKCS Quad 30). Note charts only shows selected taxa and not all recorded species, charts also show the total number palynomorphs counted from each sample. (*M/S = Marnock Shale)

Figure 4: palynofloral biozones defined from 30/07a-7 and 30/07a-9 "reference section" plotted against timescale from "a concise Geologic time scale: 2016" (0gg et al 2016)

Figure 5: Diagram showing the biozones defined in this study alongside the zones defined for the Barrents Sea (Paterson & Mangerud, 2019) and NW Europe (Kürschner et al., 2010)

Figure 6: Chronostratigraphy of members as outlined in Goldsmith et al. 2003, McKie & Williams 2009, Archer et al 2010 and this Study plotted against timescale from "a concise Geologic time scale:2016" (0gg et al 2016)

Figure 7: Correlation of biozones in wells analysed UKCS Quad 30

Figure 8: Correlation of biozones in wells analysed UKCS Quad 22

Figure 9: Correlation of biozones in wells analysed UKCS Quad 29

Figure 10: Correlation of biozones in wells analysed Norwegian Quads 7,15 and 16

Figure 11: A map showing the thickness and distribution of the Julius member across the Central North Sea. Thicknesses are measured thicknesses encountered whilst drilling.

Figure 12: A North-South correlation of Key wells analysed from the Central North Sea. Note the lateral extent of the Julius Member

Figure 13: A map showing palynomorph abundance across the Central North Sea at different time slices throughout the Skagerrak Formation

Figure 14: correlation of wells from UKCS quads 22 and 30 where a potential regional upper Joanne member unconformity can be identified.

Table 1: Summary of the total abundance of palynomorphs observed in each processed palynology sample. Total abundances have been split into bins ranging from Barren (= 0 in-situ Triassic palynomorphs counted) to Abundant (200 or more in-situ Triassic palynomorphs counted)

Plate 1 descriptions

1) *Aratrisporites scabratus* from 30/07a-7 at 14470ft, V46_4
2) *Araucariacites* spp. from 7/8-4 at 3855.2ft, X29_1
3) *Callialasporites* spp. from 7/8-4 at 3855.2m, W32_1
4) *Calamospora* spp. from 30/07a-7 at 11486.6ft, Y46_4
5) *Inaperturopollenites* spp. from 30/07a-9 at 13550ft, R54_2
6) *Classopollis torosus* from 30/07a-9 at 12500ft, K38_4
7) *Cyclotriletes* spp. – sub triangular from 30/07a-7 at 11150ft, X53_2
8) *Densoisporites* spp. from 22/24b-5Z at 11703.10ft, N45_2
9) *Illinites kosankei* from 30/07a-7 at 11486.6ft, X44_1
10) *Limbosporites lundbladiae* from 30/07a-9 at 11900ft, R43
11) *Todisporites* spp. from 30/07a-7 at 11600ft, N47_1
12) *Ovalipollis pseudoalatus* from 30/12b-2 at 13840-50ft, R46_2
13) *Protodiploxypinus decus* from 30/07a-9, 13550ft, E41_4
14) *Porcellispora longdonensis* from 30/07a-7 at 11200ft, E48
15) *Protodiploxypinus doubingeri* from 30/07a-7 at 11600ft, Q40_3
16) *Protodiploxypinus fastidiosus* from 30/07a-7 at 11374.2, D45
17) *Protodiploxypinus sittleri* from 30/07a-7 at 11600ft, L46_1
18) *Triadispora crassa* from 30/07a-7at 11700ft, W33
19) *Striate saccate* spp. from 30/07a-9 at 11280ft, K31_2
20) *Retisulcites perforatus* from 30/02c-4 at 16860ft, S45
21) *Jerseyiaspora punctispinosa* from 30/07a-9 at 14310ft, W41
22) *Spheripollenites* spp. from 30/07a-7 at 11200ft, E43_1
23) *Plaesiodictyon mosellanum* from 30/07a-7 at 11326.5ft, N44_4

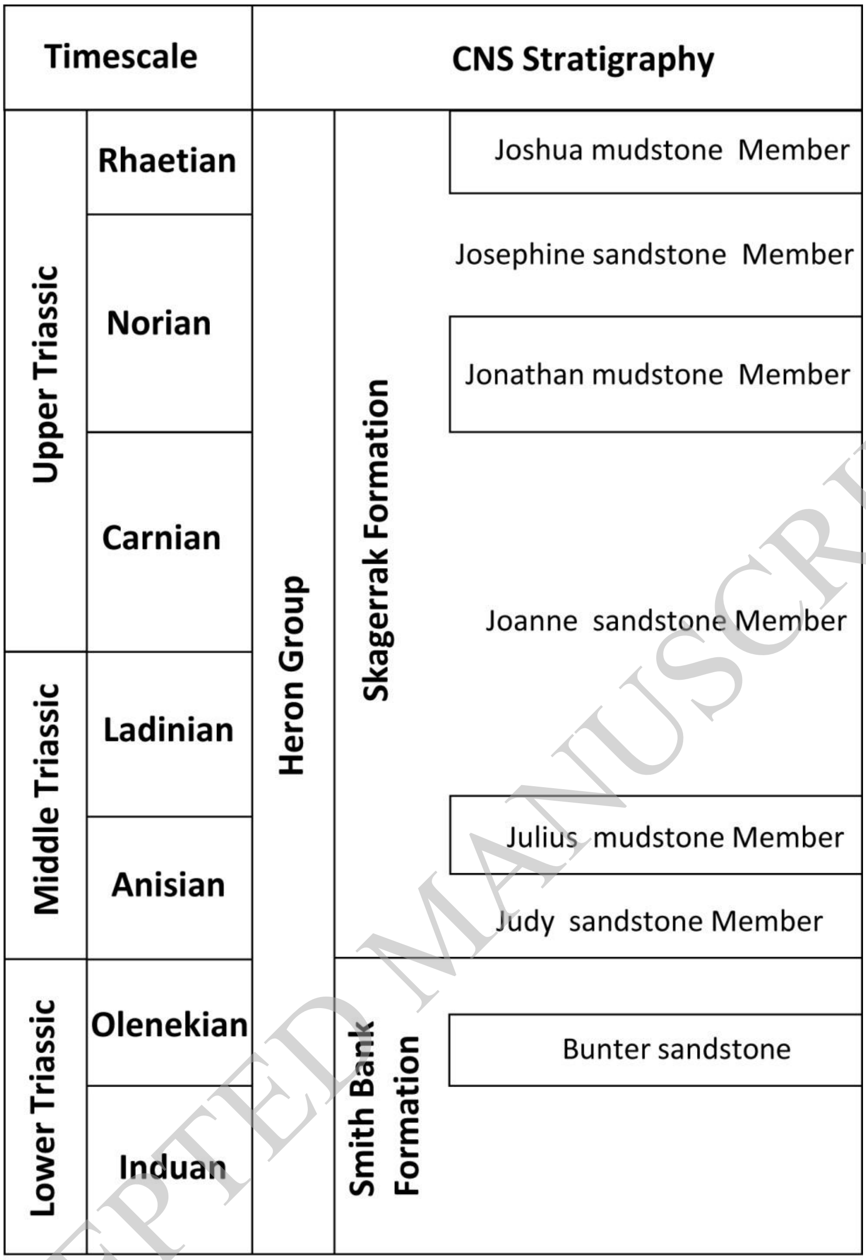

Timescale
CNS Stratigraphy
Upper Triassic
Middle Triassic
Lower Triassic
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Heron Group
Skagerrak Formation
Smith Bank Formation
Joshua mudstone Member
Josephine sandstone Member
Jonathan mudstone Member
Joanne sandstone Member
Julius mudstone Member
Judy sandstone Member
Bunter sandstone

Figure 1:

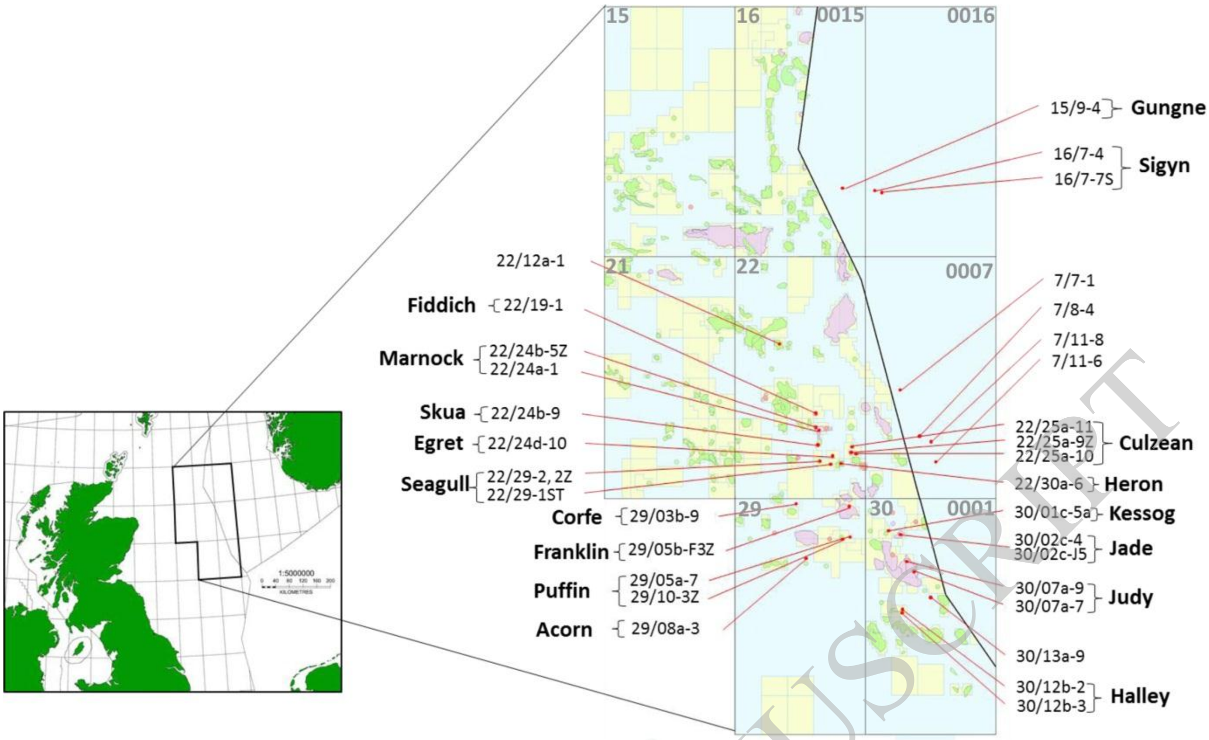

15
16
0015
0016
21
22
0007
29
30
0001
15/9-4 Gungne
16/7-4
16/7-7S
Sigyn
22/12a-1
Fiddich 22/19-1
Marnock 22/24b-5Z 22/24a-1
Skua 22/24b-9
Egret 22/24d-10
Seagull 22/29-2, 2Z 22/29-1ST
Corfe 29/03b-9
Franklin 29/05b-F3Z
Puffin 29/05a-7 29/10-3Z
Acorn 29/08a-3
7/7-1
7/8-4
7/11-8
7/11-6
22/25a-11
22/25a-9Z
22/25a-10
Culzean
22/30a-6 Heron
30/01c-5a Kessog
30/02c-4
30/02c-J5
Jade
30/07a-9
30/07a-7
Judy
30/13a-9
30/12b-2
30/12b-3
Halley
1:5000000
KILOMETRES

Figure 2:

Figure 3A:

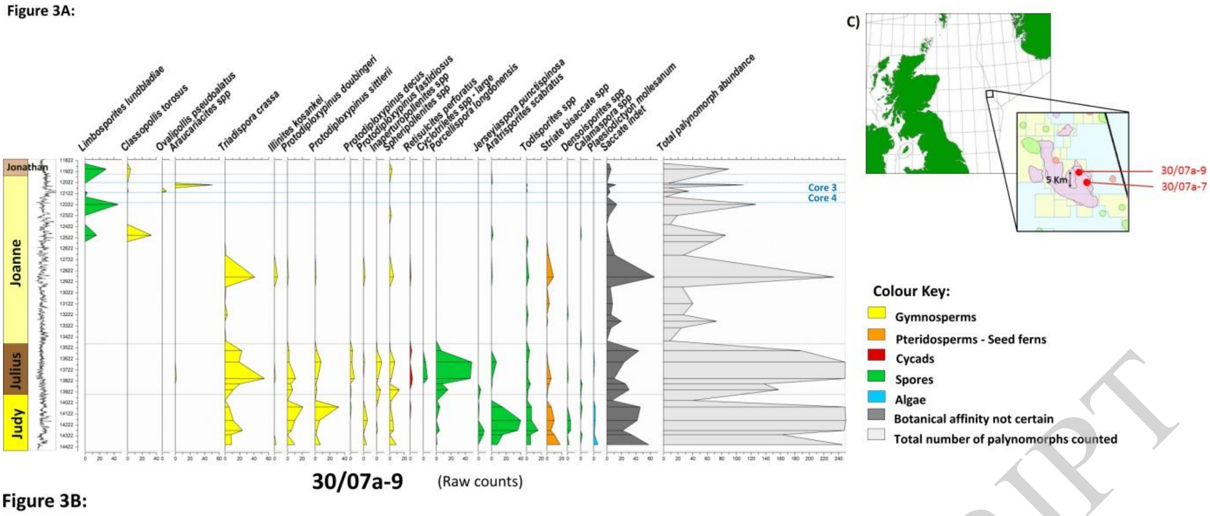
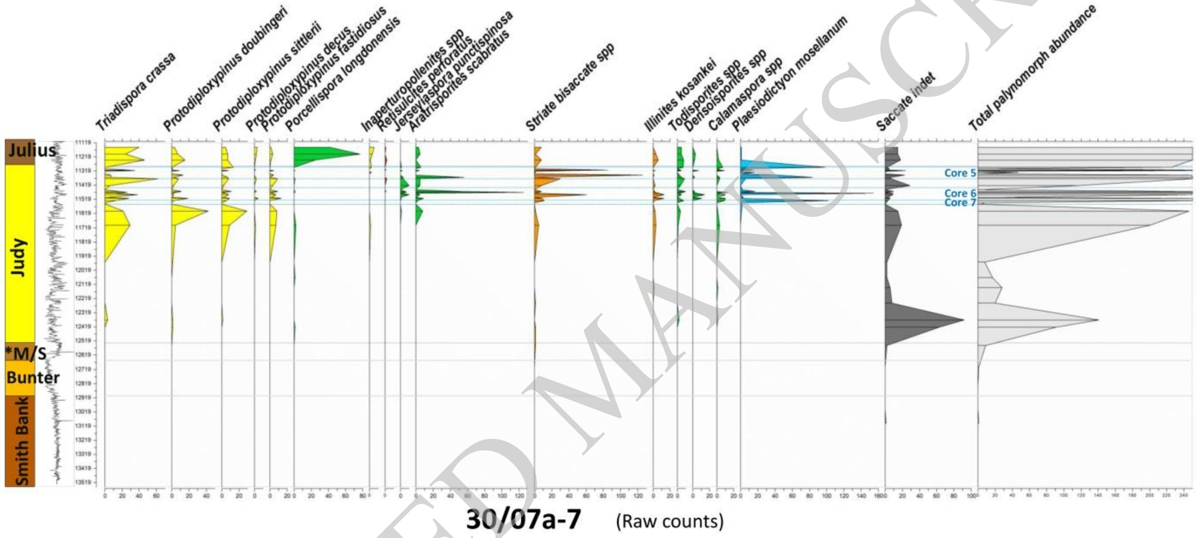
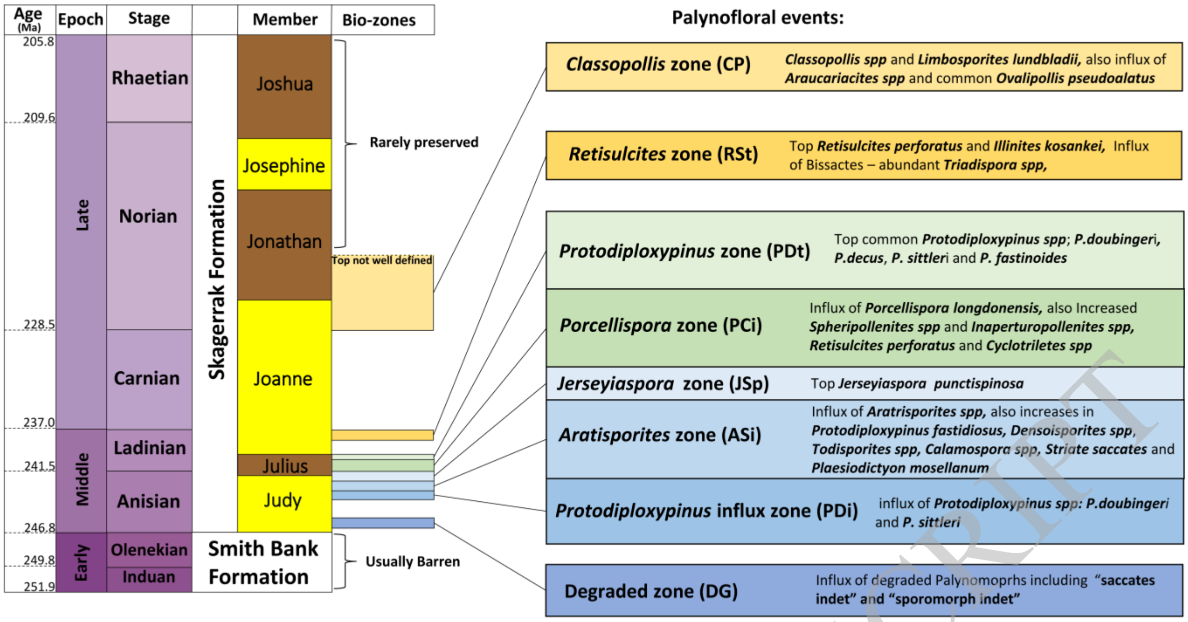


Figure 3B:

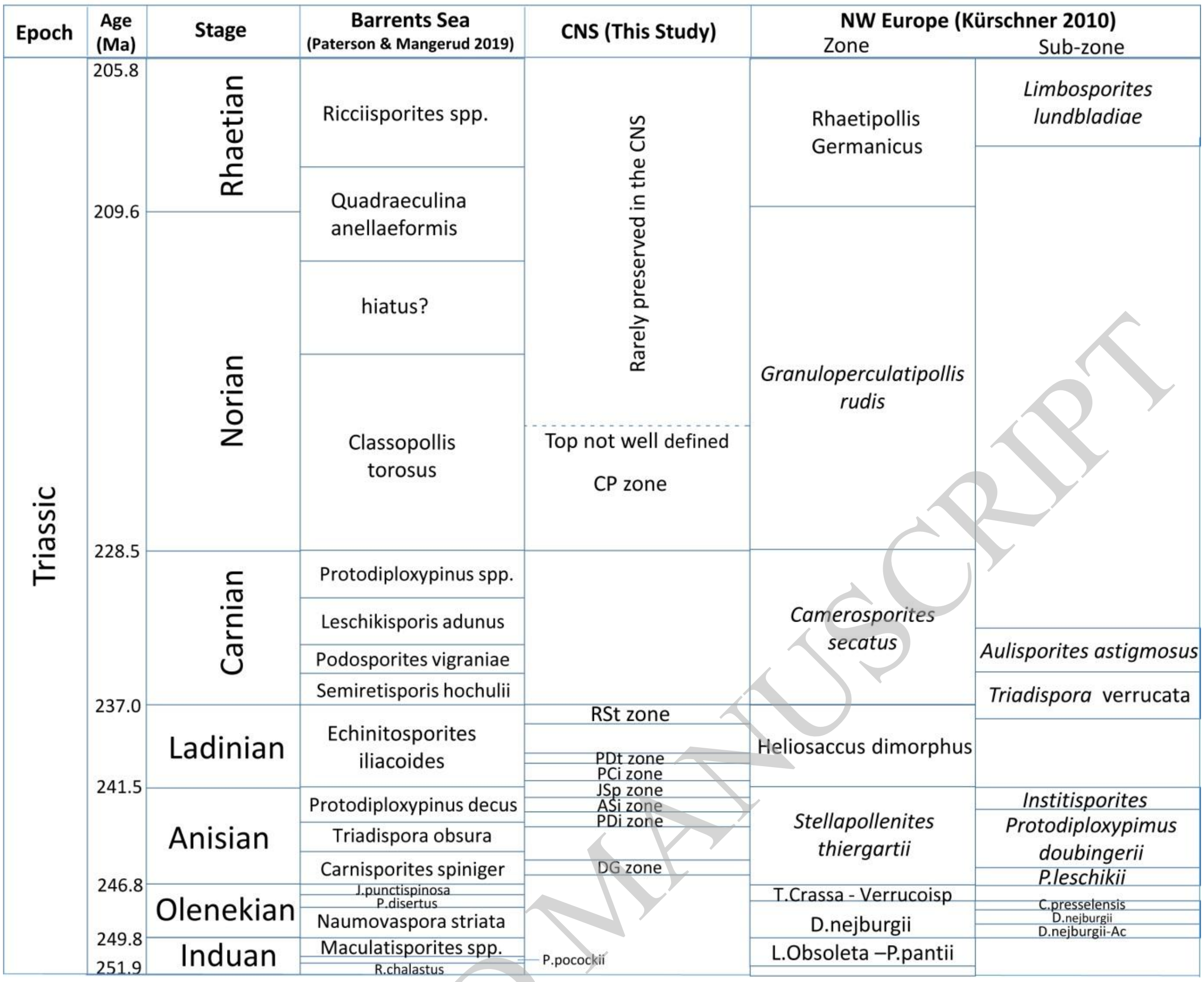




Age (Ma)
Epoch
Stage
Member
Bio-zones
Palynofloral events:
205.8
209.6
228.5
237.0
241.5
246.8
249.8
251.9
Late
Middle
Early
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Skagerrak Formation
Joshua
Josephine
Jonathan
Joanne
Julius
Judy
Smith Bank Formation
Rarely preserved
Top not well defined
Usually Barren
Classopollis zone (CP)
Classopollis spp and Limbosporites lundbladii, also influx of Araucariacites spp and common Ovalipollis pseudoalatus
Retisulcites zone (RSt)
Top Retisulcites perforatus and Illinites kosankei, Influx of Bissactes – abundant Triadispora spp,
Protodiploxypinus zone (PDt)
Top common Protodiploxypinus spp; P.doubingeri, P.decus, P. sittleri and P. fastinoides
Porcellispora zone (PCi)
Influx of Porcellispora longdonensis, also Increased Spheripollenites spp and Inaperturopollenites spp, Retisulcites perforatus and Cyclotriletes spp
Jerseyiaspora zone (JSp)
Top Jerseyiaspora punctispinosa
Aratisporites zone (ASi)
Influx of Aratrisporites spp, also increases in Protodiploxypinus fastidiosus, Densoisporites spp, Todisporites spp, Calamospora spp, Striate saccates and Plaesiodictyon mosellanum
Protodiploxypinus influx zone (PDi)
influx of Protodiploxypinus spp: P.doubingeri and P. sittleri
Degraded zone (DG)
Influx of degraded Palynomoprhs including "saccates indet" and "sporomorph indet"

Figure 4:

Figure 5:


Epoch
Age (Ma)
Stage
Barrents Sea (Paterson & Mangerud 2019)
CNS (This Study)
NW Europe (Kürschner 2010)
Zone
Sub-zone
Triassic
205.8
209.6
228.5
237.0
241.5
246.8
249.8
251.9
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Ricciisporites spp.
Quadraeculina anellaeformis
hiatus?
Classopollis torosus
Protodiploxypinus spp.
Leschikisporis adunus
Podosporites vigraniae
Semiretisporis hochulii
Echinitosporites iliacoides
Protodiploxypinus decus
Triadispora obsura
Carnisporites spiniger
J.punctispinosa
P.disertus
Naumovaspora striata
Maculatisporites spp.
R.chalastus
Rarely preserved in the CNS
Top not well defined
CP zone
RSt zone
PDt zone
PCi zone
JSp zone
ASi zone
PDi zone
DG zone
P.pocockii
Rhaetipollis Germanicus
Granuloperculatipollis rudis
Camerosporites secatus
Heliosaccus dimorphus
Stellapollenites thiergartii
T.Crassa - Verrucoisp
D.nejburgii
L.Obsoleta –P.pantii
Limbosporites lundbladiae
Aulisporites astigmosus
Triadispora verrucata
Institisporites
Protodiploxypimus doubingerii
P.leschikii
C.presselensis
D.nejburgii
D.nejburgii-Ac

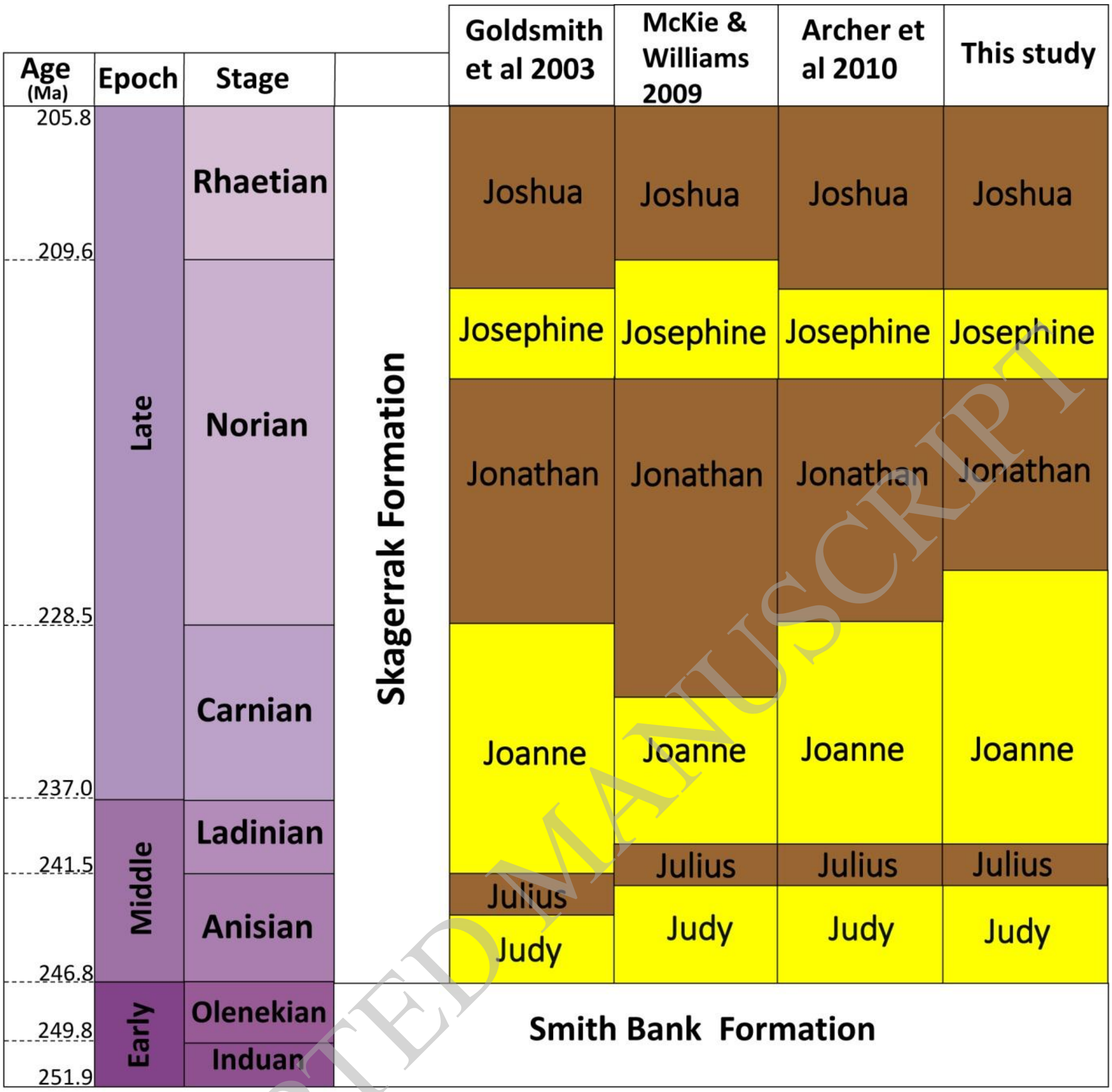

Age (Ma)
Epoch
Stage
Goldsmith et al 2003
McKie & Williams 2009
Archer et al 2010
This study
205.8
209.6
228.5
237.0
241.5
246.8
249.8
251.9
Late
Middle
Early
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Skagerrak Formation
Joshua
Josephine
Jonathan
Joanne
Julius
Judy
Smith Bank Formation

Figure 6:

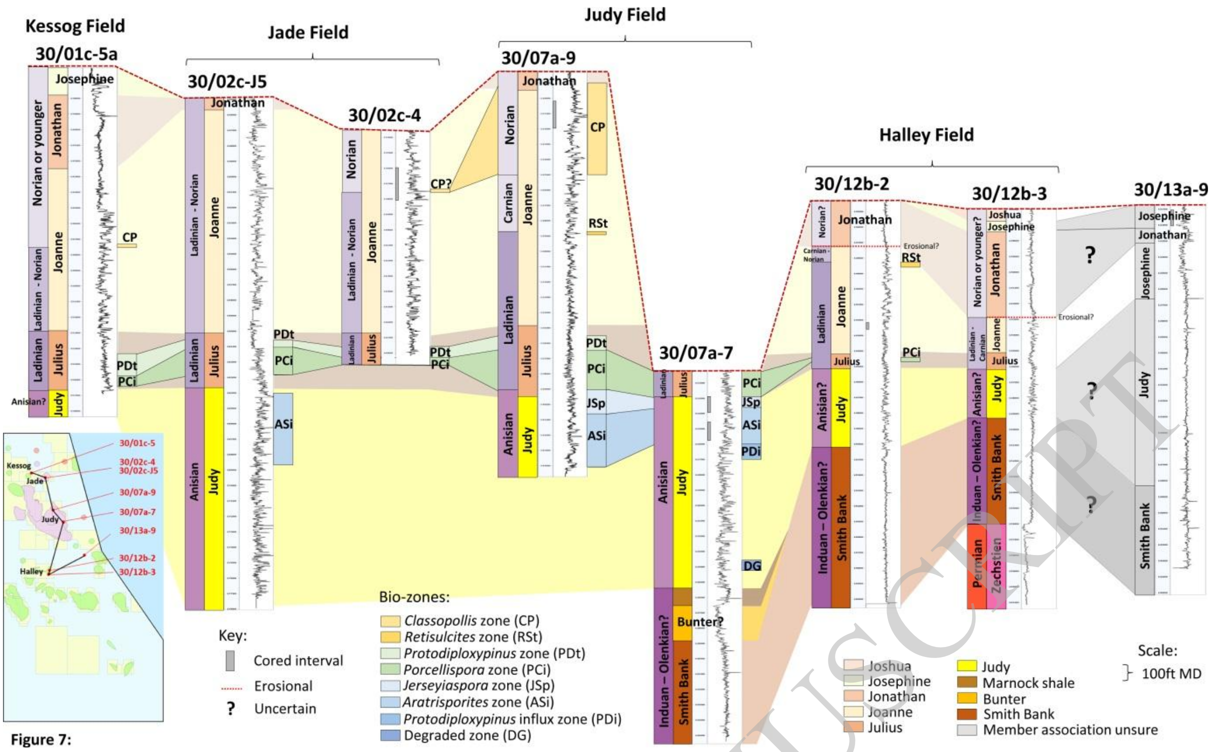

Kessog Field
30/01c-5a
Jade Field
30/02c-J5
30/02c-4
Judy Field
30/07a-9
30/07a-7
Halley Field
30/12b-2
30/12b-3
30/13a-9
Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)
Key:
Cored interval
Erosional
? Uncertain
Joshua
Josephine
Jonathan
Joanne
Julius
Judy
Marnock shale
Bunter
Smith Bank
Member association unsure
Scale:
100ft MD

Figure 7:

Figure 8:

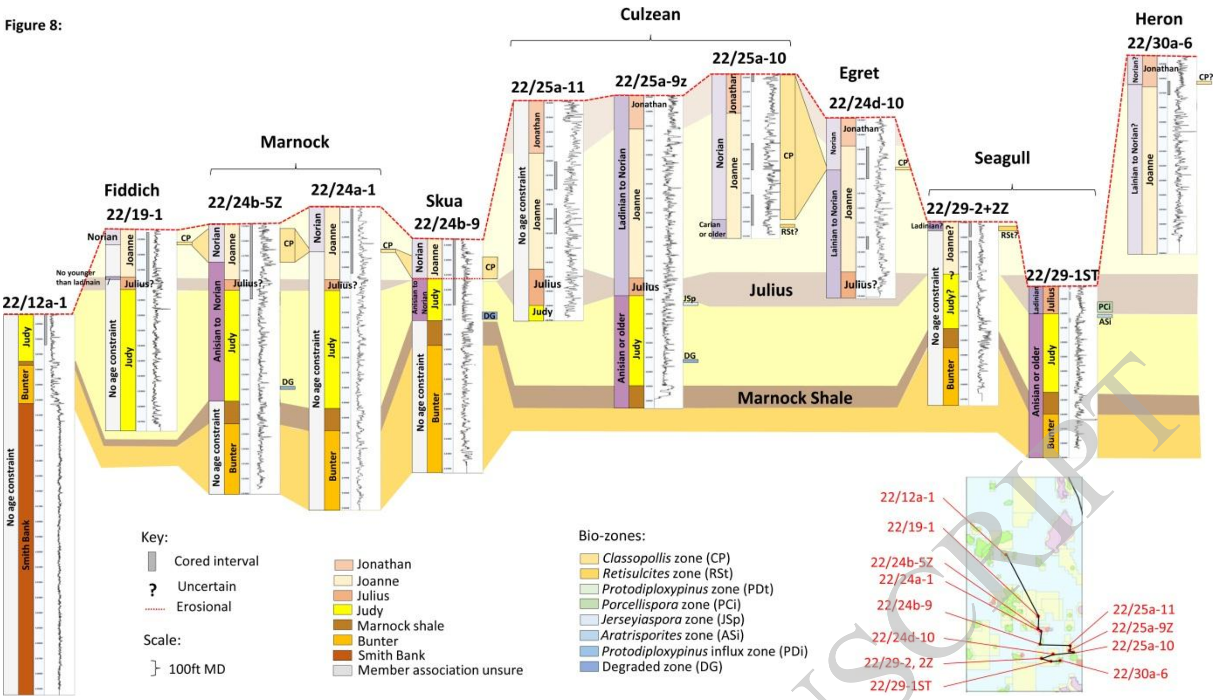
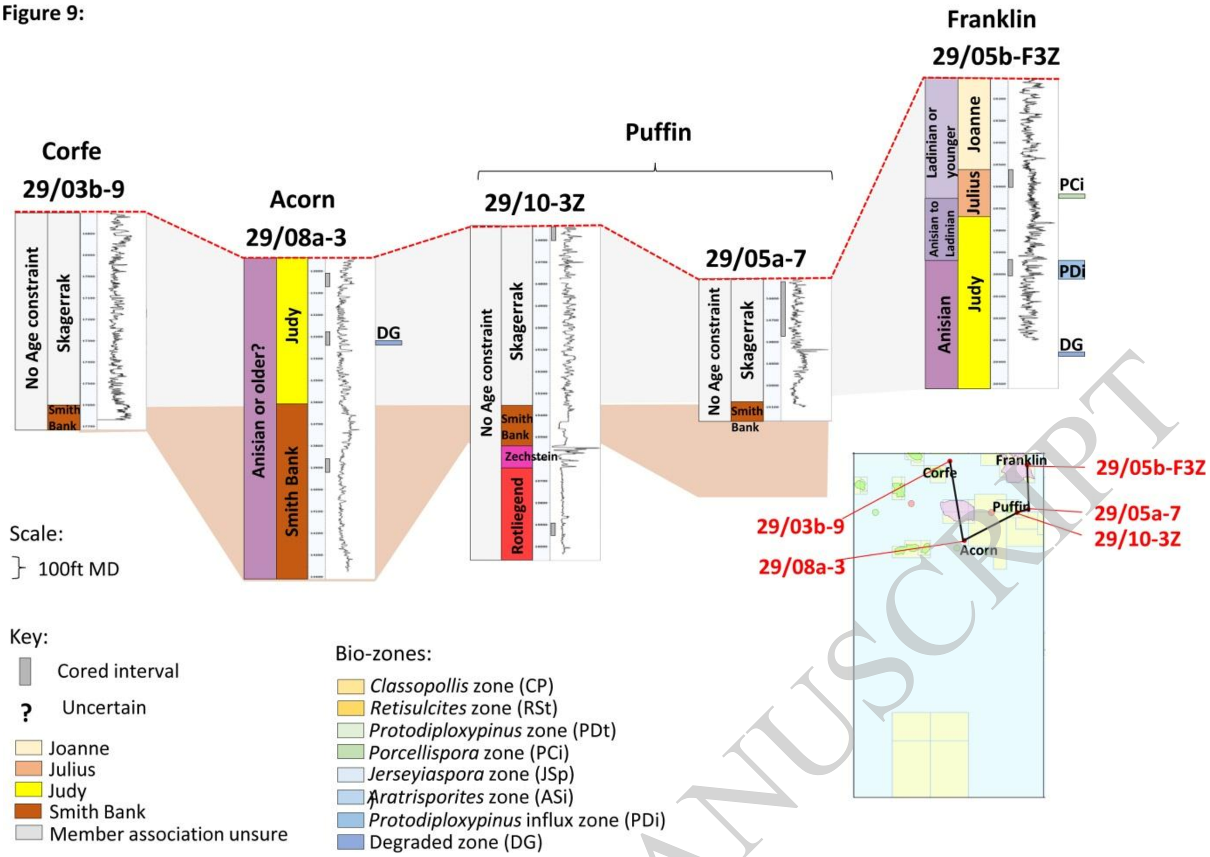

Culzean
Heron
22/30a-6
22/25a-10
22/25a-11
22/25a-9z
Egret
22/24d-10
Marnock
Seagull
Fiddich
22/19-1
22/24b-5Z
22/24a-1
Skua
22/24b-9
22/29-2+2Z
22/12a-1
22/29-1ST
Julius
Marnock Shale
Key:
Cored interval
Uncertain
Erosional
Scale:
100ft MD
Jonathan
Joanne
Julius
Judy
Marnock shale
Bunter
Smith Bank
Member association unsure
Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)
22/12a-1
22/19-1
22/24b-5Z
22/24a-1
22/24b-9
22/24d-10
22/29-2, 2Z
22/29-1ST
22/25a-11
22/25a-9Z
22/25a-10
22/30a-6

Figure 9:



Corfe
29/03b-9
No Age constraint
Skagerrak
Smith Bank
Acorn
29/08a-3
Anisian or older?
Judy
Smith Bank
DG
Puffin
29/10-3Z
No Age constraint
Skagerrak
Smith Bank
Zechstein
Rotliegend
29/05a-7
No Age constraint
Skagerrak
Smith Bank
Franklin
29/05b-F3Z
Ladinian or younger
Anisian to Ladinian
Anisian
Joanne
Julius
Judy
PCi
PDi
DG
Scale:
100ft MD
Corfe
Franklin
Puffin
Acorn
29/05b-F3Z
29/03b-9
29/05a-7
29/10-3Z
29/08a-3
Key:
Cored interval
? Uncertain
Joanne
Julius
Judy
Smith Bank
Member association unsure
Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)

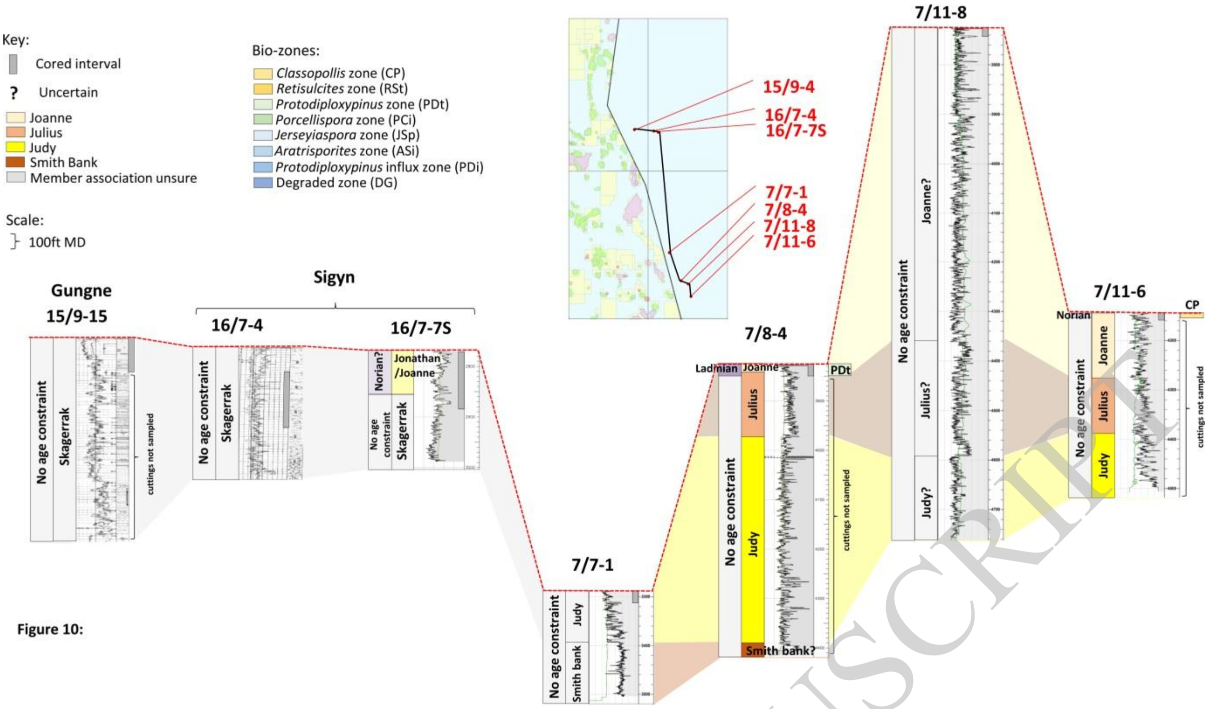

Key:
Cored interval
? Uncertain
Joanne
Julius
Judy
Smith Bank
Member association unsure
Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)
Scale:
100ft MD
15/9-4
16/7-4
16/7-7S
7/7-1
7/8-4
7/11-8
7/11-6
Gungne
15/9-15
Sigyn
16/7-4
16/7-7S
No age constraint
Skagerrak
cuttings not sampled
Norian?
Jonathan /Joanne
7/7-1
Judy
Smith bank
7/8-4
Ladinian
Joanne
Julius
Judy
Smith bank?
PDt
7/11-8
Joanne?
Julius?
Judy?
Norian
CP

Figure 10:

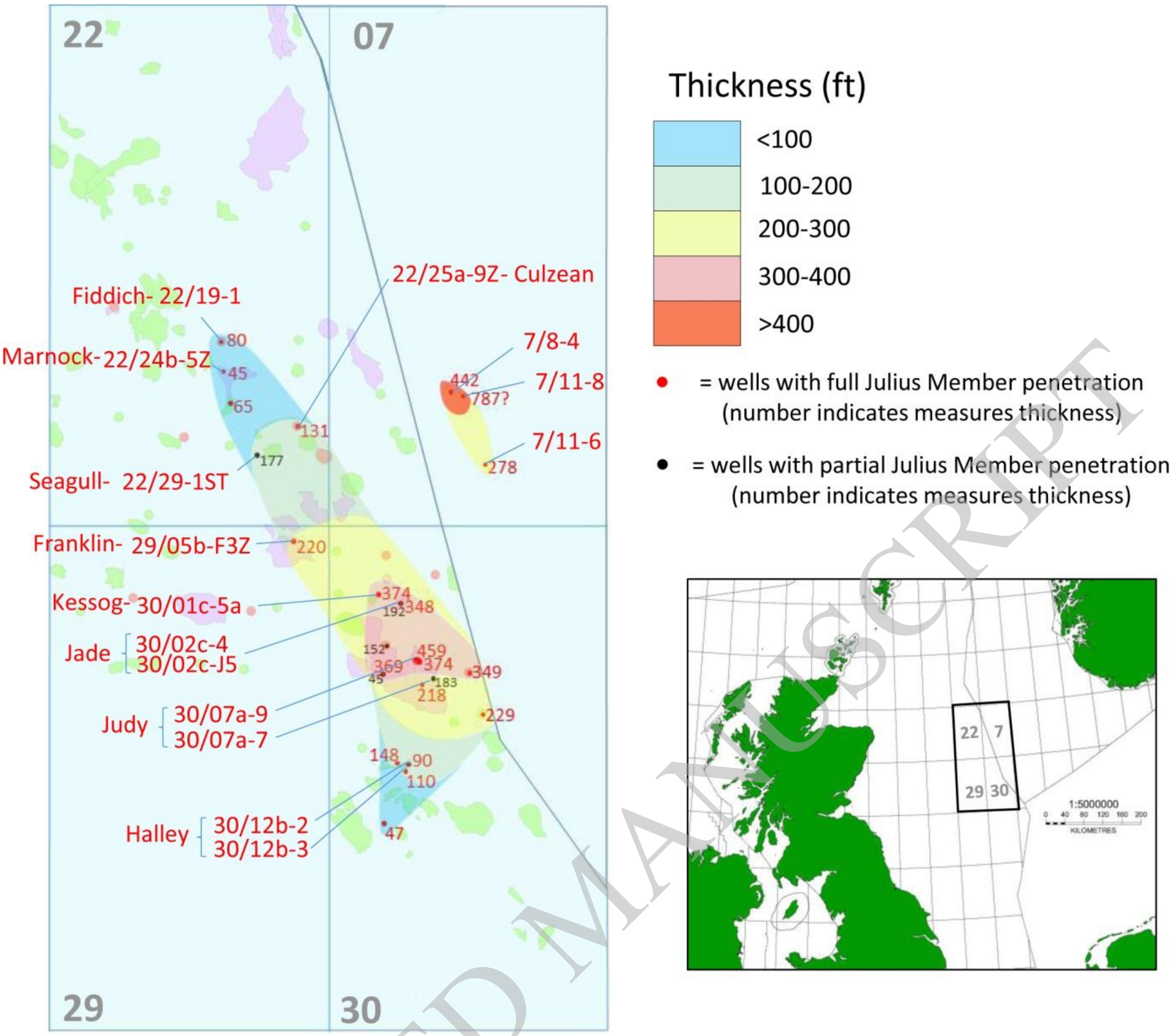
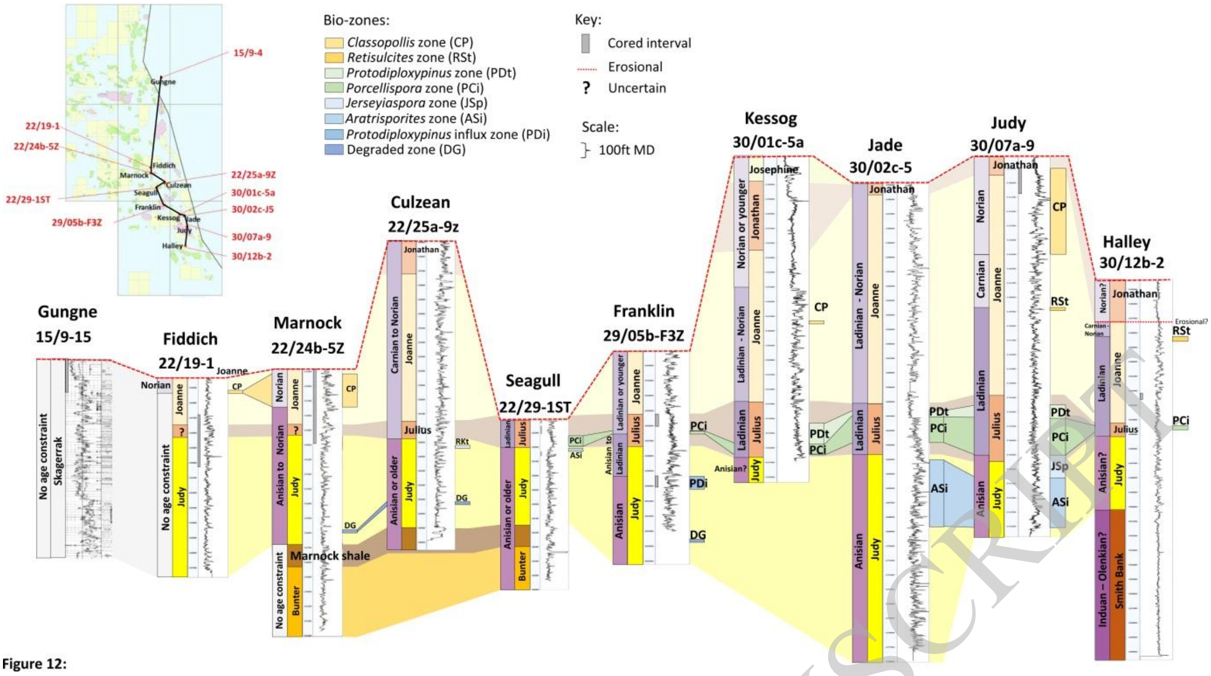

22
07
29
30
Thickness (ft)
<100
100-200
200-300
300-400
>400
= wells with full Julius Member penetration (number indicates measures thickness)
= wells with partial Julius Member penetration (number indicates measures thickness)
22/25a-9Z- Culzean
Fiddich- 22/19-1
Marnock- 22/24b-5Z
Seagull- 22/29-1ST
Franklin- 29/05b-F3Z
Kessog- 30/01c-5a
Jade 30/02c-4 30/02c-J5
Judy 30/07a-9 30/07a-7
Halley 30/12b-2 30/12b-3
7/8-4
7/11-8
7/11-6
1:5000000
KILOMETRES

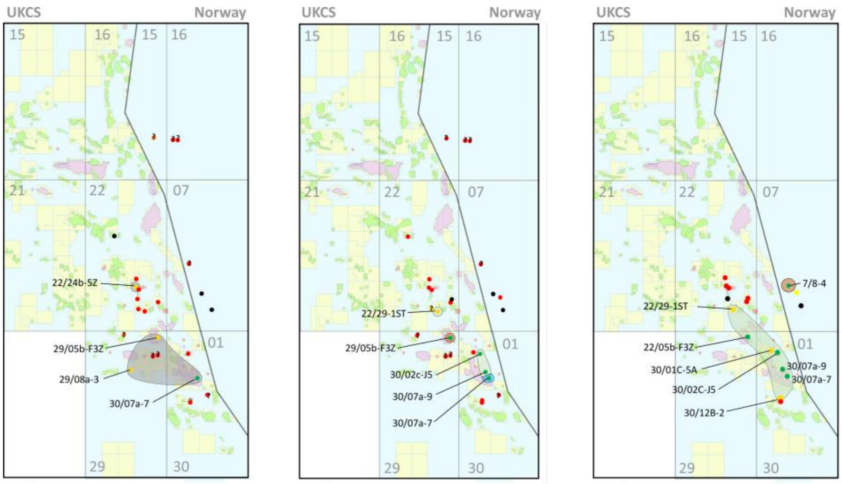
Figure 11:



Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)
Key:
Cored interval
Erosional
? Uncertain
Scale:
100ft MD
Gungne
15/9-15
Fiddich
22/19-1
Marnock
22/24b-5Z
Culzean
22/25a-9z
Seagull
22/29-1ST
Franklin
29/05b-F3Z
Kessog
30/01c-5a
Jade
30/02c-5
Judy
30/07a-9
Halley
30/12b-2
Marnock shale

Figure 12:

Figure 13:



A) Lower part of the Judy Member
Age: Anisian (DG bio-zone)

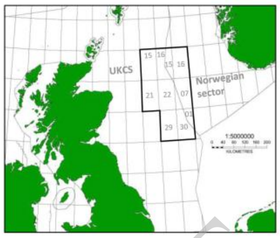
- Areas with an influx of *"Saccates undiff"* and *"Sporomorph undiff"*

B) Upper part of the Judy Member
Age: Anisian (Pdi,Asi and RKt bio-zones)

- Dominated saccates; *Protodiploxypinus*, *Triadispora* and *"Saccates undiff"* forms
- Common *Aratrisporites* taxa
- Common Algae; eg *Plaesiodictyon mosellanum*

C) Julius Member
Age: Ladinian (Pci and PDt bio-zones)

- Common to abundant *Porcellispora longdonensis*
- Influx of *Calliasporites spp* and *Araucariacites spp*



Colour Key of Palynomorph recovery from wells analysed

- Good to Abundant
- Moderate
- Poor to Barren
- Interval not analysed
- ? Unsure if member is present

Figure 13: (continued)

D) Lower part of Joanne Member
Age: Ladinian (RSt bio-zone)

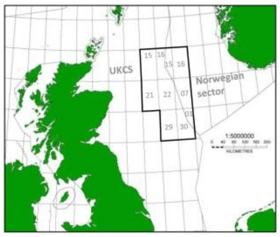
- Common *"Granulate sporomorph"*
- Common saccates; eg *Protodiploxypinus*, *Triadispora and "Saccate undiff"* forms
- Common saccates; eg *Triadispora*, *Illinites and "Saccate undiff"* forms

E) Upper part of Joanne Member
Age: Norian (CP biozone)

- Areas where *Classopollis torrosus* is present
- Common *Classopollis torrosus* and *Limbosporites lundbladii*

F) Jonathan Member
Age: Norian (CP biozone)

- Common *Classopollis torrosus* and *Limbosporites lundbladiae*
- Influx of *Calliasporites spp* and *Araucariacites spp*



Colour Key of Palynomorph recovery from wells analysed

- Good to Abundant
- Moderate
- Poor to Barren
- Interval not analysed
- ? Unsure if member is present

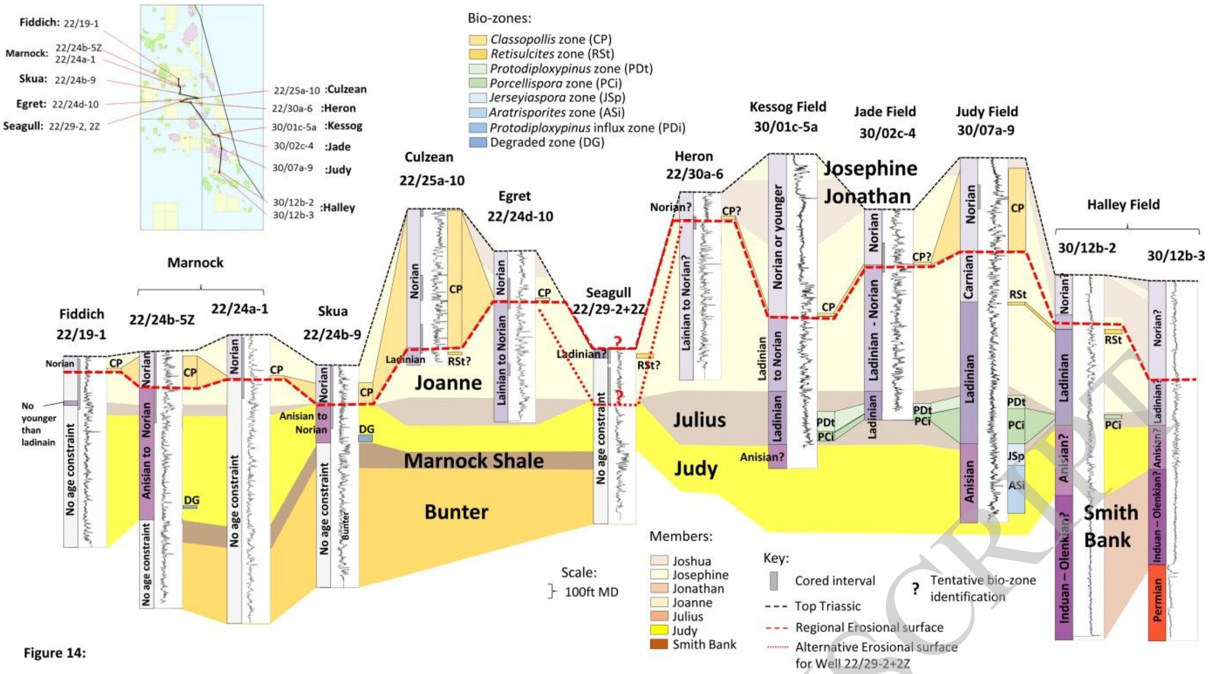

Bio-zones:
Classopollis zone (CP)
Retisulcites zone (RSt)
Protodiploxypinus zone (PDt)
Porcellispora zone (PCi)
Jerseyiaspora zone (JSp)
Aratrisporites zone (ASi)
Protodiploxypinus influx zone (PDi)
Degraded zone (DG)
Members:
Joshua
Josephine
Jonathan
Joanne
Julius
Judy
Smith Bank
Key:
Cored interval
Tentative bio-zone identification
Top Triassic
Regional Erosional surface
Alternative Erosional surface for Well 22/29-2+2Z
Scale: 100ft MD
Fiddich 22/19-1
Marnock
22/24b-5Z
22/24a-1
Skua 22/24b-9
Culzean 22/25a-10
Egret 22/24d-10
Seagull 22/29-2+2Z
Heron 22/30a-6
Kessog Field 30/01c-5a
Jade Field 30/02c-4
Judy Field 30/07a-9
Halley Field
30/12b-2
30/12b-3
Joanne
Marnock Shale
Bunter
Julius
Judy
Josephine
Jonathan
Smith Bank

Figure 14:

	Total number of samples analysed	Palynomorph recovery (number of samples)					
		Abundant (counts >200)	Good (counts = 100-200)	Moderate (counts = 20-99)	Poor (counts = 10-19)	Very Poor (counts <10)	Barren (Counts = 0)
7/7-1	6					5	1
7/8-4	5	2		2		1	
7/11-6	2			1		1	
7/11-8	15			2	2	10	1
15/9-15	6				4	1	1
16/7-4	3					3	
16/7-7s	5					3	2
22/12a-1	2					2	
22/19-1	3				1	2	
22/24a-1	9			2		5	2
22/24a-5z	16			2	6	8	
22/24b-9	8			2	2	4	
22/24d-10	6				2	4	
22/25a-11	5				2	2	1
22/25a-10	12			2	1	7	2
22/25a-9z	18			5	6	6	1
22/29-1st	11			2	2	7	
22/29-2 +2Z	6			1	1	2	2
22/30a-6	11		1		3	7	
29/3b-9	5				5		
29/5b-F3Z	15	3		3	4	4	1
29/08a-3	10			3	1	6	
29/10-3Z	7					7	
29/05a-7	12					10	2
30/01c-5a	9			2	1	4	2
30/02c-4	16	2		2	4	7	1
30/02c-J5	20	2	3	3	3	8	1
30/07a-7	38	17	2	5	2	9	3
30/07a-9	32	7	6	12	2	5	
30/12b-2	8		1	1	1	3	2
30/12b-3	12				1	8	3
30/13a-9	11					7	4
Total	**344**	**33**	**13**	**52**	**56**	**158**	**32**

Table 1:

Plate 1