**QUEEN'S
UNIVERSITY
BELFAST**

Late Cretaceous to Palaeogene carbon isotope, calcareous nannofossil and foraminifera stratigraphy of the Chalk Group, Central North Sea

Eldrett, J. S., Vieira, M., Gallagher, L., Hampton, M., Blaauw, M., & Swart, P. K. (2021). Late Cretaceous to Palaeogene carbon isotope, calcareous nannofossil and foraminifera stratigraphy of the Chalk Group, Central North Sea. *Marine and petroleum geology*, 124, [104789]. <https://doi.org/10.1016/j.marpetgeo.2020.104789>

Published in:
Marine and petroleum geology

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

© 2020 Elsevier Ltd. All rights reserved.

This manuscript is distributed under a Creative Commons Attribution-NonCommercial-NoDerivs License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Journal Pre-proof

Late Cretaceous to Palaeogene carbon isotope, calcareous nannofossil and foraminifera stratigraphy of the Chalk Group, Central North Sea

James S. Eldrett, Manuel Vieira, Liam Gallagher, Matthew Hampton, Maarten Blaauw, Peter K. Swart

PII: S0264-8172(20)30572-9

DOI: <https://doi.org/10.1016/j.marpetgeo.2020.104789>

Reference: JMPG 104789

To appear in: *Marine and Petroleum Geology*

Received Date: 19 August 2020

Revised Date: 21 October 2020

Accepted Date: 27 October 2020

Please cite this article as: Eldrett, J.S., Vieira, M., Gallagher, L., Hampton, M., Blaauw, M., Swart, P.K., Late Cretaceous to Palaeogene carbon isotope, calcareous nannofossil and foraminifera stratigraphy of the Chalk Group, Central North Sea, *Marine and Petroleum Geology* (2020), doi: <https://doi.org/10.1016/j.marpetgeo.2020.104789>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier Ltd.

James Eldrett: Conceptualization, Writing-Original Draft, Visualization. **Manuel Vieira:** Conceptualization, Validation, Writing-Review & Editing. **Liam Gallagher** and **Matthew Hampton:** Formal analyses, Validation, Writing-Review & Editing. **Maarten Blaauw:** Software, Validation, Writing-Review & Editing. **Peter Swart:** Formal analyses, Validation, Resources, Writing- Review & Editing.

**Late Cretaceous to Palaeogene Carbon isotope, calcareous
nannofossil and foraminifera Stratigraphy of the Chalk Group,
Central North Sea.**

¹James S. Eldrett, ²Manuel Vieira, ³Liam Gallagher, ³Matthew Hampton, ⁴Maarten
Blaauw, ⁴Peter K. Swart

¹Shell International Exploration & Production B.V., Lange Kleiweg 40, 2288 GK Rijswijk,
Netherlands

²Shell UK Ltd., 1 Altens Farm Road, Nigg, Aberdeen, AB12 3FY, United Kingdom

³Network Stratigraphic Consulting Limited, Harvest House, Cranborne Road, Potters
Bar, Hertfordshire EN63JF, United Kingdom

⁴School of Natural and Built Environment, Queen's University Belfast, Belfast BT7 1NN,
United Kingdom

⁵Rosenstiel School of Marine and Atmospheric Sciences, Department of Marine
Geosciences, University of Miami, Miami FL 33149, United States

Keywords

Late Cretaceous, Chalk, Calcareous Nannofossils; Carbon isotope Stratigraphy;
Micropalaeontology

Abstract

A highly resolved record of stable carbon isotope values ($\delta^{13}\text{C}$) of the Late Cretaceous to Palaeogene (Cenomanian – Danian) was generated from ditch-cuttings material recovered from the Shearwater A9 hydrocarbon production well, Shearwater Field, Central North Sea. The profile of $\delta^{13}\text{C}$ values was integrated with calcareous nannofossil and foraminifera biostratigraphy to provide an integrated stratigraphy for the Late Cretaceous Chalk Group. Detailed correlation between Shearwater A9 carbon isotope stratigraphy and associated biostratigraphic events with other similar records from both the Boreal and Tethyan Realms, including several proposed and/or ratified Global Boundary Stratotype Sections and Points had enabled the identification of major Stage and sub-Stage boundaries. This study provides a long-term and near-continuous stratigraphic record of the Late Cretaceous and earliest Palaeogene from more basinal facies of the Central North Sea. The record is punctuated with several short duration hiatal intervals, and a longer hiatus is identified whereby most of the Cenomanian is missing at this location.

1. Introduction

The Late Cretaceous Epoch (Cenomanian-Maastrichtian Stages; 100Ma – 66Ma) marked a major turning point in global climate from a period characterized by sustained global warmth during the Cenomanian-Turonian (Huber et al. 2002) towards a cooler state in the Maastrichtian (Bowman et al. 2013; Linnert et al. 2014; Thibault et al. 2016a). Throughout the Late Cretaceous a series of environmental perturbations in the

Earth System and dramatic changes in the global biota are recorded, including major global Oceanic Anoxic Events (OAEs), emplacement of several Large Igneous Provinces (LIPs), and extra-terrestrial bolide impacts. All of these events influenced the abundance and diversity of life on Earth, most notably at the Cretaceous-Palaeogene boundary Event (KPge). Furthermore, the Late Cretaceous was characterized by a long-term relative second order sea-level rise leading to the development of several epicontinental seaways, which in Europe was typified by the deposition of widespread chalk deposits across a wide and temperate Boreal Seaway (Surlyk et al. 2003). These chalk deposits form a prolific hydrocarbon play, particularly in the Norwegian and Danish North Sea where high-porosity and permeability reservoir chalks had been preserved and exploited through the development of numerous oil and gas fields (i.e., Ekofisk; Dan, Hod; Surlyk et al. 2003). In the United Kingdom (U.K.) sector of the North Sea, the Chalk Group (Gp.) was buried more deeply and consequently reservoir potential was degraded due to diagenesis; however some commercial success was achieved when the chalk was found to be fractured or re-sedimented thus creating secondary porosity/permeability (i.e., Curlew C; see discussion in Drake et al. 2015).

In order to understand both the major climate events of the Late Cretaceous and the reservoir geology of the European Chalk Gp., detailed and integrated stratigraphic frameworks need to be developed. Even though the chalk lithologies of the Late Cretaceous of North-western Europe are conducive for calcareous microfossil analyses (i.e. calcareous nannofossils; foraminifera), in more deeply buried sections in the basin centers, the chalk can become indurated which limits the recovery of diverse age-diagnostic taxa. In these cases, stable carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope

stratigraphy can provide a powerful tool for correlation, with the first detailed carbon isotope stratigraphy on bulk carbonate samples from the English Chalk published forty years ago (Scholle & Arthur, 1980). Since this pioneering work, $\delta^{13}\text{C}$ chemostratigraphy is increasingly being used and refined as a tool for regional to global correlation of Cretaceous Chalk successions (i.e. Jenkyns et al. 1994; Jarvis et al. 2006; Voigt et al. 2010; 2012; Thibault et al. 2012; 2016b; Wendler, 2013; Jelby et al. 2014; Jarvis et al. 2015; Chenot et al., 2016, 2018; Perdiou et al. 2016; Deville de Periere et al. 2019). However, many of these studies are geographically limited to where the chalk sequences are near the surface and have been cored (i.e. Trunch borehole, Norfolk, U.K); quarried (i.e. Salzgitter-Salder; Germany); or directly crop out at surface (i.e. Eastbourne, U.K. and localities in Denmark and NW Germany). Some of the deeper basins (i.e. Central North Sea; Danish Basin) are presently deeply buried and remain mostly inaccessible for academic study. Some research has been conducted on core material recovered from hydrocarbon exploration and production wells that penetrate these deeper basin centers (i.e. Adda-3; Danish Basin, Perdiou et al. 2016). However, for many hydrocarbon wells core material is sparsely collected and stratigraphically limited. Recently, Metzger et al. (2014) demonstrated that a reliable carbon isotope stratigraphy can be recorded from ditch-cuttings material from the Ordovician Utica shale, New York, USA. Ditch-cutting samples are commonly collected during drilling and can provide the maximum resolution for subsurface correlation as many of these hydrocarbon wells penetrate vastly expanded sections. Therefore, this study aims to determine whether a high-resolution and reliable record of $\delta^{13}\text{C}$ values can be obtained

for the Late Cretaceous Chalk Gp, using ditch-cuttings material from the Shearwater hydrocarbon Field, Central North Sea (**Figure 1a**).

2. Geological Background

2.1. Central North Sea

The geological evolution of the Central North Sea occurred in several phases. Initially, prolonged extension occurred during the Permian–Triassic with coeval sedimentation of thick successions of Zechstein salt followed by Middle Jurassic pre-rift doming and culminating into the Mid-Cimmerian Unconformity. The Late Jurassic was characterized by a rifting phase causing uplift and tilting of fault blocks on rift flanks, which during the subsequent period of extension in the Early Cretaceous were eroded, marking the development of the base Cretaceous unconformity (BCU) over the entire Central Graben (Gowers et al., 1993). The thermal subsidence of the North Sea Basin during the Late Cretaceous, combined with a global eustatic sea-level rise associated with peak greenhouse climate state conditions, led to the inundation of landmasses and the widespread occurrence of shallow epi-continental seaways. Regionally oligotrophic to mesotrophic oceanic conditions prevailed and provided the setting suitable for widespread chalk deposition (**Figure 1b**), which were punctuated by episodes of higher surface water productivity and when combined with reduced oxygen levels led to development of marl deposition characteristic of OAE-2 in the North Sea Basin (e.g. Plenus Marl). The Sub-Hercynian and Laramide Compressional tectonic pulses of the Late Cretaceous to Early Palaeogene resulted in intra-plate compression and basin inversion with greater basin restriction and siliciclastic input, ultimately leading to the

cessation of chalk deposition in the Danian and subsequent deposition of turbidite sand reservoirs of the Lista and Sele Formations (Fms; Mudge et al. 2015; Eldrett et al. 2015a).

2.2. Overview of Shearwater Field

The Shearwater Field was discovered in 1988 in the Central North Sea (CNS; block 22/30b; **Figure 1a**) and comprises sandstone gas-condensate reservoirs under high-pressure and high-temperature (HPHT) conditions in the Jurassic aged Pentland, Fulmar and Heather Fms. The Cretaceous Chalk Gp. overburden and seal across the Shearwater Field can be subdivided into several Fms: Hydra, Plenus Marl, Herring, Hod (Founder, Mackerel equivalent; see Figure 1), Tor and Ekofisk Fms (Jones et al. 2018; **Figure 1c**). The Tor and Hod Fms comprise approximately 1128 m (3700') of the total thickness of the Chalk Gp. on Shearwater. The Hod Fm is characterized by a pelagic marl succession that comprises a series of rhythmic periodites of cleaner chalk and argillaceous chalk couplets at a scale of approx. 1m per couplet. Approximately 30m (100') below the top of the Hod Fm., an interval referred to as the 'Hod Mass Flows' occurs (see Jones et al. 2018). This interval consists of a number of discrete clean limestones interbedded with the pelagic marls which otherwise dominate the Hod Fm. These chalk debris flows are variable in thickness, often with a blocky boxcar log motif. In addition to the low gamma-ray values, the limestones of the debris flows display increased density and faster sonic interval transit times, suggesting that they are cleaner, lower porosity and more brittle than the background marls (Jones et al. 2018). The limestones are interpreted as mass flows representing redeposited chalks, which in

some parts of the North Sea Basin are often a dominant depositional component of the Hod and Tor Fms (e.g. Curlew C Field, Drake et al. 2015). However, as no core is available from the Hod in the Shearwater Field wells this interpretation remains uncertain (Jones et al. 2018). In general, the Chalk Gp. is characterized by low porosity and associated gas saturation/relative permeability is generally too low to allow for any gas to flow into the well during drilling. However, within re-sedimented Hod Mass Flows, the porosity is higher resulting in increased gas influxes into recently drilled wells (i.e. SW A9S1) and bleeding of gas into the casing annuli. The source of the gas is considered *in situ*, flowing from fracture network bound within the mass flow units. These higher porosity/permeability gas bearing zones are not only considered a potential drilling hazard; but should also be isolated and be part of any abandonment program. Therefore, an understanding of the stratigraphic position of the Hod Mass Flows and potential lateral variations is critical. The permeability of the Chalk has also evolved through the field life cycle, with the total stress reduction being largest close to the crest of the structure, directly above the depleting Fulmar, between the base of the Chalk Gp. and the top Fulmar reservoir, and to some extent in the Hod Fm. (see Jones et al 2018). In addition, this portion of the overburden is characterized by vertical and horizontal extension that promotes the opening of fractures, enhancing permeability and allowing hydrocarbons in the Hod 'Mass Flows' to become more mobile over time as a result of the overburden stress changes (Jones et al. 2018).

The overlying Tor Fm. is an approximately 488m (1,600') thick interval dominated by cleaner chalks than the underlying Hod Fm. It contains a number of higher porosity layers which appear to be correlatable over large distances (20–30 km) based on offset

159 wells. Above the Tor, the Palaeocene-age Ekofisk Fm. is characterized by a basal,
160 more argillaceous unit overlain by clean hard chalks. This grades up into the overlying
161 Maureen Fm., which is typically a mixture of claystones, cemented sandstones and
162 reworked chalk (Kilhams et al. 2015). The matrix porosities of the chalks and marls
163 present in the Shearwater Chalk Gp. typically range between 5 and 15%, and reduce
164 markedly with depth which is in line with the published burial depth trends for North Sea
165 chalks as a result of significant mechanical and chemical compaction (Swarbrick et al.
166 2010).

167

168

169 **Figure 1. a.** Location Map showing the Shearwater Field and other nearby fields and
 170 discoveries (source Oil and Gas Authority, UK). Shearwater well locations and well paths plotted
 171 for SW A9S1 and SW A9S3. **b.** Palaeogeographic map of the Turonian (ca. 91 Ma; after Surlyk
 172 et al. 2003; Eldrett et al. 2015b; 2017; Engelke et al. 2017) with locations of other localities
 173 discussed in the text: 1. Salzgitter-Salder, Germany; 2. Contessa, Italy; 3. Eastbourne, U.K; 4.
 174 Shearwater Field (UK; this study); 5. Stevns-1; Denmark; **c.** Lithostratigraphic sub-division of the

Chalk Gp. in the Central North Sea plotted against the global timescale (Gradstein et al. 2012) and nannofossils CC zones (Sissingh, 1977), NP zones (Martini, 1971) and UC zones (Burnett, 1998).

3. Material and Methods

Four hundred and seventy-four (474) ditch-cutting samples spanning the Chalk Gp. in the Shearwater SW A9 well (comprising sidetracks S1 and S3) were collected at 10-foot (3.048 meter) intervals. Samples from the SWA9S1 well covered the Maureen Fm. to middle part of the Tor Fm, whereas the SWA9S3 well covered the middle Tor Fm. to the Hydra Fm. The samples were analyzed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RMAS), Florida, USA. The carbonate materials were reacted with phosphoric acid using a common acid bath at 90°C and the CO_2 released analyzed using a Finnigan-MAT 251. The data were reported relative to V-PDB (Vienna Pee Dee Belemnite) using the conventional notation. In-house reference material (OCC; $\delta^{13}\text{C} = 3.01\text{‰}$; $\delta^{18}\text{O} = -5.28\text{‰}$) was used for quality assurance purposes and to report instrument precision. Replicate analyses yielded a precision $< 0.1\text{‰}$ for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values. Errors are reported as 1 S.D. Carbon isotope stratigraphy is used for refined stratigraphy and global-scale correlations; for the late Campanian-Maastrichtian interval, two distinct nomenclatures exist for carbon isotope events (Thibault et al., 2012a; Voigt et al., 2012). In this paper we have chosen to use the nomenclature of Thibault et al., 2012a which was specifically applied to an ultra-high-resolution signal within the Danish Basin and the most application to this study.

198

199 Nannofossil analyses were conducted on a total of 96 samples across the two
200 wellbores, in addition to the wellsite existing data. Preparation consists in the simple
201 smear slide technique as described by Bown & Young in Bown (1998) and analysis
202 involved counting all specimens within a standard traverse (60 fields of view at 1000
203 magnification) plus the subsequent scanning of the remainder of the slide for rare
204 species. In richly nannofossiliferous samples, abundant species counts were estimated,
205 with their counts from the first traverses being multiplied to equate with a full 100 field of
206 view traverse (Styzen, 1997).

207 A total of 94 foraminiferal analyses were conducted across the two wellbores, in
208 addition to the wellsite's existing data. Indurated chalks have traditionally been
209 processed for micropalaeontological recovery utilizing 'Glaubers' Salts method, but in
210 this study additional acetic acid processing was necessary at times to breakdown the
211 lithology to liberate a meaningful number of microfossils. A biostratigraphic age model
212 was developed using the Bayesian software Bacon v2.4.3 (see Blaauw and Christen,
213 2011; <https://CRAN.R-project.org/package=rbacon>). The last occurrences (LO) and first
214 occurrences (FO) of the regional biostratigraphic marker events and their associated
215 uncertainties (after Thibault, 2016) were used as input (see Supplemental information).
216 The Bacon model uses a statistical method known as Markov chain Monte Carlo
217 (MCMC; Brooks et al., 2011) to estimate the stratigraphy, based on piece-wise linear
218 interpolation. For each run of the MCMC, it models the sedimentation time of each
219 piece-wise section, and constrains these sedimentation times through prior information
220 on the sedimentation time and how it can vary over core depth (Blaauw and Christen,

2011). The priors were set at: mean accumulation rate of 200 years/cm with sixty-five 20m sections. Millions of iterations were run, each giving a likely estimate of the age for any depth of the wellbore. The parameters of the age-depth model were then used to obtain age estimates for every 10m depth intervals. For other uses of Bayesian age-depth modelling in comparably ancient sites, see De Vleeschouwer & Parnell (2014) or Sprain et al. (2019).

4. Results

The two Shearwater A9 sidetrack wells (S1 and S3) were spliced together using the well petrophysical logs to create a composite section that is presented in **Figure 2** and discussed below. The raw stable isotope data is provided in *supplementary information*.

The $\delta^{13}\text{C}$ values range between +3.1‰ and +0.1‰ throughout most of the Chalk Gp; with numerous intervals of enrichment and depletion recorded throughout. The uppermost part of the studied interval in the Maureen Fm. is characterized by more negative values (-2.25 to -2.87‰). The $\delta^{18}\text{O}$ values vary between -8.9‰ and -2.1‰, becoming increasingly more negative with increasing depth.

Overall microfossil recovery is poor with low to very low abundance and diversity, however applying the Acetic Acid processing technique markedly improved overall fossil recovery. Abundance is generally low and preservation poor, particularly so in the Herring Formation sections.

In calcareous nannoplankton preparations, recovery is reasonably good in the Campanian Hod and Maastrichtian Tor sections, but in common with foraminifera

243 recovery drops off in to the Herring Formation where low diversity, low abundance and
244 poor to very poor preservation is recorded where the chalk can be described as hard,
245 indurated and argillaceous. Despite the less than ideal lithologies, the recovery of age-
246 diagnostic marker taxa is good and utility is found in both LOs and FOs within the
247 stratigraphy (see Table 1).

248

249 **Figure 2.** Summary of results for Shearwater A9 composite section. Stable $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$
 250 records plotted against depth; lithostratigraphy, lithology and gamma-ray petrophysical log. The
 251 interpreted isotope excursions are plotted (green = positive isotope excursion; pink = negative
 252 isotope excursion). The boreal nannofossils zonation (Burnett, 1998; Fritsen, 1999) and

253 *identified maker events are plotted (left column are last occurrences [LO]; right column are first*
254 *occurrences [FO]. The interpreted Stage and sub-stage intervals are plotted on the far right.*

255

Bioevent	depth (m)	Depth (ft)	next sample (m)	next sample (feet)	Sampling uncer- tainty (m)	sampling uncertainty (feet)	Age (Ma)	Uncertain- ty (Ma)	Reference
FO <i>Cribrosphaerella daniae</i>	3739.9	12270	3742.9	12280	-3.0	10	66.8	0.5	Burnett et al. (1998), Thibault (2016), Boussaha et al. (2016)
FO <i>Nephrolithus frequens</i>	3886.2	12750	3889.2	12760	-3.0	10	68.5	0.5	Burnett et al. (1998), Thibault (2016), Boussaha et al. (2016)
LO <i>Calculites obscurus</i>	3886.2	12750	3883.2	12740	3.0	-10	69.1	0.5	Burnett et al. (1998), Thibault (2016)
LO <i>Reinhardtites levis</i>	4139.2	13580	4136.1	13570	3.0	-10	70	0.6	Burnett et al. (1998), Anthonissen & Ogg (2012), Thibault (2016), Boussaha et al. (2016)
LO <i>Broinsonia parca constricta</i>	4224.5	13860	4215.4	13830	9.1	-30	70.5	0.3	Burnett et al. (1998), Thibault (2016), Boussaha et al. (2016)
LO <i>Eiffelithus eximius</i>	4276.3	14030	4267.2	14000	9.1	-30	73.8	0.5	Burnett et al. (1998), Thibault (2016), Boussaha et al. (2016)
LO <i>Helicolithus trabeculatus</i>	4285.5	14060	4276.3	14030	9.1	-30	69.9	0.5	Burnett et al. (1998)
LO <i>Heteromarginatus bugensis</i>	4306.8	14130	4297.7	14100	9.1	-30	73.1	0.6	Burnett et al. (1998), Boussaha et al. (2016)
FO <i>Monomarginatus quaternarius</i>	4547.6	14920	4550.7	14930	-3.0	10	79.98 5	0.9	Burnett et al. (1998)
FO <i>Broinsonia parca constricta</i>	4581.1	15030	4590.3	15060	-9.1	30	81.38	0.2	Anthonissen & Ogg (2012)
FO <i>Broinsonia parca parca</i>	4639.1	15220	4645.2	15240	-6.1	20	81.43	0.2	Anthonissen & Ogg (2012)
LO <i>Lithastrinus septenarius</i>	4672.6	15330	4666.5	15310	6.1	-20	85.56	0.2	Anthonissen & Ogg (2012)
FO <i>Arkhangelskiella cymbiformis cymbiformis</i>	4721.4	15490	4727.4	15510	-6.1	20	83.2	0.5	Burnett et al. (1998)
LO <i>Quadrum gartneri</i>	4791.5	15720	4788.4	15710	3.0	-10	86.44	0.5	Anthonissen & Ogg (2012)
LO <i>Quadrum eptabrachium</i>	4791.5	15720	4788.4	15710	3.0	-10	84.95	1.31	Burnett et al. (1998)
FO <i>Reinhardtites levis</i>	4797.6	15740	4803.6	15760	-6.1	20	81.2	0.5	Burnett et al. (1998)
OCC <i>Dicarinella concavata</i>	4815.8	15800	4821.9	15820	-6.1	20	89.91	0.5	Burnett et al. (1998)
FO <i>Tortololithus virginica</i>	4901.2	16080	4907.3	16100	-6.1	20	88.01 5	0.2	Burnett et al. (1998)
LO <i>Helicolithus turonicus</i>	4910.3	16110	4907.3	16100	3.0	-10	89.8	0.3	Burnett et al. (1998)
FO <i>Quadrum eptabrachium</i>	4919.5	16140	4925.6	16160	-6.1	20	91.84	2.065	Burnett et al. (1998)
FO <i>Eiffelithus eximius</i>	4989.6	16370	4992.6	16380	-3.0	10	93.11	0.17	Burnett et al. (1998); Anthonissen & Ogg (2012)

Table 1. Main calcareous nannofossil and foraminifer bio-events in the Shearwater A9 well.

5. Discussion

5.1. Carbonate diagenetic overprint

This study provides high-resolution stratigraphic data for the Chalk sequences in the HPHT area of the CNS. However, as with modern and other ancient carbonate systems, diagenetic alteration that is commonly observed in fine-grained carbonate sedimentary rocks remains a concern when interpreting $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (Swart, 2015 and references therein). Deep burial cementation and recrystallization can result in the addition of isotopically depleted calcite to the bulk carbonate pool, shifting the bulk oxygen isotope towards lower values (Padden et al., 2002). However, during burial diagenesis, carbon isotope values are less prone to diagenetic alteration than oxygen isotope values (Marshall, 1992; Padden et al., 2002) as the carbon isotope system is rock-dominated and the $\delta^{13}\text{C}$ values are not significantly influenced by temperature. In order to ascertain the possible global significance of the measured changes in the $\delta^{13}\text{C}$ values, diagenetic or local lithological influences on the records must first be accounted for and if possible excluded.

Like many previous publications (i.e. Mitchell et al. 1997, Jarvis et al. 2015; Perdiou et al. 2016; Deville de Periere et al. 2019) the present study uses the relationship or covariance between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ to evaluate depositional and post-depositional controls on the recorded isotope values (see **Figure 3**). However, caution should be expressed when interpreting $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ covariance trends as in recent sediments

positive covariance trends have been shown to be artefacts (see Swart et al. 2009, 2015, Swart and Oehlert, 2018). Furthermore, Oehlert & Swart (2019) applied a rolling window regression on $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from the Great Bahama Bank and observed that variations in the nature of the correlation could be attributed to changes in sediment source and diagenetic style associated with marine hardgrounds and periods of reduced sedimentation.

In this study, there is a strong co-variance between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values using reduced major axis regression (RMA) within the Maureen Fm ($r^2=0.92$; albeit with very low number of data points), whereas the Ekofisk - Tor formations exhibit moderate covariance (RMA; $r^2=0.54$), and the Hod-Herring interval exhibits weak correspondence (RMA; $r^2=0.0056$). Given the potential challenges in interpreting covariance trends in recent and ancient sediments as discussed above, the strong co-variance in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values from the Maureen Fm compared to the other formations is cautiously interpreted to reflect a meteoric overprint (i.e., positive covariation of coupled $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, respectively; cf. Allan and Matthews, 1982; Lohmann, 1988) and/or a potential change in provenance or sediment mixing (Swart and Eberli 2005; Oehlert and Swart, 2019). The long-distance flow of meteoric water through the Paleocene Montrose Group (of which the Maureen Fm. is part) has been documented (Stewart et al. 2000), whereas a change in sediment source and mixing is also supported by a major lithological change between the carbonate rich Chalk Gp. and the siliciclastic Maureen Fm., the latter comprise massive reworked chalk turbidites that originate from more shallow marine shelf regions (Kilhams et al. 2015). The low carbonate content of the Maureen Fm. makes these rocks more susceptible to post depositional alteration of

301 $\delta^{13}\text{C}$ values as the pore water will no longer be buffered to the same extent as high
302 carbonate content rocks (Swart et al. 2015).

303 In addition, the Hod-Herring interval exhibits a trend towards more negative $\delta^{18}\text{O}$
304 values with depth, coupled with invariant pattern of $\delta^{13}\text{C}$ values [$r^2=0.0056$] is indicative
305 of some diagenetic alteration with burial precipitation at elevated temperatures (cf.
306 Choquette and James, 1987; Huck et al., 2014). The increasing impact of burial
307 diagenesis with depth is expressed by a significant negative trend in the oxygen isotopic
308 values from -2 ‰ at 4175.76m (13,700') to -8‰ at 4998.72m (16,400') at a rate of
309 $\sim 0.7\text{‰}/100\text{m}$. This is in good agreement with results obtained from deep wells in the
310 Danish Sub-basin (Jørgensen, 1987, Smit et al. 2018) and Chalks from NW Germany
311 (Schönfeld et al. 1991) and UK (Swarbrick et al. 2010) that showed progressive
312 (isotopically light) cement production and loss of porosity due to chemical compaction
313 with increasing burial depth (rate of $\sim 0.6\text{‰}/100\text{m}$). These observations indicate
314 significant diagenetic influence of the Shearwater dataset and seemingly indicate poor
315 reliability of the Chalk Gp stable isotope record (both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) for
316 chemostratigraphic purposes (see also Jeans et al. 2012).

317

Figure 3. Co-variance of $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ values in the Shearwater wells. Shearwater wells plotted by shape and coloured by lithostratigraphy. Reference fields plotted from Moore (1989); with fields of well-preserved foraminifera (after Veizer and Prokoph 2015; O'Brien et al. 2017) most likely reflecting unaltered $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ values indicative of primary Turonian-Maastrichtian seawater. Regression lines after Reduced Major Axis Regression (RMA) with associate slope, intercept and r^2 values plotted.

However, this interpretation does have some challenges. Despite a diagenetic overprint resulting in slightly more negative $\delta^{18}\text{O}$ values compared to well preserved planktonic foraminifera (after Veizer and Prokoph, 2015; O'Brien et al. 2017; illustrated in **Figures 3** and **4**), the overall trend is similar to the generally increasing oxygen and

decreasing carbon isotope values observed through the Late Cretaceous (cf. Jenkyns et al., 1994). A comparison between the Shearwater Chalk $\delta^{18}\text{O}$ with those from low latitude sites compiled from Veizer and Prokoph (2015) and O'Brien et al. (2017) exhibits similar temporal trends (**Figure 4**). It appears that diagenetic alteration of the $\delta^{13}\text{C}$ values is relatively limited (with the potential exception of marine hardgrounds or periods of low sedimentation rate) with the carbon isotope values measured in the Shearwater wells (average $+2.3\text{‰}$ $\delta^{13}\text{C}$) in line with those published for marine limestones (see Moore, 1989 and references therein). The shallowest sample analyzed in the Maureen Fm appears an outlier with $\delta^{13}\text{C}$ value = -2.9‰ . Furthermore, the close similarity between the Shearwater bulk carbonate rock $\delta^{13}\text{C}$ record with numerous other records from different oceans and palaeoenvironments, measured on both marine and terrestrial materials (Jenkyns et al. 1994; Jarvis et al. 2002; 2006; 2015; Voigt et al. 2010; Wendler et al. 2013; Surlyk et al. 2013; Joo and Sageman, 2014; Eldrett et al. 2015b; Thibault et al. 2016a, 2016b; Perdiou et al. 2016; Chenot et al., 2016, 2018; Linnert et al. 2018; Farouk et al. 2018; Razmjooei et al. 2018; 2020; Deville de Periere et al. 2019), indicates that diagenesis did not significantly alter the C-isotope record of the Chalk Gp interval and allows potential for global correlation and calibration.

Figure 4. Comparison of $\delta^{18}\text{O}$ values from Shearwater Chalk interval from wells SW A9S1 and SW A9S3 (filled circles and diamonds) with those from well-preserved planktonic foraminifera obtained from DSDP/ODP and TDP sites (crosses and lines) that are interpreted to reflect primary Turonian to Maastrichtian sea-water values (after O'Brien et al. 2017). Wavy red horizontal lines indicate hiatal surfaces.

5.2. Age model and rock accumulation rates

An age-depth model was generated for Shearwater A9 by comparing the well-based stable $\delta^{13}\text{C}$ isotope record to independently calibrated chalk $\delta^{13}\text{C}$ isotope values (Jarvis et al. 2006; 2015; Voigt et al., 2012; Thibault et al. 2012; 2016b; Deville de Periere et al. 2019) and constrained by nannofossil biostratigraphy (**Figure 5**). To validate the accuracy of the age calibration, the regional marker bio-events identified in Shearwater SWA9 were plotted with uncertainties (after Thibault, 2016) and a Bayesian Bacon age model was developed to compare with and independently constrain the $\delta^{13}\text{C}$ line of correlation (LOC). The $\delta^{13}\text{C}$ LOC generally plots mostly within the 95% Bayesian Bacon age model uncertainties, supporting the stratigraphic interpretation based on carbon isotopes. The age-depth plot illustrates that sedimentation is relatively continuous throughout the Chalk Gp. Several hiatuses are identified in the studied section, including the top of the Tor Fm (4238.2m; 13905'); intra-Hod Fm (4722.3m; 15493' and 4767.4m; 15641'); top of the Herring Fm (4901.5m; 16,081'); intra-Herring Fm (4938.1m; 16201') and its base (5007.8m; 16,430'). The apparent rock accumulation rate (compacted) is relatively high in the cleaner limestones of the Herring and basal

Hod Fm (6-8 cm/kyr). The interval of the Hod Fm., characterized by marl deposition, exhibits lower sedimentation rates (~4 cm/kyr), whilst the cleaner limestones of the overlying Tor Fm., display higher apparent rock accumulation rates (6-10 cm/kyr). These calculated trends in apparent rock accumulation rate may represent condensation and preservation of more fine-grained organic material characteristic of the Hod Fm., during marine transgression, and/or greater compaction of the marls compared to the more indurated clean limestones of the overlying Tor and underlying Herring Fms. The calculated rock accumulation rates account for well-path deviation by using the True Vertical Depth Sub-Sea (TVDSS); and are comparable with Late Cretaceous Chalk sequences in North America (i.e. Austin Chalk Gp; Coniacian age, Texas, USA ~4-6cm/kyrs; Eldrett et al. 2015b).

382

Figure 5. Stratigraphy and Bayesian age–depth modeling for Shearwater A9 from Cenomanian to Selandian Stages (Global Timescale after Gradstein et al. 2012). Shearwater lithostratigraphy and lithology plotted in measured depth along hole (AHD) in feet and meters. Bayesian Bacon age–depth model based on biostratigraphic markers is presented: grey-scales indicate all possible age–depth models, dotted lines indicate the mean and 95% confidence ranges, red dashed line is the mean. Biostratigraphic markers plotted as circles with horizontal bars representing uncertainty ranges; ellipses are student-t distributions (see Table 1; and supplemental information). Age model derived from the carbon isotope correlation plotted as black line. The angle of correlation represents apparent rock accumulation rate in cm/kyrs. Inset graphs display the MCMC (Markov chain Monte Carlo) run (left), prior (green curve) and posterior (grey-filled curve) distributions for accumulation rate (center left), variability/memory (center right) and hiatus size (right).

395

396 **5.3. Regional Comparison and calibration of Stage boundaries**

397 Several substantial shifts in $\delta^{13}\text{C}$ values are recorded in Shearwater SWA9. The
398 potential diagenetic alteration or overprint of the $\delta^{13}\text{C}$ values has been assessed as
399 minimal for the Chalk Gp and thus can be applied for regional and/or global
400 chemostratigraphic correlation. In this section, a brief discussion of the major isotope
401 events and associated biostratigraphic constraints are discussed in stratigraphic order
402 from oldest to youngest.

403

404 **5.3.1. Turonian-Coniacian Boundary (Navigation)**

405 No global stratotype section and point exists presently for the Turonian-Coniacian,
406 although the Salzgitter-Salder quarry (Germany) has been submitted to the Cretaceous
407 Subcommittee for consideration, where the base of the Coniacian is defined by the
408 first occurrence of inoceramid bivalve *Cremnoceramus deformis erectus* (Kauffman et
409 al. 1996, Walaszczyk et al. 2010). The distinct Navigation carbon isotope excursion
410 (CIE) is also used as a secondary isotopic marker of the stage boundary in Europe
411 (Jarvis et al., 2006; Voigt & Hilbrecht, 1997). In the English Chalk reference curve
412 (Jarvis et al. 2006), the Navigation Event is expressed by a sharp decrease in $\delta^{13}\text{C}$
413 values of around -0.4‰ to a minimum of $\sim 1.6\text{‰}$, at the end of a long-term fall within
414 the Upper Turonian above the Hitchwood $\delta^{13}\text{C}$ event (Jarvis et al. 2006). This interval
415 generally corresponds with an interval of Chalk hardground development and increased
416 carbonate cementation that may contribute to the decrease in $\delta^{13}\text{C}$ values. However,

the Navigation Event is also expressed across many other European Chalk sections (e.g. Contessa, Italy; Salzgitter-Salder, Germany) and in both organic and carbonate matter globally (see Joo and Sageman, 2014; Jarvis et al. 2015; Olde et al. 2016; Jones et al. 2017) indicating that this event is of global significance that can be used as the Stage boundary marker.

In the Shearwater A9 composite section, the Late Turonian is interpreted as missing with no apparent fall in $\delta^{13}\text{C}$ values marking the Navigation Event. A hiatus is picked at 4901.5m (~16,081'), with an increase in $\delta^{13}\text{C}$ values below correlated to the h1 isotope marker of Jarvis et al. (2006) and corresponding with the East Cliff $\delta^{13}\text{C}$ event (Jarvis et al. 2006). This interpretation suggests a hiatal duration of ~0.4 Myrs, with the Turonian-Coniacian Boundary (Navigation event) and early Coniacian Beeding and Light Point events missing. This interpretation is consistent with the biostratigraphic constraints, which indicate Coniacian down to 4901m (16,080') based on first occurrence of *Tortolithus virginica* and the continued presence of *in situ* *M. staurophora*.

Figure 6. Comparison of stable $\delta^{13}\text{C}$ values for the Turonian Stage between Shearwater A9 and other chalk sequences from the United Kingdom (U.K): Culver Cliff and Trunch borehole (after Jarvis et al. 2006) and the Contessa quarry, Italy (after Stoll and Schrag, 2000). Correlation of positive (green) and negative (cream) carbon isotope excursions defining named carbon isotope events (Jarvis et al., 2006) are shown by horizontal coloured bands. Wavy red horizontal lines indicate hiatal surfaces; thick red horizontal lines are stage and sub-stage boundaries. Question marks indicate uncertain correlation and isotope event assignment.

5.3.2. Intra-Turonian sub-Stages

The middle–Late Turonian sub-Stage boundary is placed at the minimum in $\delta^{13}\text{C}$ values (4940.8m; 16,210') and interpreted to represent the Southerham $\delta^{13}\text{C}$ events (after Jarvis et al. 2006) marking the sub-Stage boundary (**Figure 6**). Calcareous nannoplankton recovery is very low and poorly preserved across this interval; with the last occurrence of *Helicolithus turonicus* at 4953m (16,250') and the first occurrence of *Marthasterites furcatus* at 4928.6m (16,170'). Regionally the abundance event of *Helicolithus turonicus* is a marker for the middle Turonian; however poor nannofossil recovery (max. species abundance ~ 4 specimens) limits the use of this marker, while the first occurrence of *M. furcatus* is likely an unreliable age diagnostic event for the middle Turonian (Lees, 2008). The global stratigraphic location of the first occurrence of *M. furcatus* has been demonstrated as diachronous, ranging from the early Turonian through early Coniacian (Burnett, 1998; Burnett and Whitham, 1999; Lees, 2002; Wiese et al. 2004), which led Lees (2008) to preclude it from being a useful marker-species over any great distance (Eldrett et al. 2015b). The base of the Herring Fm. is interpreted

at middle-Early Turonian based on the positive $\delta^{13}\text{C}$ values assigned to the Round Down Event, supported by the first occurrences of *Eiffelithus eximius* (4989.6m; 16,370') and *Eprolithus eptapetalus* (5004.8m; 16,420') indicative of nannofossil zone UC7. The last occurrences of *Helenea chiastia* (4992.6m; 16,380); *Axopodorhabdus albianus* (4998.7m; 16,400') and *Rhagodiscus asper* (5010.9m; 16,440') are usually associated with the latest Cenomanian; however, are interpreted here as potentially reworked as are in close proximity to the unconformable boundary between the Herring and Hydra Fms (ca. 5014m; 16,450').

5.3.3. Coniacian-Santonian Boundary (Michel Dean)

The GSSP for the base of the Santonian is defined at the Cantera de Margas quarry, Olazaguita, Spain and marked by the first occurrence of the inoceramid bivalve *Platyceramus undulatoplicatus* and secondarily by the first occurrence of the planktonic foraminifera *Sigalia carpatica* (Lamolda et al., 2014). In addition, several peaks of $\delta^{13}\text{C}$ values are recognized between the Kingsdown and Bedwell events (Lamolda et al. 2014), with the Michel Dean event corresponding with the boundary (Jarvis et al. 2006; Thibault et al. 2016b) and astronomically dated at 86.3 Ma (Thibault et al. 2016b).

In Shearwater A9; the Coniacian-Santonian boundary is not clearly defined using biostratigraphy with the absence of the foraminifera *Sigalia carpatica* and other globally recognized bio-events. The record of $\delta^{13}\text{C}$ values exhibits a broad increase between 4892m (16,050') and 4800.6m (15,750'). There appears a good comparison between the Shearwater A9 well and other English Chalk sections (i.e. Jarvis et al. 2006). Based

on correlation with these other Chalk sections; some of the established perturbations in $\delta^{13}\text{C}$ values within the Chalk are tentatively assigned in Shearwater A9 (Figure 7). These $\delta^{13}\text{C}$ CIE include the East Cliff (4885.9m; 16,030'); White Fall (4873.7m; 15,990') and Kingsdown (4846.3m; 15,900'). The Bedwell $\delta^{13}\text{C}$ is not clearly expressed in Shearwater A9; and the Michael Dean event that corresponds with the Coniacian-Santonian Boundary is potentially recognized at 4812.8m (15,790'). This interpretation is somewhat supported by the isolated occurrences of the Coniacian - Early Santonian restricted foraminiferal species *Dicarinella primitiva*? and *D. concavata*? at 4815.8m (15,800'). Furthermore, the increased abundance of the nannoplankton species *Helicolithus trabeculatus* at 4821.9m (15,820'; acme recorded at 4840.2m; 15,880') indicates penetration of nannoplankton Subzone UC11ii (after Fritsen, 1999) corresponding to the Santonian-Coniacian boundary interval (see Thibault et al. 2016b).

Figure 7. Correlation of the Coniacian-Santonian Boundary Event between Shearwater SW A9 and published carbon isotope curves of the English Chalk: Culver Cliff; Dover and Trunch borehole (after Jarvis et al. 2006). Coniacian-Santonian Boundary calibrated to 86.3 Ma, corresponding with the Michel Dean $\delta^{13}\text{C}$ event (after Thibault et al. 2016). Events Sa2; Sa1; Co2 and Co1 correspond with global sequence boundaries. Correlation of positive (green) and negative (cream) carbon isotope excursions defining named carbon isotope events (Jarvis et al., 2006) are shown by horizontal coloured bands. Wavy red horizontal lines indicate hiatal surfaces; thick red horizontal lines are stage and sub-stage boundaries, dashed red lines indicative tentative correlation. Question marks indicate uncertain correlation and isotope event assignment. Adapted after Al-Husseini (2018).

5.3.4. Santonian/Campanian Boundary Event (SCBE)

At the time of writing, there is no GSSP for the Santonian-Campanian boundary. However, the favored bio-horizon marking the base of the Campanian is the extinction of the crinoid *Marsupites testudinarius* (Gale et al., 2008). The occurrence of this taxon is restricted to certain environments, preventing widespread applicability (Gradstein et al. 2012). In addition, many sections considered as a GSSP do not have consistent macrofossil or microfossil records. When available the limited nannofossil data provide some constraints (i.e. FO of *B. parca parca*; see Dubicka et al. 2017) but a general lack of consistent nannofossil marker species in Boreal mid-Campanian successions, provincialism of several key taxa, and possible diachroneity between biotic provinces (e.g. Burnett, 1998) prevent precise correlation (Jarvis et al. 2002). Therefore, additional marker events have been sought, including the beginning of magnetic Chron C33r (Ogg

and Hinnov, 2012) and the positive shift in $\delta^{13}\text{C}$ termed the Santonian-Campanian Boundary Event (SCBE). The SCBE is a short positive excursion (150 kyr, Thibault et al., 2016) classified as a “heavy event” by Jarvis et al. (2002, 2006), with a carbon isotope variance typically around $\sim 0.3\text{‰}$ (Jarvis et al., 2006).

In Shearwater A9, the interval between 4669.5m - 4645.1m (15,320-15,240') records a slight $\sim 0.4\text{‰}$ increase in $\delta^{13}\text{C}$ values from background values between 2.5‰-2.7‰, reaching a maximum of 3.12‰. This interval is tentatively assigned to the SCBE (**Figure 8**). When compared with other Boreal Chalk sections in United Kingdom and Europe such as the Trunch borehole (Norfolk, UK; Jarvis et al. 2006); Seaford Head (Sussex, UK; Thibault et al. 2016) and the Lägerdorf section (Germany; Voigt et al. 2010), the carbon isotope trends observed in Shearwater A9 for the Santonian-Campanian interval appear consistent (**Figure 8**). Similar comparisons can be made with numerous other sections, including Danes Dyke (Yorkshire, UK; de Pierere et al. 2019), Gubbio - la Bottaccione (Italy; Thibault et al. 2016; Chenot et al. 2018; Sabatino et al. 2018), Poigny (France; Chenot et al. 2016), Bocieniec (Poland; Dubicka et al. 2017) and Postalm (Austria; Wolfgring et al. 2018).

In Shearwater A9; the first occurrence of the calcareous nannofossil *Broinsonia parca parca* is recorded at 4639m (15,220'). This bio-event is a favoured marker in the Tethyan realm for the position of the Santonian-Campanian boundary (Gardin et al., 2001; Tremolada, 2002). *B. parca parca* is also found in the Boreal Realm but its position is much above the last occurrence of *Marsupites* (Hampton et al., 2007; Dubicka et al., 2017). In Shearwater A9, the first occurrence of *B. parca parca* occurs at the top of SCBE, which is consistent with its occurrence in the Lägerdorf section

(Figure 8). This interpretation is further constrained by the FO of *Arkhangelskiella cymbiformis* morphogroup at 4721.3m (15,490'). A single specimen of *Quadrum eptabrachium* is recorded at 4721.3m (15,490'), occurring at the base of the Hod Mass Flow and is regarded as reworked., the LO of *in situ* *Q. eptabrachium* is recorded at 4791.46m (15720') and is considered to be Santonian in age (Nannofossil zone UC11iii). In Shearwater A9 the Santonian-Campanian boundary is placed at 15270' $\pm$ 10' and assigned an age of 84.19 $\pm$ 0.38 Ma (after Thibault et al. 2016b). It should be noted that a number of additional $\delta^{13}\text{C}$ excursions have been identified in the Campanian (Jenkyns et al. 1994; Jarvis et al., 2002; 2006; Thibault et al., 2016b; Razmjooei et al., 2018) that are not resolved in this contribution as they tend to be of such small amplitudes (0.1‰ to 0.3‰) that they necessitate very high resolution to identify them with confidence. In the case of ditch-cuttings material, this may only be possible with highly deviated or horizontally drilled wellbores where stratigraphic resolution is increased through cross-cutting strata whilst maintaining standard sampling resolution (~3m-10m (10'-30'; see Drake et al. 2015).

Figure 8. Correlation of the Santonian-Campanian Boundary Event (SCBE) between Shearwater SWA9 and published carbon isotope curves from Seaford Head (UK; Thibault et al. 2016), Trunch borehole (UK; Jarvis et al. 2006) and Lägerdorf (Germany; Voigt et al. 2010). Correlation of positive (green) and negative (cream) CIEs defining named carbon isotope events (Jarvis et al., 2006) are shown by horizontal coloured bands. Wavy red horizontal lines indicate hiatal surfaces; thick red horizontal lines are stage and sub-stage boundaries.

5.3.5. Campanian-Maastrichtian Boundary (CMB)

At the Maastrichtian GSSP of Tercis les Bains (southwestern France), the Campanian-Maastrichtian boundary is defined by the arithmetic mean of 12

biostratigraphic criteria of equal importance. Among these criteria are several
 macrofossils (ammonites, inoceramid bivalves) and microfossils (calcareous
 nannofossils, dinoflagellate cysts, benthic and planktonic foraminifers). The LO of the
 ammonite *Pachydiscus neubergicus* lies closely above the boundary level and was
 chosen as a guiding event for the boundary (Odin and Lamaurelle, 2001). For relevance
 to this study, the LO of *P. neubergicus* is also recorded from ~10 m below the last
 occurrences of the calcareous nannofossils *Uniplanarius gothicus* and *U. trifidus* and
 last occurrence of *Eiffellithus eximius* and *Broinsonia parca constricta* (Gardin and
 Monechi, 2001; Odin and Lamaurelle, 2001). However, both *U. gothicus* and *U. trifidus*
 are inferred to be mostly restricted to the Tethyan realm. Rare occurrences of *U. trifidus*
 are recorded in the southern part of the Boreal realm (NW Germany, Schönfeld et al.,
 1996; Niebuhr et al., 2011), but mostly absent further north (Perch-Nielsen, 1985;
 Thibault et al., 2012, 2015; Sheldon et al., 2014, Boussaha et al., 2016). Therefore, the
 only geographically widespread nannofossil bio-events that can be used to constrain the
 CMB in Northwestern Europe are the last occurrences of *E. eximius* and *B. parca*
constricta. In addition, the base Maastrichtian level at the GSSP is just below a 0.6‰
 negative shift in $\delta^{13}\text{C}$ (CMBc; Thibault et al. 2012).

In Shearwater A9; the $\delta^{13}\text{C}$ record can be correlated to other key sections; Stevns-1
 (Danish Basin; Thibault et al. 2012, 2016a) and Gubbio (Italy; Voigt et al. 2012) with
 remarkable consistency (see **Figure 9**). A decline in $\delta^{13}\text{C}$ values of approximately ~1‰
 is recorded in Shearwater A9 between 4288.5m (14,070') and 4236.7m (13,900'), and
 this has been interpreted as the CMBc carbon isotope event at 4251.9m (13,950'),
 marking the Campanian-Maastrichtian Boundary (ca. 72.1 Ma). The highest microfaunal

evidence of Late Campanian age is the LO of *Globotruncana aff. arca* at 13,940 (SWA9S1) to 14,030' (SWA9S3). This boundary coincides with trace red-brown chalk lithologies that are regionally characteristic of the Late Campanian and are equivalent to the 'Upper Red Unit' of King (1989).

Several other low amplitude positive and negative excursions named M1-M4 have also been correlated across the Campanian-Maastrichtian interval in the Boreal Realm (Thibault et al., 2012; Surlyk et al., 2013). A tentative correlation of these named $\delta^{13}\text{C}$ events between the Stevns-1 borehole and the outcrop section at Gubbio with the Shearwater A9 well is presented in **Figure 9** and only possible due to the high-resolution $\delta^{13}\text{C}$ datasets obtained from these localities (see Stoll and Schrag. 2001; Thibault et al., 2012; Voigt et al. 2012; this study). In the Boreal Realm, the last occurrence of *Tranolithus orionatus* and *B. parca constricta* are recorded within $\delta^{13}\text{C}$ isotope M1- interval. In Shearwater A9, these bio-events are recorded at 4221.5m (13,850') and 4224.52m (13,860'), respectively, in an interval tentatively assigned to the M1- event. There remains some uncertainty as the slight positive $\delta^{13}\text{C}$ event M1+ is not recognized in Shearwater A9, possibly due to a missing section (~4236.7m; 13,900'). The other named isotope events are consistent between the sections; with the first occurrences of *N. frequens* and *Cribrosphaerella daniae* occurring above the positive M3-(a) and M4+ $\delta^{13}\text{C}$ events, respectively. In the Boreal Realm, the last occurrence of *Reinhardtites levis* is restricted to the M2+ $\delta^{13}\text{C}$ event. In Shearwater A9, *R. levis* is recorded up to 4002m (13,130'). However, this interval is characterized by relatively sparse floral assemblages and the range top of this species is not consistent throughout the section, so it is likely that many of these shallower sporadic occurrences are

608 reworked. More consistent occurrences are recorded from 4136.2m (13,580'); where
 609 the last occurrence of *in-situ* *R. levis* is interpreted and corresponds with the M2+ $\delta^{13}\text{C}$
 610 event identified in Shearwater A9. The interval between the LO *R. levis* and the FO *N.*
 611 *frequens* contains relatively sparse floral assemblages and is assigned to UC20a -
 612 UC19. The absence of *Lithraphidites quadratus* prevents recognition of the top of
 613 UC19; this may be a regional phenomenon as this marker species appears to be either
 614 rare or absent in the boreal chalk sea (Thibault et al., 2012a, 2015; Boussaha et al.,
 615 2016; this study) compared to Tethyan regions where it has frequent occurrence,
 616 defining zone UC19 (Burnett, 1998).

617

618 **Figure 9.** Correlation of the $\delta^{13}\text{C}$ curve of Shearwater SWA9 with Stevns-1 (Thibault et al.
 619 2012), and the Gubbio section with magnetostratigraphic and $\delta^{13}\text{C}$ tie-points. $\delta^{13}\text{C}$ curve

compiled after Thibault et al. (2012) and Stoll and Schrag (2001). Stevns-1 nannofossil zonation and carbon-isotope stratigraphy after Thibault et al. (2012). Gubbio carbon-isotope stratigraphy after Voigt et al. (2012) and nannofossil and foraminifer biostratigraphy after Gardin et al. (2012). Adapted after Surlyk et al. (2013).

5.3.6. Cretaceous-Palaeogene Boundary Event (KPge)

The base-Danian GSSP has been fixed in a section of Oued Djerfane, 8 km west of El Kef, Tunisia. The GSSP level has been defined at the rusty coloured base of a 50 cm thick boundary clay. A similar layer occurs in many K/Pg sections worldwide and it includes an iridium anomaly used as a golden spike and dated with geochronology and astrochronology at 65.95 Ma (Kuiper et al. 2008), although calibrated later to 66.030 ± 0.051 Ma (Renne et al. 2013). The boundary is also marked by a 2-3‰ negative carbon isotopic excursion in calcite and organic matter (Keller and Lindinger, 1989; Gradstein et al. 2012). In Shearwater A9, there is a progressive decrease in $\delta^{13}\text{C}$ values from 1.45‰ (~3724.65m; 12,220') to a minimum of 0‰ at 3694.17m (12,120'). Based on correlation to the El Kef GSSP, this negative excursion in $\delta^{13}\text{C}$ values within the lowermost Ekofisk Fm., is assigned to the K-Pg boundary event (**Figure 10**). This interval is also characterized by calcareous nannofossil assemblages characterized by 'disaster taxa' including abundant *Thoracosphaera* spp. in association with rare *Biscutum castrorum*, *Placozygus sigmoides*, *Neocrepidolithus* spp., *Cyclagelosphaera alta* and rare occurrences of reworked Late Cretaceous taxa. Key biostratigraphic markers that supports the assignment of the K/Pg interval to ~3700.27m (12,140') to 3712.46m (12180') is the last occurrence of the planktonic foraminifera *Pseudotextularia*

643 *elegans* at 3724.65m (12,200') and the first occurrence of the calcareous nannofossil
 644 *Nephrolithus frequens* at 3712.46m (12,180'). The latter is associated with the last
 645 abundant occurrence of *Arkhangelskiella cymbiformis* var. *maastrichtiana* from
 646 13724.65m (12,200') indicating penetration of the Late Maastrichtian nannofossil
 647 Subzone UC20i-iii.

648

649 Figure 10. Carbon isotope correlation between the Danian GSSP located at El Kef in
 650 Tunisia (after Gradstein et al. 2012) and Shearwater A9, Central North Sea.

651

652

653 **6. Conclusions**

654 Profiles of bulk carbonate stable $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values were generated from ditch-
655 cuttings material recovered from the Shearwater A9 production well, Shearwater Field,
656 Central North Sea. Diagenetic alteration of the primary depositional signal was
657 evaluated and although deep burial cementation and alteration appear to affect $\delta^{18}\text{O}$
658 isotope values, the $\delta^{13}\text{C}$ values are interpreted as having little diagenetic or lithological
659 overprint. The recovered $\delta^{13}\text{C}$ profile was integrated with nannofossil and foraminifera
660 biostratigraphy to provide a high-resolution record of Late Cretaceous to Palaeogene
661 stratigraphy of deeply buried strata of the Chalk Gp, Central North Sea. A precise
662 correlation between the Shearwater A9 profile of $\delta^{13}\text{C}$ values and other published
663 Boreal and Tethyan sections support the robustness of the recovered $\delta^{13}\text{C}$ record.
664 These correlations have aided the identification of many of the Late Cretaceous Stage
665 and sub-stage boundaries from the Shearwater A9 well, providing a long-term near
666 continuous record of the Late Cretaceous to Palaeogene from the basinal deposits of
667 the Central North Sea. Several hiatuses were identified that were relatively short in
668 duration (<0.5 myrs). However, at this location most of the Cenomanian (including OAE-
669 2) is missing in a much longer hiatus associated with a middle Turonian event. This
670 study has demonstrated the application of stable isotope stratigraphy on ditch-cuttings
671 material from hydrocarbon exploration and production wells. This potentially opens-up a
672 highly resolved rock archive (particularly in stratigraphically expanded sections and/or
673 deviated or long horizontally drilled wells) for potential palaeo-climate study.

674

675 **Acknowledgements**

676 Help with the stable isotope analyses at the University of Miami was provided by
 677 Amel Saied and Greta Mackenzie. Permission to publish the data and interpretations
 678 herein were kindly provided by Shell UK Ltd, and their partners Esso Exploration and
 679 Production UK Ltd, and Arco British Ltd. The interpretations and opinions presented
 680 here are those of the authors only and do not in any way represent the views of Shell
 681 UK Ltd, Esso Exploration and Production UK Limited, or Arco British Ltd.

682

683 **References:**

- 684 Allan, J.R., Matthews, R.K., (1982). Isotopes signature associated with early meteoric diagenesis.
 685 Sedimentology 29, 797-817.
- 686 Al-Husseini, M. (2018). Orbital-forcing of Cenomanian–Santonian glacio-eustasy. Orbitalscale.net
- 687 Anthonissen, D. E., & Ogg, J. G. (2012). Cenozoic and Cretaceous biochronology of planktonic
 688 foraminifera and calcareous nannofossils. In *The geologic time scale* (pp. 1083-1127). Elsevier.
- 689 Blaauw, M., & Christen, J.A. (2011). Flexible paleoclimate age-depth models using an autoregressive
 690 gamma process. Bayesian Analysis 6, 457-474.
- 691 Boussaha, M., Thibault, N., & Stemmerik, L. (2016). Integrated stratigraphy of the late Campanian–
 692 Maastrichtian in the Danish Basin: revision of the Boreal calcareous nannofossil zonation.
 693 Newsletters on Stratigraphy, 49(2), 337-360.
- 694 Bowman, V. C., Francis, J. E., & Riding, J. B. (2013). Late Cretaceous winter sea ice in
 695 Antarctica?. *Geology*, 41(12), 1227-1230.

- 696 Brooks, S., Gelman, A., Jones, G., and Meng, X.-L., eds., (2011), Handbook of Markov Chain Monte
697 Carlo: Boca Raton, Florida, CRC Press, 619 p
- 698 Burnett, J.A., (1998). Upper Cretaceous. In: Bown, P.R. (Editor), Calcareous Nannofossil Biostratigraphy.
699 British Micropalaeontological Society Publications Series. Chapman & Hall, London, pp. 132-199
- 700 Burnett, J. A., & Whitham, F. (1999). Correlation between the nannofossil and macrofossil
701 biostratigraphies and the lithostratigraphy of the Upper Cretaceous of NE England. Proceedings of
702 the Yorkshire Geological Society, 52(4), 371-381.
- 703 Choquette, P.W., James, N.P., (1987). Diagenesis 12; Diagenesis in limestones; 3. The deep burial
704 environment. Geoscience Canada 14, 3-35.
- 705 Chenot, E., Pellenard, P., Martinez, M., Deconinck, J. F., Amiotte-Suchet, P., Thibault, N., ... &
706 Robaszynski, F. (2016). Clay mineralogical and geochemical expressions of the “Late Campanian
707 Event” in the Aquitaine and Paris basins (France): Palaeoenvironmental implications.
708 Palaeogeography, Palaeoclimatology, Palaeoecology, 447, 42-52.
- 709 Chenot, E., Deconinck, J.F., Puceat, E., Pellenard, P., Guiraud, M., Jaubert, M., Jarvis, I., Thibault, N.,
710 Cocquerez, T., Bruneau, L., Razmjooei, M.J., Boussaha, M., Richard, J., Sizun, J.P., Stemmerik, L.,
711 (2018). Continental weathering as a driver of Late Cretaceous cooling: new insights from clay
712 mineralogy of Campanian sediments from the southern Tethyan margin to the Boreal realm. Global
713 and Planetary Change 162, 292e312. Craig, H. (1957). Isotopic standards for carbon and oxygen and
714 correction factors for mass-spectrometric analysis of carbon dioxide. Geochimica et cosmochimica
715 acta, 12(1-2), 133-149.
- 716 Deville de Periere , M. D., Pellenard, P., & Thibault, N. (2019). The Santonian–Campanian Boundary
717 Event (SCBE) in Boreal Basins: New geochemical and mineralogical data from the Northern Chalk
718 Province (East Yorkshire, UK). Cretaceous Research, 95, 61-76.
- 719 Drake, S. J., Large, S. C., McQueen, A. R., & Hale, M. J. (2015). Curlew-C: realising production from a
720 UK Central North Sea chalk field. Proceedings of the Geologists' Association, 126(3), 314-327.

- 721 Deegan, C.E., & Scull, B.J. (1977). A standard lithostratigraphic nomenclature for the Central and
722 Northern North Sea. Vol. 1. HMSO, 1977.
- 723 De Vleeschouwer, D., & Parnell, A.C. (2014). Reducing time-scale uncertainty for the Devonian by
724 integrating astrochronology and Bayesian statistics. *Geology* 42(6), 491-494.
- 725 Dubicka, Z., Jurkowska, A., Thibault, N., Razmjooei, M. J., Wójcik, K., Gorzelak, P., & Felisiak, I. (2017).
726 An integrated stratigraphic study across the Santonian/Campanian boundary at Bocieniec, southern
727 Poland: A new boundary stratotype candidate. *Cretaceous Research*, 80, 61-85.
- 728 Eldrett, J. S., Ma, C., Bergman, S. C., Lutz, B., Gregory, F. J., Dodsworth, P., ... & Ramezani, J. (2015b).
729 An astronomically calibrated stratigraphy of the Cenomanian, Turonian and earliest Coniacian from
730 the Cretaceous Western Interior Seaway, USA: Implications for global chronostratigraphy.
731 *Cretaceous Research*, 56, 316-344.
- 732 Eldrett, J., Tripsanas, E., Davis, C., McKie, T., Vieira, M., Osterloff, P., & Sandison, T. (2015a).
733 Sedimentological evolution of Sele Formation deep-marine depositional systems of the Central North
734 Sea. *Geological Society, London, Special Publications*, 403(1), 63-98.
- 735 Engelke, J., Linnert, C., Mutterlose, J., & Wilmsen, M. (2017). Early Maastrichtian benthos of the chalk at
736 Krons Moor, northern Germany: implications for Late Cretaceous environmental change.
737 *Palaeobiodiversity and Palaeoenvironments*, 97(4), 703-722.
- 738 Farouk, S., Faris, M., Elamri, Z., Ahmad, F., & Wagreich, M. (2018). Tethyan plankton bioevents
739 calibrated to stable isotopes across the upper Santonian–lower Campanian transition in north-
740 western Tunisia. *Cretaceous Research*, 85, 128-141.
- 741 Gale, A. S., Montgomery, P., Kennedy, W. J.,
742 Hancock, J. M., Burnett, J. A., & McArthur, J. M. (1995). Definition and global correlation of the
743 Santonian-Campanian boundary. *Terra Nova*, 7(6), 611-622.
- 744 Fritsen, A. (1999), A Joint Chalk Stratigraphic Framework, vol. 1, pp. 206, Joint Chalk Res. Prog. Topic V.
Norw. Pet. Directorate.

- 745 Gale, A. S., Voigt, S., Sageman, B. B., & Kennedy, W. J. (2008). Eustatic sea-level record for the
746 Cenomanian (Late Cretaceous)—extension to the Western Interior Basin, USA. *Geology*, 36(11),
747 859-862.
- 748 Gardin, S., Monechi, S., (2001). Calcareous nannofossil distribution in the tercis geological site (Landes,
749 SW France) around the Campanian-Maastrichtian boundary. *Dev. Palaeontol. Stratigr.* 19, 272–284.
- 750 Gardin, S., Del Panta, F., Monechi, S., Pozzi, M., (2001). A tethyan reference section for the Campanian
751 and Maastrichtian stages: the Bottaccione section (Central Italy). Review of the data and new
752 calcareous nannofossil results. In: Odin, G.S. (Ed.), *The Boundary between the Campanian and the*
753 *Maastrichtian Styages: Characterization and Correlation From Tercis-les Bains to Europe and Other*
754 *Continents. Dev. Paleont. Stratigr Vol. 19. pp. 820–833.*
- 755 Gowers, M.B., Holtar, E. and Swensson, E. (1993) The structure of the Norwegian Central Trough
756 (Central Graben area). In: *Petroleum Geology of the Northwest Europe: Proceedings of the 4th*
757 *Conference (Ed J.R. Parker), pp. 1245–1254. The Geological Society of London.*
- 758 Gradstein, F. M., Ogg, J. G., Schmitz, M. D., & Ogg, G. (2012). *The Geologic Time Scale 2012 Vol. 2.*
- 759 Hampton, M. J., Bailey, H. W., Gallagher, L. T., Mortimore, R. N., & Wood, C. J. (2007). The
760 biostratigraphy of Seaford Head, Sussex, southern England; an international reference section for
761 the basal boundaries for the Santonian and Campanian Stages in chalk facies. *Cretaceous*
762 *Research*, 28(1), 46-60.
- 763 Huber, B. T., Norris, R. D., & MacLeod, K. G. (2002). Deep-sea paleotemperature record of extreme
764 warmth during the Cretaceous. *Geology*, 30(2), 123-126.
- 765 Huck, S., Stein, M., Immenhauser, A., Skelton, P.W., Christ, N., Föllmi, K.B., Heimhofer, U., (2014).
766 Response of proto-North Atlantic carbonate-platform ecosystems to OAE1a-related stressors.
767 *Sedimentary Geology*

- 768 Jarvis, I., Mabrouk, A., Moody, R. T., & de Cabrera, S. (2002). Late Cretaceous (Campanian) carbon
769 isotope events, sea-level change and correlation of the Tethyan and Boreal realms.
770 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 188(3-4), 215-248.
- 771 Jarvis, I. A. N., Gale, A. S., Jenkyns, H. C., & Pearce, M. A. (2006). Secular variation in Late Cretaceous
772 carbon isotopes: a new $\delta^{13}\text{C}$ carbonate reference curve for the Cenomanian–Campanian (99.6–
773 70.6 Ma). *Geological Magazine*, 143(5), 561-608.
- 774 Jarvis, I., Trabucho-Alexandre, J., Gröcke, D. R., Uličný, D., & Laurin, J. (2015). Intercontinental
775 correlation of organic carbon and carbonate stable isotope records: evidence of climate and sea-
776 level change during the Turonian (Cretaceous). *The Depositional Record*, 1(2), 53-90.
- 777 Jeans, C., Hu, X., & Mortimore, R. (2012). Calcite cements and the stratigraphical significance of the
778 marine $\delta^{13}\text{C}$ carbonate reference curve for the Upper Cretaceous Chalk of England. *Acta Geologica*
779 *Polonica*, 62(2), 173-196.
- 780 Jelby, M. E., Thibault, N., Surlyk, F., Ullmann, C. V., Harlou, R., & Korte, C. (2014). The lower
781 Maastrichtian Hvidskud succession, Møns Klint, Denmark: calcareous nannofossil biostratigraphy,
782 carbon isotope stratigraphy, and bulk and brachiopod oxygen isotopes. *Bulletin of the Geological*
783 *Society of Denmark*, 62(89), e104.
- 784 Jenkyns, H. C., Gale, A. S., & Corfield, R. M. (1994). Carbon-and oxygen-isotope stratigraphy of the
785 English Chalk and Italian Scaglia and its palaeoclimatic significance. *Geological Magazine*, 131(1),
786 1-34.
- 787 Johnson, H., Lott, G. K., Cordey, W. G., RWO'B, K., Wilkinson, I. P., Riding, J. B., & Hine, N. M. (1993).
788 Lithostratigraphic Nomenclature of the UK North Sea: Vol. 2 Cretaceous of the Central and Northern
789 North Sea. British Geological Survey for the United Kingdom Offshore Operators Association.
- 790 Jones, D. W., Taylor, B. J., Gill, C. E., Bevaart, M., van Bergen, P. F., Watson, J. S., ... & Hodzic, M.
791 (2018, January). The Shearwater Field—understanding the overburden above a geologically complex
792 and pressure-depleted high-pressure and high-temperature field. In *Geological Society, London,*
793 *Petroleum Geology Conference series* (Vol. 8, No. 1, pp. 429-443). Geological Society of London.

- 794 Jones, M. M., Sageman, B. B., & Meyers, S. R. (2018). Turonian Sea Level and Paleoclimatic Events in
795 Astronomically Tuned Records From the Tropical North Atlantic and Western Interior Seaway.
796 *Paleoceanography and Paleoclimatology*.
- 797 Joo, Y. J., & Sageman, B. B. (2014). Cenomanian to Campanian carbon isotope chemostratigraphy from
798 the Western Interior Basin, USA. *Journal of Sedimentary Research*, 84(7), 529-542.
- 799 Jørgensen, N. O. (1987). Oxygen and carbon isotope compositions of Upper Cretaceous chalk from the
800 Danish sub-basin and the North Sea Central Graben. *Sedimentology*, 34(4), 559-570.
- 801 Keller, G., & Lindinger, M. (1989). Stable isotope, TOC and CaCO₃ record across the Cretaceous/Tertiary
802 boundary at El Kef, Tunisia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 73(3-4), 243-265.
- 803 Kauffman, E. G., Kennedy, W. J., & Wood, C. J. (1996). The Coniacian stage and substage boundaries.
804 *Bulletin de l'Institut Royal des Sciences naturelles de Belgique, Sciences de la Terre*, 66(Suppl.), 81-
805 94.
- 806 Kilhams, B., Hartley, A., Huuse, M., & Davis, C. (2015). Characterizing the Paleocene turbidites of the
807 North Sea: Maureen Formation, UK Central Graben. *Geological Society, London, Special*
808 *Publications*, 403(1), 43-62.
- 809 King, C., Bailey, H.W., Burton, C.A. & King, D. 1989. Cretaceous of the North Sea. In: Jenkins, D.G. &
810 Murray, J.W. *Stratigraphical index of fossil foraminifera*, Second edition, 372-417.
- 811 Kuiper, K. F., Deino, A., Hilgen, F. J., Krijgsman, W., Renne, P. R., & Wijbrans, A. J. (2008).
812 Synchronizing rock clocks of Earth history. *science*, 320(5875), 500-504.
- 813 Lamolda, M. A., Paul, C. R. C., Peryt, D., & Pons, J. M. (2014). The global boundary stratotype and
814 section point (GSSP) for the base of the Santonian Stage," Cantera de Margas", Olazagutia,
815 northern Spain. *Episodes*, 37(1), 2-13.
- 816 Lees, J. A. (2002). Calcareous nannofossil biogeography illustrates palaeoclimate change in the Late
817 Cretaceous Indian Ocean. *Cretaceous Research*, 23(5), 537-634.

- 818 Linnert, C., Robinson, S. A., Lees, J. A., Pérez-Rodríguez, I., Jenkyns, H. C., Petrizzo, M. R., ... &
819 Falzoni, F. (2018). Did Late Cretaceous cooling trigger the Campanian–Maastrichtian Boundary
820 Event?. *Newsletters on Stratigraphy*, 51(2), 145-166.
- 821 Lohmann, K.C., 1988. Geochemical patterns of meteoric diagenetic systems and their application to
822 studies of paleokarst. In: James, N.P., Choquette, P.W. (Eds.), *Paleokarst*. Springer, pp. 58-80.
- 823 Marshall, J. D. (1992). Climatic and oceanographic isotopic signals from the carbonate rock record and
824 their preservation. *Geological magazine*, 129(2), 143-160.
- 825 Martini, E. (1971). Standard Tertiary and Quaternary calcareous nannoplankton zonation. In *Proc. II*
826 *Planktonic Conference, Roma 1970*, Roma, Tecnoscienza (Vol. 2, pp. 739-785).
- 827 Metzger, J. G., Fike, D. A., & Smith, L. B. (2014). Applying carbon-isotope stratigraphy using well cuttings
828 for high-resolution chemostratigraphic correlation of the subsurface. *AAPG bulletin*, 98(8), 1551-
829 1576.
- 830 Mitchell, S. F., Ball, J. D., Crowley, S. F., Marshall, J. D., Paul, C. R., Veltkamp, C. J., & Samir, A. (1997).
831 Isotope data from Cretaceous chalks and foraminifera: Environmental or diagenetic
832 signals?. *Geology*, 25(8), 691-694.
- 833 Moore, C.H., 1989. Diagenetic environments of porosity modification for their recognition in the geologic
834 record. In: Moore, C.H. (Ed.), *Carbonate Diagenesis and Porosity*. In: *Developments in*
835 *Sedimentology*, vol.46, p.338.
- 836 Mudge, D. C. (2015). Regional controls on Lower Tertiary sandstone distribution in the North Sea and NE
837 Atlantic margin basins. *Geological Society, London, Special Publications*, 403(1), 17-42.
- 838 Niebuhr, B., Hampton, M. J., Gallagher, L. T., & Remin, Z. (2011). Integrated stratigraphy of the
839 Krons Moor section (northern Germany), a reference point for the base of the Maastrichtian in the
840 Boreal Realm. *Acta Geologica Polonica*, 61(2), 193-214.
- 841 Perch-Nielsen, K. (1985). Cenozoic calcareous nanofossils. *Plankton stratigraphy*, 427-554.

- 842 O'Brien, C. L., Robinson, S. A., Pancost, R. D., Damste, J. S. S., Schouten, S., Lunt, D. J., ... &
 843 Farnsworth, A. (2017). Cretaceous sea-surface temperature evolution: Constraints from TEX86 and
 844 planktonic foraminiferal oxygen isotopes. *Earth-science reviews*, 172, 224-247.
- 845 Odin, G. S., & Lamaurelle, M. A. (2001). The global Campanian-Maastrichtian stage boundary. *Episodes*,
 846 24(4), 229-238.
- 847 Ogg, J. G., & Hinnov, L. A. (2012). The geologic time scale 2012. Chapter, 26, 731-791.
- 848 Olde, K., Jarvis, I., Pearce, M., Uličný, D., Tocher, B., Trabucho-Alexandre, J., & Gröcke, D. (2015). A
 849 revised northern European Turonian (Upper Cretaceous) dinoflagellate cyst biostratigraphy:
 850 Integrating palynology and carbon isotope events. *Review of Palaeobotany and Palynology*, 213, 1-
 851 16.
- 852 Oehlert, A. M., & Swart, P. K. (2019). Rolling window regression of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values in carbonate
 853 sediments: Implications for source and diagenesis. *The Depositional Record*, 5(3), 613-630.
- 854 Padden, M., Weissert, H., Funk, H., Schneider, S., Gansner, C., (2002). Late Jurassic lithological
 855 evolution and carbon-isotope stratigraphy of the western Tethys. *Eclogae Geologicae Helveticae* 95,
 856 333–346.
- 857 Perdiou, A., Thibault, N., Anderskov, K., Van Buchem, F., Buijs, G.J.A., Bjerrum, C.J., 2015. Orbital
 858 calibration of the late Campanian carbon isotope event in the North Sea. *J. Geol. Soc.* 173 (3), 504–
 859 517.
- 860 Razmjooei, M. J., Thibault, N., Kani, A., Dinarès-Turell, J., Pucéat, E., Shahriari, S., ... & Cocquerez, T.
 861 (2018). Integrated bio-and carbon-isotope stratigraphy of the Upper Cretaceous Gurpi Formation
 862 (Iran): A new reference for the eastern Tethys and its implications for large-scale correlation of stage
 863 boundaries. *Cretaceous Research*, 91, 312-340.
- 864 Razmjooei, M. J., Thibault, N., Kani, A., Ullmann, C. V., & Jamali, A. M. (2020). Santonian-Maastrichtian
 865 carbon-isotope stratigraphy and calcareous nannofossil biostratigraphy of the Zagros Basin: Long-

range correlation, similarities and differences of carbon-isotope trends at global scale. *Global and Planetary Change*, 184, 103075.

Renne, P.R., Deino, A.L., Hilgen, F.J., Kuiper, K.F., Mark, D.F., Mitchell, W.S., Morgan, L.E., Mundil, R. and Smit, J., (2013). Time scales of critical events around the Cretaceous-Paleogene boundary. *Science*, 339(6120), pp.684-687.

Sabatino, N., Meyers, S. R., Voigt, S., Coccioni, R., & Sprovieri, M. (2018). A new high-resolution carbon-isotope stratigraphy for the Campanian (Bottaccione section): Its implications for global correlation, ocean circulation, and astrochronology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 489, 29-39.

Schönfeld, J., Sirocko, F., & Jørgensen, N. O. (1991). Oxygen isotope composition of Upper Cretaceous chalk at Lägerdorf (NW Germany): its original environmental signal and palaeotemperature interpretation. *Cretaceous Research*, 12(1), 27-46.

Schönfeld et al. 1996: New results on biostratigraphy, geochemistry and correlation from the standard section for the Upper Cretaceous white chalk of northern Germany (Lägerdorf - Krons Moor - Hemmoor). C. Spaeth (Ed.), Jost Wiedmann Memorial Volume; Proceedings of the 4th International Cretaceous Symposium, Hamburg, 1992. Mitteilung aus dem Geologische Paläontologischen Institut der Universität Hamburg 77 (1996), pp. 545-575

Scholle, P. A., & Arthur, M. A. (1980). Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool. *AAPG Bulletin*, 64(1), 67-87.

Sheldon, E., Morigi, C., & Møller, S. D. (2014). Calcareous nannofossil and foraminifer biostratigraphy of the Campanian–Maastrichtian chalk of the Femern Bælt (Denmark–Germany). *Geological Survey of Denmark and Greenland (GEUS) Bulletin*, 31, 31-34.

Sissingh, W. (1977) Biostratigraphy of Cretaceous Calcareous Nannoplankton. *Geologie en Mijnbouw*, 56, 37-65.

- 890 Smit, F.W.H., van Buchem, F.S.P., Holst, J.C., Lüthje, M., Anderskov, K., Thibault, N., Buijs, G.J.A.,
 891 Welch, M.J. and Stemmerik, L. (2018). Seismic geomorphology and origin of diagenetic geobodies in
 892 the Upper Cretaceous Chalk of the North Sea Basin (Danish Central Graben). *Basin Research*,
 893 30(5), 895-925.
- 894 Stewart, R. N. T., Haszeldine, R. S., Fallick, A. E., Wilkinson, M., & Macaulay, C. I. (2000). Regional
 895 distribution of diagenetic carbonate cement in Palaeocene deepwater sandstones: North Sea. *Clay*
 896 *Minerals*, 35(1), 119-133.
- 897 Stoll, H. M., & Schrag, D. P. (2001). Sr/Ca variations in Cretaceous carbonates: relation to productivity
 898 and sea level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 168(3-4), 311-336.
- 899 Sprain, C.J., Renne, P., Vanderkluysen, L., Pande, K., Self, S., Mittal, T. (2019). The eruptive tempo of
 900 Deccan volcanism in relation to the Cretaceous-Paleogene boundary. *Science* 363(6429), 866-870.
- 901 Styzen, M. J. (1997). Cascading counts of nanofossil abundance. *Journal of Nannoplankton Research*,
 902 19(1), 49.
- 903 Swart, P. K., & Eberli, G. (2005). The nature of the $\delta^{13}\text{C}$ of periplatform sediments: Implications for
 904 stratigraphy and the global carbon cycle. *Sedimentary Geology*, 175(1-4), 115-129.
- 905 Swart, P. K., Reijmer, J. J., & Otto, R. (2009). A reevaluation of facies on Great Bahama Bank II:
 906 Variations in the $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and mineralogy of surface sediments. *Int. Assoc. Sedimentol. Spec.*
 907 *Publ*, 41, 47-59.
- 908 Swart, P. K. (2015). The geochemistry of carbonate diagenesis: The past, present and
 909 future. *Sedimentology*, 62(5), 1233-1304.
- 910 Swart, P. K., & Oehlert, A. M. (2018). Revised interpretations of stable C and O patterns in carbonate
 911 rocks resulting from meteoric diagenesis. *Sedimentary Geology*, 364, 14-23.
- 912 Surlyk, F., Dons, T., Clausen, C. K., and Higham, J.: Upper Cretaceous, in: The Millennium Atlas:
 913 petroleum geology of the central and northern North Sea, edited by: Evans, D., Graham, C., Armour,
 914 A. and Bathurst, P., Geol. Soc. London, 213–233, 2003.

- Surlyk, F., Rasmussen, S. L., Boussaha, M., Schiøler, P., Schovsbo, N. H., Sheldon, E., ... & Thibault, N. (2013). Upper Campanian–Maastrichtian holostratigraphy of the eastern Danish Basin. *Cretaceous Research*, 46, 232-256.
- Swarbrick, R. E., Lahann, R. W., O'Connor, S. A., & Mallon, A. J. (2010, January). Role of the Chalk in development of deep overpressure in the Central North Sea. In Geological Society, London, Petroleum Geology Conference series (Vol. 7, No. 1, pp. 493-507). Geological Society of London.
- Thibault, N., Harlou, R., Schovsbo, N., Schiøler, P., Minoletti, F., Galbrun, B., ... & Surlyk, F. (2012). Upper Campanian–Maastrichtian nannofossil biostratigraphy and high-resolution carbon-isotope stratigraphy of the Danish Basin: towards a standard $\delta^{13}\text{C}$ curve for the Boreal Realm. *Cretaceous Research*, 33(1), 72-90.
- Thibault, N., Anderskov, K., Bjerager, M., Boldreel, L. O., Jelby, M. E., Stemmerik, L., & Surlyk, F. (2015). Upper Campanian–Maastrichtian chronostratigraphy of the Skælskør-1 core, Denmark: correlation at the basinal and global scale and implications for changes in sea-surface temperatures. *Lethaia*, 48(4), 549-560.
- Thibault, N. (2016). Calcareous nannofossil biostratigraphy and turnover dynamics in the late Campanian–Maastrichtian of the tropical South Atlantic. *Revue de micropaléontologie*, 59(1), 57-69.
- Thibault, N., Harlou, R., Schovsbo, N. H., Stemmerik, L., & Surlyk, F. (2016a). Late Cretaceous (late Campanian–Maastrichtian) sea-surface temperature record of the Boreal Chalk Sea. *Climate of the Past*, 12(2), 429-438.
- Thibault, N., Jarvis, I., Voigt, S., Gale, A. S., Attree, K., & Jenkyns, H. C. (2016b). Astronomical calibration and global correlation of the Santonian (Cretaceous) based on the marine carbon isotope record. *Paleoceanography and Paleoclimatology*, 31(6), 847-865.
- Tremolada, F. (2002). Aptian to Campanian calcareous nannofossils biostratigraphy from the Bottaccione section, Gubbio, central Italy. *Rivista Italiana di Paleontologia e Stratigrafia (Research In Paleontology and Stratigraphy)*, 108(3).

- Veizer, J., & Prokoph, A. (2015). Temperatures and oxygen isotopic composition of Phanerozoic oceans. *Earth-Science Reviews*, 146, 92-104. Voigt & Hilbrecht, 1997
- Voigt, S., Friedrich, O., Norris, R. D., & Schönfeld, J. (2010). Campanian–Maastrichtian carbon isotope stratigraphy: shelf-ocean correlation between the European shelf sea and the tropical Pacific Ocean. *Newsletters on Stratigraphy*, 44(1), 57-72.
- Voigt, S., Gale, A. S., Jung, C., & Jenkyns, H. C. (2012). Global correlation of Upper Campanian–Maastrichtian successions using carbon-isotope stratigraphy: development of a new Maastrichtian timescale. *Newsletters on Stratigraphy*, 45(1), 25-53.
- Voigt, S., & Hilbrecht, H. (1997). Late Cretaceous carbon isotope stratigraphy in Europe: correlation and relations with sea level and sediment stability. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 134(1-4), 39-59.
- Walaszczyk, I., Wood, C. J., Lees, J. A., Peryt, D., Voigt, S., & Wiese, F. (2010). The Salzgitter-Salder Quarry (Lower Saxony, Germany) and Słupia Nadbrzeżna river cliff section (central Poland): a proposed candidate composite Global Boundary Stratotype Section and Point for the Coniacian Stage (Upper Cretaceous). *Acta Geologica Polonica*, 60(4), 445-477.
- Wiese, F., Čech, S., Ekrt, B., Košťák, M., Mazuch, M., & Voigt, S. (2004). The Upper Turonian of the Bohemian Cretaceous Basin (Czech Republic) exemplified by the Úpohlavý working quarry: integrated stratigraphy and palaeoceanography of a gateway to the Tethys. *Cretaceous Research*, 25(3), 329-352.
- Wendler, I. (2013). A critical evaluation of carbon isotope stratigraphy and biostratigraphic implications for Late Cretaceous global correlation. *Earth-Science Reviews*, 126, 116-146.
- Wolfgring, E., Wagreich, M., Dinarès-Turell, J., Gier, S., Böhm, K., Sames, B., ... & Popp, F. (2018). The Santonian–Campanian boundary and the end of the Long Cretaceous Normal Polarity-Chron: Isotope and plankton stratigraphy of a pelagic reference section in the NW Tethys (Austria). *Newsletters on Stratigraphy*, 51(4), 445-476.

Highlights:

- A 37 Myr-long Late Cretaceous to Paleogene stratigraphy generated for the North Sea Chalk Group.
- Stable isotope values generated from ditch-cuttings material
- Diagenetic alteration of the primary depositional signal was evaluated
- Integrated with nannofossil and foraminifera biostratigraphy
- Precise correlations between the Shearwater Field and other published Boreal and Tethyan sections

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: