

Article

A Multiple-Proxy Geochemical Investigation of a Shallow Core from Doggerland: Implications for Palaeolandscape and Paleoenvironmental Reconstruction

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Abstract

The exploration of Doggerland, the prehistoric landscape that once connected Britain to the continent, remains one of Europe's most significant archeological challenges. This paper presents a study into the palaeolandscape and the paleoenvironmental development of Doggerland, through the geochemical analyses of a core (ELF019) taken from the southern North Sea. The thermal properties divided the core into three sedimentary zones based on the variations in organic matter and carbonate content. Organic biomarkers were used to distinguish between terrestrial and aquatic vegetation inputs, revealing alternating freshwater, terrestrial, and marine input influences. Chemostratigraphy defined six depositional zones that corresponded with the identified thermal and biomarker data. Radiocarbon dating of peat-derived humic fractions anchored the key environmental transition between freshwater and saline deposition to the Greenlandian period of the Lower Holocene (10,243–10,199 Cal BP). The integrated geochemical evidence suggests a transformation from freshwater silts, low organic content, and sandy clay deposit to saline clay marine deposit. The progressive transformation may reflect the inundation sequence that led to the final submergence of Doggerland.

Keywords: Doggerland; Holocene; submerged; palaeolandscape; reconstruction; chemostratigraphy; core sediment

1. Introduction

During the Late Pleistocene and early Holocene, the areas of Britain and continental Europe were connected by a land bridge known as Doggerland, which now lies beneath the southern North Sea (Gaffney et al., 2009; Ward et al., 2006). Submergence of this area occurred within a relatively short period of time following sea level rise, whilst the inundating landscape was also impacted by significant events, including the Storegga tsunami (Bateman et al., 2021; Walker et al., 2020). The final submergence occurred approximately 8150 ± 30 Cal BP, with exception of a littoral extension off the eastern coast of England and, perhaps, a remnant of the Dogger Island (Gaffney et al., 2020; Weninger et al., 2008). The whole of Doggerland was fully submerged by 7000 BP (Gaffney et al., 2020; Weninger et al., 2008). Awareness of the archeological significance of Doggerland increased sharply during the first decades of the twentieth century; largely as a result to the large quantities of prehistoric material recovered through trawling or dredging (Ballin, 2017; Van der



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[Plicht et al., 2016](#)). The potential of the area to retain well-preserved Pleistocene/early Holocene landscapes, and that these might contain critical information on human response to climate change, was also of considerable interest ([Fitch et al., 2005](#)). Today, Doggerland is seen as a key area to understand the development of northwestern Europe in the late Paleolithic and early Mesolithic ([Gaffney et al., 2009](#); [Ward et al., 2006](#)). Cores from the inundated landscape are now understood to provide an outstanding natural archive and hold significant geochemical information, from which past ecological conditions can be reconstructed ([Blumenberg et al., 2022](#); [Mulder & Alexander, 2001](#); [Yamoah et al., 2016](#)). For example, in a recent study, the determination of carbonate-rich lake sediments at the depth of 32.9 to 34.5 m below present sea level implied that a part of Doggerland had not yet been transgressed by marine water during the late glacial ([Bennike et al., 2023](#)). Moreover, radiocarbon dates of samples from the Netherlands and Doggerland concluded that the region's vegetation and faunal biomass fluctuated significantly during the last glaciation—55k–5k Cal BP ([Van Geel et al., 2024](#)).

The core used for this study (ELF019) was previously investigated with initial results discussed in [Finlay et al. \(2022\)](#). Using X-ray Fluorescence scanning (XRF), this study concluded that the core could be split into six chemostratigraphic zones, based on variations in elemental data and variations produced by Principal Component Analysis (PCA). The authors hypothesized that each elemental ratio was a proxy for the following mineral/geological variations:

- Si/Rb ~quartz/clay.
- Ca/Rb ~carbonate/clay.
- S/Rb ~Organic material/clay.
- Br/Ti ~Salinity.

No other geochemical analysis was undertaken to confirm the control on this elemental data. Core logging data was also available to the authors, who observed that the Si/Rb values corresponded to observed changes in grain sizes, and ecological analysis of biostratigraphy data suggested that the salinity proxy was also valid. However, there was no data available to validate the authors' hypothesis that variations in Ca/Rb and S/Rb were carbonate and organically driven. To achieve this additional Thermogravimetric analysis (TGA) and Gas Chromatography–Mass Spectrometry (GC–MS) lipid analysis was also required.

TGA and GC-MS lipid analysis provide quantitative variations in carbonate content, organic content, and the presence of material derived from aquatic and terrestrial vegetation. However, this is only produced for spot analysis down a core, and so key changes may be missed if not sampled. The scanning XRF data utilized by [Finlay et al. \(2022\)](#) has the unique advantage of producing data over a continuous core section. Therefore, if the XRF results can be proven by separate TGA and GC-MS analysis, it is possible to provide a continuous record of sedimentological and paleoenvironmental changes throughout core ELF019, and therefore the surrounding area.

This study, therefore, builds on the work of [Finlay et al. \(2022\)](#) by undertaking the following:

1. A new TGA chemical zonation of core ELF019.
2. A re-evaluation of the elemental chemostratigraphy presented in [Finlay et al. \(2022\)](#).
3. An integrated XRF, TGA, and GC-MS geochemical investigation of core ELF019, which, by combining the continuous XRF data and quantitative spot sampling data, provides a reconstructed paleodepositional history of core ELF019.

For the first time, by integrating these separate geochemical approaches, this study demonstrates how integrated geochemical analyses can support the reconstruction of marine palaeolandscapes.

2. Materials and Methods

2.1. Material and Samples' Description

Core ELF019 was 4.43 m in length, and was collected as a part of the Europe's Lost Frontiers (ELF) project, an ERC-funded research program that aimed to understand the palaeolandscape and inundation processes associated with the loss of Doggerland (Gaffney et al., 2017). A total of 78 cores from 60 different locations from the Southern River (Figure 1) were collected using a vibracore. After collection, all 78 cores were stored in a cold (2.0 ± 0.5 °C) and dry store at the University of Wales (Trinity St David). Core ELF019 was sampled with several factors taken into consideration; the modern sediments at the top were ignored as they were outside the overall research goals. In addition, when the research program began, the core had already been sampled by other project team specialists. Sampling the same areas was essential for comparability during the analysis. During sampling, any area that appeared to be distinct on the basis of its physical properties, such as colour or the sediment type (mud, soil, silt, etc.), was sampled. Fifteen individual samples were taken for lipid and thermal analysis, whilst only the top three metres were scanned. Following the results from a study of other project cores, a zone, two metres from the seabed surface, was most likely to be associated with the Holocene transition. Section 3.1 contains further details about the core and the sample depths.

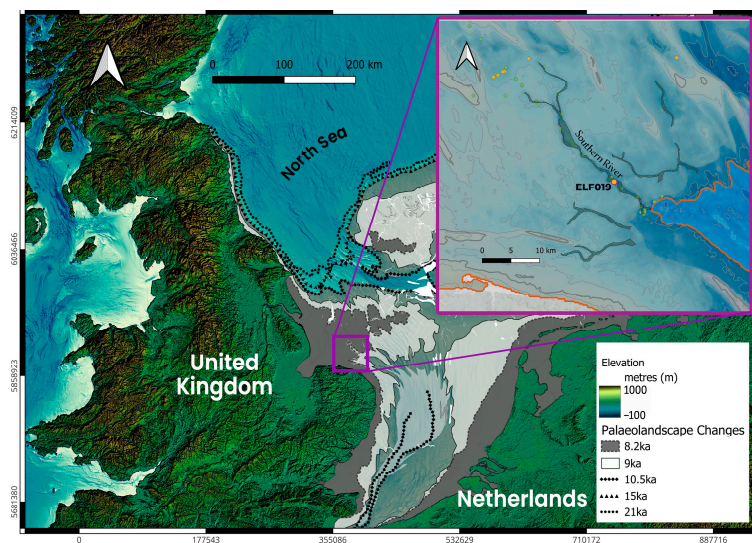


Figure 1. The location of the Southern River and core ELF019.

2.2. Thermal Analysis

TGA is a common method for classifying and characterizing sediments, allowing differentiation of samples based on their organic matter and carbonate content (Bensharada et al., 2022b; Heiri et al., 2001; Konare et al., 2010). A TGA Q5000IR (TA Instruments, New Castle, DE, USA) was used for the analysis. Details on the preparation technique and the TGA method can be found in Bensharada et al. (2022b). The percentages of organic matter and carbonate content were utilized to identify, characterize, and classify the sedimentary deposits of the core, distinguishing between various horizons and layers (Duplisea, 2000; Radomirović et al., 2021). The moisture content was ignored as it does not provide significant information to this study and was difficult to measure accurately (Bensharada et al., 2022a).

2.3. Lipid Analysis

An Agilent 7890A GC–MS coupled with a 0975C MS detector (5301 Stevens Creek Blvd. Santa Clara, CA, USA) was used to identify the natural sources of extractable lipids from their distinctive biomarkers, which can then be used to distinguish between aquatic and terrestrial vegetation (Bensharada et al., 2022a; Ficken et al., 2000; Hu et al., 2009; Rielley et al., 1991; Sikes et al., 2009). Details on the sample preparation procedure and the GC-MS method can be found in Bensharada et al. (2022a).

For this study, only the three biomarker groups, *n*-alkanes, fatty acids, and sterols, were used as indicators of environmental conditions and sources (Jiménez Martínez et al., 2019; Meyers & Ishiwatari, 1993; Sikes et al., 2009). For biomarker identification, the Exacted Ion Chromatogram (EIC) was used to identify the *n*-alkanes and fatty acids. The EIC for the *n*-alkanes was *m/z* 57, for the fatty acids this was *m/z* 73, and for the sterols were *m/z* 255 and *m/z* 273, with a range of *m/z* −0.30 to +0.70. The peak areas of the identified biomarkers were used for semiquantitative analysis. Whilst only these three biomarkers were used in this study, other organic compounds such as *n*-alkanols and monounsaturated fatty acids were detected in some of the samples. That data was not considered, as they were only detected in a few samples and were not at any significant abundance to justify any further discussion.

The Carbon Preference Index (CPI) of the *n*-alkanes is a ratio used to distinguish terrestrial and marine inputs. Terrestrial plants produce a CPI higher than 4, while for marine inputs it is lower than 4. The CPI was calculated as in Equation (1) (Collister et al., 1994; Sikes et al., 2009).

$$\text{CPI} = (\sum \text{odd } n\text{-alkanes C15 to C33}) / (\sum \text{even } n\text{-alkanes C14 to C34}) \quad (1)$$

The marine *n*-alkanes proxy ratio ($P_{\text{mar-aq}}$) is designed to separate between terrestrial inputs, emergent aquatic plants, aquatic plants, and marine macrophytes (Sikes et al., 2009). The *n*-alkanes proxy ratio (P_{aq}) was initially defined by Ficken et al. (2000), with no marine input included as it was developed on lakes sediments. The authors concluded that $P_{\text{aq}} < 0.1$ corresponds to terrestrial plants, 0.1–0.4 corresponds to emergent macrophytes, and 0.4–1 corresponds to submerged/floating macrophytes. This P_{aq} was tested and confirmed to be a valid proxy in marine sediment through comparison with SedaDNA, environmental, pollen, diatoms, and lithostratigraphic analyses by Gaffney et al. (2020). However, $P_{\text{mar-aq}}$ has been developed by Sikes et al. (2009) to include coastal marine sediment, establishing a new parameter renamed as $P_{\text{mar-aq}}$, and this was used in the present study. The $P_{\text{mar-aq}}$ low value of 0.01–0.25 corresponds to terrestrial inputs, ~0.4–0.6 corresponds to emergent aquatic plants, while high values >0.6 correspond to aquatic plants and marine macrophytes, as seen in Sikes et al. (2009). The $P_{\text{mar-aq}}$ ratio was calculated using Equation (2).

$$P_{\text{mar-aq}} = (\text{C23} + \text{C25}) / (\text{C23} + \text{C25} + \text{C29} + \text{C31}) \quad (2)$$

2.4. X-Ray Fluorescence

The XRF analysis was undertaken using an Itrax core scanner, manufactured by Cox Analytical Systems, Östergårdsgatan 7, 431 53 Mölndal, Sweden, at Aberystwyth University, applying the method that was described in detail in Finlay et al. (2022). Scanning XRF is a tool, commonly utilized for analyzing sediment cores, and its advantages and limitations are discussed in multiple published works (Finlay et al., 2022; Rothwell & Croudace, 2015). PCA, a statistical method, was used to identify patterns in the data in multiple dimensions and to help understand the compositional controls on elemental variations within the core.

An in-depth description of how PCA was used, and the obtained PCA of elemental data for core ELF019 can be found in [Finlay et al. \(2022\)](#).

2.5. Radiocarbon Analysis

The ^{14}C dating was carried out at the Accelerator Mass Spectrometry (AMS) laboratory in the Scottish Universities Environmental Research Centre (SUERC). A detailed description of the applied methodology can be found in [Dunbar et al. \(2016\)](#). The obtained ^{14}C ages were quoted in conventional years BP, while they were calibrated using an IntCal13 atmospheric calibration curve ([Dunbar et al., 2016](#)).

3. Results

3.1. Lithological Description

The lithological description was carried out at the University of Wales (Trinity St David). Core ELF019's location, length, place of store, sample number, a full lithological description of the sampled area, along with a photograph of the core are presented in Table 1.

Table 1. The core location, sampling date, samples' depths, lithological description, and the core photo.

Core Name	ELF019	Location of Samples	Cold Store, Lampeter
Easting	389,810.11	Northing	5,888,140.79
Sample Number	Depth (m)	Lithological Description	Core Photo
1	0.38	Pale grey silt with fine laminations of sand at the top and organic material in the middle. Laminations are discontinuous and wavy, 1–3 mm thick.	
2	0.59	Pale grey silt with thin grey sand laminated up to 3 mm thick with organic laminations 1–2 mm thick.	
3	0.71	Pale grey silt with discontinuous and thick laminations.	
4	1.17	Pale grey silt with black organic flecks. Sand filled void at top of unit with shell fragments. Discrete patches of shell. Broken inset molluscs.	
5	1.28	Mid grey/brownish grey silt with common shell fragments. Bottom 1 cm thin discontinuous organic laminations.	
6	1.33	Dark brownish grey organic silt, coarsening downwards to medium fine sand with common shell fragments and discrete lumps of plant material.	
7	1.44	Pale, brownish, grey slightly sandy silt with occasional shell fragments. Occasional pale grey discontinuous laminations 1–3 mm.	
8	1.64	Mid grey medium sand with occasional sandy silt laminations discontinuous 2–3 mm thick. Some thicker sandy silt laminations discontinuous 2–3 mm thick. Some thicker sandy silt laminations up to 1 cm, towards base. Occasional shell fragments.	
9	1.69	Pale brownish grey silt to fine sandy silt, laminated 0.5 cm thick laminations at top becoming finer at depth. Below 1.9 m laminations commonly contain dark organic material.	
10	1.98	Dark brown organic silt.	
11	2.03	Grey slightly sandy silt bedded with fine grain sands, some discontinuous black organic laminations towards base.	

Table 1. *Cont.*

Core Name	ELF019	Location of Samples	Cold Store, Lampeter
Easting	389,810.11	Northing	5,888,140.79
Sample Number	Depth (m)	Lithological Description	Core Photo
12	2.32	Greyish brown fine sand becoming sandy silt with depth. Occasional black-stained patches. Occasional black sandy laminations towards base.	
13	2.93	Greyish brown fine sand becoming sandy silt with depth. Occasional black-stained patches. Occasional black sandy laminations towards base.	
14	3.31	Greyish brown fine sand becoming sandy silt with depth. Occasional black-stained patches. Occasional black sandy laminations towards base.	
15	4.30	Orange, brown medium sand with grey, brown clay silt laminations, dipping steeply; discontinuous.	

3.2. TGA Results

The fifteen samples were thermally analyzed, using TGA, to measure the percentages of organic matter and carbonate content, which are listed in Table 2. Based on the TGA results, there are two major alterations in the sediment at sample 10 (1.98 m) and sample 4 (1.17 m). Hence, we divided the core into three depositional areas, labelled as A, B, and C in Figure 2. Area C, at the base of the core, is 2.32 m in length and provided six samples, from sample 15 (4.30 m) to sample 10 (1.98 m) (Table 2 and Figure 2). Area B is 0.52 m in length and includes six samples, from sample 9 (1.69 m) to sample 4 (1.17 m). This area contains the sample with the highest percentage of organic matter (11.60%; Table 2 and Figure 2). Additionally, this area contains the sample with the highest percentage of carbonates (13.90%). Area A, at the top of the core, is 0.33 m in length, and includes three samples, from sample 3 (0.71 m) to sample 1 (0.38 m). The determination of these three major lithological areas was central for our interpretation of core ELF019's environmental history.

Table 2. The samples depths and numbers, the percentages of carbonate content, the percentages of organic matter, thermal area, CPI, $P_{\text{mar-aq}}$, and the percentage of palmitic acid. ND = not detected.

Sample Number	Depth (m)	Organic %	Carbonate %	Thermal Area	CPI	$P_{\text{mar-aq}}$	Palmitic Acid %
1	0.38	6.26	3.69	A	3.07	0.64	65.86
2	0.59	3.19	4.20		3.35	0.79	54.09
3	0.71	5.23	4.83		3.25	0.72	ND
4	1.17	8.19	5.36	B	3.22	0.41	ND
5	1.28	9.53	7.16		4.86	ND	38.50
6	1.33	9.81	7.35		5.14	ND	32.60
7	1.44	11.53	13.89		3.60	0.69	17.25
8	1.64	11.58	1.51		2.25	0.55	ND
9	1.69	9.16	2.80		2.50	0.58	ND
10	1.98	1.08	0.62	C	8.86	ND	13.38
11	2.03	4.17	4.08		3.40	0.43	ND
12	2.32	3.50	2.90		2.26	0.57	ND
13	2.93	3.96	3.90		2.57	0.25	ND
14	3.31	3.94	4.09		2.17	0.37	ND
15	4.30	3.99	4.07		2.08	0.35	ND

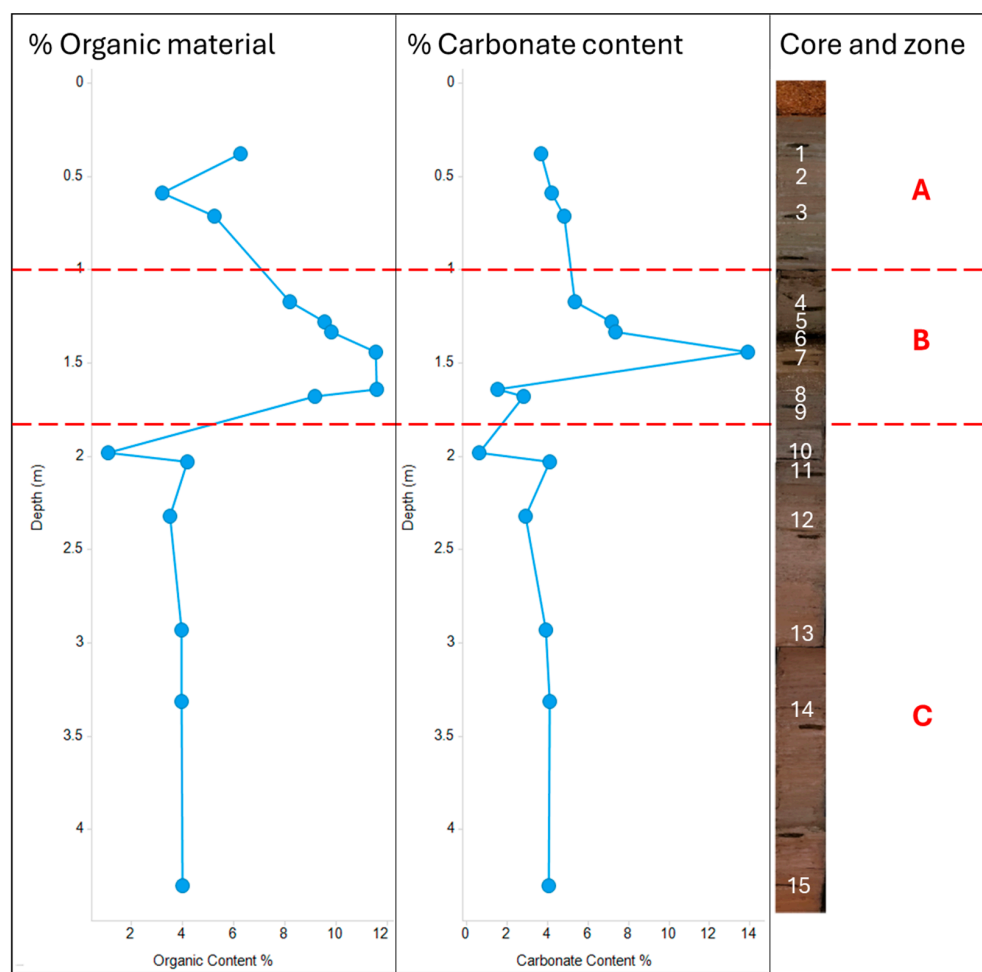


Figure 2. TGA results (percentage of organic matter and carbonate), compared to a visual image of the core. The core is split into three zones: A, B, and C, with zone B being the most carbonate and organic-rich. The core photo displays a subtle variation over this change with a distinctive dark band coincident with peak organic and carbonate material. While zone A and C show stability in the percentage of organic and carbonate contents.

3.3. Lipid Results

After applying the EIC for the *n*-alkanes (m/z 57), the fatty acids (m/z 73), and for the sterols (m/z 255 and m/z 273) with a range of m/z -0.30 to $+0.70$, the ratios of CPI, $P_{\text{mar-aq}}$, and the percentages of palmitic acid were calculated and these are presented in Table 2.

The five samples from 15 (4.30 m) to 11 (2.03 m) produced similar *n*-alkane profiles; the CPI ratios are within the limit of aquatic input (Table 2) (Collister et al., 1994; Sikes et al., 2009). Moreover, the corresponding $P_{\text{mar-aq}}$ ratios of these samples further indicated contributions of emergent aquatic plants, except for sample 13 (0.25), which generated a $P_{\text{mar-aq}}$ ratio consistent with that of terrestrial sources (Table 2) (Eglinton & Hamilton, 1967; Ficken et al., 2000; Sikes et al., 2009). Fatty acids were restricted to myristic acid and palmitic acid, which could be produced by land or aquatic vegetation, and these results may indicate a lake, river, or estuarine environment (He et al., 2016; Meyers & Ishiwatari, 1993).

The first major change in the lipid data was observed at sample 10 (1.98 m), where the *n*-alkanes were dominated by heptacosane and nonacosane (Figure 3D). This change was accompanied by a major increase in the CPI value, reaching its highest value (8.86) among all fifteen samples (Table 2). These changes were not only observed in the *n*-alkanes pattern, but also in the fatty acids and sterol profiles; indeed, this sample is the richest in fatty acids. The even-numbered fatty acids from caprylic to ceric were all detected, in addition to the

odd-numbered pelargonic, margaric, and heptacosylic acids. The percentage of palmitic acid was 13.38%; this percentage indicates terrestrial sources (Ali et al., 2004). These land-derived compounds were accompanied with a determination of one main terrestrial sterol (β -sitosterol) (Xiao et al., 2013). This sample presented substantial indicators of terrestrial input.

Samples 9 (at 1.69 m) and 8 (at 1.64 m) indicated a return to aquatic inputs, as the *n*-alkane distribution pattern was dominated by the mid-chain heneicosane and tricosane (e.g., Figure 3C). The CPI ratios dropped to the limit of aquatic sources (<4) and the $P_{\text{mar-aq}}$ of these samples indicated emergent aquatic plants (Sikes et al., 2009). The two ubiquitous compounds, palmitic acid and ergostanol, were detected in both samples; however, they did not provide information that could assist the interpretation (Mackenzie et al., 1982).

The next significant change in the lipid data started at sample 7 (1.44 m) and continued to sample 5 (1.28 m). The *n*-alkane distribution patterns were dominated by heptacosane and nonacosane (e.g., Figure 3B), with a considerable increase in CPI ratios to the value expected from terrestrial sources (CPI > 4) (Table 2) (Rielley et al., 1991; Sikes et al., 2009). This change was accompanied by the detection of three sterols, the ubiquitous ergostanol and two typical terrestrial sterols (campesterol and β -sitosterol) (Xiao et al., 2013). Even though sample 7 (1.44 m) produced a CPI slightly lower than 4 (3.60), which is just within the limit of aquatic vegetation, the *n*-alkanes, sterols, and fatty acids' combined results strongly indicated that terrestrial vegetation was the principal source of lipids in this area.

The samples from 4 (1.17 m) to 1 (0.38 m), which cover the sampled, upper part of the core, produced similar *n*-alkane profiles, with odd-over-even carbon numbers, and were dominated by the mid-chain compounds, with the most prevalent being heneicosane and tricosane (e.g., Figure 3A). The CPI decreased to the limit of aquatic inputs, while $P_{\text{mar-aq}}$ ratios suggested that the aquatic inputs were marine macrophytes (Table 2) (Collister et al., 1994; Sikes et al., 2009). In addition, the fatty acids, myristic, palmitic, stearic, and arachidic, were identified only in samples 2 (0.59 m) and 1 (0.38 m) (Table 2). It was notable that the percentages of palmitic increased sharply to above 40%, the limit of aquatic vegetation (Table 2) (Ali et al., 2004). Notably, sterols were not detected in these samples.

3.4. XRF and Chemostratigraphy

As previously mentioned, the XRF results for the core were previously published within Finlay et al. (2022). To summarize the relevant information from that paper, the chemostratigraphy utilized variations in the elemental geochemical composition to identify chemical zonation, reflecting the changes in its depositional environment. The PCA obtained suggested that the key chemostratigraphic variations within the core were based on changes in the following: detrital minerals (Si—quartz and Ti—heavy minerals), clay minerals (Rb), organic matter or salts (S), carbonate materials (Ca), and salinity (Br and Cl) (Finlay et al., 2022) (Figure 4). Therefore, the following ratios of these elements were used to produce chemical zonation: Si/Rb (quartz/clay—changes in detrital grain size), Ca/Rb (carbonate/clay—marine/fine terrestrial sediment), S/Rb (organic material or sulfides, e.g., Gypsum/clay), Cl/Rb (chlorides, e.g., Halite/clay), and Br/Rb (salts/clay). When these ratios were plotted by depth, they split the core into six chemostratigraphic zones (Figure 4). Previous comparison of this data with other available ecological and biostratigraphic data enabled confirmation of the compositional controls on the chemostratigraphic zonation (Finlay et al., 2022). Chronologically, they indicated the following: C6 was interpreted as freshwater silts, C5 was suggested to be freshwater clays with some organic content, C4 indicated freshwater sands, C3 was a coarse sediment of an uncertain marine/fluvial system, C2 was interpreted as estuarine clay, and C1 represented interbedded estuarine sandy silts and silty clays.

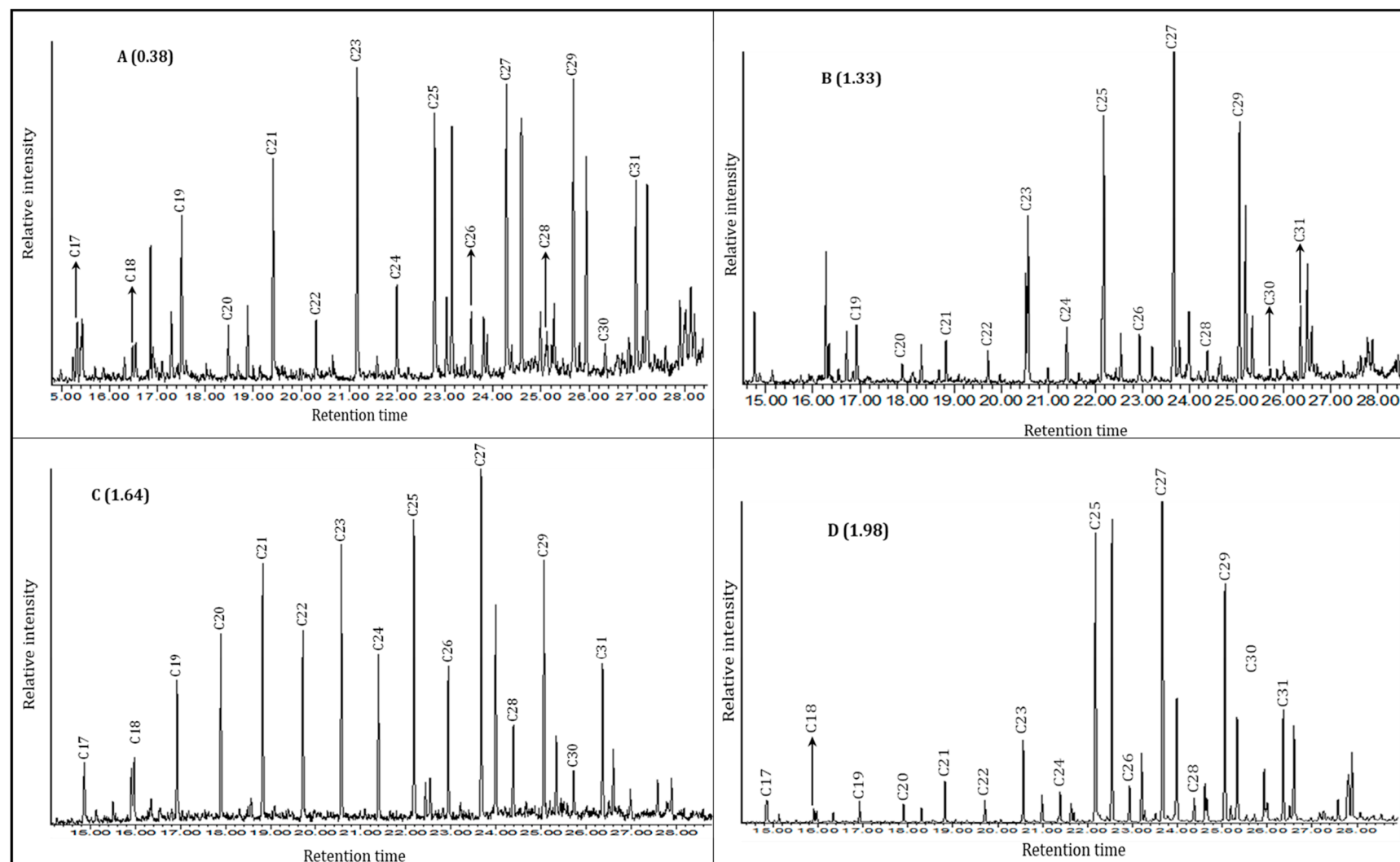


Figure 3. The *n*-alkane profiles of sample 1 (A), sample 6 (B), sample 8 (C), and sample 10 (D) shown as extracted ion chromatograms using m/z 57 for *n*-alkanes.

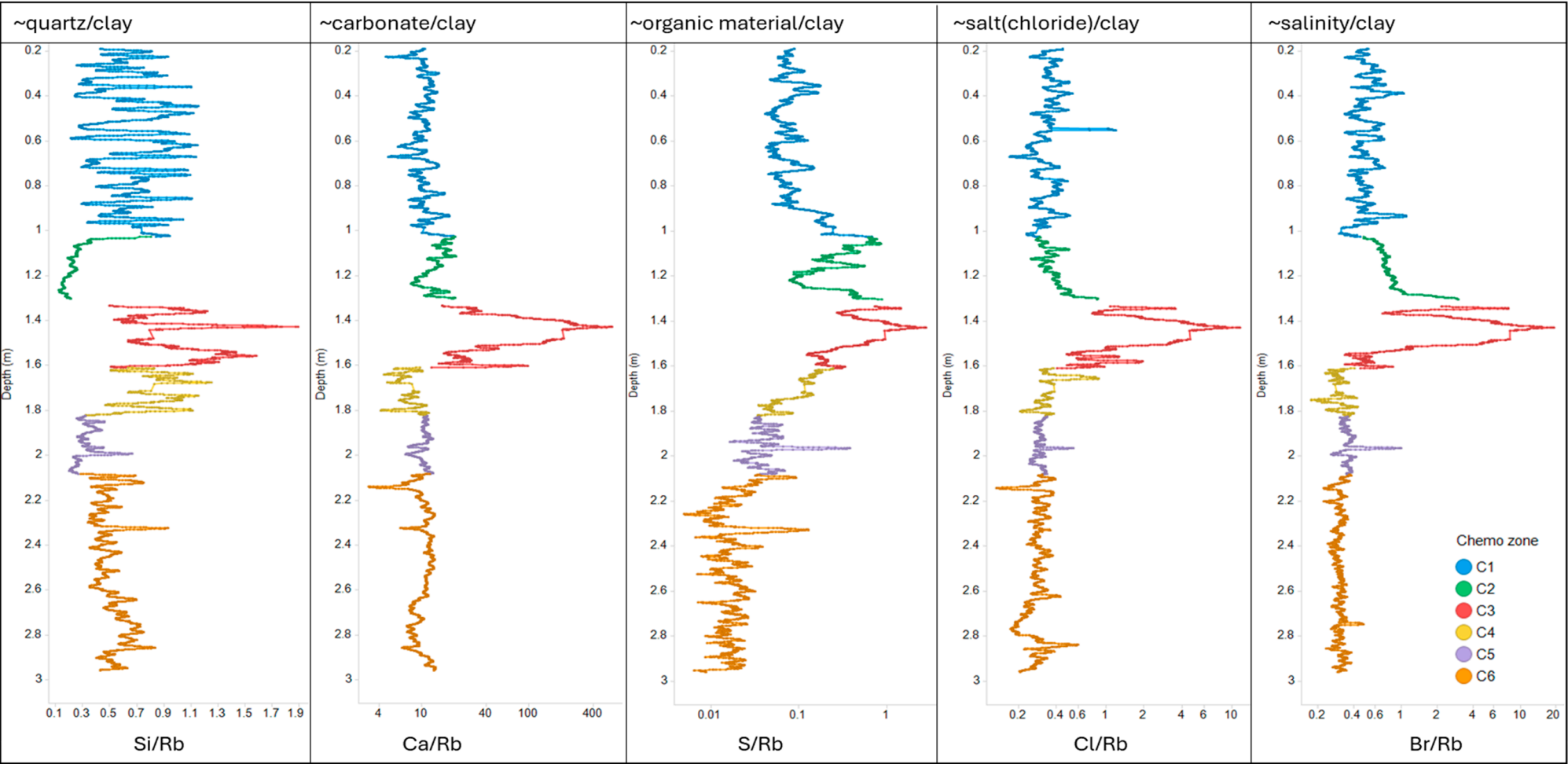


Figure 4. Chemostratigraphic zonation of core ELF019 based on variations in Si/Rb ~quartz/clay, Ca/Rb ~carbonate/clay, S/Rb ~organic material/clay, Cl/Rb ~chloride salts/clay, and Br/Rb ~wetland salinity/clay (modified from [Finlay et al., 2022](#)).

3.5. Radiocarbon Analysis

The chronology of the core was established through the ^{14}C dating of three samples, from three different depths using humic acid fragments from peat. Depth 1.38 m: dated 10,720–11,080 Cal BP. Depth 1.35 m: dated 10,243–10,199 Cal BP. Depth 1.32 m: dated 9933–10,225 Cal BP. The lack of datable fractions such as peat, soil, or organic sediments in the remaining parts of the core denied further opportunities for dating. The most reliable and consistent dates collected from the sample at 1.35 m lay within the Greenlandian period.

4. Discussion

4.1. Integrated Geochemical Interpretation of Core ELF019

An advantage of XRF core scanning is that it can collect continuous data over an entire core section (rather than relying on individual sampling as necessary for lipid and TGA). This enabled significant geochemical and chemostratigraphic boundaries to be identified with precision. However, the XRF data are relative values and although trends can be established, absolute values (e.g., of carbonate from Ca and organic matter from S) cannot be quantified. The comparison of elemental data with the TGA results for ELF019 addresses this issue (Figure 5).

Both S/Rb (a proxy for organic content), the percentage of organic content from TGA, and Ca/Rb (a proxy for carbonate content) and the percent of carbonate from TGA follow the same trends (Figure 5). This not only confirms the elemental proxies, but the results also suggest that S/Rb and Ca/Rb were substantially valid proxies for both the organic matter and carbonate contents in the sediment. Overall, the TGA data revealed variations in the percentage of organic matter and carbonate content, leading to the identification of three depositional areas (Figure 2). Area C contains the bottom two metres of the core and displays the lowest organic and carbonate percentages. Despite the considerable length of this zone, it showed high stability in percentages of organic matter and carbonate content (Table 2 and Figure 2). This may indicate the relative consistency in sedimentary composition and depositional environment over time. This observed high stability may suggest a steady sedimentation process with minimal environmental disturbance (Brett et al., 2007). Area B, in the central section of the core, is the richest area in both organic matter and carbonate content, which may imply inconsistent depositional silting or complex sedimentary dynamics (Gaffney et al., 2020; Bonomo et al., 2013; Brett et al., 2007). The increase in the percentage of organic matter suggests an increase in biological input compared to area C. The increase in the carbonate content may indicate an enhanced presence of marine organisms. This was also indicated by the presence of very small shell fragments in samples from this area (Bonomo et al., 2013). Area A, at the top, contains lower percentages of organic matter and carbonate content in comparison to area B (Table 2 and Figure 2). That suggests an environmental shift and a decrease in the biological input of organic material (Rocci et al., 2021).

A summary of the chemostratigraphic zonation and facies for ELF019 is presented in Table 3. This illustrates the changes in depositional environments from freshwater silt, clay, sand, and low carbonate at the bottom of the core (C6, C5, and C4), to fine-grained saline deposition (C2 and C1) at the top of the core, and through to what Finlay et al. (2022) described as a higher energy unit containing carbonate salts and with a high organic content (C3). A revaluation of chemozone C3 from Finlay et al. (2022) was undertaken in this paper. Previously, the high S, Cl, and Br contents had not been fully considered, whereas Figure 4 clearly demonstrates that chemozone C3 was highly enriched in all those elements that were likely to be salts. Therefore, chemozone C3 was reinterpreted in this study as comprising high levels of carbonate salt and some organic material, possibly a calcrete. This highlighted the difficulty in interpreting paleoenvironment data using elemental data alone.

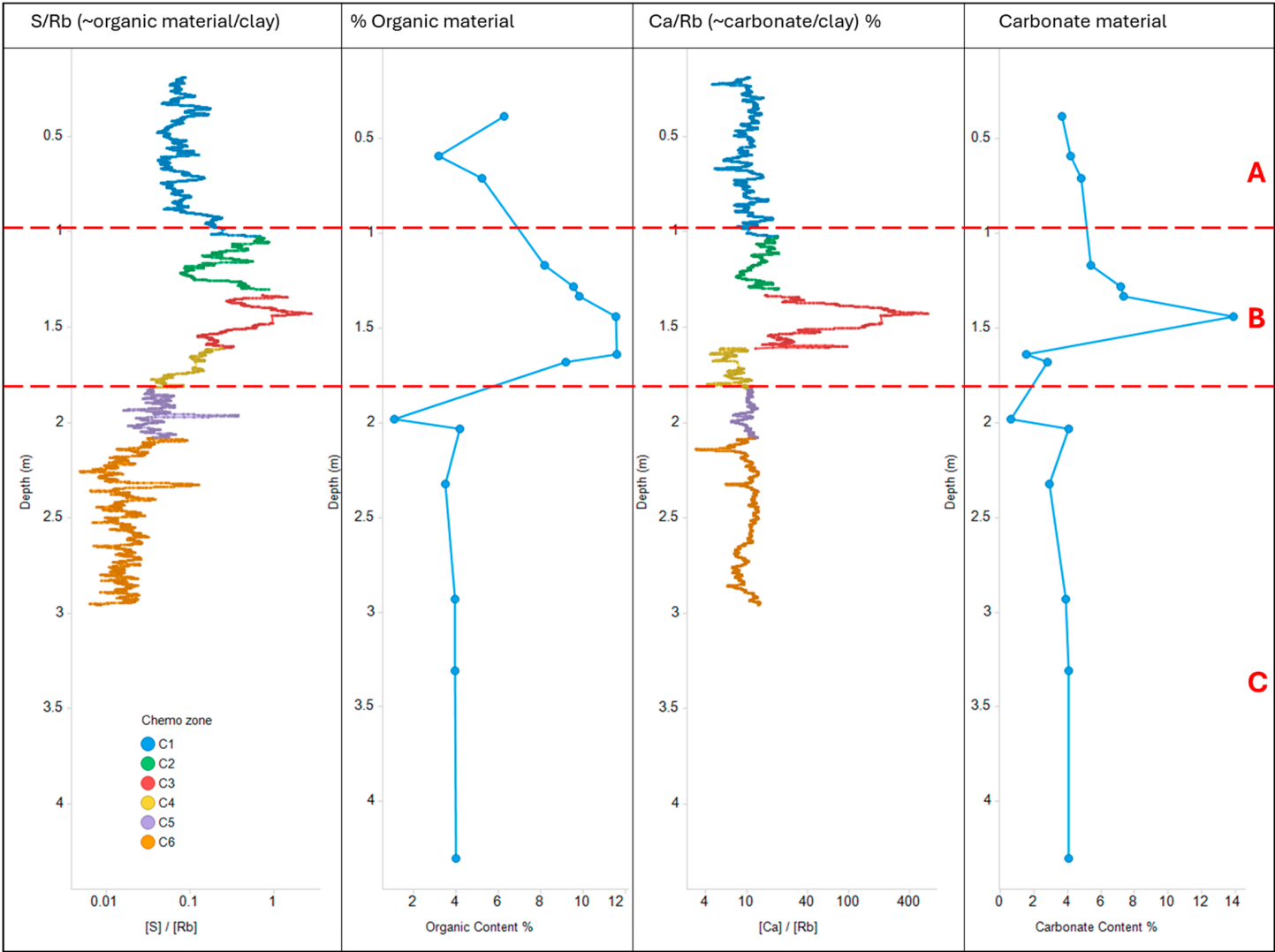


Figure 5. Comparison of chemostratigraphy and TGA zonation. The S/Rb and Ca/Rb chemostratigraphy trends match the % organic material and carbonate material TGA trends, respectively, confirming they do act as organic and carbonate proxies. Also, the changes in TGA zonation match chemostratigraphic boundaries; A–B TGA zonation at the same depth as chemozone 1–2; TGA zone B–C at the same depth as chemozone 4–5.

Table 3. The final integrated, detailed geochemical results of the three chemical approaches dividing the core into six geochemical areas.

Chemozone	Depth (m)	Chemo Facies	Carbonate Content %	Organic Content %	CPI	$P_{\text{mar-aq}}$	Integrated Geochemical Facies
C1	0.19	Saline-interbedded silts/clays with some carbonate and organic content	~4–5 (Medium)	~3–6 (Medium)	Marine Vegetation	Marine Vegetation	Marine low-energy depositional environment with ~4–5% carbonate content and ~3–6% marine vegetation organic matter
C2	1.03	Saline clay with some organic material and decreasing downhole carbonate content	~5–7 (Medium)	~8–10 (High)	Marine Vegetation	Marine Vegetation	Marine very-low-energy depositional environment with ~5–7% carbonate content and ~8–10% marine vegetation organic matter
C3	1.33	Carbonate salt, with some organic content	~14 (High)	~12 (High)	Terrestrial Vegetation	Terrestrial Vegetation	Calcrete with a ~14% carbonate content and ~12% terrestrial vegetation organic matter
C4	1.52	Freshwater sand, low carbonate, and decreasing downhole organic content	~2–3 (Low)	~9–12 (High)	Marine Vegetation	Terrestrial Vegetation	Freshwater sands with ~2–3 carbonate content and ~9–12% terrestrial vegetation organic matter
C5	1.82	Freshwater clay with low carbonate and organic content	~1–4 (Low)	~1–4 (Low)	Terrestrial Vegetation	Terrestrial Vegetation	Freshwater clays with ~1–4% carbonate content and terrestrial vegetation organic matter
C6	2.08	Freshwater silt with low carbonate and very low organic content	~3–4 (Medium)	~4 (Medium)	Marine Vegetation	Emergent aquatic Vegetation	Freshwater silts with ~3–4% carbonate content and ~4% emergent aquatic vegetation organic matter

The chemostratigraphic zones and facies produced by [Finlay et al. \(2022\)](#)—(Figure 4)—were based on qualitative XRF data from trends in elemental variations, which have been used as proxies for depositional settings. The new $P_{\text{mar-aq}}$ and CPI data in this study enabled further confirmation of these proxies. When this was undertaken, a substantial correlation in the data was observed (Table 3). The freshwater zones (C6, C5, and C4) at the bottom part of the core contained terrestrial vegetation and emergent aquatic vegetation lipids and a mix of marine and terrestrial vegetation (Table 2). The possible calcrete (chemozone C3) contained organic material likely to represent terrestrial vegetation, supporting the interpretation of this being a dried fluvial/freshwater facies. The fact that this chemozone was overlain by a clay-rich unit, with low porosity and permeability, likely explains how the salts were protected from dissolution during flooding. Finally, the chemo facies that were identified, according to the lipid analysis, as being saline at the top of the core (C2 and C1), contained organic marine vegetation material.

The final integration of all geochemical analyses for core ELF019 suggested six detailed geochemical zones (Table 3); C6—from 2.96 cm to 2.08 cm—was considered to represent freshwater silts with ~3–4% carbonate content and ~4% organic matter (emergent aquatic vegetation/terrestrial vegetation). C5—from 2.08 cm to 1.82 cm—was interpreted as comprising freshwater clays with ~1–4% carbonate content and ~1–4% organic matter (terrestrial vegetation).

C4—from 1.82 cm to 1.52 cm—was interpreted as comprising freshwater sands with ~2–3% carbonate content and ~9–12% organic matter (terrestrial vegetation). C3—from 1.52 cm to 1.33 cm—was interpreted as comprising coarse sediment of a non-marine (fluvial?) system, with ~14% carbonate content and ~12% organic matter (terrestrial vegetation). This area contains the three dated samples: 10,720–11,080 Cal BP at 1.38 m, 10,243–10,199 Cal BP at 1.35 m, and 9933–10,225 Cal BP at 1.32 m, suggesting a late-mid Greenlandian date (Roberts, 2023). This period spans a time when the coastlines of Doggerland appear to have begun diminishing quite rapidly, ultimately leaving the British Isles separated from continental Europe, probably by no later than 9000 BP (Walker et al., 2020). By the end of the period covered by these dates, northwest Europe was entering the Holocene Climate Optimum, and Doggerland would have been rapidly transforming into a littoral fringe around the modern-day continent. C2—from 1.30 cm to 1.03 cm—was interpreted as comprising a marine, very-low-energy depositional environment, with ~5–7% carbonate content (likely shell remains) and ~8–10% organic matter (marine vegetation). Finally, C1—from 1.03 cm to 0.19 cm—was interpreted as representing a low-energy marine depositional environment, with ~4–5% carbonate content (likely shell remains) and ~3–6% organic matter (marine vegetation).

It is important to note that these variations in environmental deposition were detected by all analytical techniques at approximately the same depths. The integration of all the data allowed the authors to confidently establish a paleoenvironmental/depositional history of the core. Significantly, this enabled the exact point at which two key paleoenvironmental variations occurred: At 1.52 m (core depth), where a freshwater low-energy deposition environment succeeded in a freshwater high-energy deposition environment. A second boundary occurred at 1.33 m (core depth), where there was a division between freshwater and saline deposition. These data provided significant insight into past environmental conditions and demonstrate that comprehensive geochemical studies can assist in the investigation and simulation of the inundation processes that characterize the history of drowned landscapes, including Doggerland.

4.2. The Geoarchaeology Setting of Core ELF019

Core ELF019 sits within the Southern River, and its geomorphological and environmental history, combined with the analyses presented here, suggests a landscape that would have been attractive to Holocene hunter gatherers. This reflects the emergence of fluvial systems and organic rich silts overlying basal sands, and the development of wetlands and perhaps lagoonal conditions prior to inundation after 10k BP. The Southern River would have also been surrounded by mixed woodlands typical of Holocene environments. These, and the fresh water and emerging estuarine environments, would have provided complex environmental niches that were highly attractive to hunter–fisher communities of the time.

The Southern River is of considerable significance in archeological terms. Aside from the resource value of river systems to hunter-gather populations in general, the Southern River incorporates, or passes through, topographic features that may have been significant to early communities. Coring suggests that a saddle at the head of the river could have been associated with a freshwater spring, whilst the lower river cuts through a chalk outcrop with the potential to hold, as yet unproven, lithic resources. However, it is extremely

significant that the area of the Southern River estuary provided the only lithic artefact recovered by the ELF project, recovered by a dredge of the estuary during 2019, and during a joint ELF/VLIZ expedition to the area.

Overall, the importance of studies, as presented here, is not simply to provide a coherent environmental sequence for an individual core, but to place this within a larger geomorphological, topographical, and archeological context. The detailed landscape mapping, and integration of interdisciplinary analyses of the many cores provided by Europe's Lost Frontiers, is gradually generating a detailed picture of the landscape at a local and regional scale (Gaffney & Fitch, 2022). The grand challenge, following the provision of such a rich and detailed backdrop, will be the capacity of archeologists to explore this landscape and refine their understanding of the human communities who lived there.

5. Conclusions

This study highlights the significance of Doggerland as a natural archive for understanding the Late Pleistocene to early Holocene environments, as well as the impacts of abrupt high-energy events such as the Storegga tsunami and/or the gradual sea level rising. Integration of TGA, lipid, and XRF analysis has enabled a paleodepositional history of the 4.43 m sediment from core ELF019 to be established. During the study, it was confirmed, through comparison with the TGA results, that the S/Rb and Ca/Rb ratios were valid proxies to estimate the percentage of organic matter and carbonate content in the sediment. This enabled new insights into the depositional history of the core to be built on the conclusions of (Finlay et al., 2022), including specific boundaries in the paleoenvironmental sequence to be established.

This study enables the core to be split into six zones

- Chemozone 1: Marine low-energy depositional environment with ~4–5% carbonate content and ~3–6% marine vegetation organic matter.
- Chemozone 2: Marine very-low-energy depositional environment with ~5–7% carbonate content and ~8–10% marine vegetation organic matter.
- Chemozone 3: Calcrete with a ~14% carbonate content and ~12% terrestrial vegetation organic matter.
- Chemozone 4: Freshwater sands with ~2–3 carbonate content and ~9–12% terrestrial vegetation organic matter.
- Chemozone 5: Freshwater clays with ~1–4% carbonate content and terrestrial vegetation organic matter.
- Chemozone 6: Freshwater silts with ~3–4% carbonate content and ~4% emergent aquatic vegetation organic matter.

Zonational change revealed a sedimentary transition from a consistent and steady freshwater deposit with strong signs of emergent aquatic vegetation as inundation proceeded. This was associated with unstable and inconsistent deposits and complex sedimentary dynamics. This deposit was dated to the Greenlandian period, 10,243–10,199 Cal BP. Following this, a further zonational shift provided evidence that the sediment was transformed into a more stable, marine environment with sediments rich in clay and marine vegetation lipids. The results of this research demonstrate the capacity of an integrated and efficient multi-proxy geochemical methodology to provide a comprehensive understanding of significant zonational change within paleoenvironmental landscapes, and the opportunity to apply such a methodology in sediment cores relating to a wide variety of contexts.

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References

- Ali, H. A. M., Mayes, R. W., Lamb, C. S., Hector, B. L., Verma, A. K., & Ørskov, E. R. (2004). The potential of long-chain fatty alcohols and long-chain fatty acids as diet composition markers: Development of methods for quantitative analysis and faecal recoveries of these compounds in sheep fed mixed diets. *The Journal of Agricultural Science*, 142(1), 71–78. [\[CrossRef\]](#)
- Ballin, T. B. (2017). Rising waters and processes of diversification and unification in material culture: The flooding of Doggerland and its effect on north-west European prehistoric populations between ca. 13 000 and 1500 cal BC. *Journal of Quaternary Science*, 32(2), 329–339. [\[CrossRef\]](#)
- Bateman, M. D., Kinnaid, T. C., Hill, J., Ashurst, R. A., Mohan, J., Bateman, R. B. I., & Robinson, R. (2021). Detailing the impact of the Storegga Tsunami at Montrose, Scotland. *Boreas*, 50(4), 1059–1078. [\[CrossRef\]](#)
- Bennike, O., Odgaard, B., Wiberg-Larsen, P., & Nørgaard-Pedersen, N. (2023). Submarine lateglacial lake deposits from jutland bank, the north sea. *Quaternary International*, 669, 12–19. [\[CrossRef\]](#)
- Bensharada, M., Stern, B., & Telford, R. (2022a). Introduction to geochemical studies within Europe’s lost frontiers. In *Europe’s lost frontiers: Volume 1: Context and methodology* (pp. 154–164). Archaeopress Publishing Ltd. [\[CrossRef\]](#)
- Bensharada, M., Telford, R., Stern, B., & Gaffney, V. (2022b). Loss on ignition vs. thermogravimetric analysis: A comparative study to determine organic matter and carbonate content in sediments. *Journal of Paleolimnology*, 67(2), 191–197. [\[CrossRef\]](#)
- Blumenberg, M., Schlömer, S., Reinhardt, L., Scheeder, G., Pape, T., & Römer, M. (2022). Biomarker insights into a methane-enriched Holocene peat-setting from “Doggerland” (central North Sea). *The Holocene*, 32(10), 1015–1025. [\[CrossRef\]](#)
- Bonomo, M., Leon, D. C., Osterrieth, M., Steffan, P., & Borrelli, N. (2013). Paleoenvironmental studies of Alfar archaeological site (mid-Holocene; Southeastern Pampas of Argentina): Silicophytoliths, gastropods and archaeofauna. *Quaternary International*, 287, 34–46. [\[CrossRef\]](#)
- Brett, C. E., Hendy, A. J. W., Bartholomew, A. J., Bonelli, J. R., Jr., & McLaughlin, P. I. (2007). Response of shallow marine biotas to sea-level fluctuations: A review of faunal replacement and the process of habitat tracking. *Palaeos*, 22(3), 228–244. [\[CrossRef\]](#)
- Collister, J. W., Rieley, G., Stern, B., Eglinton, G., & Fry, B. (1994). Compound-specific $\delta^{13}\text{C}$ analyses of leaf lipids from plants with differing carbon dioxide metabolisms. *Organic Geochemistry*, 21(6–7), 619–627. [\[CrossRef\]](#)
- Dunbar, E., Cook, G. T., Naysmith, P., Tripney, B. G., & Xu, S. (2016). AMS ^{14}C dating at the Scottish Universities Environmental Research Centre (SUERC) radiocarbon dating laboratory. *Radiocarbon*, 58(1), 9–23. [\[CrossRef\]](#)
- Duplisea, D. E. (2000). Benthic organism biomass size-spectra in the Baltic Sea in relation to the sediment environment. *Limnology and Oceanography*, 45(3), 558–568. [\[CrossRef\]](#)
- Eglinton, G., & Hamilton, R. J. (1967). Leaf Epicuticular Waxes: The waxy outer surfaces of most plants display a wide diversity of fine structure and chemical constituents. *Science*, 156(3780), 1322–1335. [\[CrossRef\]](#)

- Ficken, K. J., Li, B., Swain, D. L., & Eglinton, G. (2000). An n-alkane proxy for the sedimentary input of submerged/floating freshwater aquatic macrophytes. *Organic Geochemistry*, 31(7–8), 745–749. [\[CrossRef\]](#)
- Finlay, A., Bates, R., Bensharada, M., & Davies, S. (2022). Applying chemostratigraphic techniques to shallow bore holes: Lessons and case studies from Europe’s lost frontiers. In *Europe’s lost frontiers: Volume 1: Context and methodology* (pp. 137–153). Archaeopress Publishing Ltd. [\[CrossRef\]](#)
- Fitch, S., Thomson, K., & Gaffney, V. (2005). Late Pleistocene and Holocene depositional systems and the palaeogeography of the Dogger Bank, North Sea. *Quaternary Research*, 64(2), 185–196. [\[CrossRef\]](#)
- Gaffney, V., Allaby, R., Bates, R., Bates, M., Ch’ng, E., Fitch, S., Garwood, P., Momber, G., Murgatroyd, P., & Pallen, M. (2017). Doggerland and the lost frontiers project (2015–2020). In *Under the sea: Archaeology and palaeolandscapes of the continental shelf* (pp. 305–319). Springer. [\[CrossRef\]](#)
- Gaffney, V., & Fitch, S. (2022). *Europe’s lost frontiers: Volume 1: Context and methodology* (Vol. 1). Archaeopress Publishing Ltd. [\[CrossRef\]](#)
- Gaffney, V., Fitch, S., Bates, M., Ware, R. L., Kinnaird, T., Gearey, B., Hill, T., Telford, R., Batt, C., & Stern, B. (2020). Multi-proxy characterisation of the Storegga tsunami and its impact on the early Holocene landscapes of the southern North Sea. *Geosciences*, 10(7), 270. [\[CrossRef\]](#)
- Gaffney, V., Fitch, S., & Smith, D. N. (2009). *Europe’s lost world: The rediscovery of Doggerland..* Council for British Archaeology. [\[CrossRef\]](#)
- He, J., Zhang, S., Zhang, X., Qian, Y., He, H., & Wu, H. (2016). Composition and distribution characteristics and geochemical significance of n-alkanes in core sediments in the northern part of the South Yellow Sea. *Journal of Chemistry*, 2016(1), 4741939. [\[CrossRef\]](#)
- Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology*, 25(1), 101–110. [\[CrossRef\]](#)
- Hu, J., Peng, P. A., & Chivas, A. R. (2009). Molecular biomarker evidence of origins and transport of organic matter in sediments of the Pearl River estuary and adjacent South China Sea. *Applied Geochemistry*, 24(9), 1666–1676. [\[CrossRef\]](#)
- Jiménez Martínez, A. E., Schleder, A., Sanz, J., Bahniuk, A., & Froehner, S. (2019). Use of fatty acids as tracer of organic matter input associated with level of land urbanization. *Environmental Science and Pollution Research*, 26(31), 31685–31698. [\[CrossRef\]](#)
- Konare, H., Yost, R. S., Doumbia, M., McCarty, G. W., Jarju, A., & Kablan, R. (2010). Loss on ignition: Measuring soil organic carbon in soils of the Sahel, West Africa. *African Journal of Agricultural Research*, 5(22), 3088–3095. [\[CrossRef\]](#)
- Mackenzie, A. S., Brassell, S. C., Eglinton, G., & Maxwell, J. R. (1982). Chemical fossils: The geological fate of steroids. *Science*, 217(4559), 491–504. [\[CrossRef\]](#)
- Meyers, P. A., & Ishiwatari, R. (1993). Lacustrine organic geochemistry—An overview of indicators of organic matter sources and diagenesis in lake sediments. *Organic Geochemistry*, 20(7), 867–900. [\[CrossRef\]](#)
- Mulder, T., & Alexander, J. (2001). The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, 48(2), 269–299. [\[CrossRef\]](#)
- Radomirović, M., Mijatović, N., Vasić, M., Tanaskovski, B., Mandić, M., Pezo, L., & Onjia, A. (2021). The characterization and pollution status of the surface sediment in the Boka Kotorska Bay, Montenegro. *Environmental Science and Pollution Research*, 28(38), 53629–53652. [\[CrossRef\]](#)
- Rielley, G., Collier, R. J., Jones, D. M., & Eglinton, G. (1991). The biogeochemistry of Ellesmere Lake, UK—I: Source correlation of leaf wax inputs to the sedimentary lipid record. *Organic Geochemistry*, 17(6), 901–912. [\[CrossRef\]](#)
- Roberts, N. (2023). Holocene climate changes and human consequences. *Handbook of Archaeological Sciences*, 1, 321–337. [\[CrossRef\]](#)
- Rocci, K. S., Lavalley, J. M., Stewart, C. E., & Cotrufo, M. F. (2021). Soil organic carbon response to global environmental change depends on its distribution between mineral-associated and particulate organic matter: A meta-analysis. *Science of the Total Environment*, 793, 148569. [\[CrossRef\]](#)
- Rothwell, R. G., & Croudace, I. W. (2015). Twenty years of XRF core scanning marine sediments: What do geochemical proxies tell us? In *Micro-XRF studies of sediment cores: Applications of a non-destructive tool for the environmental sciences* (pp. 25–102). Springer. [\[CrossRef\]](#)
- Sikes, E. L., Uhle, M. E., Nodder, S. D., & Howard, M. E. (2009). Sources of organic matter in a coastal marine environment: Evidence from n-alkanes and their $\delta^{13}\text{C}$ distributions in the Hauraki Gulf, New Zealand. *Marine Chemistry*, 113(3–4), 149–163. [\[CrossRef\]](#)
- Van der Plicht, J., Amkreutz, L., Niekus, M. J. L. T., Peeters, J. H. M., & Smit, B. I. (2016). Surf’n Turf in Doggerland: Dating, stable isotopes and diet of Mesolithic human remains from the southern North Sea. *Journal of Archaeological Science: Reports*, 10, 110–118. [\[CrossRef\]](#)
- Van Geel, B., Van Der Plicht, J., Kasse, C., & Mol, D. (2024). Radiocarbon dates from the Netherlands and Doggerland as a proxy for vegetation and faunal biomass between 55 and 5 ka cal bp. *Journal of Quaternary Science*, 39(2), 248–260. [\[CrossRef\]](#)
- Walker, J., Gaffney, V., Fitch, S., Muru, M., Fraser, A., Bates, M., & Bates, R. (2020). A great wave: The Storegga tsunami and the end of Doggerland? *Antiquity*, 94(378), 1409–1425. [\[CrossRef\]](#)
- Ward, I., Larcombe, P., & Lillie, M. (2006). The dating of Doggerland–post-glacial geochronology of the southern North Sea. *Environmental Archaeology*, 11(2), 207–218. [\[CrossRef\]](#)

- Weninger, B., Schulting, R., Bradtmöller, M., Clare, L., Collard, M., Edinborough, K., Hilpert, J., Jöris, O., Niekus, M., & Rohling, E. J. (2008). The catastrophic final flooding of Doggerland by the Storegga Slide tsunami. *Documenta Praehistorica*, 35, 1–24. [[CrossRef](#)]
- Xiao, X., Fahl, K., & Stein, R. (2013). Biomarker distributions in surface sediments from the Kara and Laptev seas (Arctic Ocean): Indicators for organic-carbon sources and sea-ice coverage. *Quaternary Science Reviews*, 79, 40–52. [[CrossRef](#)]
- Yamoah, K. K. A., Chabangborn, A., Chawchai, S., Välranta, M., Wohlfarth, B., & Smittenberg, R. H. (2016). Large variability in n-alkane $\delta^{13}\text{C}$ values in Lake Pa Kho (Thailand) driven by wetland wetness and aquatic productivity. *Organic Geochemistry*, 97, 53–60. [[CrossRef](#)]

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