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On the application of contemporary bulk sediment organic carbon isotope and geochemical datasets for Holocene sea-level reconstruction in NW Europe

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Abstract

Bulk organic stable carbon isotope ($\delta^{13}C$) and element geochemistry (total organic carbon (TOC) and organic carbon to total nitrogen (C/N)) analysis is a developing technique in Holocene relative sea-level (RSL) research. The uptake of this technique in Northern Europe is limited compared to North America, where the common existence of coastal marshes with isotopically distinctive C_3 and C_4 vegetation associated with well-defined inundation tolerance permits the reconstruction of RSL in the sediment record. In Northern Europe, the reduced range in $\delta^{13}C$ values between organic matter sources in C_3 estuaries can make the identification of elevation-dependent environments in the Holocene sediment record challenging and this is compounded by the potential for post-depositional alteration in bulk $\delta^{13}C$ values. The use of contemporary regional $\delta^{13}C$, C/N and TOC datasets representing the range of physiographic conditions commonly encountered in coastal wetland sediment sequences opens up the potential of using absolute values of sediment geochemistry to infer depositional environments and associated reference water levels. In this paper, the application of contemporary bulk organic $\delta^{13}C$, C/N and TOC to reconstruct Holocene RSL is further explored. An extended contemporary regional geochemical dataset of published $\delta^{13}C$, C/N and TOC observations ($n = 142$) from tidal-dominated C_3 wetland deposits (representing tidal flat, saltmarsh, reedswamp and fen carr environments) in temperate NW Europe is compiled, and procedures implemented to correct for the ^{13}C Suess effect on contemporary $\delta^{13}C$ are detailed. Partitioning around medoids analysis identifies two distinctive geochemical groups in the NW European dataset, with tidal flat/saltmarsh and reedswamp/fen carr environments exhibiting characteristically different sediment $\delta^{13}C$, C/N and TOC values. A logistic regression model is developed from the NW European dataset in order to objectively identify in the sediment record geochemical groups and, more importantly, group transitions, thus allowing the altitude of reference water levels to be determined. The application of this method in RSL research is demonstrated using the Holocene sediments of the Mersey Estuary (UK), in which $\delta^{13}C$, C/N and TOC variability is typical of that encountered in Holocene sediments from C_3 coastal wetlands in NW Europe. Group membership was predicted with high probability in the depositional contexts studied and the accuracy of group prediction is verified by microfossil evidence. The method presented facilitates the application of $\delta^{13}C$, C/N and TOC analysis in RSL reconstruction studies in C_3 vegetated wetlands throughout temperate NW Europe.

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Keywords: Stable carbon isotope; Organic geochemistry; Sea level changes; North West Europe; Holocene; Estuary; Coastal wetland

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Abbreviations: C/N, carbon/nitrogen; HAT, highest astronomical tide; MHWS, mean high water of spring tide; OD, Ordnance Datum; PAM, partitioning around medoids; POC, particulate organic carbon; POM, particulate organic matter; RSL, relative sea-level; RWL, reference water level; SLI, sea-level index point; TOC, total organic carbon

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1. INTRODUCTION

A detailed knowledge of relative sea-level (RSL) change is necessary to understand coastal evolution and coastline response to processes operating over a range of spatial and temporal scales. Additionally, RSL records contribute to a better understanding of viscoelastic earth structure, ice sheet configuration and melt history through their use in glacial isostatic adjustment model development (e.g. Bradley et al., 2011), which in turn has societal relevance for the effective projection of, and planning for, future sea-level change (Shennan et al., 2009). Sediments accumulating in low energy tidal-dominated coastal wetlands can provide a natural archive of RSL change (Edwards, 2013). In temperate regions, minerogenic tidal flats occupying lower-intertidal areas are replaced by vegetated saltmarshes at higher elevations, and (where intact) ultimately by organogenic reedswamp and wet woodland (e.g. fen carr) environments in upper inter-tidal and supra-tidal zones respectively (Waller et al., 1999). This vertical zonation reflects the reducing frequency and duration of tidal flooding with increasing ground elevation within the tidal frame. Changes in RSL, whether driven by external factors (e.g. vertical changes in ocean level (Fairbanks, 1989), or land level (Bradley et al., 2011)), or by internal factors (e.g. through the promotion of sediment accumulation on inter-tidal vegetated surfaces (e.g. Kirwan and Murray, 2007), or due to sediment compaction (e.g. Brain et al., 2012)) result in the displacement of zones and, typically, the accumulation of intercalated minerogenic and organogenic deposits over Holocene time-scales (Allen, 2003). RSL records generated from unconsolidated coastal sediment deposits comprise a series of sea-level index points (SLIs) – dated sediment horizons with a known altitude (relative to a local datum) and relationship (indicative meaning) to a reference water level (RWL) (Edwards, 2013). The indicative meaning of coastal depositional environments is determined from contemporary observation (Shennan, 1982). SLIs are often derived from transgressive (organogenic to minerogenic) or regressive (minerogenic to organogenic) lithostratigraphic overlaps in intercalated coastal sediment sequences (Tooley, 1982). The indicative range (the possible altitudinal envelope of inferred RWLs) at lithostratigraphic overlaps is minimal (typically ±20 cm, depending on tidal range) and the availability of organic material enables lithostratigraphic overlaps to be placed in a chronological framework, thus permitting the reconstruction of RSL time-altitude changes with defined temporal and vertical errors.

The indicative meaning at lithostratigraphic overlaps is usually determined by the characteristics of the preserved microfossil assemblages (van de Plassche, 1986), particularly the composition of diatoms (e.g. Zong, 1997), foraminifera (e.g. Edwards and Horton, 2000) and pollen (e.g. Bernhardt and Willard, 2015), as informed by contemporary surveys. Microfossil analysis is necessary to determine the sedimentary environments (e.g. tidal flat, saltmarsh, reedswamp, wet woodland) represented in depositional sequences, and to ensure a conformable facies sequence at lithostratigraphic overlaps. The application of microfossils as sea-level indicators has several limitations, however. These include: (i) an assumption of unchanged optima and tolerance of biota in relation to a RWL (Gehrels, 2002); (ii) the vertical range restriction of different biological indicators within the tidal frame (Gehrels et al., 2001); (iii) the susceptibility to chemical and mechanical damage in the journey from biocoenose to thanatocoenose, and in the final fossil stage (e.g. Birks and Birks, 1980; Kato et al., 2003). The use of microfossils to quantitatively estimate past RWLs using transfer functions may suffer additional drawbacks, including the absence of equivalent modern analogues (e.g. Wilson and Lamb, 2012), problems of spatial autocorrelation (e.g. Telford and Birks, 2005) and a large amount of unexplained variability in contemporary training sets (e.g. Zong and Horton, 1999).

1.1. Bulk organic δ^{13}C, C/N and TOC as sea-level indicators

The application of stable carbon isotope analysis (δ^{13}C analysis), used in conjunction with supporting geochemistry (particularly the ratio of organic carbon to total nitrogen (C/N) and total organic carbon content (TOC)) is gaining traction as a viable sea-level indicator (Khan et al., 2015a). When used in combination with microfossil indicators, an increase in the precision of inferred palaeotidal levels has been achieved (e.g. Kemp et al., 2013; Cahill et al., 2016). Used in isolation, these geochemical techniques prove to be effective alternative sea-level indicators and can prevent redundancy of potential SLIs at lithostratigraphic overlaps in the event of poor microfossil preservation (Goslin et al., 2015; Khan et al., 2015b). In North America, the application of δ^{13}C and C/N analysis in palaeosea-level research (Kemp et al., 2010, 2012, 2013; Milker et al., 2015; Cahill et al., 2016), and in palaeoseismology (Engelhart et al., 2013) has proved particularly effective due to the common existence of isotopically distinctive vegetated coastal marshes. For example, on the southern Atlantic coast of New Jersey, saltmarshes are typically colonized by plants which utilize the C_4 photosynthetic pathway (e.g. *Spartina patens*: δ^{13}C between $-14.0‰$ and $-13.8‰$ (Kemp et al., 2012)), whilst plants utilizing the C_3 photosynthetic pathway are frequent in more upland brackish and freshwater marshes (e.g. *Phragmites australis*: δ^{13}C between $-25.2‰$ and $-24.6‰$ (Kemp et al., 2012)). This can facilitate the identification of saltmarsh and upland brackish/freshwater marsh deposits in the sediment record using δ^{13}C because sediment δ^{13}C values faithfully reflect the relative contributions of organic carbon from C_3 and C_4 plants at the time of formation (Stout et al., 1975; Chmura et al., 1987). The presence or absence of agglutinated foraminifera can further distinguish between brackish and freshwater marsh deposits respectively and used together with bulk organic δ^{13}C measurements have been shown to provide a precise indication of past RSL (Kemp et al., 2012).

Since the exploration and development of δ^{13}C and C/N analysis of marsh deposits specifically for application in sea-level research (e.g. Wilson et al., 2004, 2005a), the uptake and application of this method in European sea-level research is, by comparison, more limited

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