Quaternary Science Reviews 54 (2012) 26–39

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Quantitative vertical zonation of salt-marsh foraminifera for reconstructing former sea level; an example from New Jersey, USA.

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A R T I C L E I N F O

Article history:
Received 11 March 2011
Accepted 17 September 2011
Available online 17 November 2011

Keywords:
Salt marsh
Foraminifera
New Jersey
Discriminant function
Cluster analysis
Sea level
Quantitative paleoenvironmental reconstruction

A B S T R A C T

We present a quantitative technique to reconstruct sea level from assemblages of salt-marsh foraminifera using partitioning around medoids (PAM) and linear discriminant functions (LDF). The modern distribution of foraminifera was described from 62 surface samples at three salt marshes in southern New Jersey. PAM objectively estimated the number and composition of assemblages present at each site and showed that foraminifera adhered to the concept of elevation-dependent ecological zones, making them appropriate sea-level indicators. Application of PAM to a combined dataset identified five distinctive biozones occupying defined elevation ranges, which were similar to those identified elsewhere on the U.S. mid-Atlantic coast. Biozone A had high abundances of *Jadammina macrescens* and *Trochammina inflata*; biozone B was dominated by *Miliammina fusca*; biozone C was associated with *Arenoparrella mexicana*; biozone D was dominated by *Tiphotrocha comprimata* and biozone E was dominated by *Haplophragmoides manilaensis*. Foraminiferal assemblages from transitional and high salt-marsh environments occupied the narrowest elevational range and are the most precise sea-level indicators. Recognition of biozones in sequences of salt-marsh sediment using LDFs provides a probabilistic means to reconstruct sea level. We collected a core to investigate the practical application of this approach. LDFs indicated the faunal origin of 38 core samples and in cross-validation tests were accurate in 54 of 56 cases. We compared reconstructions from LDFs and a transfer function. The transfer function provides smaller error terms and can reconstruct smaller RSL changes, but LDFs are well suited to RSL reconstructions focused on larger changes and using varied assemblages. Agreement between these techniques suggests that the approach we describe can be used as an independent means to reconstruct sea level or, importantly, to check the ecological plausibility of results from other techniques.

1. Introduction

Low energy coastal sediments in temperate regions have provided detailed records of Holocene sea-level changes (Stuiver and Daddario, 1963; Kraft, 1971; Peteet Carmichael, 1980; Gehrels et al., 1996; Nikitina et al., 2000; Horton et al., 2009). Such reconstructions are contingent upon appropriate selection and application of sea-level indicators to accurately estimate former sea level. A sea-level indicator is a physical, biological or chemical feature possessing a systematic and quantifiable relationship to elevation in the tidal frame (Shennan, 1986; van de Plassche, 1986). This relationship, known as the indicative meaning, incorporates the elevational range occupied by a sea-level indicator (indicative range) in relation to a contemporaneous tide level (reference water level). This approach is reliant upon a detailed understanding of the modern characteristics of the chosen sea-level indicator. Further, a quantitative technique is necessary to provide objective estimates of relative sea level (RSL) on the basis of similarity between sea-level indicators preserved in sub-fossil sedimentary material and

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doi:10.1016/j.quascirev.2011.09.014

those documented from modern settings (Jackson and Williams, 2004).

Assemblages of foraminifera are sea-level indicators because their distribution on modern salt marshes reflects frequency and duration of tidal inundation and permits recognition of elevation-dependent ecological zones (Scott and Medioli, 1978; Gehrels, 1994; Horton and Edwards, 2006). Some studies have documented a potential precision of $<\pm0.1$ m in high salt-marsh settings (Scott and Medioli, 1978; Gehrels et al., 2001; Leorri et al., 2008b; Kemp et al., 2009b). Foraminifera are commonly preserved in salt-marsh sediment and are well suited to quantitative analysis because they form low diversity, high abundance assemblages (Gehrels, 2007).

Use of salt-marsh foraminifera for RSL reconstruction requires selection and application of a suitable technique to exploit the modern relationship between foraminifera and tidal elevation to interpret downcore assemblages. The vertical zonation concept uses the elevational range of discrete groups of modern salt-marsh foraminifera as the basis for assigning an indicative meaning to assemblages enumerated from core material (Scott and Medioli, 1978). This approach has frequently been used in a qualitative fashion where modern zones are determined subjectively and assignment of core samples to one of these groups is reliant upon the judgment of a researcher. Later studies used unconstrained cluster analysis to quantitatively define assemblages of foraminifera on modern salt marshes (de Rijk, 1995; Horton, 1999; Patterson et al., 2000; Edwards et al., 2004). This approach required a subjective decision on how many groups were present and is influenced by limitations of agglomerative hierarchical clustering, such as the legacy effect of previous cluster decisions (Kaufman and Rousseeuw, 1990). Alternatively, discriminant functions have assigned samples to zones that were defined in a qualitative fashion (Jennings and Nelson, 1992). These approaches have been widely superseded by transfer functions (Guilbault et al., 1995; Horton et al., 1999a; Edwards and Horton, 2006; Massey et al., 2006; Gehrels et al., 2008; Leorri et al., 2008b; Woodroffe, 2009), which are empirically derived equations for producing quantitative estimates of past environmental conditions from paleontological data (Sachs et al., 1977). They have produced accurate and precise estimates of former RSL in an objective and reproducible fashion (Gehrels et al., 2005; Horton and Edwards, 2006). The validity of these reconstructions has been confirmed by comparison with tide-gauge records (Gehrels et al., 2005; Kemp et al., 2009b). However, each of the numerical techniques used in transfer functions have underlying assumptions about the nature of species responses to environmental changes (Birks, 1995). The ecological plausibility of all reconstructions should be reviewed out of concern for biased (e.g. residual structure) or inaccurate estimates despite seemingly high precision (Birks, 1995). Wright et al. (2011) proposed that the similarity between surface and fossil assemblages should be quantified and accompany any RSL reconstruction. Further, there is potential for transfer function-derived RSL reconstructions to be influenced by spatial autocorrelation, resulting in overly optimistic estimates of uncertainty (Telford and Birks, 2005; 2009; Zong et al., 2010). Problems associated with transfer functions have led recently to the return of the vertical zonation concept to reconstruct RSL (Long et al., in press).

In this paper, we present an alternative means to reconstruct RSL based upon modern and fossil assemblages of salt-marsh foraminifera using partitioning around medoids (PAM) in combination with linear discriminant functions (LDF). This quantitative and objective approach is not underpinned by assumptions about the distribution and response of foraminifera and provides a probabilistic estimate of the faunal origin of core samples based on similarity between modern and fossil assemblages of foraminifera. We develop a new modern training set of foraminifera from three salt marshes in southern New Jersey, USA (Fig. 1) and compare these with published studies from the U.S. mid-Atlantic coast. To illustrate an application of this approach, estimates of former salt-marsh elevation are provided by LDFs for samples in a core of salt-marsh sediment collected from one of the study sites. These estimates are compared with results from a transfer function.

2. Modern setting

The southern New Jersey coast is characterized by barrier islands protecting a lagoon system from the open Atlantic Ocean. Inlets separate the islands and allow exchange of water between the ocean and the lagoons. The coast between Great Bay and Cape May (Fig. 1) includes nine open inlets and islands which typically decrease in size from north to south (Ferland, 1990). Large areas of formerly open-water lagoon have been infilled by washover material and accretion of salt-marsh sediment (Daddario, 1961; Meyerson, 1972; Thorbjarnarson et al., 1985; Psuty, 1986; Ferland, 1990).

Modern salt marshes in this region form extensive platforms dissected by tidal channels of varying size (Ferland, 1990). Tidal flat environments are rare as the coast is experiencing erosion (Dolan et al., 1979; Fitzgerald et al., 2008). Low-marsh settings are vegetated by *Spartina alterniflora* (tall form). High-marsh floral zones are dominated by *Spartina patens* with *S. alterniflora* (short form) and *Distichlis spicata* (Daddario, 1961). The border between salt marsh and freshwater upland is vegetated by *Phragmites australis, Typha* spp. and *Scirpus* spp.; it is typically narrow and representative of brackish conditions (Daddario, 1961; Stuckey and Gould, 2000).

The region has a semidiurnal, microtidal (range <2 m) regime. Tidal ranges (MLLW to MHHW) are slightly larger on the ocean side of the barrier islands (1.4 m at Atlantic City; Fig. 1) than in the lagoons. At the study sites around Great Bay (Fig. 1), tidal ranges were estimated by VDatum (Hess et al., 2003; Parker et al., 2003) to be 1.1 m at Leeds Point and Bass River and 1.3 m at Brigantine Barrier.

3. Methods

3.1. Sampling design

At three sites we established transects across the modern salt marsh that were positioned to include the full range of floral environments (Fig. 1). Two transects (upland to tidal creek) were sampled at Leeds Point (A–A′ and B–B′) and one each at Bass River (C–C′; upland to bay) and Brigantine Barrier (D–D′; back-barrier upland to lagoon). Sampling stations along the transects reflected changes in elevation and vascular vegetation. At each sampling station we collected a 10 cm^2 surface (0–1 cm) sediment sample for foraminiferal analysis. Use of surface samples assumes that infaunal foraminifera (Ozarko et al., 1997; Culver and Horton, 2005; Tobin et al., 2005) are not a significant part of assemblages.

Sample altitudes were established using Real Time Kinematic (RTK) satellite navigation, where the base station (Leica GPS1200+) made a minimum of 2000 observations. Orthogonal heights were converted to tidal altitudes using VDatum. Due to differences in tidal range among the three sites, it was necessary to express elevations in the combined dataset as a standardized water level index (SWLI) following the approach described by Horton and Edwards (2006). Reconstructed SWLIs were back-transformed to tidal elevations based on modern tidal characteristics at Leeds Point.

Core EF10 was selected for analysis from Leeds Point following stratigraphic investigation. The core was recovered in