Palaeogeography, Palaeoclimatology, Palaeoecology 440 (2015) 66–77

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

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

Bioturbation trends across the freshwater to brackish-water transition in rivers

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 21 August 2015
Accepted 22 August 2015
Available online 2 September 2015

Keywords:
Brackish-water ichnological model
Neoichnology
Trace fossils
Freshwater
Brackish water
Deltas
Estuaries

ABSTRACT

Most existing ichnological models predict an increase in burrow density and diversity from the zone of persistent brackish-water into the realm of persistent freshwater. Herein we compare the neoichnology of five tidal–fluvial channels with varying tidal magnitudes, saltwater incursion distances, and river discharge. The results indicate that there is a noticeable diminution in the sizes of marine traces and a corresponding decrease in their distribution (reduced abundance of burrowed versus unburrowed beds) with decreasing salinity. From the landward limit of saltwater incursion into the wholly freshwater tidal backwater, there is no concurrent increase in terrestrial or freshwater burrow forms; rather, burrow diversities remain low (range: 10 to 35% of the "open marine" signature) and burrow densities decrease from BI 0–3 to BI 0–1 in both sand and mud units.

The five modern systems described in this study do not support the hypothesis that there is an increase in bioturbation from the brackish-water reaches of channels into freshwater reaches. In fact, freshwater channels, including those in the tidal backwater zone, are characterized by very low trace-fossil diversities (1 to 2 forms) as well as low and sporadically distributed bioturbation intensities (BI 0–1).

1. Introduction

Burrowing organisms are sensitive to the physical and chemical conditions of their habitats. In deltas and estuaries, temporal and spatial changes in water salinity strongly affect organism behavior and distribution (Carriker, 1967; Remane and Schlieper, 1971; Schäfer, 1972; Wolff, 1973; Perkins, 1974; Dörjes and Howard, 1975; Chapman and Brinkhurst, 1981; Croghan, 1983; Hudson, 1990; Gingras et al., 1999, 2008; Pearson and Gingras, 2006; Hauck et al., 2009; Sisulak and Dashtgard, 2012; Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2015). Stresses imposed by fluctuating and generally reduced salinities produce a distinctive bioturbate signature that allows for the differentiation of brackish-water environments from their fully marine counterparts (Pemberton et al., 1982; Wightman et al., 1987; Gingras et al., 1999; Buatois et al., 2005; MacEachern and Gingras, 2007). Herein, we evaluate the ichnological trends across the tidal–fluvial transition of five modern channel systems: the Middle/North Arm and Main Channel of the Fraser River, British Columbia, Canada; the Palix River of Willapa Bay, Washington, USA; and the Kouchibouguac and Kouchibouguacis rivers, New Brunswick, Canada. The diversity and density of burrowing in these rivers are compared to their measured salinity profiles. From these comparisons, we test the validity of the commonly reproduced infaunal diversity graph (e.g., Remane and Schlieper, 1971; Barnes, 1989; Hudson, 1990; Pickerill and Brenchley, 1991; Buatois et al., 1997) that indicates an increase in faunal and trace diversity from brackish-water settings into the freshwater realm (Fig. 1).

Based on a foundation established by previous workers (Schafer, 1956; Seilacher, 1963; Howard and Frey, 1973, 1975; Dörjes and Howard, 1975; Howard et al., 1975; Majou and Howard, 1975), Pemberton et al. (1982) recognized that brackish-water trace fossils recur in predictable associations in a manner that parallels benthic communities. This informal "brackish-water ichnological model" is commonly used to decipher rock-record strata representing marginal-marine environments (e.g., Wightman et al., 1987; Pemberton and Wightman, 1992; Wightman and Pemberton, 1997; Buatois et al., 2005; MacEachern and Gingras, 2007). The ichnological characteristics of sediments across the marine to brackish-water transition are well defined, but the transition from brackish-water to freshwater is more poorly known. Some workers have reported that the freshwater reaches of rivers are characterized by trails, trackways, and grazing traces predominantly produced by terrestrial and freshwater organisms. These freshwater trace associations are of high density but low diversity, and correspond to trace assemblages that include trace fossils common to both the *Scoyenia* and *Mermia* ichnofacies (Buatois et al., 1997; Buatois and Mangano, 2011). On the other hand, a relatively unbioturbated brackish-water to freshwater transition was observed

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http://dx.doi.org/10.1016/j.palaeo.2015.08.030
0031-0182/

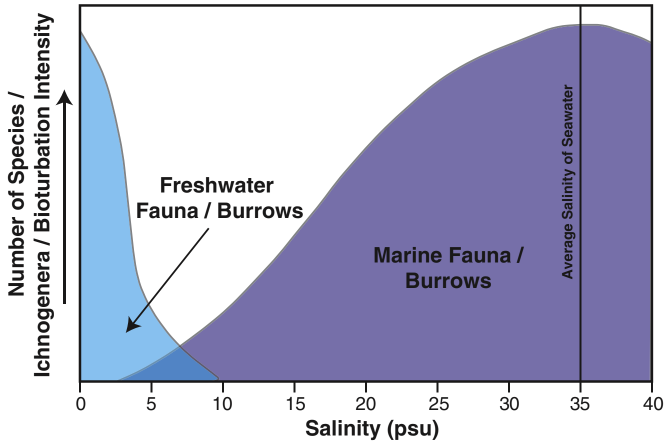

Fig. 1. The relative number of marine and freshwater species at various ambient salinities (at the bed) between saltwater and fresh water and the corresponding diversity of traces and bioturbation intensity (modified from Remane and Schlieper, 1971; Barnes, 1989; Hudson, 1990; Buatois et al., 1997).

in Paleozoic and Mesozoic rocks by Miller (1984), Miller and Labandeira (2002), and Miller et al. (2002). Our modern observations of intertidal and subtidal deposits from Willapa Bay estuary, USA (Gingras et al., 1999), transgressive embayments in Kouchibouguac National Park, New Brunswick, Canada (Hauck et al., 2009), and deltaic distributary channels of the Fraser River Delta, British Columbia, Canada (Dashtgard et al., 2012; Sisulak and Dashtgard, 2012; Johnson and Dashtgard, 2014; La Croix and Dashtgard, 2015) do not exhibit the landward increase in trace diversity and density into the freshwater part of the system, and show an unbioturbated transitional zone from brackish-water to freshwater.

2. Study areas

2.1. Fraser River, British Columbia, Canada

The Fraser River is 1375 km long and drains 228,000 km^2 of mountainous terrain in British Columbia, Canada (Fig. 2A). River flow varies from approximately 1000 $m^3\ s^{-1}$ during low flow to 15,200 $m^3\ s^{-1}$ during high flow. Mean annual discharge is 8642 $m^3\ s^{-1}$. Tides are mixed semidiurnal. The mean tidal amplitude at the mouth of the river is 3.0 m and ranges from 2.1 to 4.9 m through the neap-spring tidal cycle.

2.2. Palix River, Willapa Bay, Washington, USA

Willapa Bay is a sheltered body of water in the southwest corner of Washington State, USA (Fig. 2B). Five small rivers discharge into the bay. The Palix River flows from the southeast and constitutes one of the sources of freshwater supplied to the estuary. The Palix River is approximately 11 km long, and consists of the South Fork, Middle Fork, Cannon River, and mainstream Palix River. The drainage basin is approximately 110 km^2 and the average discharge from the Palix is estimated to be 5 $m^3\ s^{-1}$ (maximum discharge estimated at 100 $m^3\ s^{-1}$).

Tidal range in Willapa Bay varies from 2 to 3 m. A large volume of water is exchanged through the estuary as a result of a tidal prism that is at least 700,000 m^3; approximately 45% of the bay's total volume (Engineers, U.S.A.C.o., 1975).

2.3. Kouchibouguac National Park, New Brunswick, Canada

Kouchibouguac National Park is situated on the Northumberland Strait in the southern Gulf of St. Lawrence, Canada (Fig. 2C). The bay contains 29 km of arcuate barrier islands fronting a series of lagoons and estuaries, of which the St. Louis and Kouchibouguac lagoons are the most prominent. The Kouchibouguacis River debouches into St. Louis Lagoon, whereas the Kouchibouguac and Black rivers empty into Kouchibouguac Lagoon. The catchment basin for the Kouchibouguac River is approximately 228 km^2, with a mean annual discharge of 3.74 $m^3\ s^{-1}$ (Robinson et al., 2004). No drainage or discharge data has been published for the Kouchibouguacis River, but these values are probably similar given the comparable drainage area and dimensions of the two rivers (Hauck et al., 2009). Kouchibouguac Bay is microtidal, with a mean tidal range of 0.67 m and a maximum range of 1.25 m.

3. Methods

This paper synthesizes the results from three previously published studies of the neoichnology of rivers (Gingras et al., 1999; Hauck et al., 2009; La Croix and Dashtgard, 2015), where data were collected mainly from intertidal sediments. The exception to this is the Kouchibouguac and Kouchibouguacis rivers where the shallow water depths enabled both intertidal and subaqueous sampling to 3 m water depth (from maximum high tide). Although these rivers differ markedly in drainage-basin area, discharge characteristics and climate, their deposits are influenced by tides and brackish-water, and a brackish-water to freshwater transition is present in all systems. Datasets include surficial sediment samples, shallow cores, box cores, and water salinity measurements. Surficial sediment samples were used to determine the textural characteristics of the substrates inhabited by the bioturbating organisms. Shallow cores collected subaqueously in 10 cm diameter × 30 cm long PVC tubes (i.e., "shrimp guns") were x-radiographed, and trace diversities and densities were recorded therein. Box cores (18 cm × 8 cm × 30 cm) were collected at intertidal stations for X-ray imaging of in situ sedimentological and ichnological structures. In total, 364 sediment samples and 136 box cores from 56 stations were collected across the Fraser River's tidal–fluvial transition. From the Palix River, 50 box cores and 60 sediment samples from 6 stations were utilized. Finally, 57 sediment samples and 26 box cores were analyzed from 57 stations along the Kouchibouguacis and Kouchibouguac rivers, as well as in the adjacent tidal inlets.

Water salinity data from the Fraser River were employed from published studies (Hughes and Ages, 1975; Ages, 1979; Chapman, 1981; Chapman and Brinkhurst, 1981; Kostaschuk and Atwood, 1990). Measurements of water salinity in the Palix River at Willapa Bay are published in Gingras et al. (1999) and Schoengut (2011). Finally, salinity data was collected from the Kouchibouguac area by Hauck et al. (2009) and supplemented by salinity assessments in Patriquin and Butler (1976).

The Palix River and the rivers in Kouchibouguac National Park are effectively homopycnal, such that there is no significant vertical salinity gradient in the shallow channels. By contrast, salinity gradients in the Fraser River distributaries are moderately to highly stratified (Hughes and Ages, 1975; Ages, 1979; Kostaschuk and Atwood, 1990), resulting in a relatively large salinity gradient between the channel bottom and water surface. The salinity profiles in this study are for the upper 3 m of the water column in the Main Channel and North/Middle arms of the Fraser River, as these measurements reflect the component that impacts the infauna inhabiting intertidal channel bars.

4. Results

4.1. Fraser River

4.1.1. Water salinity and sediment grain size distribution

Water salinities throughout the lower Fraser River vary dramatically throughout the year. During high flow periods (the summer freshet during May to August), water in the channels is fresh (0 psu), except