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Unbioturbated sediments on a muddy shelf: Hypoxia or simply reduced oxygen saturation?

Shahin E. Dashtgard [a,*], John W. Snedden [b], James A. MacEachern [a]

[a] Applied Research in Ichnology and Sedimentology (ARISE) Group, Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, British Columbia V5A 1S6, Canada
[b] Institute for Geophysics, The University of Texas at Austin, 10100 Burnet Road, Austin, TX 78558-4445, United States

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ABSTRACT

X-radiographs of sediment box cores acquired from the western Gulf of Mexico reveal limited bioturbation in sediment deposited in bathymetries greater than 35 m. Between 15 and 35 m, sediments are thoroughly bioturbated with averaged bioturbation indices (for all beds in a core) between 2.1 and 5.6, and trace diversities between 2 and 9 distinct burrow forms. Below 35 m water depth, box cores exhibit trace diversities of 1–3, and core-averaged bioturbation indices range between 0.3 and 3.6. There is an overall decrease in trace diversity and bioturbation indices in the offshore direction.

Cross-shore ichnological trends are compared to dissolved oxygen contents of bottom waters. Above 35 m, dissolved oxygen (DO) contents show pronounced variability, ranging from 100% DO saturation through to hypoxia (<2.0 mg l^{-1}), and reflect the periodic introduction of oxygen-depleted waters into otherwise fully oxygen-saturated seawater. Below 35 m, DO content of bottom waters is consistently at 60–75% saturation. DO decreases by an average of 0.117 mg l^{-1} per one-meter increase in water depth, such that bottom waters in 100 m water depth contain an average of 4.55 mg l^{-1} DO.

The data reveal a direct correlation between: a) the density of infauna and the diversity and density of burrows, and b) DO of bottom water. The degree of bioturbation is significantly reduced in waters that are oxic, but below 80% DO saturation. Based on these observations, we suggest that it is inappropriate to link low bioturbation intensities and diversities to hypoxia (<2.0 mg l^{-1}), and by extension, anoxia (0 mg l^{-1}). Instead, reduced oxygen contents (4.3–5.3 mg l^{-1}) that lie well above hypoxic levels have a dramatic impact on the health of infaunal communities, and this is reflected by severe reductions in the ichnological character of sediments.

1. Introduction

Fine-grained sediments deposited near or below storm-wave base are commonly manifested as black mudstones and shales that appear unbioturbated. The paucity of bioturbation in these deposits has been regularly attributed to either hypoxia/anoxia (e.g., Bromley and Ekdale, 1984; Wetzel, 1991; Pemberton, 1992; Uchman and Wetzel, 2011) or to a lack of lithologic contrast that masks pervasive bioturbation (e.g., MacEachern et al., 1999; Gingras et al., 2011; Shank and Plint, 2013). These two contrasting scenarios for explaining the presence of unbioturbated or "under-bioturbated" mudstones deposited in marine environments rely solely upon interpretations of ancient sedimentary strata, and have not been vetted against modern examples. Re-examination of data collected from the muddy, storm-dominated western Gulf of Mexico (GOM) provides an opportunity to evaluate the neoichnological character of a mud-dominated shelf and to compare bioturbation trends to infaunal population distributions and seawater oxygenation. Through this comparison, the dominant control on bioturbation in marine muds is proposed and these data are presented as a possible analog for interpreting unburrowed marine mudstones and shales in the rock record.

Ocean hypoxia occurs when the DO content of seawater drops below either 2.0 mg l^{-1} (Tyson and Pearson, 1991) or 3.0 mg l^{-1} (Ritter and Montagna, 1999), and an ocean basin is considered anoxic when the DO content of seawater drops to 0 mg l^{-1} (Tyson and Pearson, 1991). Once hypoxia is established, benthic communities experience elevated mortality rates (Diaz and Rosenberg, 2008), with the degree and duration of oxygen depletion affecting the magnitude of mortality in the faunal community. In oxic waters, Ritter and Montagna (1999) demonstrated that the abundance and diversity of benthic communities increased exponentially as O_2 concentrations increased from 3.0 to 6.0 mg l^{-1}, and healthy (unstressed) infaunal communities can exist when DO is 80% saturation or higher.

Many black shales appear to be unbioturbated or exhibit bioturbation indices (BI) of 1–2. In more proximal positions, such shales commonly pass into muddy sandstones and sandy mudstones and exhibit burrowing intensities of BI 5–6 (e.g., MacEachern and Pemberton, 1992, 1994; MacEachern et al., 1999; Dashtgard et al., 2008). This

* Corresponding author.
E-mail addresses: sdashtgard@gmail.com (S.E. Dashtgard), jsnedden@ig.utexas.edu (J.W. Snedden), jmaceach@sfu.ca (J.A. MacEachern).

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situation has led to the hypothesis that dark shales must be pervasively bioturbated, but the bioturbation is not apparent owing to a lack lithologic contrast between the burrows and the host media. Most burrows in these fine-grained settings tend to be confined to the sediment–water interface as pascichnia and surface trails, and consist mainly of dark, fecal strings that are not apparent unless the host media contains considerable interstitial silt and/or sand.

Counter to the "lack of contrast" hypothesis is the more widely employed "ocean anoxia" or "hypoxia" hypothesis. Ocean anoxia (DO = 0 mg l^{-1}), or more likely hypoxia (<2.0 mg l^{-1}), is commonly used to explain the high abundance of preserved organic carbon (e.g., Rhoads and Morse, 1971; Rice et al., 1986; Heinrichs and Reeburgh, 1987; Savrda and Bottjer, 1989; Pederson and Calvert, 1990; Calvert et al., 1992; Cowie and Hedges, 1992; Lee, 1992; Wignall and Pickering, 1993; Hedges and Kiel, 1995; Leithold and Dean, 1998) and the paucity of burrowing in black shales (e.g., Bromley and Ekdale, 1984; Savrda and Bottjer, 1987, 1991; Ekdale and Mason, 1988; Föllmi and Grimm, 1990; Savrda, 1992, 2007; Diaz and Rosenberg, 1995). Ideally, such an interpretation should be confirmed by using geochemical or other datasets (e.g., Tyson and Pearson, 1991; Wignall, 1991; Wignall and Hallam, 1991; Schieber, 2003; Martin, 2004) as independent lines of evidence. Unfortunately, many workers appeal to anoxia to explain the paucity of burrowing in black shales without evaluating ancillary data (cf. Schieber, 2003; Martin, 2004 for summaries), and anoxia may not occur in these settings. Work by MacEachern et al. (1999) on the apparently unburrowed marine shale of the Lower Cretaceous Westgate Fm of Alberta, Canada showed that benthic foraminferal suites were of high diversity and high abundance, indicating that the seawaters were not anoxic.

1.1. Study area and methods

The study area lies in the western GOM, adjacent to Corpus Christi, Texas, USA (Fig. 1). A second dataset is derived from core and ichnological data published by Hill (1985) from core sites that are adjacent to and overlap with the main study area. Water depths (WD) range from intertidal to 180 m, although samples were acquired between 10 and 140 m WD only. Tides are microtidal (0.3–0.5 m range), and the area is subjected to intermittent hurricanes (Hayes, 1967; Snedden et al., 1988; Snedden and Nummedal, 1991).

Twenty-two box cores were acquired in 1984–85, and x-radiographs were taken from all box cores (Fig. 2; Snedden, 1985). The box corer is 20 cm by 30 cm by 60 cm (depth: width: length) and the resulting x-radiographs are 10 to 50 cm long by 25 cm wide. To

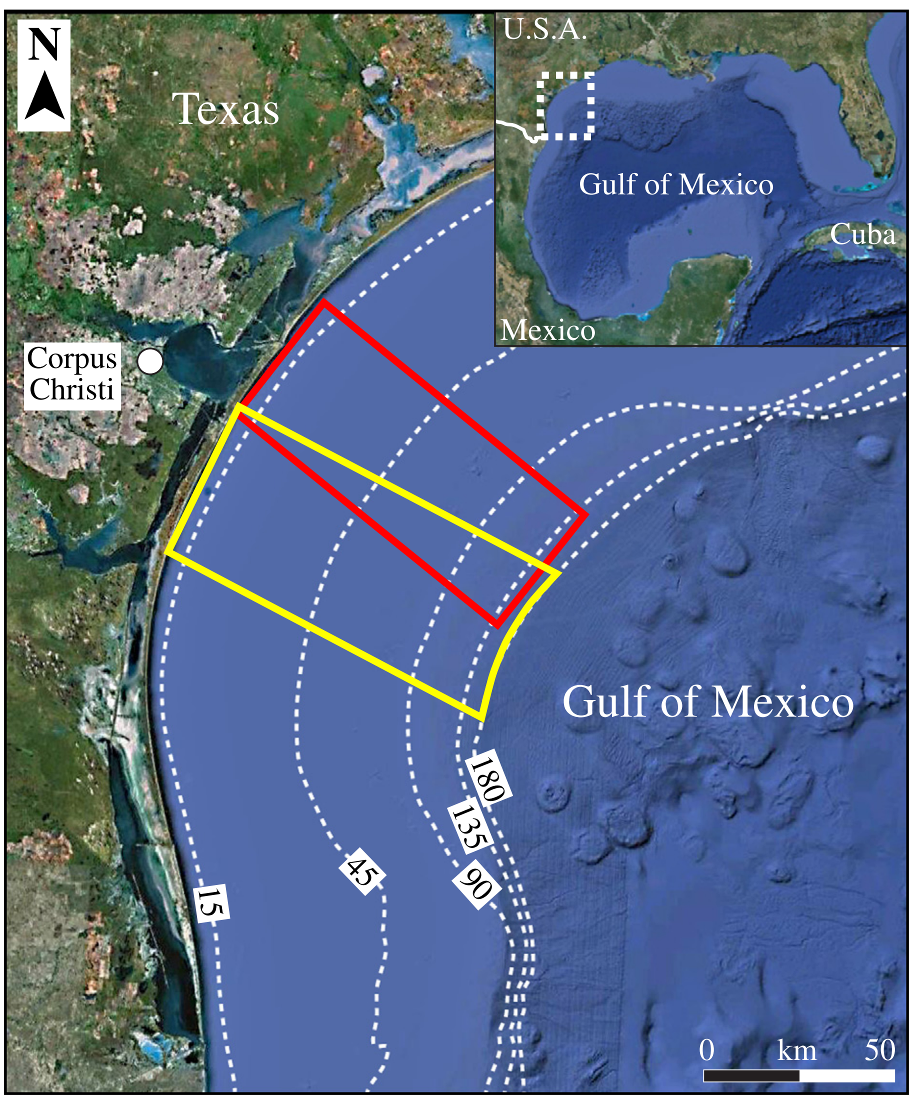

Fig. 1. Location map of the study area (red box) and of the data derived from Hill (1985) (yellow box). Contour lines are in metres.
Image source: Google Earth.