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Volumetric budget calculation of sediment and carbon storage and export for a late Holocene mid-shelf mudbelt system (NW Iberia)

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ABSTRACT

Confined fine-grained depoenters (mudbelts) on continental shelves play an important role as common and major fluviogenic submarine depocenters along the source-to-sink pathway and in global sedimentary and carbon cycles. This study provides a complete high-resolution isopach-based budget analysis using closely-spaced, high-resolution seismic-reflection data of an exemplary mid-shelf mudbelt system located on the open and narrow continental shelf of NW Iberia.

The budget analysis reveals that 3.957–4.227 km^3 of sediments [i.e., 4073 to 4351 Mt (dry)] are stored in this depocenter. In conjunction with river-discharge estimates, we calculate that, over the past 5300 yr, approximately 34% to 36% of total fluvial sediments supplied to the ocean remain in the shelfal mud depocenter and the balance bypasses the shelf. Total accumulation values for TOC and $CaCO_3$ amount to 40.31 to 43.46 t and 174.73 to 186.68 Mt, respectively. High-resolution isopach analysis shows high regional morphodynamic variability of the main sediment transit routes, an aspect easily overlooked by core-based or low-resolution profiling studies. The budget analysis reveals persistent low accumulation over the past 5300 yr and thus clarifies that a uniformitarian view of applying modern accumulation rates to the late Holocene can significantly underestimate effective sediment off-shelf transport.

1. Introduction

In the study of source-to-sink systems, continental shelves play a major role because they host permanent and temporary depocenters. These depocenters occupy a pivotal position within the entire source-to-sink system, which consists of multiple, genetically linked segments (coastal lowlands, shelf, slope, and deep ocean basin) (Moore, 1969). Consequently, erosion or deposition in one part of the system leads to sediment-storage modifications within the adjacent segment. Because continental shelf systems vary greatly in tectonic setting, local physiography, hydrodynamic conditions, and sediment supply (type, volume, and place of input), among other factors, a general understanding must be based on numerous system-specific studies. Many of the involved processes—ranging from sediment delivery to gravity flows—that give a shelf its morphological character have been documented for narrow active continental margins and wide passive continental margins with high sediment input from rivers (Nittrouer et al., 2007; Gerber et al., 2010). The current study presents the sedimentary budget of a typical narrow passive continental shelf having low sediment input from rivers and a globally representative mud depocenter.

On modern storm- and wave-dominated siliciclastic continental shelves, mud depocenters ("mudbelts") are common depositional elements that represent the most proximal main sinks for fluviogenic material supplied to the ocean. The individual development of a mud depocenter depends on a focused sediment supply and the specific hydrographic conditions interacting with the local morphology (McCave, 1972; McKee et al., 2004; Nittrouer et al., 2007). As is true globally for most mid-shelf mudbelts, the NW Iberian mudbelt is due to sedimentary buildup resulting from post-glacial shelf drowning caused by Holocene transgression and the subsequent sea-level highstand (stabilization) that results in today's relatively weak hydrodynamic conditions (e.g., Grossman et al., 2006). More specifically Nittrouer and Sternberg (1981) have shown that sediment deposition on a narrow high energy shelf is most effective when peak river flow and maximum oceanic dispersal are out of phase.

Sediment transport on the shelf is controlled by a number of autogenic and allogenic factors such as sediment concentration, morphology (e.g., width and gradient), wave regime, wind climate (e.g., direction, frequency and intensity), and tidal and alongshore currents (Nittrouer and Wright, 1994; Sánchez-Arcilla and Simpson, 2002). These factors vary laterally, so mud deposition and remobilization within a shelf environment also vary (e.g. Spinelli and Field, 2003). Budgetary calculations for sedimentary deposition on shelves that employ high-density data grids and isopach analysis (e.g., Eittreim et al., 2002; Brommer et al., 2009; Miller

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and Kuehl, 2010; Gerber et al., 2010) have drastically reduced the error range of accumulation rates and depocenter volumes when compared to estimates based on only a few seismic lines and selected cores. In contrast to the common two-dimensional representation of shelf morphology, high-resolution three-dimensional isopach analysis reveals in much more detail the dynamic interactions among local basement morphology, hydrographic regime, and sediment availability. The current study presents a detailed sediment budget for the NW Iberian mudbelt that is developed from a high-resolution isopach map based on closely-spaced high-resolution seismic-reflection data, in conjunction with sediment-porosity, -density and -grain-size data.

1.1. Regional setting

The NW Iberian shelf is relatively narrow, ranging in width from 30 km in the north to 40 km off the Minho River mouth to the south (Fig. 1). The shelf break occurs at 160–180 m water depth. The mid-shelf region, at water depths of 100–140 m, hosts the NW Iberian mudbelt. Fine sands with a minimum mud content of $>25\%$ at the mudbelt′s margins transition to a mud content of $>90\%$ at its center (Fig. 2b; Dias et al., 2002a; Lantzsch et al., 2009). The mudbelt onlaps plutonic and metamorphic outcrops on the inner shelf and downlaps onto well-sorted fine sands on the outer shelf (Ray Salgado, 1993; Dias et al., 2002a; Oliveira et al., 2002; Vitorino et al., 2002a; Lantzsch et al., 2009). Upper Cretaceous to Pleistocene limestone and sandstone, barren of sediments, crop out on the outer shelf south of 42°00′N (Fig. 2a). The NW Iberian mudbelt can be morphologically subdivided according to the nomenclature of Lantzsch et al. (2009) into three distinct regional sectors: the Douro Mud Patch (DMP) located south of the River Lima and west of the River Douro [see Figs. 1 (inset) and 2c]; the Galician Mudbelt (GMB), which lies approximately between the Ría de Arosa and the Minho River mouths; and the Muros Mud Patch (MMP) northwest of the Ría de Muros (Fig. 2a).

1.2. Sediment input

In recent years, several papers have been published on the origin, dispersal pathways, and deposition of fine-grained sediments along the modern NW Iberian continental shelf (Dias et al., 2002a; Araújo et al., 2002; Vitorino et al., 2002a, 2002b; Jouanneau et al., 2002; Martins et al., 2007; Lantzsch et al., 2010). River discharge along the relatively linear Portuguese coastline enters the shelf predominantly through the Minho and Lima estuaries (Fig. 1) and, further south through the Douro estuary (Fig. 2c). In contrast, in the northern Spanish part of the study area, four deep rías (the Muros, Arosa, Pontevedra, and Vigo) enter the ocean by cutting deeply into the rugged and irregular coastline. They represent the drowned remains of Tertiary river valleys (Oliveira et al., 2002; Ray Salgado, 1993). Today, multiple rivers flow into each of the four rías. The Douro (length 927 km; catchment area 95,682 km^2) and the Minho (length 300 km; catchment area 17,081 km^2) are the largest river basins in the region (Araújo et al., 2002; Dias et al., 2002a) (Fig. 1).

For the Galician rías, most of the sediment being discharged by rivers is assumed to be trapped inside the rías, resulting in negligible export to the shelf (Jouanneau et al., 2002; Ray Salgado, 1993). The total annual sediment supply from all of the above-mentioned rivers to the shelf is estimated at 2.25×10^6 t. Available sediment input data are derived from theoretical calculations using catchment size and meteorological records (Oliviera et al., 1982; Dias et al., 2002a). The result represents a pre-dam building scenario and is the best available sediment input estimate for the late Holocene.

Prior to multiple dam constructions the Douro alone contributed approximately 79% of all sediment reaching the NW Iberian continental shelf (Dias et al., 2002a). Sediment input from the Douro occurs in a pulsed manner with average discharge rates changing by a factor of 5 between summer and winter months (Morán-Tejeda et al., 2011) and daily fluctuations changing up to 10 fold during rain storms (Chełmicki and Siwek, 2009). The highest depositional rates for the late Holocene in the entire region are recorded off the Douro estuary in the southern sector (Fig. 2c), (Drago et al., 1998; Jouanneau et al., 2002).

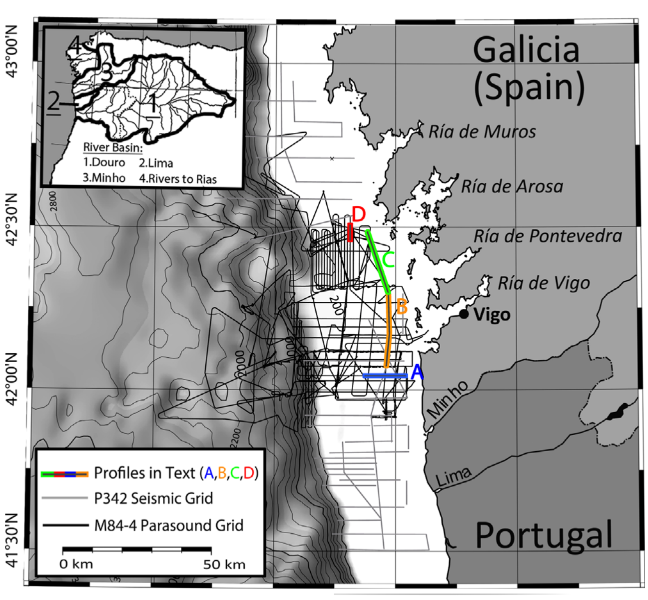

Fig. 1. NW Iberian sediment-acoustic profile locations. Highlighted in color are the locations of the profiles presented in the text (A–D). The map inset shows the major river basins running into to study area.

1.3. Oceanographic and depositional regime

The NW Iberian shelf is exposed in the northwest to high-energy swells from the North Atlantic; farther south, the regime is dominated by lower-energy southwest- to southeast-moving swells. A strong seasonal contrast occurs between winter and summer hydrographic regimes (Pérez et al., 2001; Dias et al., 2002a; Martins et al., 2002, 2012). The fast (13.5 ± 5.7 cm/s) northward-flowing Iberian Poleward Current (IPC) (Incarbona et al., 2010) dominates during fall, winter, and spring (Martins et al., 2002, 2012; Pérez et al., 2001), favoring occasional coastal downwelling (Frouin and Ambar, 1990; Álvarez-Salgado et al., 2003). Whether a weaker poleward flow is maintained throughout the summer season remains a subject of debate (Coelho et al., 2002; Colas, 2003; Peliz et al., 2005; Relvas et al., 2007). Increased near-bottom wave-orbital velocities caused by the frequent winter storms can lead to sediment remobilization and northward long-shore transport by currents (Vitorino et al., 2002b) that eventually deposit the sedimentary load in the mid-shelf mudbelt depocenter (Jouanneau et al., 2002). Data from a current meter mooring located at 41°25′N on the 85-m isobath revealed poleward currents with intensities of 0.10–0.15 m s^{-1} and in some cases exceeding 0.2 m s^{-1} (Vitorino et al., 2002a). Consistent northward velocities of 0.2–0.3 m s^{-1} are also reported by Haynes and Barton (1990), Vitorino et al. (2002a), and Torres and Barton (2007) for the northern part of the western Iberian shelf outside the upwelling season. By contrast, during the late-spring and summer months, lower-energy conditions prevail, punctuated by occasional wind-driven upwelling, a southerly-directed along-shelf current, and flow rates of 0.05–0.15 m s^{-1} (Coelho et al., 2002; Huthnance et al., 2002). There is no known significant cross-shelf