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Determination of grain-size characteristics from electromagnetic seabed mapping data: A NW Iberian shelf study

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ABSTRACT

The electric conductivity and magnetic susceptibility of sediments are fundamental parameters in environmental geophysics. Both can be derived from marine electromagnetic profiling, a novel, fast and non-invasive seafloor mapping technique. Here we present statistical evidence that electric conductivity and magnetic susceptibility can help to determine physical grain-size characteristics (size, sorting and mud content) of marine surficial sediments. Electromagnetic data acquired with the bottom-towed electromagnetic profiler MARUM NERIDIS III were analysed and compared with grain size data from 33 samples across the NW Iberian continental shelf. A negative correlation between mean grain size and conductivity (R=−0.79) as well as mean grain size and susceptibility (R=−0.78) was found. Simple and multiple linear regression analyses were carried out to predict mean grain size, mud content and the standard deviation of the grain-size distribution from conductivity and susceptibility. The comparison of both methods showed that multiple linear regression models predict the grain-size distribution characteristics better than the simple models. This exemplary study demonstrates that electromagnetic benthic profiling is capable to estimate mean grain size, sorting and mud content of marine surficial sediments at a very high significance level. Transfer functions can be calibrated using grains-size data from a few reference samples and extrapolated along shelf-wide survey lines. This study suggests that electromagnetic benthic profiling should play a larger role for coastal zone management, seafloor contamination and sediment provenance studies in worldwide continental shelf systems.

1. Introduction

Estimation of grain-size distribution is fundamental for understanding the composition, distribution and dynamics of coastal and continental shelf sediments. Conventionally, grain size is determined by taking and analysing sediment samples, which is time consuming, expensive and limited in spatial coverage. To reduce the number of sediment samples the development of remote techniques to predict grain-size characteristics is vital.

A novel promising technique for marine sediment characterisation is an electromagnetic (EM) profiling method introduced by Müller et al. (2012). In contrast to traditional marine EM methods (e.g Cheesman et al., 1990; Evans, 2001) it provides not only information about the electric conductivity but also about magnetic susceptibility. Both parameters offer complementary information about seafloor sediments:

In marine environments, the electric conductivity of sediment grains is generally negligible compared to the conductive saltwater in the pore space. Under such conditions, sediment electric conductivity can be considered as a function of pore-water content and tortuosity. In fully water-saturated sediments the water content corresponds to porosity. The conductivity-porosity relationship has been investigated for many years. Several empirical or semi-empirical formulas have been developed to describe this relation. The most common one is Archie's law (Archie, 1942), given by $\sigma_s = a{\cdot}\sigma_w{\cdot}\Phi^m$, where σ_s and σ_w are the electric conductivity of the sediment and the water, respectively, Φ is the porosity. Factor a and exponent m account for permeability and compaction of the sediment and need to be empirically determined. Müller et al. (2012) estimated porosity from EM conductivity for NW Iberian shelf sediments using Archie's law (with m=1.6 and a=1) and showed that the so-derived porosity is in good agreement with values determined from weight loss during the drying of core samples. The porosity itself depends on the sediment's closeness of packing, which is controlled by shape, compaction and sorting of the sediment particles (Rogers and Head, 1961) and is hence related to the grain-size distribution.

The magnetic susceptibility of water (-9×10^{-6}) is very small compared to that of sediment grains (typically between $10^1{\times}10^{-6}$ and $10^4{\times}10^{-6}$ for clastic marine sediments). Consequently, susceptibility is

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mainly controlled by the mineralogical composition of the sediment. Magnetic properties prove to correlate with grain size in many different environments and have been used as particle size proxy (e.g Oldfield et al., 1985; Booth et al., 2005). In particular, ferrimagnetic iron minerals enrich in the fine fraction of marine sediments due to their usually fine crystal size in their magmatic parent rocks and can hence be used as a proxy for terrigenous mud content (Müller et al., 2012).

The above cited studies suggest that electric conductivity and magnetic susceptibility are suitable particle size proxies. Furthermore, Müller et al. (2011), Müller et al. (2012) and Baasch et al. (2015) showed that the joint interpretation of conductivity and susceptibility derived from EM profiling data can be used to identify lithofacies units and their transitions. However, no studies exist that combine electric conductivity and magnetic susceptibility data to quantify textural sediment properties, neither on land nor in marine environments. This study aims to prove that this is feasible and thus EM profiling is a suitable tool for insitu grain-size determination. For this purpose, we investigate the relationship of EM and grain-size properties by linear regression analyses between EM profiling data and surface samples collected at 33 different locations across the NW Iberian continental shelf. Three different statistical attributes are used to describe the grain-size distribution, namely mean grain size, mud content and the standard deviation of the grain-size distribution as a measure of sediment sorting.

1.1. Study area

The NW Iberian continental shelf extends over a 200-km-long and 30–50-km-wide area between Cape Finisterre (43°N) and the Douro River mouth (41°N). It is a typical example of a low accumulation non-glaciated clastic shelf system (Lantzsch et al., 2009a, 2009b) seasonally exposed to high-energetic hydrodynamic conditions (Oberle et al., 2014b). Sediment transport and distribution of fine-grained fluviogenic sediments are controlled by winter storms, longshore currents and the geomorphology of the shelf. Additionally, anthropogenic activities, in particular bottom trawling and dredging (Oberle et al., 2016a, 2016b), influence the sediment distribution on the NW Iberian shelf. Detailed descriptions of the general sedimentary setting can be found in e.g. Dias et al. (2002), Corredeira et al. (2009) and Lantzsch et al. (2010). One of the most prominent sediment features is a coast-parallel, 50-km-long and 2–3-km-wide mid-shelf mud depocentre (Dias et al., 2002). This so called ‘Galicia Mud Belt’ (Lantzsch et al., 2009b) was formed by resuspended fine material originating from fluvial sediment input mainly from the Douro River. Recent studies suggest that 60 per cent of this fluvial material have been transported off-shelf (Oberle et al., 2014a). Lantzsch et al. (2010) described three facies classes, a mixed-sand facies, a glaucony-sand facies and a mud facies. The spatial distribution of these sediment facies is shown in Fig. 1. The mixed-sand facies consists mainly of carbonate microfossil fragments, quartz and mica (Lantzsch et al., 2010). The glaucony-sand facies is characterized by a high amount of up to 50 per cent paramagnetic glaucony (Odin and Lamboy, 1988) and the mud facies has a high amount of mud (silt and clay) of up to 90 per cent at the centre of the Galicia Mud Belt. Acoustic and electromagnetic measurements showed that these main sediment facies merge in complex transition zones characterized by morphologically driven and selective sediment transport (Baasch et al., 2015). It is due to these different sediment types, compositions and origins that this study area offers an adequate variety of sediments to test the relationship of EM data and grain size under different environmental conditions.

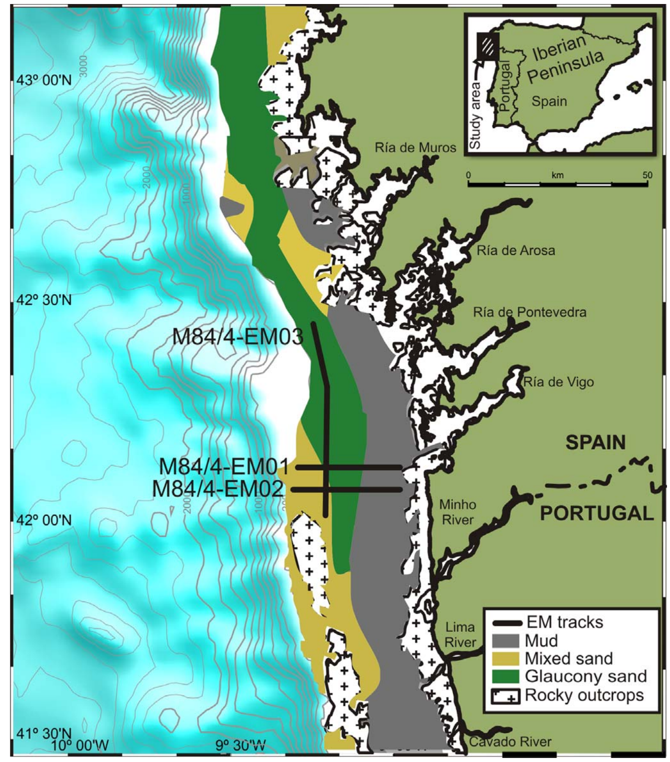

Fig. 1. NW Iberian shelf. Colours indicate sediment facies, black lines indicate EM profiles from RV Meteor cruise M84/4b. Modified from Lantzsch et al. (2010)

2. Materials and methods

2.1. Grain-size analysis

Sediment samples were taken at 105 different locations across the NW Iberian shelf during the Meteor cruise M84/4 (Hanebuth et al., 2012). 33 of these locations fall directly onto the three here presented EM profiles. A Rumohr corer (100-cm-long gravity corer), a grab sampler and a box corer were used for the sampling. The recovered cores had lengths between 10 cm and 70 cm depending on the coring device and sediment texture. Grain-size analyses were carried out with a Coulter LS 200 laser particle sizer at 10- to 20-cm depth intervals based on visual inspection. The volume distribution was divided in 92 logarithmically spaced size classes ranging from 0.39 to 2000 μm. No particles larger than 2 mm (gravel) were present. Geometric mean grain size, geometric standard deviation and mud (clay and silt) content were determined from the grain-size distribution and used to investigate the relationship between grain size and electromagnetic data. Mean grain size and standard deviation were converted into ϕ (phi) scale using the equations $\phi = \log_2([\textit{mean grain size in } \mu\text{m}]/1000)$ and $\delta\phi = \log_2([\textit{standard deviation in } \mu\text{m}])$, respectively. Note that here ϕ has an opposite sign compared to the standard inverted ϕ-scale (Wentworth, 1922). Hence, a positive correlation with mean grain size means an increase of the respective variable with increasing mean grain size. The arithmetic mean for each statistical value was calculated from all samples at each location and used as representative value for the respective sample location. Each of these locations was assigned to one of the three sediment facies defined by Lantzsch et al. (2010). Note, that this classification is solely based on the sample location and not on sedimentological analyses. We therefore speak of Mud Area, Glaucony Sand Area and Mixed Sand Area to denominate the three sample groups according to the facies names in Lantzsch et al. (2010). Table 1 summarises the average grain-size distribution characteristics for the different shelf areas.

2.2. Marine electromagnetic profiling

The principles of marine EM profiling are described by Müller et al. (2012), Baasch et al. (2015) and will only be briefly dealt with in this paper. Here we use an EM data set which has been collected along three profiles across the NW Iberian shelf partially published by Baasch

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