The Meaning of Heavy Minerals in the Recent Sedimentary Record of the Douro Estuary (Portugal)

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ABSTRACT


The relative abundance of the different heavy mineral species may be used as a tool to deduce the provenance signal of the sediment and the dominant transport mode that occurred just prior to sedimentation. In this work, the sedimentary infilling of the Douro estuary was analysed using Principal Components Analysis (PCA) in order to characterize the sedimentary sequence over the past 14 000 years. Three cores were obtained by rotary drilling in this estuary and several samples were collected. Heavy minerals were separated using SPT (sodium poly-tungstate); different species were identified and the non-opaque minerals were counted. The mineralogical composition of the fines was analysed by X-ray diffraction (CuK radiation) on random-oriented powder samples. A simple relation was obtained: the finer sediment levels are less mature and the heavy mineral assemblage, transported mainly as suspended load, is composed by minerals with platy and lamellar forms. Levels with coarser sediment have a high maturity index and much rounder, denser heavy minerals transported as bedload. In the lower levels it is detected a high abundance of euhedral heavy minerals assemblages reflecting the provenance signal of the granite and gneissic bedrock. With this information we can determine episodes where the fluvial influence was stronger and where a marked marine influence was sensed. The first episodes are represented by the finer levels and the marine influence is testified by the coarser levels.

INTRODUCTION

Heavy minerals have long been used as a tool to interpret sedimentary deposits. Generally, they are used in determining provenance, tracing transport paths, mapping dispersal patterns, depicting the action of hydraulic regimes and selection processes, locating potential economic deposits and understanding diagenetic processes (KOMAR and HALLSWORTH, 1999). In the present work, heavy mineral analysis is applied as a contributor to the interpreting of recent sedimentary infilling of the Douro estuary (Portugal), along with other mineralogical and sedimentological attributes.

For this purpose, data were obtained within the “Envi- changes” project, whose main objective is to outline an evolutionary model for this estuary since 14000 BP (DRAKO et al., 2002).

The Douro estuary is located in the northern Portuguese coast, south of Porto. This narrow funnelled estuary is partly barred by a sand barrier (Cabedelo) that develops from the south and shelters the S.Paio Bay (DRAKO et al., 2002).

Three cores were obtained by rotary drilling in this estuary: Core 1 (+3.5/-4.4m depth), 1B (-6.6/-16.2m depth) and 2 (-15.16/-39.66m depth) (Fig. 1). These cores can be considered as being representative of the continuous sedimentary sequence present in the southern margin of Douro estuary (DRAKO et al., 2002).

METHODS

The study of the heavy minerals was carried out in a total of 90 samples in three grain-size classes, medium (Φ1-2), fine (Φ2-3) and very fine (Φ3-4) sand, in the rich levels of each of the three cores that represent the sedimentary infilling.

The acquisition of heavy mineral data involved the following laboratory procedure: a) the samples were washed, oven dried at 70° and sieved at 1 interval in order to obtain the entire grain size sand distribution and its respective parameters; b) light and heavy minerals from the referred grain-size classes were separated using sodium poly-tungstate (density 2.82g/cm³) (CALLAHI, 1987); c) heavy minerals from each fraction were mounted on microscope slides in Canada balsam; d) three hundred mineral grains were counted in each slide and the non-opaque minerals were identified, analyzed by X-ray diffraction (CuK radiation) on random-oriented powder samples. A simple relation was obtained: the finer sediment levels are less mature and the heavy mineral assemblage, transported mainly as suspended load, is composed by minerals with platy and lamellar forms. Levels with coarser sediment have a high mineralogical composition of the fines was analysed by X-ray diffraction (CuK radiation) on random-oriented powder samples. A simple relation was obtained: the finer sediment levels are less mature and the heavy mineral assemblage, transported mainly as suspended load, is composed by minerals with platy and lamellar forms. Levels with coarser sediment have a high maturity index and much rounder, denser heavy minerals transported as bedload. In the lower levels it is detected a high abundance of euhedral heavy minerals assemblages reflecting the provenance signal of the granite and gneissic bedrock. With this information we can determine episodes where the fluvial influence was stronger and where a marked marine influence was sensed. The first episodes are represented by the finer levels and the marine influence is testified by the coarser levels.

ADDITIONAL INDEX WORDS: PCA, selection processes, sediment maturity

Figure 1. Core location (adapted from DRAKO et al., 2002).
RESULTS

Sedimentary Units

The sedimentological, geochemical and palaeoecological study of Core 1, 1B and 2 reveal the existence of four sedimentary units referred by DRAGO et al. (2002) as SED1, SED2, SED3 and SED4 (Figure 2).

The sedimentary sequence begins with a slightly muddy sand sequence - SED1 (according to Flemming, 2000) sediment classification. It is comprised between 13750 and 10310 BP, and it has a continental signature. SED1 is followed by succession of slightly sandy mud, sandy mud and muddy sand sediments (core 2) and an alternated succession of sandy mud and muddy sand interbedded layers (core 1) - SED2, comprised between 10310 and 5780 BP. This unit is present in both cores 2 and 1B. The lower section of this unit represents a low saline estuarine environment with intensification of marine influence towards the top (DRAGO et al., 2002). The third unit (SED3), deposited after 5750 BP, is a gravel layer, which was probably deposited under a climate of torrential rains favouring the coarse clastic supply. The morphometric study of the gravel components suggests fluvial transport and a littoral reworking, this unit being interpreted as a shingle barrier (DRAGO et al., 2002).

The last unit (SED 4), deposited from 1600 BP till present, consists of sands with few interbedded mud represented essentially at the bottom and top of this unit. Micropaleontological data, obtained in the finer levels of this unit, suggests a brackish intertidal environment with low salinity that rapidly acquired fluvial and/or subaerial characteristics towards the top (DRAGO et al., 2002). This unit appears on the top of core 1 and 2.

Heavy Mineral Data

The mean percentage of each heavy mineral species along the different sedimentary unit is represented in Table 1.

In the lower levels of SED 1, the heavy mineral suite is dominated by biotite (20%), andalusite (27%) and apatite (6%), with euhedral forms, reflecting the presence of the bedrock (granites and gneisses). Opaque minerals correspond to 44% and all other species range between 0.1 and 3% (Table 1). In the medium and upper levels, the heavy mineral suites are essentially composed by biotite (40%), amphibole (12%) and andalusite (6%) with platy and lamellar forms. Tourmaline and garnet appear both with contents of 3% (Table 1). The other minerals occur in negligible amounts ranging between 0.2 and 1.7% except for opaque minerals (32%).

The SED 2 heavy mineral assemblage is dominated by biotite (45%), amphibole (10%) and andalusite (4%). Tourmaline and garnet contents are 3% and the other minerals range between 0.2 and 1.6% (Table 1). The levels with high content of biotite (> 50%) match the muddy sand/sandy mud sequences in these cores.

In SED 3, heavy minerals appear only in Core 2 (less coarse). The heavy suite is mainly composed by lamellar and platy minerals such as biotite (49%) and amphibole (7%) and by rounded, spherical and ellipsoidal grains such as garnet (3%), andalusite (6%) with platy and lamellar forms. Tourmaline and garnet appear both with contents of 3% (Table 1). The other non-opaque minerals range between 0.1 and 3% (Table 1). In the upper levels of Core 1 and 2, the heavy mineral suite is composed by biotite (32%), amphibole (18%) and andalusite (5%) (Table 1). The other non-opaque minerals range between 0.1 and 1.7%.

The distinct heavy mineral suites that characterize the upper levels of Core 1 and 2 can be used to define a sub-unit classified as SED 4a. This sub-unit is included in the SED 4 defined by DRAGO et al. (2003) and is represented in the top of Core 2 and in a small part of Core 1 (Figure 2). The heavy mineral suite is composed by rounded grains of garnet (15%), andalusite (13%), tourmaline (8%) and staurolite (5%) (Table 1). Biotite (13%) and amphibole (5%) have platy and lamellar forms. These particles are included in medium to coarse sand levels and micropaleontological analysis could be made in this unit (SED 4a).

Finer Sediment

The mineralogical analysis of the <63 µm fraction shows the
predominance of the detrital minerals, such as quartz, feldspars and phyllosilicates (mainly micas), followed by a group of accessory minerals that includes calcite, dolomite, opal C/CT and pyrite. Some layers contain anhydrite, zeolites (mainly, clinoptilolite/heulandite), siderite and hematite. The four defined sedimentary units show different composition (Figure 2), by the evolution of the three selected mineralogical ratios:

In the lower levels of SED 1 and SED 2 of Core 1B the bedrock signature is detected in the finer grain-sizes by high feldspar content (namely 26% and 16% in average).

SED 4a and SED3 have the higher M.I., higher CM/DM, lower FD/CD (Table 2) and higher content in quartz. SED1, SED 2 and SED 4 reveal high content in mica (>5%) and the muddy sand/sandy mud sequences of these units have the highest content in mica (<10%). The FD/CD index evolution along the cores is similar to the mica content. Levels with finer sediment have higher mica percentage.

In the upper levels of Core 2 the fine sediment reveals a high average M.I. value of 5 in SED 4a and of 9 in SED 3. In SED 3 of Core 1, M.I. is equal to 4.

**Principal Component Analysis (PCA)**

When applying the “varimax normalized” rotation to the data correlation matrix used for the first PCA approach, 5 components were obtained explaining almost 70% of the data variance (Figure 3A). The first and fourth components show a strong correspondence between the platy and lamellar minerals such as biotite and amphibole with the very fine sand (φ3-4), silt and clay fractions.

On the contrary, the more equant grains such as garnet, tourmaline and staurolite are correlated with the coarser fractions (φ-1 to 2).

The second component represents the opposition between fine (φ1 to >4) and coarse sediment (φ-1 to 0), all other variables being weighted near zero.

The third component reflects the differences between mineral densities. Opaque minerals, zircon, monazite and the non identified minerals (most of them iron coated) are in the denser group and are related with fine and coarse sand. Component 5 relates apatite with sillimanite probably due to their tabular and euhedral form.
In the second PCA approach (Figure 3B), the selected first 5 components explain almost 70% of the data variance. Component 1 relates the rounded minerals with medium sand (1-2), in opposition with the angular and sub-angular/sub-rounded minerals which are correlated to the finer fractions (2-3). The second component again shows the differences between coarse and fine sediments. The third component reflects the opposition between angular and sub rounded and rounded minerals. Component 4 and 5 are very similar. They relate the coarse sand with the rounded minerals and the M.I., in opposition to fine sand that is related to angular minerals.

**DISCUSSION**

Differences in sediment grain-sizes, the importance of which is readily seen from the use of the PCA analysis, can be used as a tool to understand the sedimentary processes. There is a strong opposition between coarse to medium sand (φ<1 to 2) and fine sand to clay (φ>2 to >4). The grain size of sediment is closely related with the frequency of the mineral species.

In levels with finer sand, sandy mud and muddy sand (high FD/CD) the sediment is less mature (M.I. range between 3 and 4). The heavy mineral assemblage of these levels is composed by the less dense species, with platy and lamellar forms. The heavy minerals mean grain size is closer to the mean grain size of the entire sediment suggesting, suspended load transport (FRADIQUE and CASCALHO, 2003). According to DRAGO et al. (2002), these levels represent a brackish environment of low salinity with fluvial signature. Levels with medium to coarse sand have high M.I., low FD/CD index and much rounder, denser heavy minerals (such as garnet, zircon, tourmaline, andalusite, monazite and staurolite). The mean grain sizes of these minerals tend to be smaller than the mean grain-size of the total sediment, which may reflect bedload transport conditions (FRADIQUE and CASCALHO, 2003). These are the levels with the lowest terrigenous influence and high CM/DM as in SED4a and SED3 suggesting fluvial transport with littoral reworking.

In PCA (component 5, first approach) we can observe a high correlation between apatite, sillimanite (both euhedral) and medium to coarse sand fraction. The fine sediment analysis
reveals a high percentage of feldspars (lower levels of SED 1). The proximity of the bedrock, namely granites and gneisses, is responsible for these sediment characteristics.

CONCLUSIONS

The present work allowed the determination of different environments using sediment grain size and composition, both of the coarse and of the fine fractions, as well as the shape of the grains. Episodes of stronger fluvial influence (represented by the muddy sand-sandy mud levels) and of intensified marine influence (testified by the coarser levels with rounded and denser minerals) were identified. Such episodes can also be deduced from the mineralogical indexes that were computed.

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