PEDRO FERRARA PIRES DA ROCHA

CHARACTERIZATION OF THE SEDIMENTARY DEPOSIT OF THE COSTA DA CAPARICA INNER SHELF AS A TOOL TO SUPPORT COASTAL MANAGEMENT

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Master in Marine and Coastal Systems

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2020

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CHARACTERIZATION OF THE SEDIMENTARY DEPOSIT OF THE COSTA DA CAPARICA INNER SHELF AS A TOOL TO SUPPORT COASTAL MANAGEMENT.

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X___________________________

Pedro Ferrara Pires da Rocha

Faro, 30th of September, 2020

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Abstract:

Currently 60% of the global population is concentrated in the coastal zone and 75% of the coast is dominated by sandy beaches, thus, the susceptibility of these environments to anthropogenic impact as coastal erosion increases is unquestionable. One common and effective measure for minimizing beach erosion, which has global appeal, is artificial sand nourishment. However, locating a good sediment borrow area especially inland, has become very difficult. Offshore sediments are identified as a good solution. Hence, this study had the objective to do the characterization and definition of sedimentary units of 12 cores (3 meters long each) located between the water depths of 21 m to 27 m of the offshore borrow area of Costa da Caparica, aiming to be used for beach nourishment. Mean grain-size, carbonate content, kurtosis, sorting, skewness and the textural composition are used to characterize and define the sedimentary units of each core. The 3 meters length cores were analyzed with a resolution of 25 cm. A multivariate statistical (PERMANOVA, MDS, Cluster, SIMPER and PCA) approach was used to support the definition of the sedimentary units. The results showed four different sedimentary units. The Unit 1 characterized by medium and fine sand, the Unit 2 by coarse sand, the Unit 3 by fine sand and the Unit 4 by fine and medium sand. Unit 2 is the most observed unit, followed by the units 1, 3 and 4. The PERMANOVA showed significant difference ($p < 0,05$) between the sedimentary units corroborating with the units definition. The PCA showed correlation to medium and coarse sand with the Units 1, 2 and 4 and to fine sand with the Unit 3. The borrow area shows 3 compatible sedimentary Units, the Unit 1, 2 and 4 which can be used in future nourishment projects in Costa da Caparica.

Key-Words: Beach Nourishment. Borrow Areas. Continental Shelf. Sedimentary Units. Multivariate Statistical Analysis. Portugal.

Resumo:

Atualmente 60% da população global está concentrada nas zonas costeiras e as praias arenosas representam 75% do ecossistema costeiro. Face à crescente ocupação urbana na zona costeira os impactos antrópicos nessas áreas como a atuação da erosão é inquestionável. Uma das abordagens globalmente utilizada para mitigar os impactos da erosão costeira é a alimentação artificial de praias. Entretanto as manchas de empréstimo continentais estão cada vez mais escassas e o sedimento da plataforma continental é pontuado como uma solução. O presente estudo teve como objetivo caracterizar e definir as unidades sedimentares da mancha de empréstimo da Costa da Caparica, localizada na plataforma continental interna de Portugal, com o intuito da utilização futura desse sedimento em projetos de alimentação artificial de praia. A concentração de carbonatos, média granulométrica, curtose, assimetria, calibragem do sedimento e percentagens das diferentes classes texturais foram utilizadas para caracterizar e definir as unidades sedimentares de cada testemunho. Os 12 testemunhos de 3 metros de comprimento cada, foram analisados com resolução de 25 cm. Para apoiar a definição das unidades sedimentares foi utilizada uma abordagem estatística multivariada (PERMANOVA, MDS, Cluster, SIMPER e PCA). Os resultados mostraram quatro unidades sedimentares. A Unidade 1, caracterizada por areia média e fina, a Unidade 2 por areia grossa, a Unidade 3 por areia fina e a Unidade 4 por areia fina e média. A unidade 2 é a mais observada, seguida pelas unidades 1, 3 e 4. A PERMANOVA mostrou diferença significativa ($p < 0,05$) entre as unidades sedimentares. A PCA apresentou correlação de areia média e grossa com as Unidades 1, 2 e 4 e de areia fina com a Unidade 3. A área de empréstimo apresenta 3 Unidades sedimentares compatíveis, as Unidades 1, 2 e 4 que podem ser utilizadas para futuros projetos de alimentação de praia na Costa da Caparica.

Palavras-chave: Alimentação de Praia. Mancha de Empréstimo. Plataforma Continental. Unidades Sedimentares. Análises Estatísticas Multivariadas. Portugal.

Resumo alargado:

Atualmente 60% da população global está concentrada nas zonas costeiras e as praias arenosas representam 75% do ecossistema costeiro livre de gelo. Face à crescente ocupação urbana na zona costeira os impactos antrópicos nessas áreas como a atuação da erosão costeira é inquestionável. A maior parte da erosão costeira causada pelo impacto antrópico é resultante de atividades como ocupação desordenada na linha de costa, construções e degradação de dunas, desmatamento de margens de rios e represamento de sedimento em barragens e portos. Esses processos mudam as condições naturais dos ambientes, resultando em mudanças na quantidade de sedimento disponível, transporte natural do sedimento e hidrodinâmica. Uma das abordagens globalmente utilizada para mitigar os impactos negativos da erosão costeira é a alimentação artificial de praias. Essa abordagem consiste em dispor artificialmente areia extraída de uma mancha de empréstimo sedimentar na praia afetada pela erosão costeira. As manchas de empréstimos são depósitos sedimentares que são utilizados para repor sedimento de uma área afetada pela erosão, ou seja, uma área que tem déficit sedimentar. Entretanto as manchas continentais de empréstimo de sedimento estão cada vez mais escassas e o sedimento da plataforma continental é pontuado como uma boa solução para a crescente demanda sedimentar de áreas afetadas pela erosão costeira. Tendo isso em vista, o presente estudo teve como objetivo caracterizar e definir as unidades sedimentares presentes na mancha de empréstimo da Costa da Caparica localizada na plataforma continental interna de Portugal, com o intuito de ser usada futuramente em projetos de alimentação artificial das praias da Costa da Caparica. O presente estudo contou com a caracterização de 12 testemunhos sedimentares localizados na plataforma continental interna adjacente a região da Costa da Caparica. A área onde a mancha de empréstimo está localizada apresenta uma batimetria que varia de 21 m a 27 m. Cada testemunho sedimentar tinha um comprimento total de 3 metros dos quais foram extraídas amostras a cada 25 cm. Para caracterizar os testemunhos e definir unidades sedimentares, foram analisadas a concentração de carbonatos, média granulométrica, curtose, assimetria, calibragem do sedimento e percentagens das diferentes classes texturais.

Esses parâmetros extraídos do programa GRADISTAT foram representadas de forma gráfica usando o pacote ggplot2 no *software* R em conjunto com a foto e o *log* do respectivo testemunho. O log de cada testemunho foi elaborado com base na nomenclatura proposta por Blott Pye, (2012) e classificados como: areia cascalhenta; areia levemente cascalhenta; areia muito levemente cascalhenta; areia levemente cascalhenta e levemente ludosa; areia; areia levemente ludosa e areia muito levemente ludosa. A partir dessas representações gráficas foram definidas as unidades sedimentares. Para confirmar e apoiar a definição das unidades sedimentares foram realizadas análises estatísticas multivariadas. As análises realizadas foram, a PERMANOVA que foi utilizada para verificar se as unidades sedimentares eram diferentes, seguida pelo Post-Hoc Pair-Wise, que identificou quais eram as unidades que apresentavam diferença. A análise de agrupamento MDS e de ordenamento Cluster que foram utilizadas para identificar a semelhança entre os testemunhos, seguida pelo SIMPER (similaridade em percentagem) que mostrou quais eram as variáveis responsáveis pela semelhança entre os testemunhos. Por fim a Análise de Componentes Principais (PCA), que foi utilizada para verificar a correlação das unidades com as variáveis e como essa correlação influencia a distribuição dos dados. Os resultados da caracterização dos testemunhos mostraram que a maior parte dos sedimentos é composta por areia média seguido por areia grossa e fina e apenas uma pequena parte da mancha de empréstimo apresenta areia muito fina e uma baixa quantidade de sedimentos ludosos. Quatro diferentes unidades sedimentares foram identificadas nos testemunhos da mancha de empréstimo da Costa da Caparica. A Unidade sedimentar 1 apresenta como características principais um sedimento composto principalmente por areia média mas com contribuição também de areia fina. Esta unidade apresenta um tamanho de grão com uma média granulométrica de 284 µm, grãos bem a moderadamente bem calibrados com uma distribuição assimétrica positiva e uma curva de grãos leptocúrtica. Nesta unidade sedimentar a concentração de carbonatos varia de 1,8 % a 9,9 %. Por sua vez, a Unidade 2 apresenta a areia grosseira como principal componente textural, mas também apresenta areia muito grosseira e cascalho fino. A média granulométrica desta unidade é de 490 µm e os grãos nesta unidade apresentam uma distribuição granulométrica platicúrtica a leptocúrtica com assimetria positiva. A concentração de carbonatos nesta unidade varia de 6,4 % a 13,9 %. Em sequência, a Unidade 3 é caracterizada por ser composta maioritariamente por areia fina e possuir um tamanho médio de grão de 221 µm. Esta unidade apresenta grãos mal calibrados com uma distribuição mesocúrtica e uma assimetria positiva. A concentração de carbonatos apresenta uma variação dentro desta unidade de 5,1 % a 29,3 %, sendo este, o maior valor encontrado na área de estudo. Por fim, a Unidade 4 é representada por areia fina a média com um tamanho médio de grão de 233 µm. Os grãos dessa unidade são moderadamente calibrados e apresentam uma distribuição simétrica e leptocúrtica. Por sua vez, a concentração de carbonatos varia de 3,6 % a 17,1 %. Dentro das quatro unidades sedimentares, a Unidade 2 é a que está mais representada nos testemunhos da área de estudo, existindo em onze dos doze testemunhos. Em seguida a Unidade 1 está presente em nove testemunhos, a Unidade 3 em sete e a Unidade 4 em apenas três. Quanto às análises multivariadas, a PERMANOVA mostrou que as unidades sedimentares são significativamente diferentes ($p < 0,05$) e o Post-Hoc Pair-Wise que quase todas as unidades diferem entre si com exceção da Unidade 3 e 4 e Unidade 1 e 4, que não apresentaram significativa diferença entre si. O padrão de distribuição do Cluster e MDS corroboram com a PERMANOVA, uma vez que as amostras que não apresentam diferença significativa se agrupam entre si e as amostras que apresentam diferença não se agrupam com as demais. A PCA mostrou uma correlação entre as variáveis de areia média e grosseira com as unidades 1, 2 e 4 e uma correlação com areia fina e a Unidade 3. Por fim, é possível dizer que as Unidades 1, 2 e 4 são compatíveis com a granulometria atual das praias da Costa da Caparica e podem ser utilizadas para futuros projetos de alimentação artificial na área. Entretanto o uso da Unidade 2, por se tratar de um sedimento mais grosseiro do que o atual nas praias da Costa da Caparica pode acarretar numa praia mais estável e com menores perdas sedimentares. Porém, também pode acarretar em uma mudança do perfil e morfologia da praia, resultando em uma praia refletiva, tendo perda na qualidade balnear e na prática de surfe. Por fim, se usada individualmente a Unidade 3, acarretará em um enchimento de praia não duradouro com perdas sedimentares provavelmente maiores do que a atual.

Palavras-chave: Alimentação de Praia. Mancha de Empréstimo. Plataforma Continental. Unidades Sedimentares. Análises Estatísticas Multivariadas. Portugal.

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1 INTRODUCTION

Currently 60 % of the global population is concentrated in the coastal zone and 75 % of the coast is dominated by sandy beaches (Barbier *et al.,* 2011; Brown and Mclachlan, 1990; Mclachlan and Brown, 2006). Thus, the susceptibility of these environments to anthropogenic impacts is unquestionable (McLachlan *et al*., 2013) and needs to be address in several fields of knowledge.

1.1 Coastal erosion and its management

Most of the erosion in coastal areas caused by anthropogenic activities is principally due to sea level rise, disorderly occupation of the coastline, constructions and degradation on dunes and activities inland, a case in point being sediment trapped in dams and harbors, river margins vegetation suppression, hill slope stabilization and reduction of sediments input in the hydrological basin. All of these processes change the natural pattern of sediment inputs, bypassing and hydrodynamics in coastal zones (Mclachlan *et al*., 2013; Rangel-Buitrago *et al.,* 2018; Williams *et al.,* 2018).

These processes mainly caused or increased by anthropogenic activities have been pointed out as one of the main reasons for the increasing coastal erosion worldwide and coastal natural processes changes. Therefore, most of the beaches around the world suffer pressure at different scales (Defeo *et al.*, 2009).

Portugal is also impacted by coastal erosion. In particular the central Portuguese coast, recognized to be the most vulnerable and yet the most affected. The expected loss of territory due to coastal erosion over the next 50 years in this area is estimated to 4 % (4700ha). Hence, leading to an ecosystem service value loss increasing from €30 million per year in 2028 to over €45 million per year by 2058 (Alves *et al.,* 2009; Cardoso *et al*., 2019).

Moreover, the central Portuguese coast is not the only one being affected by the coastal erosion. Costa da Caparica, where the present study is focused on, has been suffering from problems related to erosion since 1870 (Veloso-Gomes *et al.,* 2007; Veloso-Gomes *et al.,* 2005). The exposure to wave-storm action and the continuous increase in urban pressure and tourism in this region denote as the main reasons for coastline retreat (Silva *et al.,* 2013; Veloso-Gomes *et al.,* 2009).

To hinder the erosion, some protection measures can be adopted. The coastal defense techniques can be hard or soft engineering. The hard defenses are for instance groins, seawalls, revetments rock armor and offshore structures. However, these techniques are expensive, need periodic maintenance, may increase the wave reflection destabilizing the beach and make the beach less safe for public usage and they might also degrade the quality of the landscape (Williams *et al*., 2018).

On the other hand, the soft defenses include construction of sand dunes in an artificial manner (dune building) or implementation of recovering and protection practices on the natural dunes and beach nourishment. Sand dunes are a type of measure that secures the wave energy dissipation post-storm, restoring prevents sand losses and increases the ecosystem quality (Brown *et al.,* 2016; Willians *et al*., 2018).

Beach nourishment is also a soft defense measure where imported sand is placed on a beach. Action is not taken solely to recover beaches in erosion states or to prevent flooding but also to widen sand strips for tourism and recreation purposes. One positive aspect of nourishment activity is the natural beach appearance, although periodic maintenance is required together with usually quite large volumes of sand. (Cooke *et al.,* 2012; Finkl *et al.,* 1997; Liu *et al*., 2019; Willians *et al.,* 2018).

Indeed, one challenging task in beach nourishment projects is finding a good source of sediment, denoted with a mean grain size equal or slightly bigger than the beach one, and a mineralogical composition and appearance similar to the native sand (Hannides *et al*., 2019; Wilson *et al*., 2017).

In the last decades beach nourishment has largely been applied everywhere in the world (Finkl *et al.,* 1997; Liu *et al*., 2019; USAID, 2009), examples being Copacabana beach in Brazil (Vera-cruz, 1972), regions in Australia, such as the

Gold Coast (Boak *et al*., 2001; Cooke *et al*., 2012) and Miami beach in the United States (Shivlani *et al*., 2003).

Beach nourishment is also a common practice widely used in the European countries. Currently a volume of sand of about 28 million m³ is used annually for beach nourishment projects in Europe (Hamm *et al.,* 2002; Marinho *et al.,* 2019).

Regarding beach nourishments in Europe, Hanson *et al*. (2002) have conducted a global overview of projects already undergone in Europe and identified the major nourishment projects. For instance, Germany has already performed 130 sand fills in 60 different sites, Italy 50 in 36 different sites, Netherlands about 200 fills in 30 sites, France 115 artificial nourishments in 26 sites, Spain more than 600 in about 400 sites, UK 35 fills in 32 sites and finally Denmark 118 fills in 13 locations. Table 1 summarizes these values and the respective volumes used.

Table 1: European countries with greater representation in nourishments projects. Data extracted from Hanson et al, (2002) and Hamm et al, (2002).

Country	First nourishment project	Number of nourished sites	Total fill Volume (Millions m³)
France	1962	26	12
Italy	1969	36	15
Germany	1951	60	50
Netherlands	1970	30	110
Spain	1985	400	110
Denmark	1974	13	31
United Kingdom	1950	32	20

The overview is not different for Portugal as beach nourishment measures have been applied since 1950. The first sand fill in 1950 was performed in Estoril, and the first important one was made in 2010 at Algarve involving about 0,9 Millions of m³ of sand (Hanson *et al*., 2002) at Forte Novo-Garrão Beach (Pinto *et al*., 2018).

In order to evaluate and describe those nourishments projects already made in Portugal, Pinto *et al.* (2018) have made an overview of this practice along the past 67 years (1950 to 2017). The authors pointed out that 134 projects of this nature were already made and the volume of sediments used was in the order of 33,7 10^6 m^3. Most of the nourishment projects were made on beaches located in urban centers, in areas surrounding a river mouth and harbors and sites with huge tourism and recreational activities.

The authors also pointed that the main source (88 %) of sediments used for beach nourishment in Portugal is provided by ports, recreational and fisheries dredging activities. Furthermore, the main goals of those interventions in the country are linked to mitigation of coastal erosion and for widening the beach strips for tourism and recreational activities (Figure 1 and Figure 2).

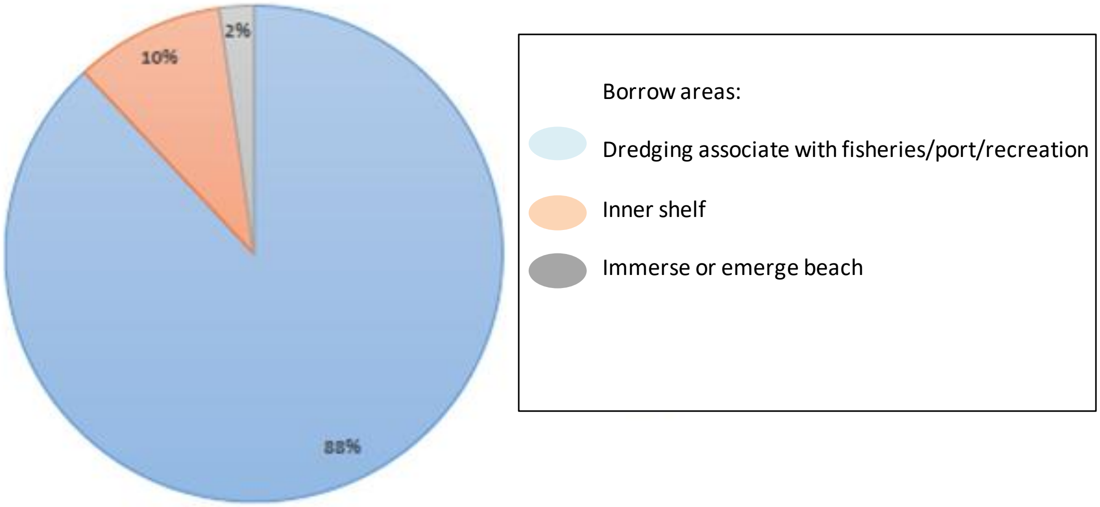

Figure 1: Sources of the sediments used in Portugal since 1970 to 2017 for beach sand fill. Blue = port, recreational and fisheries dragging activities; red = continental shelf; gray = immerse and emerge beach. Figure adapted from Pinto et al, (2018).

However, to find a good sediment supply which is economically viable with an adequate grain size and large amounts of sediment available nearby the affected area (Cooke *et al*,. 2012; Finkl *et al.,* 1997) is a challenging task and a key element for the successful sand fill.

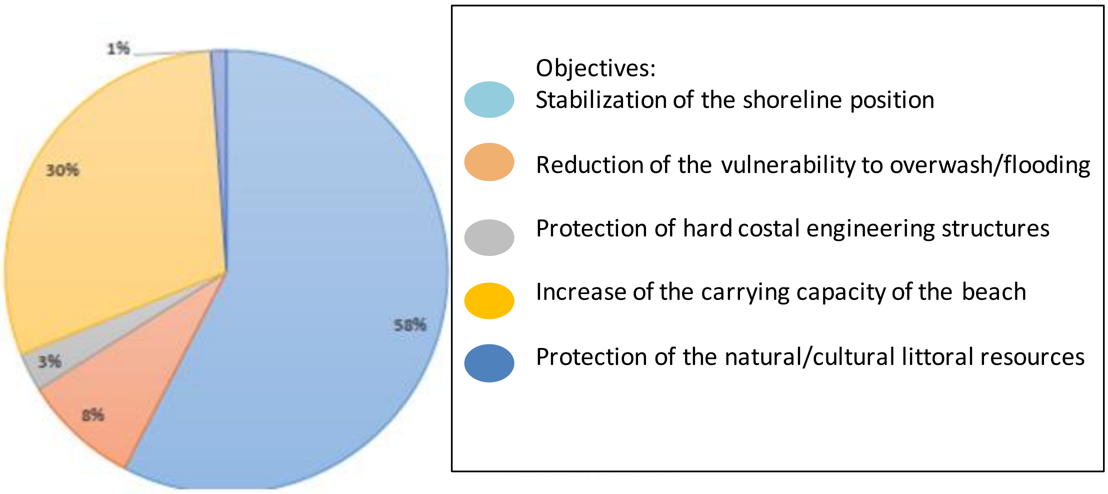

Figure 2: The goals of sand fill in the Portuguese coast. Light blue = improve in the coastal stability; brown orange= reduction of the vunerability overwash vulnerability; gray= protection of coastal engineers; yellow= widen beach strip; dark blue= protection of natural/cultural resources. Figure adapted from Pinto et al, (2018).

Finding a sediment source especially inland or in coastal systems (e.g. lagoon and estuaries) has become very difficult and thus offshore sediments are pointed out as a good solution (Finkl *et al*., 1997). In order to have effective and successful nourishment projects, knowledge, accurate descriptions and mapping those offshore sources in the continental shelf are of paramount importance.

1.1.1 Impacts, costs and benefices of nourishment projects: a Literature review

In this subsection the positive and negative aspects of beach nourishment will be discussed. In addition, it will articulate examples showcasing how costly a project of this nature can be, while citing some nourishments projects from around the world, providing the decision makers with some generic information.

Beach nourishment projects can have positive and negative aspects, generating a debate about their practice. Some authors say investing in a beach nourishment project could be described as placing money and sand directly back to the ocean. Others believe the technique is worth the investment and effort to restore the beach, even if just temporarily.

Nourished beaches provide not just storm protection and stabilization of the coast line but also vast leisure and recreational benefits (Guo *et al*., 2020; Pinto *et al.,* 2020). Furthermore, if carried out respecting similar sediments as of the natural beach, it might support the creation of additional beach habitats, for instance for sea turtles, birds and sandy beach macrofauna (Landry *et al*., 2020; Martin and Adams, 2020).

One vastly positive aspect that should be mentioned is that beach nourishment preserves the natural characteristics of the coast, since only natural material (sand) is used. Beach nourishment also avoids the construction of hard coastal engineers (e.g. groins, sea walls), while elevating the level of coastal protection, preserving the landscape and natural habitats, mitigating erosion and sustaining the natural environment (Staudt *et al*., under review).

Furthermore, economically speaking, beach nourishment has strong positive aspects. Widening a beach strip enhances immensely the economic value of the beach. Pendtleton *et al*. (2012) verified that beach nourishment in Los Angeles aggregates around US$ 3 million in value per year to the beach. Landry *et al*. (2020) estimate that an increase in beach width in North Carolina´s beaches would increase willingness to pay per household in the order of US$ 8 per year that produces aggregate economic welfare in order of US$ 28,4 million per year. Additionally, causing also an increase in the marginal value of US$ 0,48/meter due the incremental beach width. Furthermore, Parson *et al.* (2013) estimate a US$ 3/daytrip increase in economic value in Delaware beach from the current price of US$ 33/daytrip per beach users.

Additionally, other positive aspects of beach nourishment worth mentioning are the value growth of real estate properties due to the mitigation of coastal erosion, increase of recreational use and the expansion of the tourism sector (Daniel, 2001). Catma (2020) evaluates the economic value of beach width in Hilton Head Island (U.S) and discovered for which additional foot of beach width would the value increase in order of US$ 3012 of an oceanfront property.

For instance, Daniel (2001) points out some economic losses in Delaware (U.S.) if the nourishment approach would not have been applied. The author summarizes that a loss of about 2,91 % in property value would occur. A decrease of US$ 30,2 million in tourism, more than 600 beach jobs would be extinguished and a loss of US$ 20,1 million in consumers' surplus would occur. In addition, if erosion was allowed to take place, a shoreline retreat would incur a total of US$ 200 million of the present value which would be lost in the next 50 years of Delaware beaches. Meanwhile, each nourishment project costs in that region range from 4 to 7 million US$, and comparing to the other losses, it would still appear to be a reasonable solution.

The sand loss and maintenance of beach nourishment generate a debate and part of this debate is due to the durability of the replenished beach. Daniel (2001) refer to some examples in the East Coast of U.S. and points out that 26 % of nourished beaches in this area have effectively disappeared in less than 1 year, 62 % last between 2 and 5 years and just 12 % remained stable for more than 5 years.

This is also the case in some unstable beaches in China, where re-nourishments are needed due to the high sand loss rates. For instance, Liu *et al*. (2019) refer to QS Beach in Quanzhou which has an average sand loss rate in order of 5700m³/year. Taking this into consideration, the authors suggest an annual re-nourishment in the same order of the sediment losses. Moreover, in China a total of US$ 222 million has been spent and a volume of 18 million m³ of sand has been used (Liu *et al.,* 2019).

The maintenance of the nourishment usually requires new sand fills about every 3-5 years (Landry *et al.,* 2020). That is the case in Costa da Caparica, where nourishments were performed in 2007, 2008, 2009 and 2014 (Pinto *et al.,* 2018; 2020).

Although, the maintenance can be costly and often requires a large amount of sand. For instance, in Costa da Caparica € 20 million has already been spent and a sand volume of 3,5 million m³ used (Pinto *et al.,* 2018; 2020).

In Delaware (U.S.) beaches the scenario is not much different, as Daniel (2001) summarizes, the costs related to the maintenance of nourished beaches between 1989 -1998 and show a total of US$ 18.769.696 spent and a volume of

3.137.380 (m^3) and also point out that all the borrow sand comes from offshore areas.

Besides the costs involved in a nourishment project, another problem lies within finding useful sediment for the fill. Sand is the third most consumed material in the world, and the sources are becoming very scarce (López *et al*., 2018). As nourishments have to be repeated in regular intervals, finding a suitable source of sand has become more difficult, costs related heighten and environmental problems gradually increasing along time (Daniel, 2001).

Even though beach nourishment is considered to be an environmentally friendly option for mitigating coastal erosion, ecological impacts must likewise be taken into consideration. Beach ecosystems play an important role in recycling and processing nutrients and organic matter in costal zones (Defeo *et al.,* 2009). Nourishment can affect the natural beach ecology, such as the benthic macrofauna, that plays a key role in recycling, processing and making available nutrients and organic matter for the beach food chain (McLachlan and Brown, 2006).

Beach nourishment usually affects the macrofauna killing the organisms due to burial with the sand disposed on the beach, since most of the macrofauna specimens lives in the first 20 cm sediment's depth (McLachlan and Brown, 2006; Schlacher *et al*., 2012). Although, another impact that can occur is due to the change in the granulometric aspects, since the sandy beach macrofauna specimens respond directly to different grain sizes. Most species occur in fine grains and do not or rarely occur in beaches with coarse sand (McLachlan *et al*., 2013; McLachlan and Brown, 2006).

In order to access beach nourishment impacts in the macrofauna ecology, Schlacher *et al*. (2012) evaluated the sandy beach macrofauna in Burleigh Heads, Australia, before and after the sand fill procedures. The author pointed a massive abundance and richness diminishment in the macrofauna on the upper and middle levels of the beach. Although, the fauna in the middle beach recovered partially and in the lower beach mostly after five months, but in the upper beach no recover was observed. One solution that the authors suggest is to spread the sand in thin layers minimizing burial or place the sand in a shallow sub-tidal zone, followed by up-shore accretion due to hydrodynamic movements.

Moreover, Cooke *et al.* (2020) observed in Blacksmiths Beach (New South Wales, Australia) that the nourishment had a large impact on the beach vegetation and the invertebrates. However, only short-term negative impacts were observed since the vegetation recovered after 9 months and the invertebrate communities after 21 months.

On the other hand, Leewis *et al*. (2012) monitored 17 beaches in the Netherlands and did not find negative impacts directly related with nourishment practices on sandy beach macrofauna. The authors further detected that the polychaete *Scolelepis squamata* had an over-colonization after the nourishment showing to be an opportunistic species, re-colonizing the beach after nourishment. These authors also pointed out the importance to the knowledge of the sandy beach macrofauna in order to mitigate the possible effects of beach nourishment.

To mitigate the impacts that beach nourishment may cause on the sandy beach ecology, Danovaro *et al*. (2018), Speybroeck *et al*. (2006) and Wilber *et al*. (2009) advices should be considered, namely: i) choosing sands with a composition similar of the natural sediment, ii) avoiding short term sand compaction straight after the sand fill, iii) preferring to do smaller projects rather than one single nourishment, iv) executing the project in a period of low beach use by birds and other mobile organisms and during peak larval benthos recruitment, v) avoiding to create deep pits with steep side-slopes at borrow areas, vi) locating the borrowed sand areas with rapid sand accretion, and vii) developing a fauna monitoring program after the nourishment. These actions may be considered before and after a nourishment project.

Another aspect that needs attention is the frequency of nourishments and sediment characteristics. If sand fills are greater than the beach fauna and flora recovering time, and incompatible sand is mined from wrong offshore areas long-term negative impacts might occur (Cooke *et al*., 2020; Landry *et al.,* 2020; Martin and Adams, 2020).

1.1.2 Alternatives to beach nourishment to mitigate flooding and coastal erosion

Determining the best option for mitigating the coast retreat can be difficult. Decision makers must have the knowledge of different options for containing the erosion and evaluating the beach value and the costs involved in each method and then consider carefully the appropriate erosion control technique. In this subsection some other alternatives which may be applied to contain the beach erosion are presented.

Indeed, there are existing hard structures constructed to mitigate coastal erosion in Costa da Caparica. Between 1959 and 1971 a 2.5 km long seawall and seven groins with 180 m (length) each were constructed. Although, continuous losses of sand has occurred and a critical situation has been experienced since the year 2000 onwards. The coast line has continued to retreat significantly together with massive sediments removal from the beach and dunes taking place. To contain the erosion the groins were reshaped and a sand nourishment made in the order of 3 million m^3 (Veloso-Gomes *et al*., 2009).

The first alternative presented here is the managed retreat/coastal retreat. The managed retreat consists of letting the natural erosion act, allowing an area to erode. This technique involves removing or relocating infrastructures, buildings, houses and communities away from the eroding shoreline. This method usually generates social debate. Managed retreat has to be done together with valuing the coastal housing and infrastructures, and evaluating how much could potentially be lost economically and environmentally. Managed retreat is an alternative to beach nourishment, however, it is usually more expensive and is often only justified within areas which already are exposed to high risk or will become high risk in the near future (Cutler *et al.,* 2020; Landry *et al*., 2020; Lawrence *et al*., 2020; Noy, 2020; Robb *et al.,* 2020).

Another alternative for mitigating the coastal erosion is the Building with nature approach. This is a technique where the nature provides the starting point. Natural material like sand and natural processes such as wind, current and waves are used in the coastal protection project's design. That means when a nourishment project is taking place in attempt to contain coastal erosion, the other environmental factors are considered and used in favor of the sand distribution in the affected area and in adjacent areas. Furthermore, building respecting nature is more effective and environmentally friendly than conventional hard coastal defenses. Hard defenses may mitigate erosion locally but can aggravate erosion problems in adjacent areas, for instance, interrupting the sediments' by-pass through the coastline (Kok *et al*., 2020). A case in point is a mega-nourishment project performed in the Netherlands where a volume of 20 million m^3 of sand was placed on the beach. The idea behind it was to utilize the natural processes such as currents, wind and tides to spread the sand along the shoreline. Hence, creating beach width, providing additional wildlife habitats and favoring the economy with recreational and tourism activities as a result of the widened beach (Borsje *et al.,* 2017; Van-Slobbe *et al*., 2013).

Subsequently, dunes recover and/or rehabilitation is a nature based soft defense which mitigates coastal erosion and restores flooding resilience. Dunes bring multiple benefits to the beach and adjacent areas with examples of this being natural coastal protection, biodiversity and habitats. They control and avoid sea water contamination of aquifers and act as beach emergency sediments supply. The dunes' recovery and/or rehabilitation can be done through nourishments, fences and vegetation. The re-vegetation approach must be done with the dune restoration. Vegetation plays a fundamental role in dune systems, stabilizing and aiding the accumulation of sediments. This method is completely environmentally friendly and must be considered to be done congruently with nourishment projects allowing in turn dunes to strengthen the resilience of beach systems (Hanley *et al*., 2014; Gracia *et al*., 2018; Silva *et al*., 2017).

Another option is coastal hard defense structures. Examples of these include groins, seawalls, revetments rock armoring, gabions and offshore structures. Yet this approach can cause many negative effects. Hard structures usually require continuous maintenance, they may increase coastal risks, depredate the landscape, increase erosion accelerating the bottom removal of sediments in front of the structure and downdrift scouring and, additionally change the natural adaptive patterns of any coast line (Gracia *et al*., 2018; Williams *et al.,* 2018).

With currently plenty of innovative approaches available to mitigate coastal erosion, hard structures should be the last alternative to be considered.

1.2 Sedimentary settings of the Portuguese continental shelf

The sediments and the processes involved in sedimentation, such as, sediment transport and source and geochemical aspects of the continental shelf of Portugal were largely studied by several authors (Dias *et al.,*1980; Dias and Nitrouer, 1984; Dias, 1987; Dias *et al.,*2002; Drago *et al*., 1998; Lopes and Cunha, 2010; Magalhães *et al.,*1991; Magalhães and Dias, 1992; Martins *et al*., 2012; Matos *et al*., 2006; Mil-Homens *et al.,* 2006; Taborda and Dias, 1992). However, those studies were not performed in the resolution scale necessary for defining a potential borrow area for beach nourishment.

The Portuguese continental shelf represent a total area of about 28 000 km² and is located between the latitudes 36° 49´N and 41° 52´N and longitudes 7° 24´W and 10° 11´W with a narrow and variable width (average width of 75-80 km). The mean depth of the shelf is 130 m and its slope range between 3 to 11 m/km (Dias, 1987; Pereira, 1991). In general, the surface sediments deposits of the Portuguese continental shelf are mainly composed by sand (Mil-Homens *et al.,* 2006).

Dias *et al*. (1980) were one of the first to describe the sediments of the Portuguese continental shelf referring that the portion between Minho River and Nazaré canyon is relative narrow (35 to 60 km) and deep (160m) and present four textural groups: (1) unimodal sands distributed close to the coast till 40 m depth, (2) gravel at the west portion of the littoral beaches, (3) exterior shelf deposits composed by fine and medium sand with a high degree of biogenic carbonate and (4) boarder shelf deposits with fine well sorted sand composed manly by quartz grains. This portion is defined to be predominantly composed by sand that occurs between 40 m and 60 m depth. The same pattern also was observed by Dias and Nitrouer (1984).

Further south, the pattern of the surface sediments deposits between Roca Cape and Sines Cape show similar aspects. This section of the Portuguese continental shelf is also mainly represented by sand. Between the Espiche Cape and Raso Cape the inner shelf is composed by fine to medium sand. In the north portion of this section the sediment's cover is mainly composed by sand-gravel with a high concentration of biogenic sediments (Matos *et al.,*2006; Mourato, 2006).

Finally, the southern sector of the Portuguese continental shelf is located between the Cape São Vicente and Vila Real de Santo António. The main source of sediments for this sector is the Guadiana River. As a result of the low energy environment in comparison of the other sectors of the Portuguese continental shelf, the south continental shelf is where the higher concentration of mud is observed, following a different pattern of sediment's cover in relation to the other sectors (Martins *et al*., 2012).

As said before most of the continental shelf surface sediments of Portugal is composed by sand, and could thus represent good sand sources for beach nourishment, with the exception of the southern portion that is mainly composed by mud.

For a better visualization of the above description, Figure 3 presents the distribution of the surface sediments along the Cabo Carvoeiro to Cabo da Roca in the Portuguese continental shelf, in which Costa da Caparica is included.

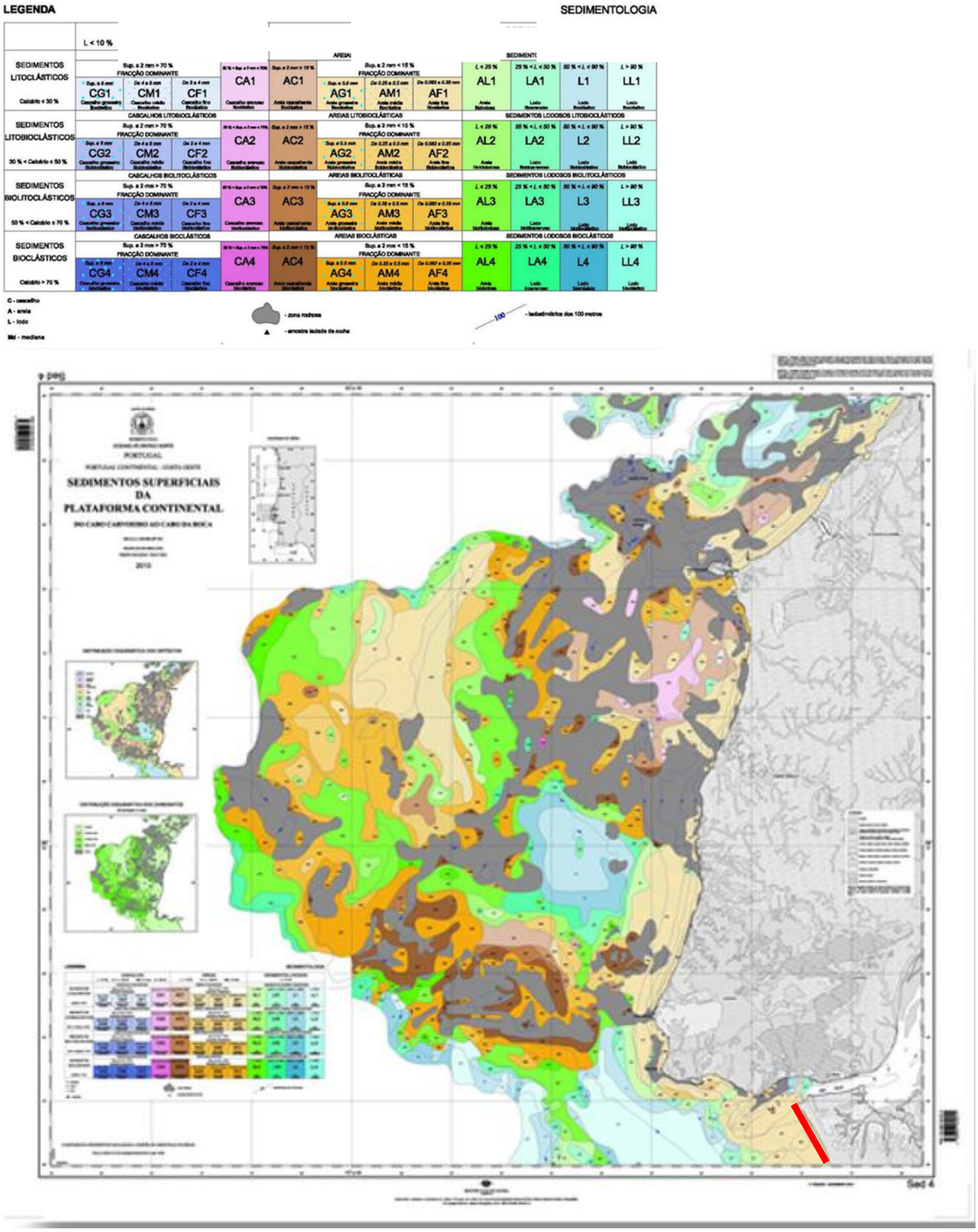

Figure 3: Cartography of the surface sediments distribution along the Cabo Carvoeiro to Cabo da Roca in Portuguese continental shelf, in which Costa da Caparica (highlighted in red) is included. Source: Instituto Hidrografíco Portugues, 2018.

In this context at the behest of the Environment Department of Portugal, a group of experts named “Grupo de Trabalho para os Sedimentos” was created

(Andrade *et al*., 2015), in order to define potential borrows areas for beach nourishment, based on the surface sediments’ distribution of the continental shelf of Portugal. Accordingly, they made a map with the locations of four potential sand sources in the Portuguese Continental shelf and in particular for offshore Costa da Caparica, where the present study is focusing (Figure 4).

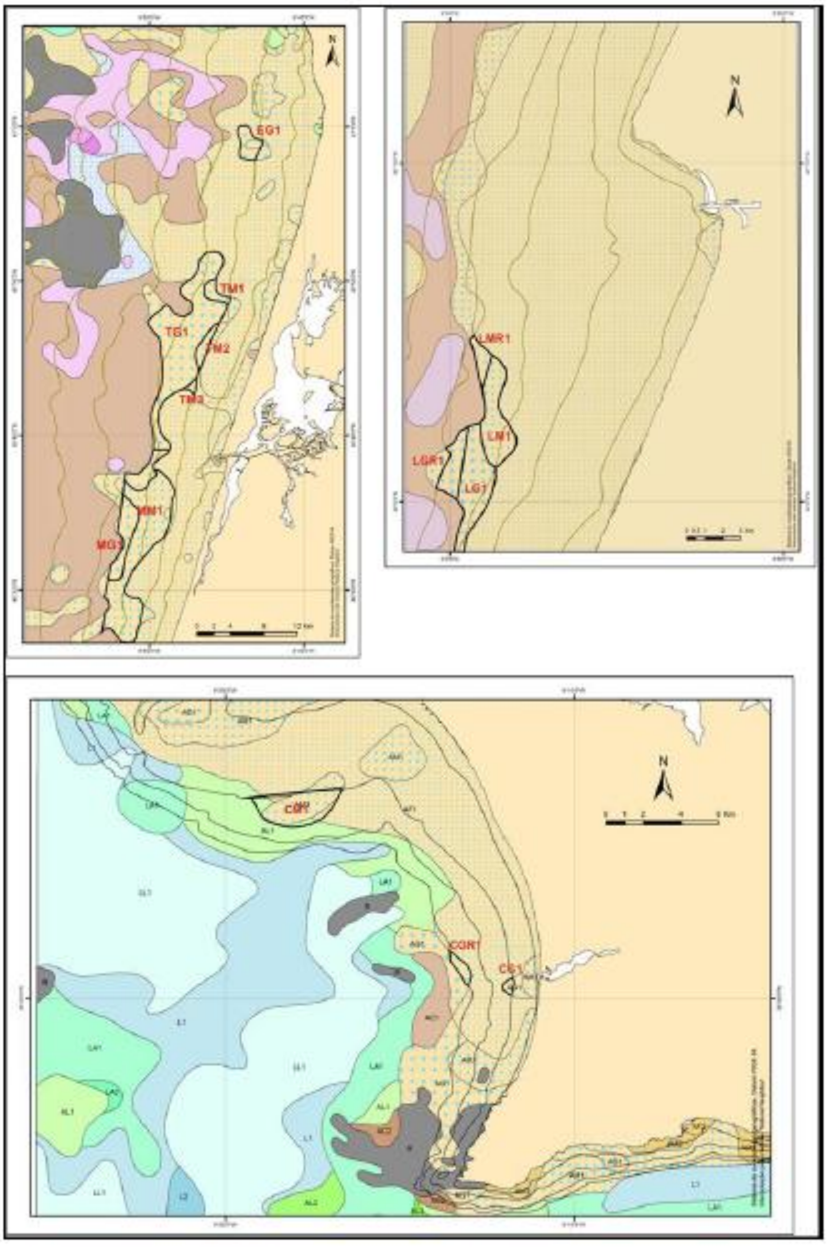

Figure 4: Potential borrow areas for beach nourishment in the Portuguese continental shelf. Extracts SED 2 Espinho-Torreira and Praia da Barra - Mira (top left), SED 3 Figueira da Foz – Leirosa (top right) and SED 5 Costa da Caparica (bottom), from the Portuguese continental shelf surface sediment maps. Figure extracted from Andrade et al. (2015).

1.3 Study area

Costa da Caparica is located on the south bank of the Tagus River, southwards Lisbon (Figure 5). The area counts with 6 km of narrow sandy beaches with the coast line orientated from NW to SE. These beaches receive a large amount of tourists during summer and surfers during winter. The coast is characterized for being under a wave climate (Figure 6) with annual averages of wave heights lower than 2 to 3 m with a predominance direction in the quadrant NNW-SSE. However during the winter season, the predominant direction is NW-SE and average heights of 3 to 4 m (Silva *et al*., 2017).

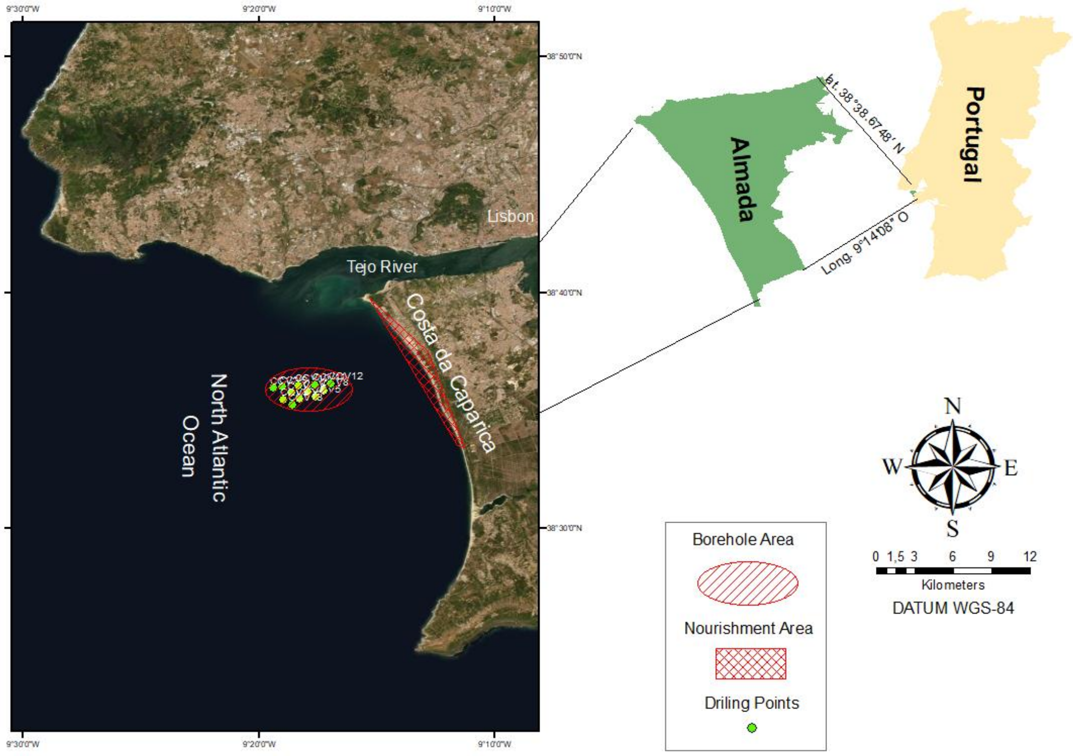

Figure 5: Study area, general view. Dash area represents the borrow area; double dash represents the nourishment site; green dots the drilling points.

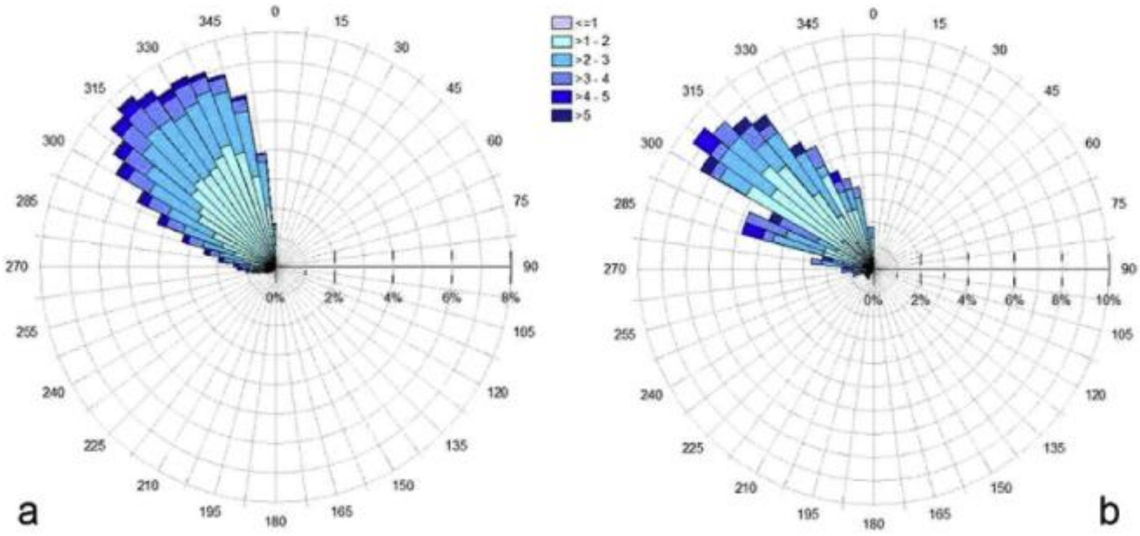

Figure 6: Offshore wave climate of Costa da Caparica from January 1979 to March 2014. (a) summer, spring and fall and (b) winter conditions. Figure extracted from Silva *et al.* (2017).

Regarding the morphosedimentary settings, Costa da Caparica is a coastal plain composed of alluvial deposits from the interaction between Tagus River and the sea. The main sediment sources for this area are i) the erosion of the cliffs southern of Fonte da Telha, transported through a north long-shore drift, ii) the Tagus river, iii) the hydrographic draining basin of Costa do Sol and iv) the wind corridor Guincho/Guia (Andrade *et al*., 2015; Mil-Homens *et al*., 2020; Pinto *et al*., 2019; Santos *et al*., 2014; Taborda and Andrade, 2014; Veloso-Gomes *et al*., 2009).

In this area, there is a historical coast line retreat of circa 200 m, between 1958 to 2014, mainly in São João da Caparica, showing the need of beach nourishment or other defense techniques for protecting the coast line (Andrade *et al*., 2015).

In the early 1970's, aiming to protect the coast line from storms and sand losses in Costa da Caparica, a groins field and seawall were build. However the sand losses didn't ceased completely and in 2007, 2008, 2009 and 2014 sand beach nourishments had to be performed (Pinto *et al.,* 2018; 2020).

2 OBJECTIVES

According to the above, the main objective of the present work is to execute all the necessary processes to characterize and define the sedimentary units of an offshore sediment source area outside of Costa da Caparica aiming to define the useful sediment for beach nourishment, therefore providing pertinent information for costal management.

In order to achieve this main objective the following sub objectives are addressed:

- Characterization of the borrow area from Costa da Caparica inner shelf, based on the synthesis of the pre-existent data from CHIMERA Project.
- Definition of the sedimentary units of the borrow area off Costa da Caparica using the Mean grain-size, carbonate content, kurtosis, sorting, skewness, core log and the textural composition and statistical multivariate analysis.

3 METHODOLOGY

3.1 Materials

The present study was based on CHIMERA project ("*Caracterização de mancHas de empréstImo na plataforMa continental para alimEntação aRtificiAl de troços costeiros – CHIMERA*"). This project was made on behalf of the Portuguese environmental agency (*Agência Portuguesa do Ambiente*). The project aimed to characterize and estimate the volume of useful sediment of four chosen potentials borrow off-shore sedimentary areas (based on Andrade *et al*. (2015)) to be used in future beach nourishment by analyzing superficial and vertical samples. The present study is dedicated to the Costa da Caparica (CC) cores study.

3.1.1 Sampling

The vertical samples correspond to 12 cores which were collected by professional divers from the company XaviSub, using a vibracore device. The used vibracorer has 3,5 meters of total length, with a head of 55 x 32 cm of area. Previously to the collection, all the samples points were georreferenced using the GPS STONEX S10 GNSS. The sampling site and drilling points are shown in Figure 7.

On board, the sediments cores were photographed, properly identified, sealed in the top, divided in two sections of 1,5 m each (Figure 8) and preserved in cooler boxes until the laboratory, where they were preserved in 4C° for posterior analysis.

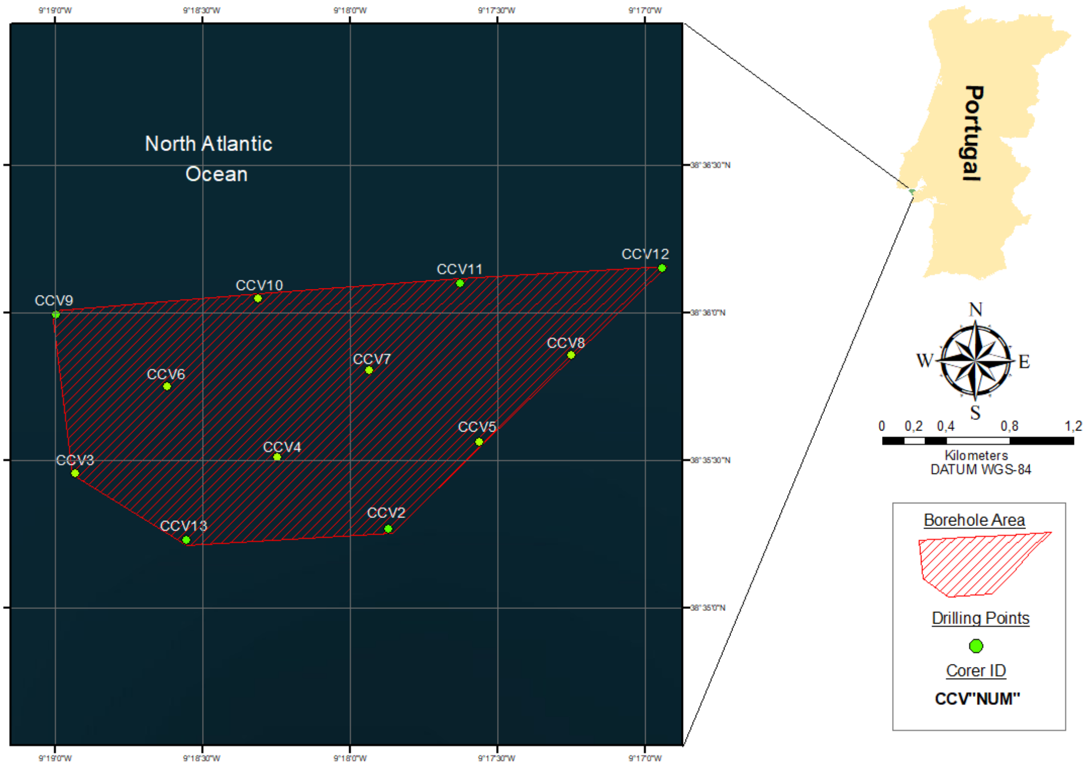

Figure 7: Study area, zoom in the drilling sites. Dash polygon indicates the study area, green dots cores location and CCV"NUM" core ID.

Figure 8: Cores sampled during the survey campaign. Figure extracted from CHIMERA Project's report (2019).

3.1.2 Pre-existing data - Project CHIMERA

The data used in the present study for characterize the Costa da Caparica study area was based on cores sediments analysis, previously obtained in the Chimera project.

The cores, with a 3 m length, were opened (with a small electric saw), described and sampled (with a 25 cm interval) for several analyses. Besides the textural types (gravel, sand and mud) percentages, and carbonate contents, statistical parameters were calculated (mean grain size, sorting, kurtosis, skewness) by using the Gradistat programme (Blott and Pye, 2001).

Each sample was washed with deionized water and dried at 100 C° in an oven.

Grain size analysis was performed using a sieving column, varying from - 2Φ (4000 μm) to 4Φ (63 μm), with an interval of 0,5Φ (Wentworth, 1922).

The carbonate concentration was obtained using a calcimeter Eijkelkamp, using around 2,5 g of sample and 1 ml of HCL. Subsequently, Equation 1 was applied for determining the percentage of $CaCO_3$. The standards (blank) are calculated using concentrations of 0,2 gr, 0,3 gr and 0,4 grams of carbonates and the obtained values were used in the Equation 1.

$$\%CaCO_3 = 100\ x\ M2x(V1 - V3)/M1x(V2 - V3)$$

Equation 1: Equation for determine the percentage of carbonates in sediment samples. M1 = Sample mass; M2 = Mass average of the CaCO3 standards; V1 = Volume (mL) of the CO2 produced by the reaction with the HCL; V2= mean CO2 volume produced by the standards of calcium carbonate; V3= mean of the alterations of the volume (mL) in the standards.

3.2 Present study

3.2.1 Grain size statistical re-analysis

The most basic property of the sediments is the grain size. This plays the predominant role in the transportation and deposition of particles, being an essential tool for classifying the sedimentary environment (Blott and Pye, 2001).

From this point of view, an exploratory data analysis was performed first to describe, them to define and characterize the sedimentary units. Accordingly, the previously grain size data computed in GRADISTAT software (Blott and Pye, 2001) was used.

The GRADISTAT is a software made for analyzing unconsolidated sediments, providing results on the grain size distribution, the percentage of grains of each size fraction and the statistics parameters (mean grain size, kurtosis, mode, standard deviation, sorting and skewness). The statistics given by the program are calculated using the arithmetic, geometric (metric units) and logarithm (phi units) methods (Blott and Pye, 2001). All the analyses regarding the present study were performed using the Geometric Method of Moments with the unit in micrometer (μm).

This method uses the metric size values based on a log normal distribution and follow the terminology proposed by Krumbein and Pettijohn (1938) where the mean grain size description is based on the Udden–Wentworth scale (Wenthworth, 1922).

For the exploratory data analyses, several analyses and plots were made using the package ggplot2 (Wickham, 2016) in the software R, using the results of the GRANDISTAT. During this process, two outliers (core 5 depth of 175 cm and core 7 depth of 50 cm) were identified and removed from the statistical analysis.

In this way, the plots created to help define the sedimentary units along the cores and to identify the limits between the units were based on the following variables: mean grain size, percentage of carbonate ($CaCO_3$), sorting, skewness, kurtosis, textural types and the core log. In addition, a photo of each core was added in each plot. The log was elaborated using the sediment names (classes) of each section of the core based on the terminology proposed by Blott and Pye (2012). The classes and the respective colors used to elaborate the logs are represented in Figure 9.

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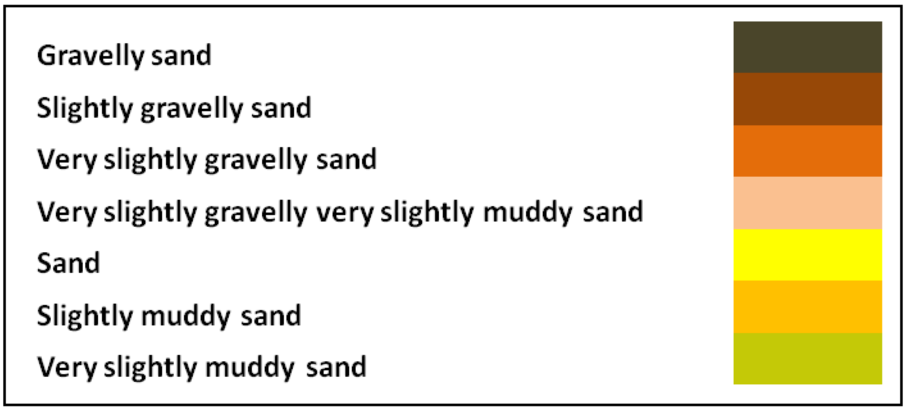

Figure 9: Classes based on the terminology proposed by Blott and Pye (2012) and used for elaborating the Logs of the studied cores and the respective used colors.

3.2.2 Multivariate Statistical analysis

In order to support and validate units' definition and correlation between cores previously determined based on the graphical tools, some statistical analyses were also performed in the present study, such as Permutational Analysis of Variance (PERMANOVA), Similarity Percentage Analysis (SIMPER), Cluster, Multi-Dimensional Scaling (MDS) and Principal Components Analysis (PCA). These statistical analyses were performed using the software Primer (Clark and Warwick, 2001; Anderson, 2001, 2005). The outliers were previously removed and, in order to respect the prerequisites of each analysis, data were standardized and centralized.

Furthermore, in order to minimize the collinearly among variables, the continuous variables used were: the percentage of each textural type and the percentage of carbonate. Two factor variables were also used, namely core depth and sedimentary units previously determined.

The PERMANOVA was used to test the hypothesis that the units defined based on the graphical tools are significantly different from each other. Subsequently, a Post-hoc Pairwise analysis (Anderson, 2001, 2005) was applied in order to highlight which are the significant differences betwee units.

The Cluster and MDS analyses are grouping analyses based on formation of groups according to the similarity between the samples, in the present case using a Euclidian Distance similarity matrix. In other words, these analyses link the samples into hierarchical groups, based on the chosen variables. The first one links the samples on a dendrogram and the second on a two-dimensional map, in such a way that the distances between the samples on the map agree with the rank order of the matching similarities taken from the similarity matrix (Clark and Warwick, 2001).

Thus, the groups formed were used to support and/or corroborate within the identification of the sedimentary units and the repetition of those units in between the cores previously observed with the graphical support.

Furthermore, in order to analyze the contribution of the variables to the formation of the groups, the SIMPER was used as a tool that discriminates the percentage of contribution of each variable for each Unit (Clark and Warwick, 2001).

On the other hand, the PCA is an ordination plot, usually in two or three dimensions, which approximate the continuum relationships between the samples reflected by the similarity between them (Clark and Warwick, 2001; Legendre and Legendre, 1983; Peres-Neto, *et al*., 1995). The PCA allows the analysis in an integrative form, namely how the sedimentary units are correlated with variables and how they influence the distribution and the similarity of the data.

All the above statistical tools were used in the present work in order to seek for the highest confidence in sedimentary units' definition and correlation.

4 RESULTS

4.1 Characterization of sediments from Costa da Caparica cores

Sedimentary characteristics of the 12 studied cores are summarized in Table 2, and individually described hereafter.

As observed in Figure 10, the general characteristics of core CCV2 are predominantly coarse sand poorly sorted with shell fragments about 1 cm in size shifting with the depth to fine and medium sand well to moderate sorted. According to the Blott and Pye (2012) classification, the sediments in this core are very slightly gravelly sand, slightly gravelly sand, sand and very slightly muddy sand.

According to Figure 11, the core CCV3 is represented by fine and very fine sand, moderately to moderately well sorted. Changing the pattern with depth to medium sand and coarse sand poorly sorted with shell fragments of about 3 to 4 cm in size. According to the Blott and Pye (2012) classification, the sediments in this core are very slightly muddy sand, sand, very slightly gravelly sand, slightly gravelly sand.

As represented in Figure 12, the core CCV4 present a main textural composition of fine and medium sand, moderately sorted. Changing the pattern along depth to coarse sand with shell fragments with 2 to 3 cm in size, the calibration is poorly sorted. According to the Blott and Pye (2012) classification, the sediments in this core are sand, very slightly muddy sand, very slightly gravelly sand.

Core CCV5 presents a main composition of fine to very fine sand, well sorted then shifting along depth to medium sand and coarse sand, moderately to well sorted and poorly sorted, respectively (Figure 13). According to the Blott and Pye (2012) classification, the sediments in this core are sand, very slightly gravelly very slightly muddy sand, very slightly gravelly sand and gravelly sand.

As presented in Figure 14, the core CCV6's has a predominant textural composition of fine sand and a moderately well sorted sediment. Shifting along depth to medium (quartz) grayish sand, poorly to moderately sorted with shell fragments. According to the Blott and Pye (2012) classification, the sediments in this core are sand, very slightly muddy sand and very slightly gravelly sand.

Core CCV7 (Figure 15) presents a predominant textural composition of fine sand, moderately well sorted. There is a shift along depth to medium sand, which is moderately to well sorted. According to the Blott and Pye (2012) classification, the sediments in this core are sand, slightly muddy sand and very slightly gravelly very slightly muddy sand.

The core CCV8's composition (Figure 16) consisting of medium poorly sorted sand, but with contributions of fine and coarse sand. Along the depth a change is observed towards a predominant composition of coarse sand with shell fragments of a size about 2 to 3 cm. According to the Blott and Pye (2012) classification, the sediments in this core are very slightly gravelly sand, sand and slightly gravelly sand.

As observed in Figure 17, core CCV9 mainly presents a textural composition of fine sand, moderately sorted, shifting along depth to a main textural composition of medium and coarse sand. According to the Blott and Pye (2012) classification, the sediments in this core are sand, very slightly muddy sand, very slightly gravelly very slightly muddy sand and very slightly gravelly sand.

The core CCV10's main characteristics are a textural composition of fine and medium sand with the calibration varying from moderately to well sorted (Figure 18). Moreover, an increase in shell fragments and coarse fraction is observed with increasing depth. According to the Blott and Pye (2012) classification, the sediments in this core are sand, very slightly gravelly sand and slightly gravelly sand.

According to Figure 19, core CCV11 presents a main textural composition of medium and fine and coarse sand, being moderately sorted, moderately well sorted and poorly sorted, respectively. In addition is observed in this core shells fragments. According to the Blott and Pye (2012) classification, the sediments in this core are sand and very slightly gravelly sand.

The core CCV12 the sediment presents a main textural composition of medium, fine and coarse (quartz) sand, poorly to moderately sorted and with shell fragments with a size about 3 cm (Figure 20). According to the Blott and Pye (2012) classification, the sediments in this core are very slightly gravelly sand and sand.

As observed in Figure 21, core CCV13 presents a predominant textural composition of fine sand, poorly to moderately sorted. A shift with the increase in depth to medium and coarse sand, poorly to well sorted is observed. According to the Blott and Pye (2012) classification, the sediments in this core are very slightly muddy sand, slightly muddy sand, gravelly sand, slightly gravelly sand and very slightly gravelly sand.

Table 2: General characteristics (main textural type, mean grain size (µm) and sorting) of the Costa da Caparica studied cores.

Core	Depth Interval (cm)	Main textural type	Mean grain size (µm)	Soarting	OBS
CCV2	0-50	Coarse sand	552	poorly soarted	Shells fragments
	50-145	Fine and medium sand	249	Mederatly well sorted	
	145-290	Medium sand	252	Mederatly to well sorted	
CCV3	0-100	Fine and very fine sand	196	Mederatly to well sorted	
	100-145	Medium and coarse sand	398	Poorly sorted	Shells fragments
	100-290	Coarse sand	748	Poorly sorted	Shells fragments and bioclasts
CCV4	0-145	Fine and medium sand	259	Moderatly sorted	
	145-179	Medium sand	296	Moderatly well sorted	
	179-218	Coarse sand	459	Poorly sorted	Shells fragments
	218-290	Medium sand	290	Well sorted	
CCV5	0-65	Fine sand	226	Well sorted	
	65-178	Coarse sand	603	Poorly sorted	
	178-290	Fine and medium sand	263	Moderatly to well sorted	
CCV6	0-100	Fine sand	210	Moderatly well sorted	
	100-214	Medium sand	296	Poorly to moderatly sorted	shells fragments
CCV7	0-125	Fine sand	210	Moderately well sorted	
	125-195	Medium sand	320	Moderately to well sorted	
	195-290	Medium and fine sand	278	Well sorted	
CCV8	0-110	Medium sand	356	Poorly sorted	
	110-140	Coarse sand	799	Poorly sorted	Shells fragments
	140-290	Medium and fine sand	269	Moderately to well sorted	
CCV9	0-100	Fine sand	210	Moderately sorted	
	100-225	Medium and coarse sand	335	Moderately to poorly sorted	
	225-290	Fine and medium sand	313	Moderately sorted	
CCV10	0-135	Fine and medium sand	259	Moderately to well sorted	
	135-198	Coarse sand	751	Poorly sorted	Shells fragments
	198-290	Medium sand	297	Well sorted	
CCV11	0-145	Medium and fine sand	280	Moderately to well sorted	
	145-200	Medium and coarse sand	375	Poorly sorted	Shells fragments
	200-290	Medium sand	318	Well sorted	
CCV12	0-145	Medium, fine and coarse sand	365	Poorly sorted	Shells fragments
	145-170	Coarse sand	475	Moderately sorted	Shells fragments
	145-290	Medium sand	350	Moderately to well sorted	
CCV13	0-145	Fine sand	173	Poorly to moderatly sorted	
	145-185	Medium and coarse sand	310	Poorly to well sorted	
	185-290	Coarse and very coarse sand	845	Moderately sorted	Bioclasts

4.2 Sedimentary units definition and characterization

The detailed observation and description of the 12 cores' sediment allowed to visually highlight 4 different sedimentary units, Unit 1 being the oldest and Unit 4 the most recent one.

The main textural composition of Unit 1, has been identified as Medium Sand with a mean grain size varying from 325 µm to 250 µm. The statistical parameters present a variation within this unit and the sorting appears to range from moderately sorted to well sorted. The skewness ranges from very negatively skewed to negatively skewed and the kurtosis from leptokurtic to very leptokurtic. The carbonate content also presents a variation ranging from 1,8 % to 9,9 %. According to the Blott and Pye (2012) classification the sediment in Unit 1 is sand.

Unit 2 has larger textural compositional variations from Medium Sand to Coarse Sand as the major sand types, together with contributions of very coarse sand and very fine gravel with a mean grain size varying from 845 µm to 315 µm. The grain parameters vary from poorly sorted to moderately sorted, positively skewed to very negatively skewed and platykurtic to leptokurtic. The carbonate concentration shows a variation from 6,4 % to 13,9 %. According to the Blott and Pye (2012) classification the sediment in Unit 2 are gravelly sand, slightly gravelly sand and very slightly gravelly sand.

In Unit 3, the mean grain size varies from 263 µm to 207 µm being mainly represented by fine sand. The carbonate concentration ranges from 5,1 % to 29,3 %. Subsequently the grain parameters represent a variation of poorly sorted to moderately well sorted, negatively skewed to symmetrical and leptokurtic to mesokurtic. According to the Blott and Pye (2012) classification the sediment in Unit 3 are very slightly muddy sand, slightly muddy sand, very slightly gravelly very slightly muddy sand and sand.

The predominant textural type of Unit 4 is fine sand, yet it also has a large contribution of medium sand. The mean grain size of this unit ranges from 171 µm to 280 µm. Regarding the $CaCO_3$, the values range from 3,6 % to 17,1 %. According to the Blott and Pye (2012) classification the sediment in Unit 4 is sand.

The grain parameters, mean grain size, $CaCO_3$ content and all the others variables used to define these units are shown in the following Figures (10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21) and described core by core in the following paragraphs.

Core CCV2 (Figure 10) comprises units 1 and 2. In this core, Unit 1 represents a total thickness of 228 cm and is characterized as having a gray toned sand with an average fine sand and medium sand content of 60 % and 25 %, respectively, and a mean grain size of 250 µm. The carbonate has a minimum concentration of 8,5 % and a maximum of 15 %. Unit 2 (47 cm thick) is characterized by a grayish and yellowish gray sand with a mean grain size of 551 µm. The carbonate concentration varies from 13,8 to 13,9 %. The limit between units on this core is clear marked.

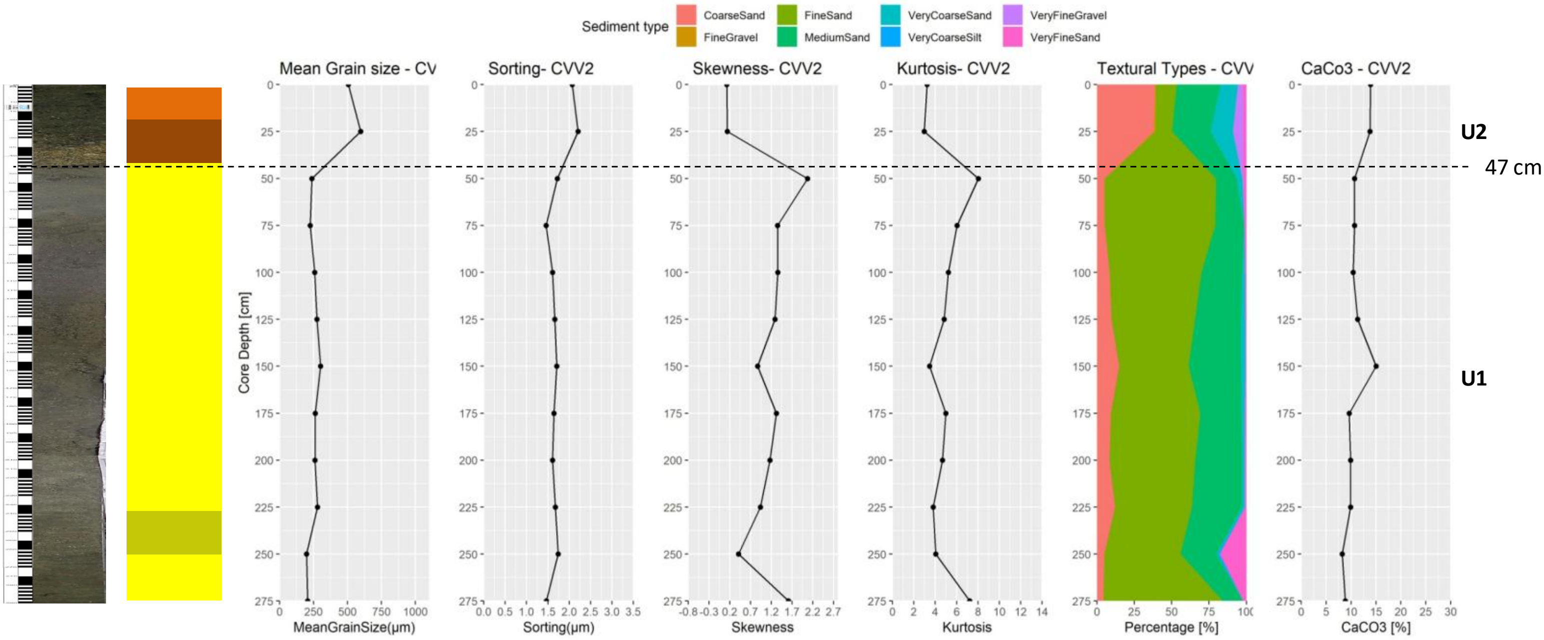

Figure 10: Core CCV2 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U2 and U1 represent the sedimentary unit observed in the present core. Log classes colour on this core: Very slightly gravelly sand (light brown), slightly gravelly sand (brown), sand (yellow) and very slightly muddy sand (green) (see Figure 9).

In core CVV3, Units 2 (152 cm thick) and 3 (123 cm thick) are observed, but not units 1 and 4. Unit 2 is represented mainly by coarse sand and very coarse sand with a mean grain size of 719 µm, being poorly sorted, fine skewed and mesokurtic distribution. The carbonate content ranges from 9,8 % and 13,1 %. Unit 3 presents fine and medium sand with respective average content of 46,6 % and 26 % and a mean grain size of 207 µm. The $CaCO_3$ content varies from

8,5 % to 11,7 %. The limit between units on this core is transitional. These characteristics are represented in Figure 11.

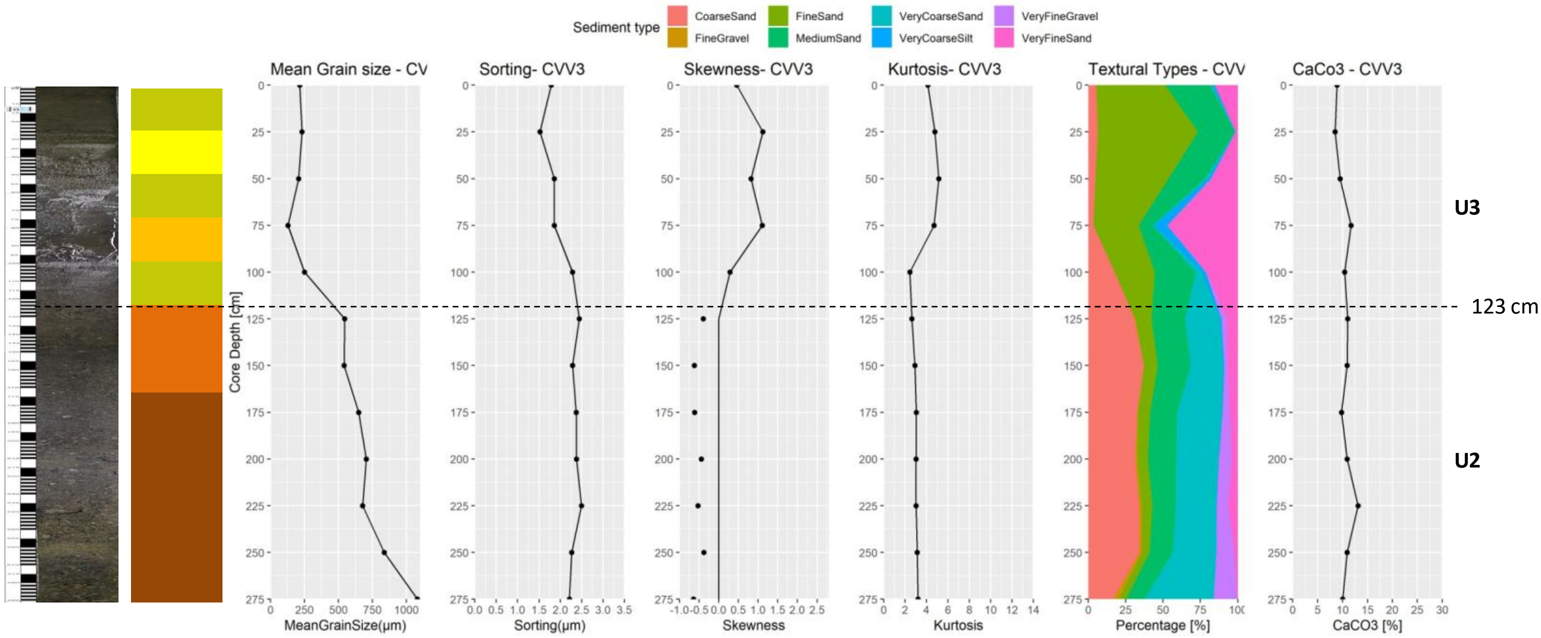

Figure 11: Core CCV3 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on this core: Very slightly muddy sand (green), sand (yellow), slightly muddy sand (orange), very slightly gravelly sand (light brown) and slightly gravelly sand (brown). (see Figure 9).

Unit 1, 2 and 3 are present in core CCV4 (Figure 12). Unit 1 (57 cm thick) is mainly represented by medium sand with a mean grain size of 289 µm, moderately well sorted with a very coarse skewed leptokurtic distribution. The carbonate content ranges from 6,6 to 9,9 %. Unit 2 has a thickness of 63 cm composed mainly of medium sand. In addition, the carbonate concentration ranges from 7,1 % to 8,6 %. Unit 3 (155 cm thick) shows yellowish to grayish sediments mainly composed of fine sand but with notable contributions of medium sand and very fine sand with the carbonate concentration varying from 5,1 to 12,9 %. The limits between units on this core are clear.

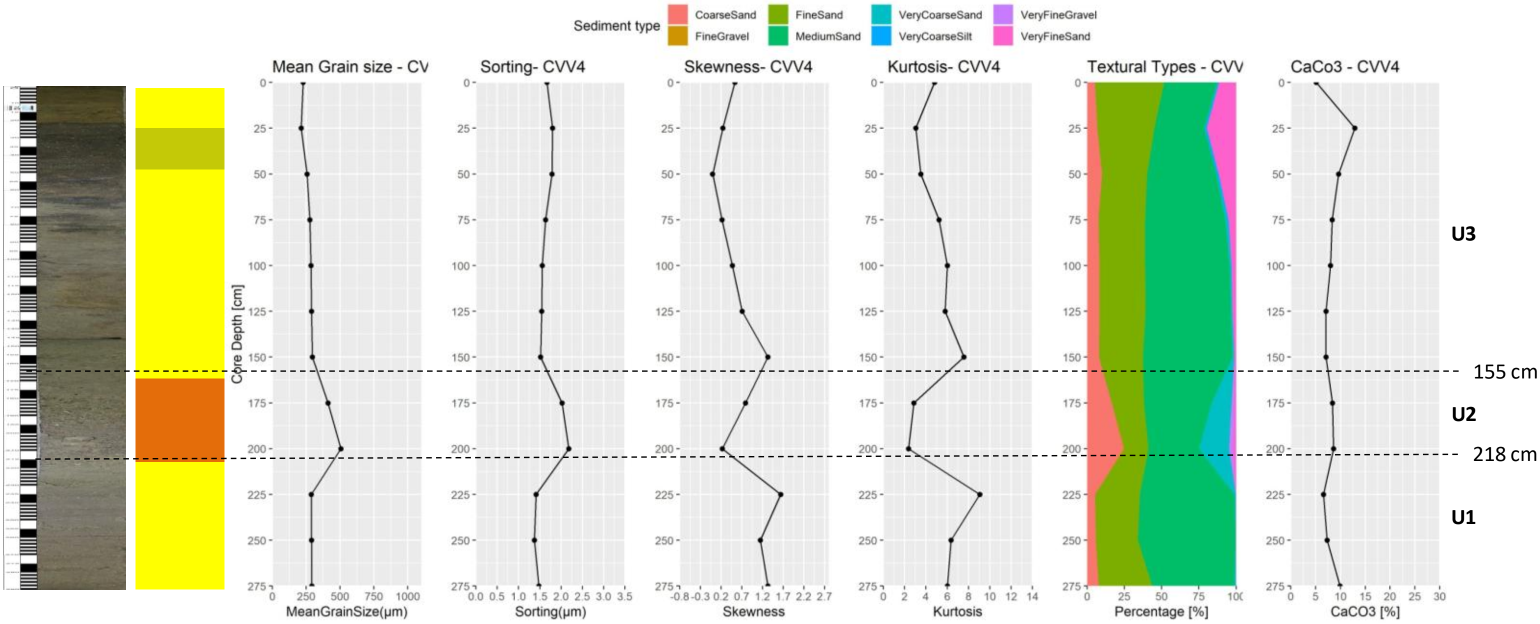

Figure 12: Core CCV4 sedimentary unit analysis From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow), very slightly muddy sand (green) and very slightly gravelly sand (light brown). (see Figure 9).

Core CCV5 (Figure 13) comprises of Units 1, 2 and 3. In this core, Unit 1 (97 cm thick) is represented mainly by fine and medium sand having a mean grain size of 262 µm. The carbonate content ranges from 9,2 % to 12 %. Unit 2 has an average composition of medium sand (49 %), fine sand (27 %) and coarse sand (22 %) with a mean grain size of 602 µm. The carbonate content varies from 11,7 to 13 %. Unit 3 is mainly represented by fine sand with a mean grain size of 232 µm. The respective unit has a thickness of 75 cm and variations in the carbonate content ranging from 7,4 to 11,6 %. The limits between units on this core is clear downwards and transitional upwards.

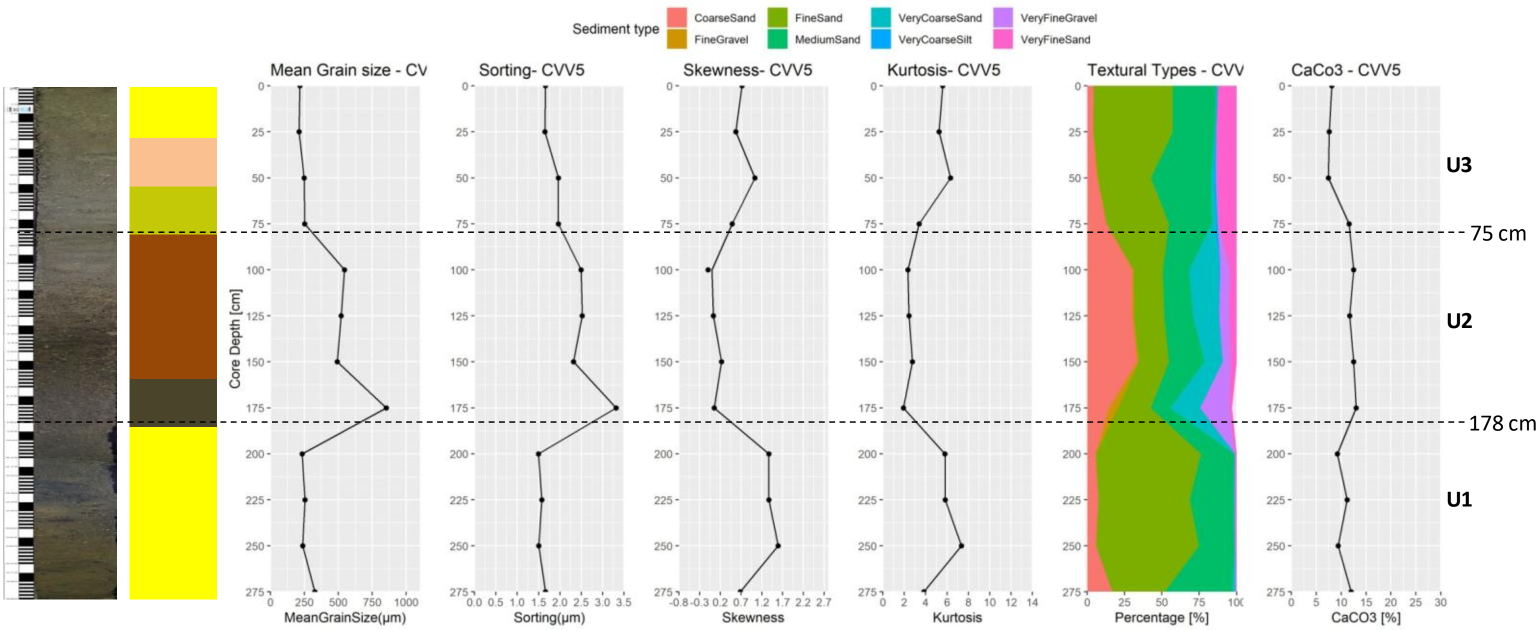

Figure 13: Core CCV5 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow), very slightly gravelly very slightly muddy sand (pink), very slightly muddy sand (green), slightly gravelly sand (brown) and gravelly sand (black). (see Figure 9).

Core CCV6 is also composed of Units 1, 2 and 3, with some variations that are shown in Figure 14, and detailed below.

In Core CCV6, the main characteristics of Unit 1 is its composition of medium sand (mean grain size = 262 µm) with the carbonate concentration varying from 6,1 % to 6,6 %). The main characteristics of Unit 2 are a variation in the $CaCO_3$ concentration from 6,4 % to 8,1 % and a composition of medium and fine sand. Unit 3 is mainly composed of fine and very fine sand (mean grain size = 209 µm). The carbonate percentage ranges from 5,6 % to 12,9 %, representing the largest variation and the highest concentration on this core. The limits between units on this core are transitional.

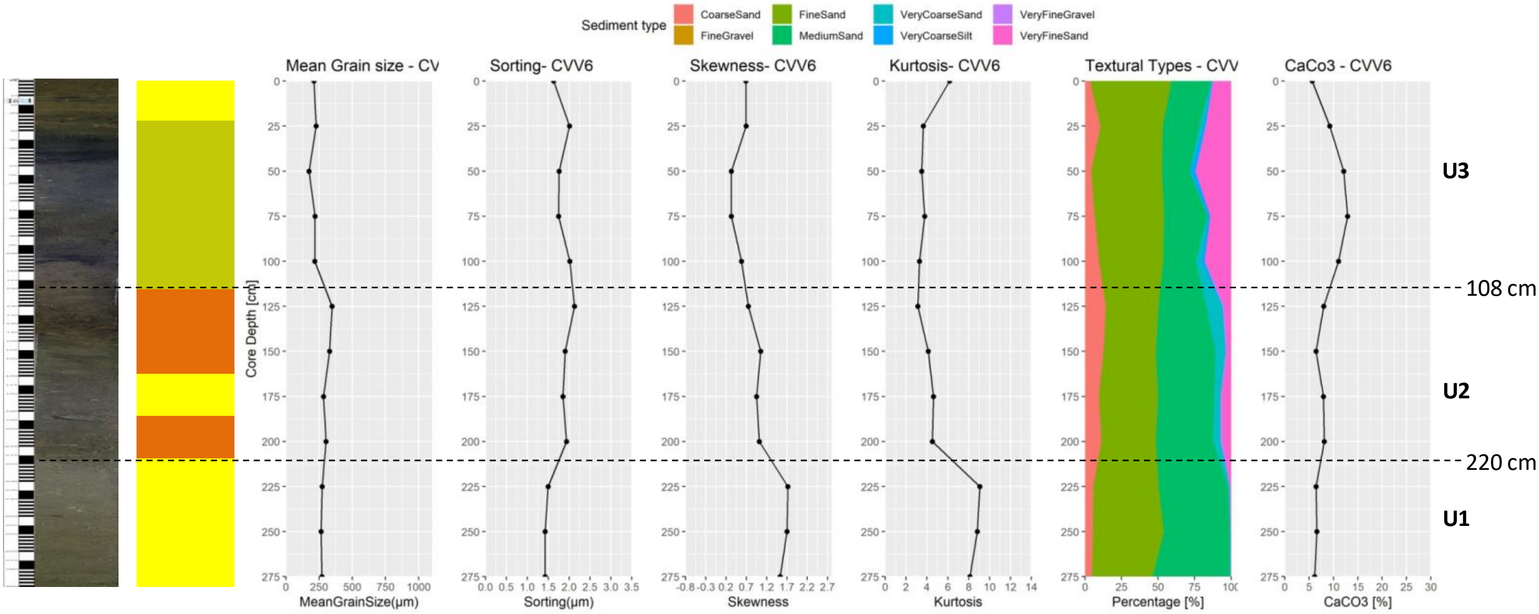

Figure 14: Core CCV6 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (μm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow), very slightly muddy sand (green), very slightly gravelly sand (light brown). (see Figure 9).

Core CCV7 (Figure 15) is represented by the Units 1 (151 cm thick), 3 (75 cm thick) and 4 (49 cm thick). Unit 1 is composed mainly by medium and fine sand with a carbonate concentration ranging from 7,1 % to 9,2 %. Unit 3 presents very coarse and medium sand with shell fragments. The referred unit demonstrates the highest variations in $CaCO_3$ content when compared to all the other cores (10,6 % to 29,3 %). The main characteristics of Unit 4 are represented by fine sand and very fine sand, with a mean grain size of 171 μm. The carbonate content varies from 3,6 % to 7,9 %. The limits between units on this core are clear marked.

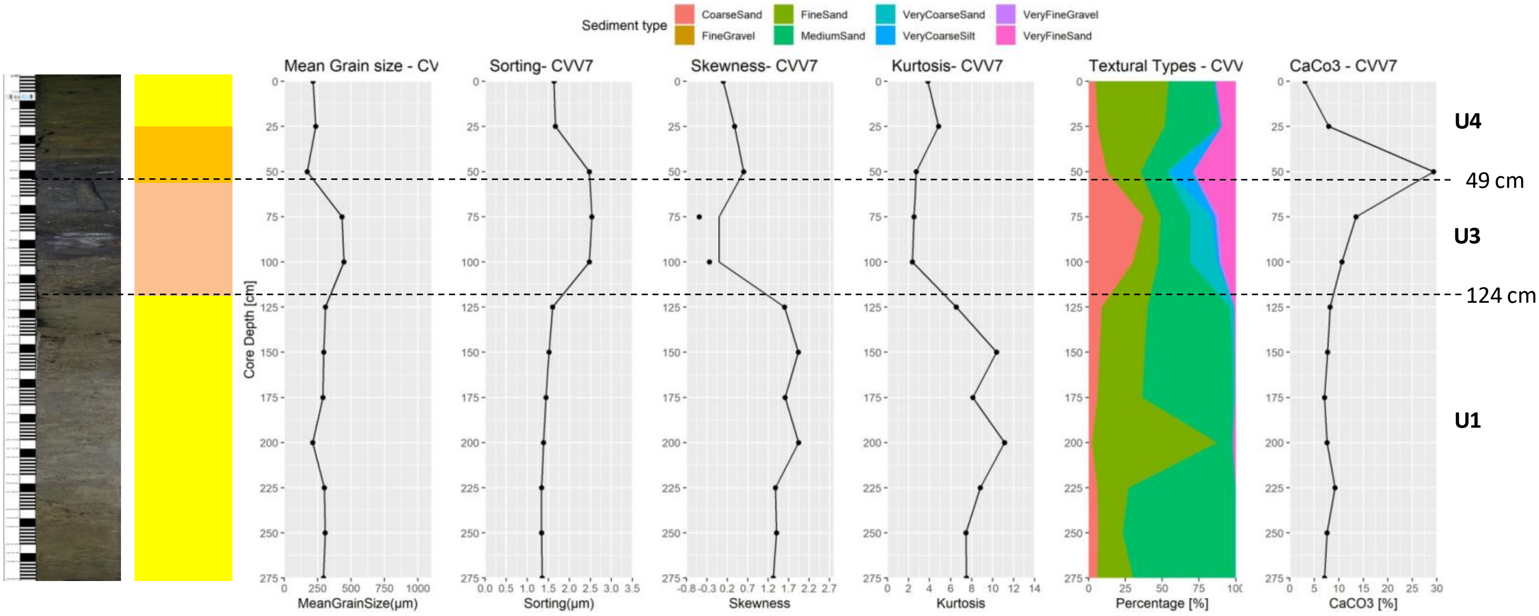

Figure 15: Core CCV7 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U3 and U4 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow), slightly muddy sand (orange) and very slightly gravelly very slightly muddy sand (pink). (see Figure 9).

Units 1 and 2 are presented in core CCV8 (Figure 16). Unit 1 (135 cm thick) shows pre-eminent characteristics which are a sediment with a composition of fine and medium sand. Regarding the $CaCO_3$, this core presents the lowest value in all the samples, ranging from 1,8 % to 9,2 %. Unit 2 (140 cm thick) is characterized by medium to fine and coarse sand, with a mean grain size of 429 µm and a carbonate concentration varying from 9,1 % to 11,6 %. The limit between units on this core is marked.

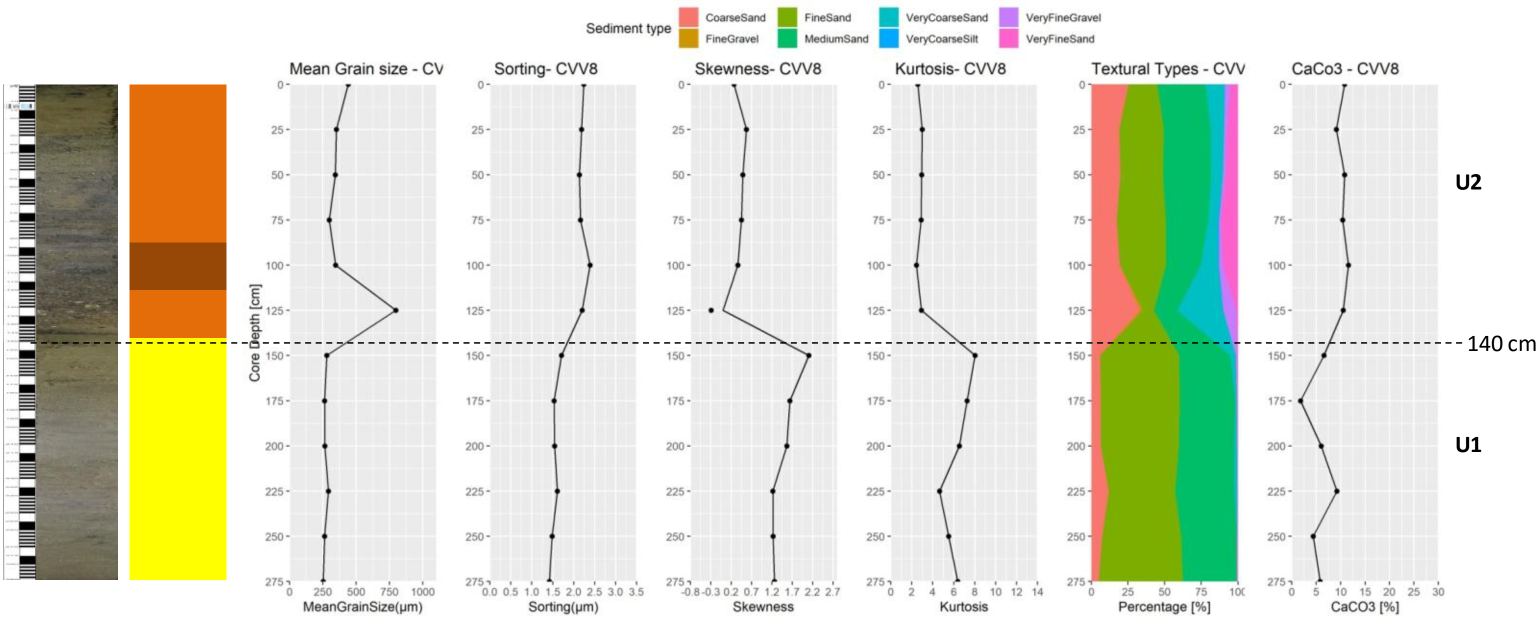

Figure 16: Core CCV8 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1 and U2 represent the sedimentary unit observed in the present core. Log classes colour on this core: Very slightly gravelly sand (light brown), slightly gravelly sand (brown) and Sand (yellow). (see Figure 9).

Core CCV9 changes the pattern in comparison with almost all the previously presented cores, since it has Unit 2 at the base of the sedimentary sequence. This core is represented solely by Unit 2 (176 cm thick) and 3 (99 cm thick), with however a transitional section that has been included in Unit 2 as unit 2 (transition) (Figure 17). Unit 2 and its transition show composed of primarily medium sand. The $CaCO_3$ content ranges from 7,3 % to 10,9 %. A mean grain size of 209 µm represents Unit 3 and a variation in the $CaCO_3$ content between 9 % and 13,7 %.

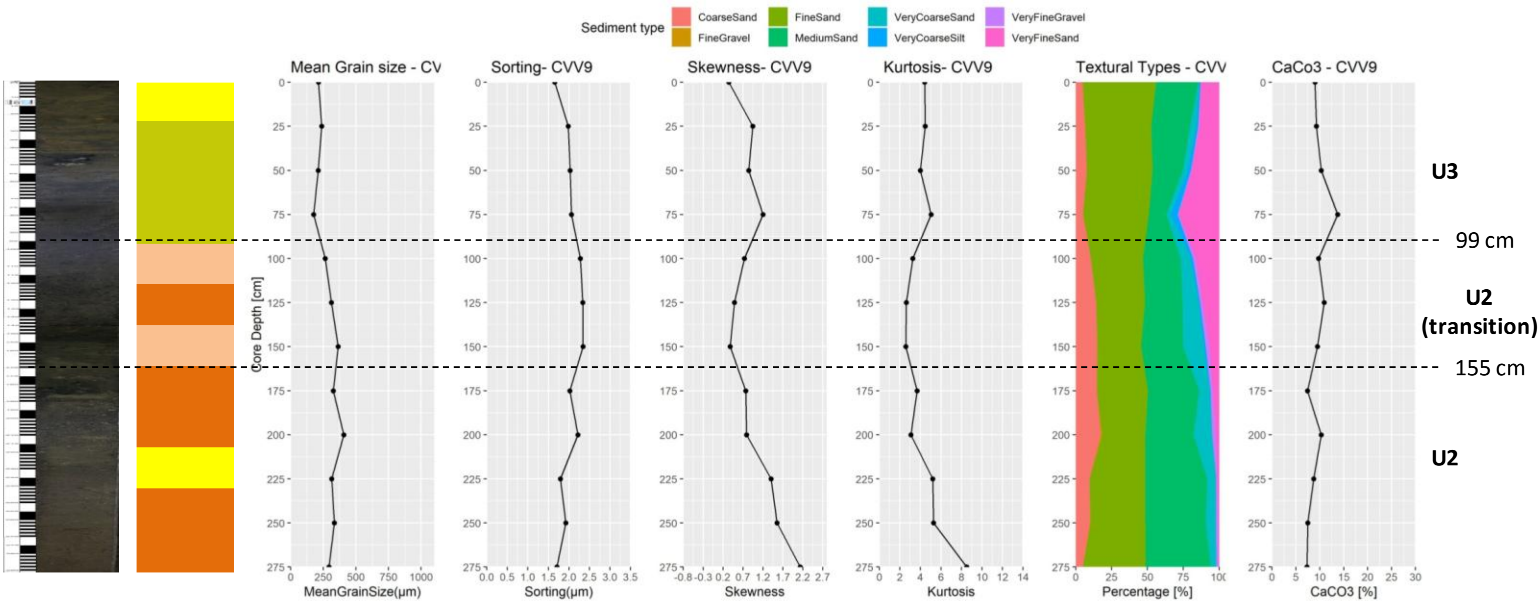

Figure 17: Core CCV9 sedimentary unit analysis From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U2, U3 and a transition between U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on the core: Sand (yellow), very slightly muddy sand (green), very slightly gravelly very slightly muddy sand (pink) and very slightly gravelly sand (light brown). (see Figure 9).

Sedimentary Units 1, 2 and 4 constitute core CCV10 (Figure 18). The main characteristics of Unit 1 (77 cm thick) is a sediment defined as medium sand with a mean grain size of 296 µm and a $CaCO_3$ ranging from 7,1 % to 8,7 %. The main characteristics of Unit 2 (75 cm thick) are that the sediment is mainly composed of coarse and medium sand (mean grain size = 484 µm) and a variation in the carbonate concentration from 9,9 % to 12,2 % presenting the higher concentration in this core. Finally, Unit 4 presents a total thickness of 123 cm characterized as mainly composed of fine and medium sand (mean grain size = 247 µm), and a $CaCO_3$ content that ranges from 8,3 % to 11,9 %. The limits between units on this core is clear downwards and transitional upwards.

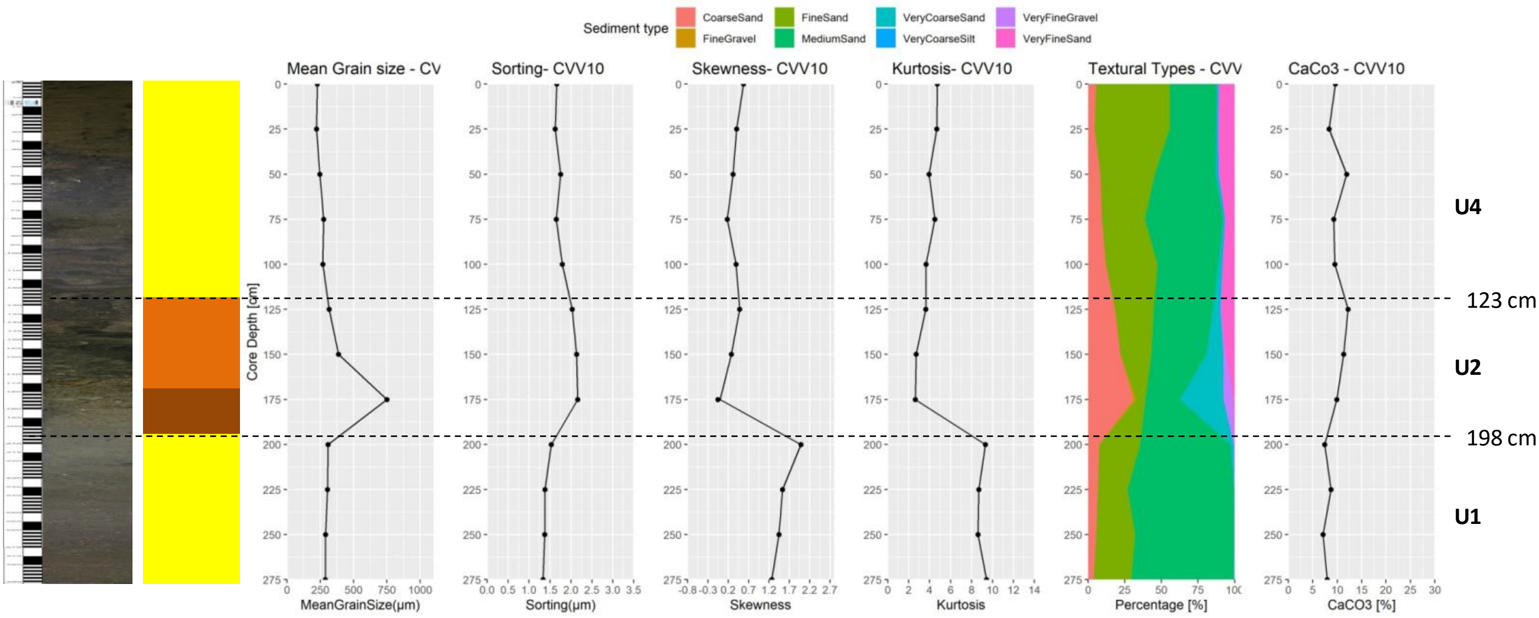

Figure 18: Core CCV10 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U2 and U4 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow), very slightly gravelly sand (light brown) and slightly gravelly sand (brown). (see Figure 9).

Core CCV11 is composed of the Units 1, 2 and 4 (Figure 19). Unit 1 represents a total thickness of 47 cm. This Unit is mainly composed of medium sand (70 %) with a mean grain size of 311 µm and the carbonate content shows a variation from 8,1 to 7,8 %. The principle aspects of Unit 2 (86 cm thick) are a composition of medium and coarse sand. The $CaCO_3$ content varies from 6,8 to 12,6 %. Unit 4 (142 cm thick) comprises medium and fine sand (mean grain size 280 µm) and a concentration of carbonate ranging from 8,6 to 17,1 %. The limits between units on this core are transitional downwards and clear upwards.

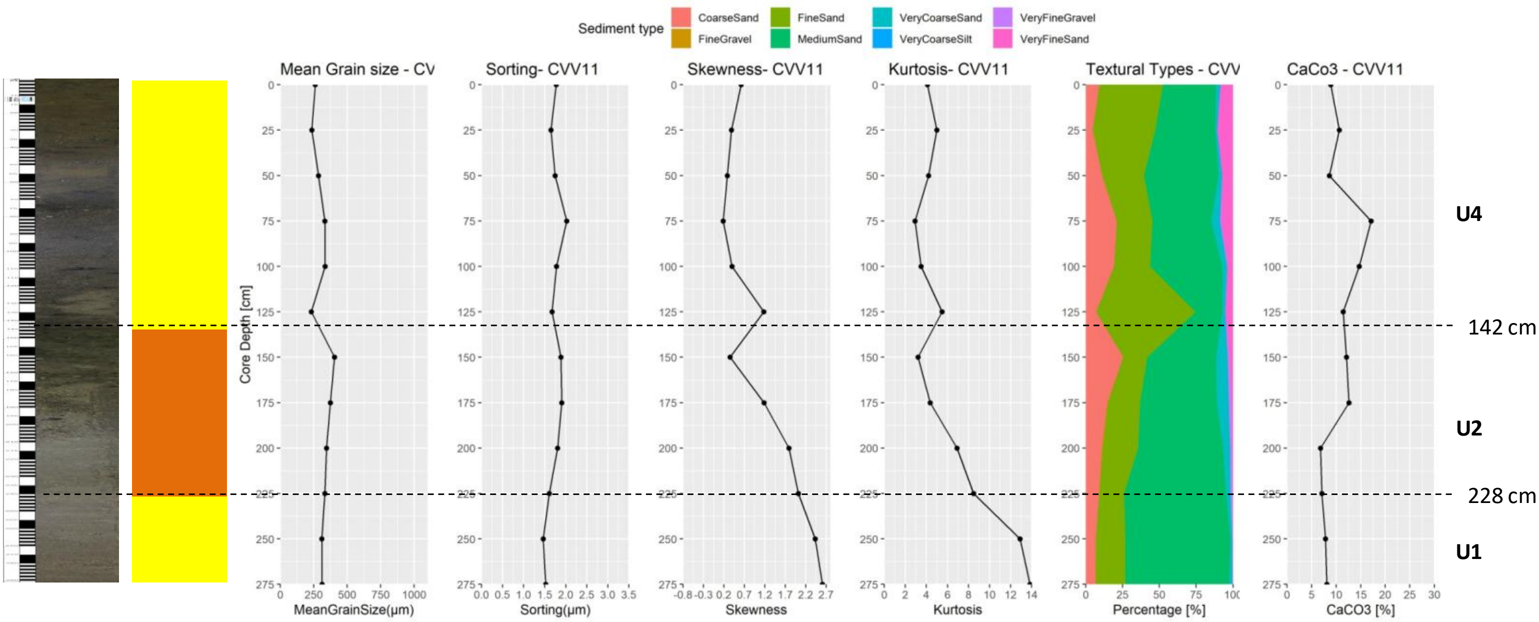

Figure 19: Core CCV11 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1, U2 and U4 represent the sedimentary unit observed in the present core. Log classes colour on this core: Sand (yellow) and very slightly gravelly sand (light brown). (see Figure 9).

Core CCV12 is represented by the Units 1 and 2 (Figure 20). Unit 1 (104 cm thick) shows a preeminent textural composition of medium and fine sand. The $CaCO_3$ content varies from 2,1 % to 8,5 %. The main aspects of Unit 2 (171 cm thick) is medium sand, presenting a mean grain size of 347 µm and a variation in the carbonate content of 6,5 % to 13,5 %. The limits between the units on this core are transitional.

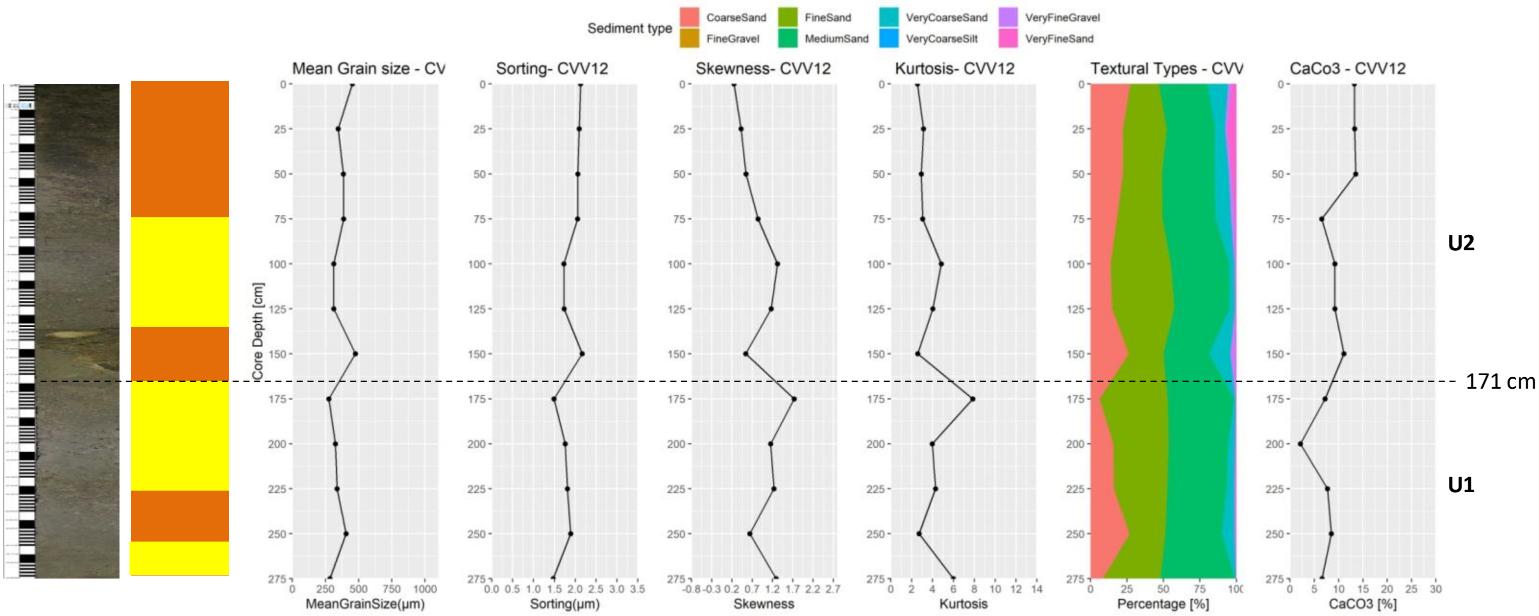

Figure 20: Core CCV12 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U1 and U2 represent the sedimentary unit observed in the present core. Log classes colour on this core: Very slightly gravelly sand (light brown) and sand (yellow). (see Figure 9).

Finally, in the core CVV13, both Units 2 (185 cm thick) and 3 (90 cm thick) are observed. Unit 2 is mainly represented by very coarse and coarse sand with a mean grain size of 845 µm, being poorly sorted with a symmetrical distribution. The carbonate content varies from 9,5 % to 12,8 %. Unit 3 presents fine and very fine sand with a mean grain size of 207 µm. The $CaCO_3$ content varies from 8,3 % to 16 %. The limit between units on this core is clear marked. These characteristics are shown in Figure 21.

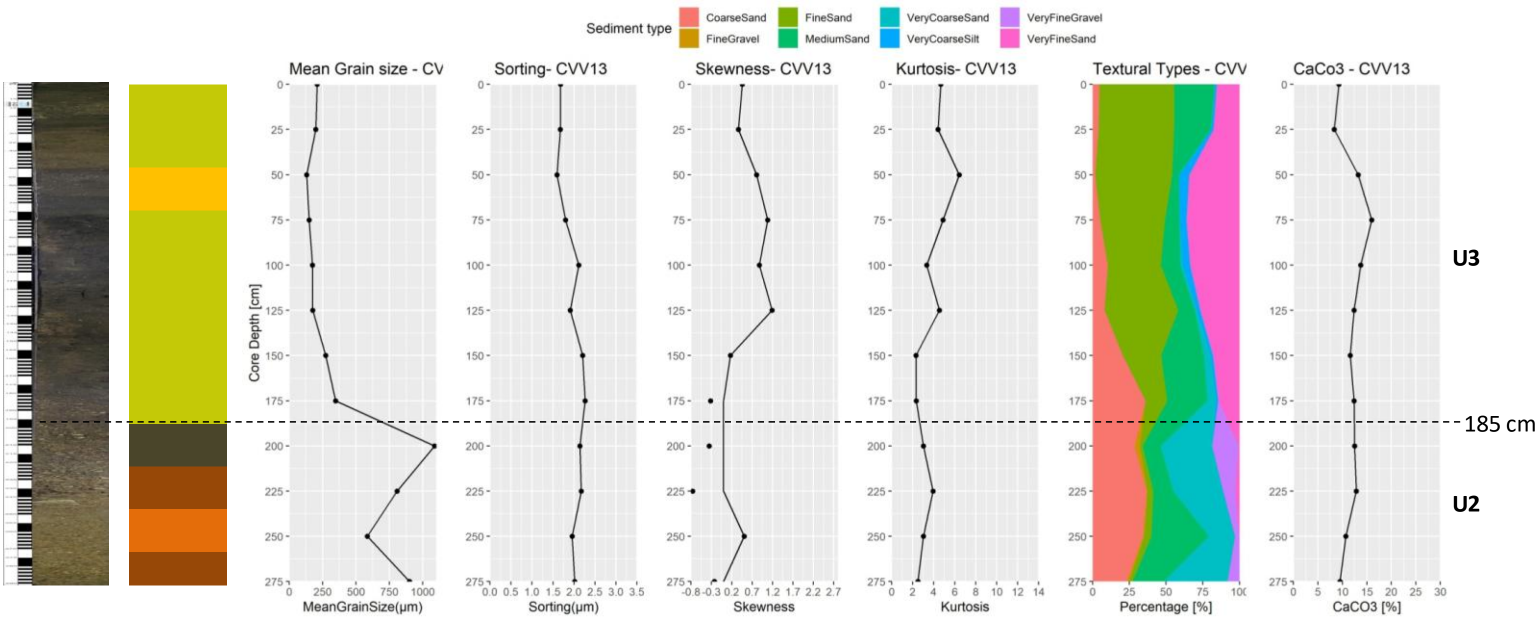

Figure 21: Core CCV13 sedimentary unit analysis. From left to right: Core photo, core log, mean grain size (µm), skewness, kurtosis, textural types (%) and Carbonate (%) of each 25 cm section in depth analyzed. Horizontal dashed line represents the limit between units. U2 and U3 represent the sedimentary unit observed in the present core. Log classes colour on this core: Very slightly muddy sand (green), slightly muddy sand (orange), gravelly sand (black), slightly gravelly sand (brown) and very slightly gravelly sand (light brown). (see Figure 9).

In summary, Unit 1 is present in nine of the 12 cores. Unit 2 is the most abundant unit, being present in eleven of the twelve analyzed cores. Unit 3 appears in seven of the twelve cores and unit 4 is the less represented unit, appearing just in three cores. Table 3 summarizes in which cores each of the four sedimentary units are present.

Table 3: Sedimentary units observed in the studied cores. Bat. = bathymetry (meters) of the cores. The presence of the observed unit in each core is marked with an X.

		Unit			
Core	Bat. (m)	1	2	3	4
CCV2	27	X	X		
CCV3	26		X	X	
CCV4	25	X	X	X	
CCV5	25	X	X	X	
CCV6	23	X	X	X	
CCV7	23	X		X	X
CCV8	23	X	X		
CCV9	21		X	X	
CCV10	21	X	X		X
CCV11	21	X	X		X
CCV12	21	X	X		
CCV13	27		X	X	

4.3 Multivariate Statistical analyses

Once the sedimentary units are visually defined based on the observation and description of mean grain-size, carbonate content, kurtosis, sorting, skewness, core log and the textural composition and their graphical representation, a PERMANOVA multivariate statistical analyses is applied to verify first that the defined units are statistically different. The analysis was applied on textural type composition data of each sedimentary unit using a Euclidian similarity matrix. The PERMANOVA indicates significant differences between the sedimentary units but not in the factors' (depth and sedimentary units) interaction. The results of the analysis are given in Table 4.

Table 4: PERMANOVA results. Analysis applied on the Euclidian distance similarity matrix. Using the factor Sedimentary Units (Se) and the factor Depth (De). Factors with a significant difference using a 95% significance level are shown in red. SS = sum of squares; df = degrees of freedom; MS =Mean Squares; Res = Residuals.

PERMANOVA significance level = 95%						
Factors	df	SS	MS	Pseudo-F	P(perm)	Unique perms
Se	3	259,79	86,598	13,007	0,001	999
De(Se)	32	228,24	7,1326	1,2346	0,113	995
Res	106	612,4	5,7773			
Total	141	1269				

Afterwards, a Post-Hoc Pairwise test was applied to identify if all the units are different between them. The results show a significant difference (p < 0,05) between Unit 2 and Unit 1, Unit 2 and Unit 3, Unit 2 and Unit 4 and Unit 1 and Unit 3. Between Unit 1 and Unit 4 and Unit 3 and Unit 4 no significant difference was observed (p > 0,05), those results being displayed in Table 5.

Table 5: Post-hoc Pairwise applied to the PEMANOVA results. Significant differences using a 95% significance level are shown in red.

PAIR-WISE TEST significance level = 95%			
Groups	t	P(perm)	Unique perms
U2, U1	4,701	0,001	999
U2, U3	3,8896	0,001	999
U2, U4	3,1334	0,001	999
U1, U3	3,3245	0,001	999
U1, U4	1,6683	0,062	999
U3, U4	1,5156	0,09	999

The information provided by PERMANOVA and Pairwise tests can also be retrieved from the MDS ordination analysis (Figure 22) and the Cluster dendrogram (Figure 23).

It is possible to recognize three distinctive groups in the MDS. The Unit 2 is notably separate from all others, the Unit 4 and Unit 1 are grouped and the Unit 3 separated from the Unit 2 and Unit 1, but part of the samples of Unit 3 are mixed with the Unit 4. These patterns follow the significant differences identified in the PERMANOVA and Pairwise.

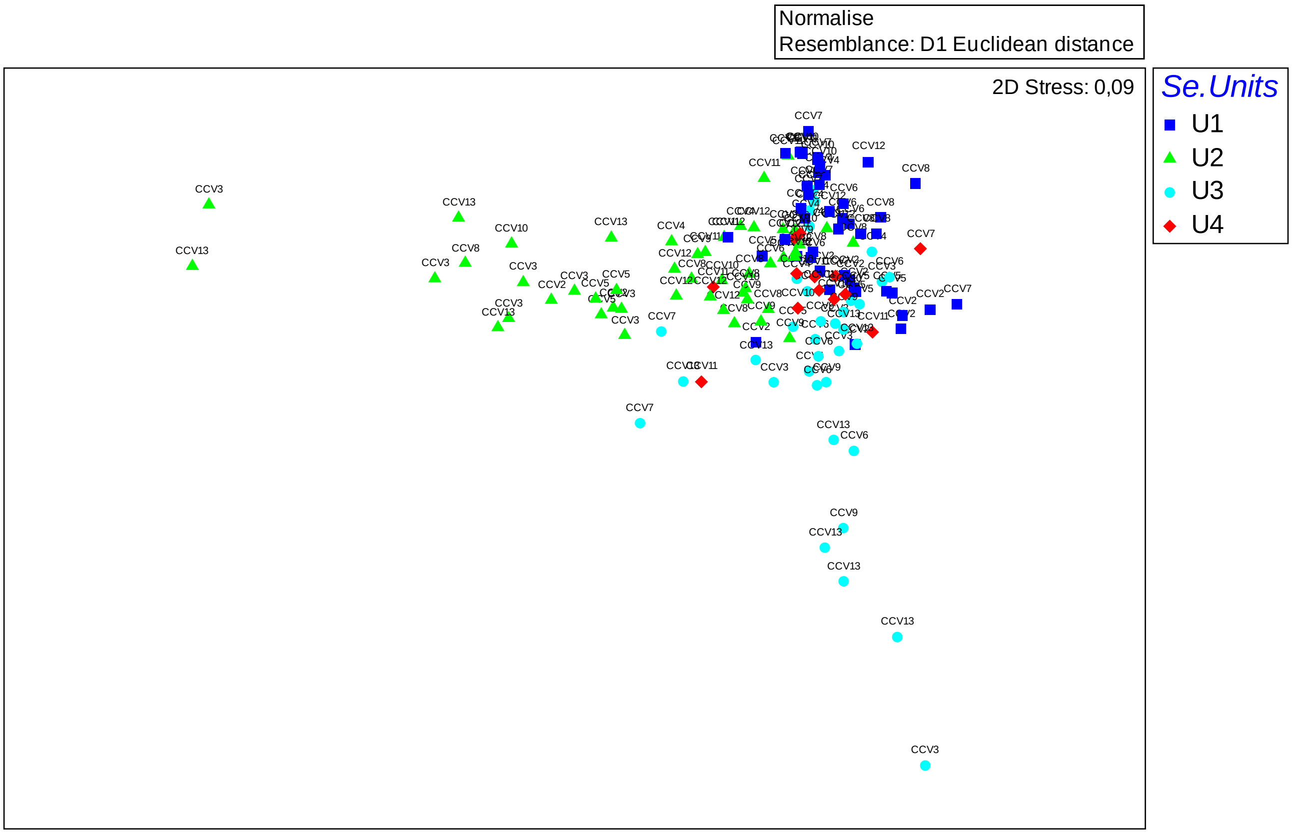

Figure 22: MDS ordering related to the sedimentary units present in the analyzed cores. Blue squares represent sedimentary unit 1, Green triangles represent sedimentary unit 2, light-blue circles represent sedimentary unit 3 and red diamond sedimentary unit 4.

Regarding the Cluster analysis (Figure 23), four different groups are recognized when doing the cut of the dissimilarity distance at circa 3,8. Group 1 is just formed by samples that represent Unit 2. However, group 2, the largest and the most mixed one, cluster Units 1, 3 and 4 but also some samples from Unit 2. The third group is mainly formed by samples from Unit 2, however with some samples of Units 1 and one sample of Unit 3. Finally, group 4, the smallest one, is composed only of samples from Unit 3. The observed patterns agree with the PERMANOVA and Pairwise tests, with significant differences between the cluster groups, in which the units that did not have significant differences are mixed and those ones that are significantly different are isolated from the others.

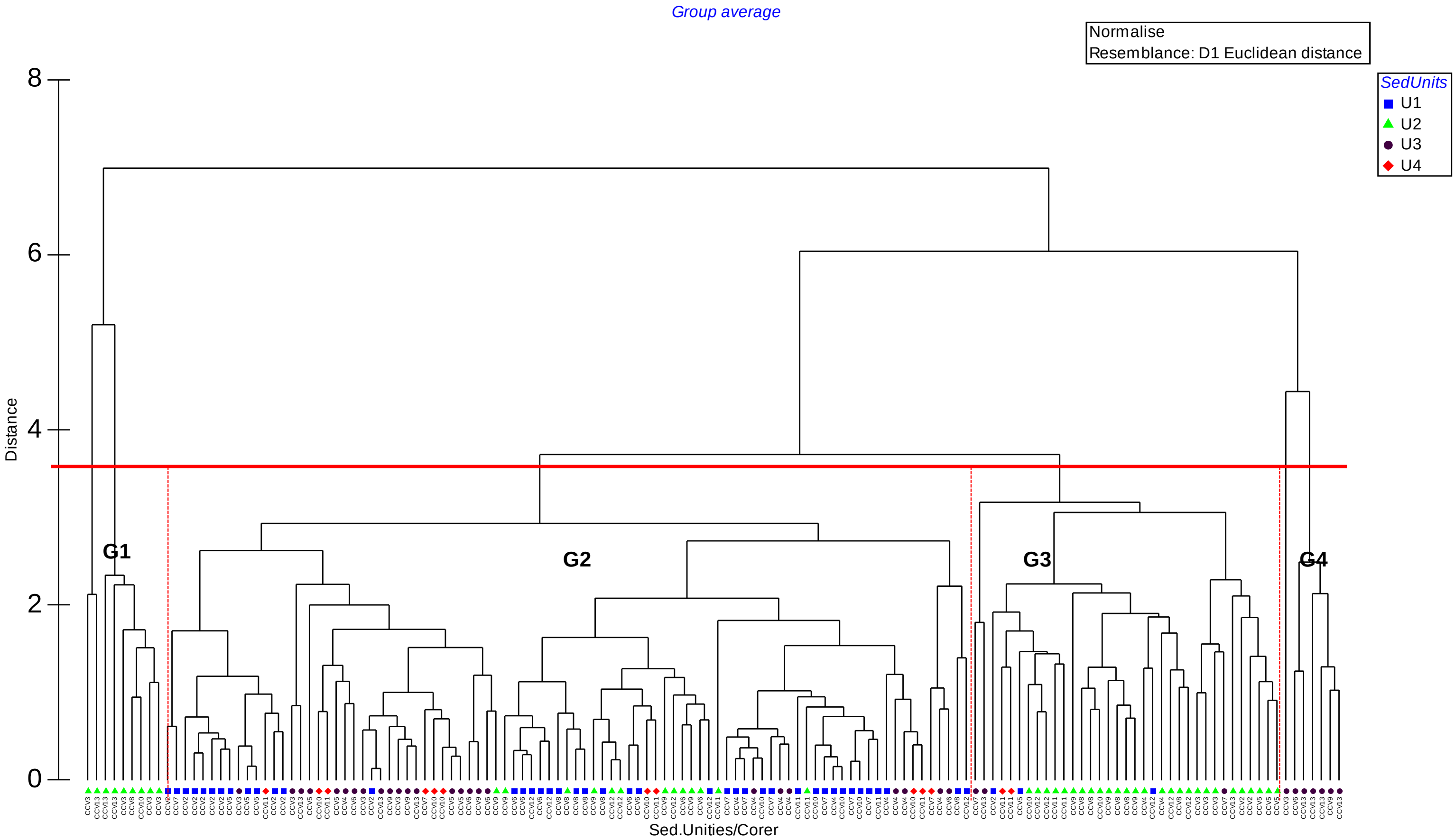

Figure 23: Hierarchical cluster analysis applied based on the Euclidian distance resemblance matrix. Dash lines represent the limits between formed groups. Solid line represents the cut used for analyze the formed groups. Blue squares represent sedimentary unit 1, Green triangles represent sedimentary unit 2, purple arrow represent sedimentary unit 3 and red diamond sedimentary unit 4.

Finally, the contribution of the variables for the average similarity inside the formed groups were tested by SIMPER analysis (Table 6). The analysis demonstrates that the variables that characterize Unit 1 are medium sand (29 %), fine sand (29 %) and $CaCO_3$ (22 %). For Unit 2, the variables are fine gravel, very fine gravel, very coarse sand and coarse sand with respectively contributions of 26 %, 22 %, 16 % and 11 %. Unit 3 is characterized by very coarse silt (34 %), very fine sand (20,33 %), $CaCO_3$ (13,38 %), coarse sand (11

%) and medium sand (10 %). Lastly, $CaCO_3$, fine sand, medium sand and coarse sand characterize Unit 4, with respective contributions of 55 %, 17 %, 11 % and 9 %. These results are given in Table 6.

Table 6: SIMPER analysis. Relative contribution (Contrib%) and cumulative contribution (Cum.%) of the textural types for the average similarity of the analyzed groups. Av. = Average; Sq.Distance = Square distance. SD = Standard deviation. Variables of greater contributions for similarity are shown in red.

Group Unity 1 Average squared distance = 3,59						Group Unity 2 Average squared distance = 8,36					
Textural type	Av.Value	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%	Textural type	Av.Value	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%
VeryFineGravel	-0,453	1,50E-02	0,35	0,42	0,42	VeryCoarseSilt	-0,305	7,09E-02	0,38	0,85	0,85
FineGravel	-0,355	1,67E-02	0,17	0,46	0,88	VeryFineSand	-0,329	0,191	0,39	2,28	3,13
VeryCoarseSilt	-0,447	2,68E-02	0,15	0,75	1,63	FineSand	-0,752	0,563	0,5	6,73	9,86
VeryCoarseSand	-0,534	3,48E-02	0,33	0,97	2,6	MediumSand	-0,259	0,576	0,42	6,89	16,75
VeryFineSand	-0,65	0,116	0,18	3,23	5,83	CaCO3	0,298	0,661	0,5	7,9	24,65
CoarseSand	-0,549	0,193	0,3	5,39	11,21	CoarseSand	0,889	0,898	0,51	10,74	35,4
CaCO3	-0,557	0,807	0,39	22,5	33,72	VeryCoarseSand	0,947	1,38	0,43	16,51	51,91
FineSand	0,5	1,06	0,49	29,47	63,18	VeryFineGravel	0,835	1,81	0,34	21,67	73,58
MediumSand	0,579	1,32	0,51	36,82	100	FineGravel	0,656	2,21	0,33	26,42	100
Group Unity 3 Average squared distance = 7,20						Group Unity 4 Average squared distance = 3,07					
Textural type	Av.Value	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%	Textural type	Av.Value	Av.Sq.Dist	Sq.Dist/SD	Contrib%	Cum.%
VeryFineGravel	-0,415	3,11E-02	0,3	0,43	0,43	FineGravel	-0,38	0	0	0	0
FineGravel	-0,321	6,03E-02	0,24	0,84	1,27	VeryFineGravel	-0,465	5,56E-03	0,37	0,18	0,18
VeryCoarseSand	-0,442	0,165	0,26	2,3	3,57	VeryCoarseSand	-0,531	2,60E-02	0,41	0,85	1,03
FineSand	0,298	0,527	0,46	7,32	10,88	VeryCoarseSilt	-9,52E-02	4,03E-02	0,49	1,31	2,34
MediumSand	-0,458	0,728	0,44	10,12	21	VeryFineSand	0,253	0,109	0,49	3,56	5,91
CoarseSand	-0,39	0,769	0,34	10,69	31,69	CoarseSand	-0,402	0,295	0,46	9,61	15,52
CaCO3	0,229	0,963	0,48	13,38	45,07	MediumSand	0,201	0,356	0,47	11,59	27,11
VeryFineSand	1,2	1,46	0,41	20,33	65,4	FineSand	0,301	0,531	0,49	17,31	44,42
VeryCoarseSilt	1,04	2,49	0,34	34,6	100	CaCO3	0,19	1,7	0,44	55,58	100

A Principle Components Analysis (PCA) was undergone using the variables: $CaCO_3$, coarse fraction (composed of fine gravel, very fine gravel, very coarse sand and coarse sand), medium sand, fine sand and very fine sand. Components 1 and 2 allowed the extraction and explanation a total of 76,5 % of the variation of the data (Table 7). The first axis PCA1 represents a total of 41,7 % of the data variation, positively correlated with medium sand and fine sand and negatively correlated with $CaCO_3$, coarse fraction and very fine sand. The second axis PC2 explains 34,8 % of the data variation and is positively correlated with coarse fraction and medium sand and negatively with $CaCO_3$, fine sand and very fine sand (Figure 24).

The PCA's pattern of distribution which separates unit 3 from the other units linked to axis 1, representing a negative correlation of this unit with the fine sediments and carbonate content. Unit 2 is separated from Units 1, 3 and 4 with a positive correlation with coarse sediments and medium sand and with axis 2. Both Units 1 and 4 appear to have a positive correlation with medium sand but Unit 4 is also correlated with fine sand as shown in Figure 24.

Table 7: PCA applied using the textural types variables present in the analyzed cores. Positives and negatives extremes coordinates of each axis are shown in red.

PCA						
Variable	PC1	PC2	PCs	%Variation	Cum.%Variation	Eigenvalues
CaCo3	-0,529	-0,189	1	41,7	41,7	2,08
Coarsefraction	-0,544	0,405	2	34,8	76,5	1,74
MediumSand	0,452	0,413				
FineSand	0,396	-0,539				
VeryFineSand	-0,251	-0,582				

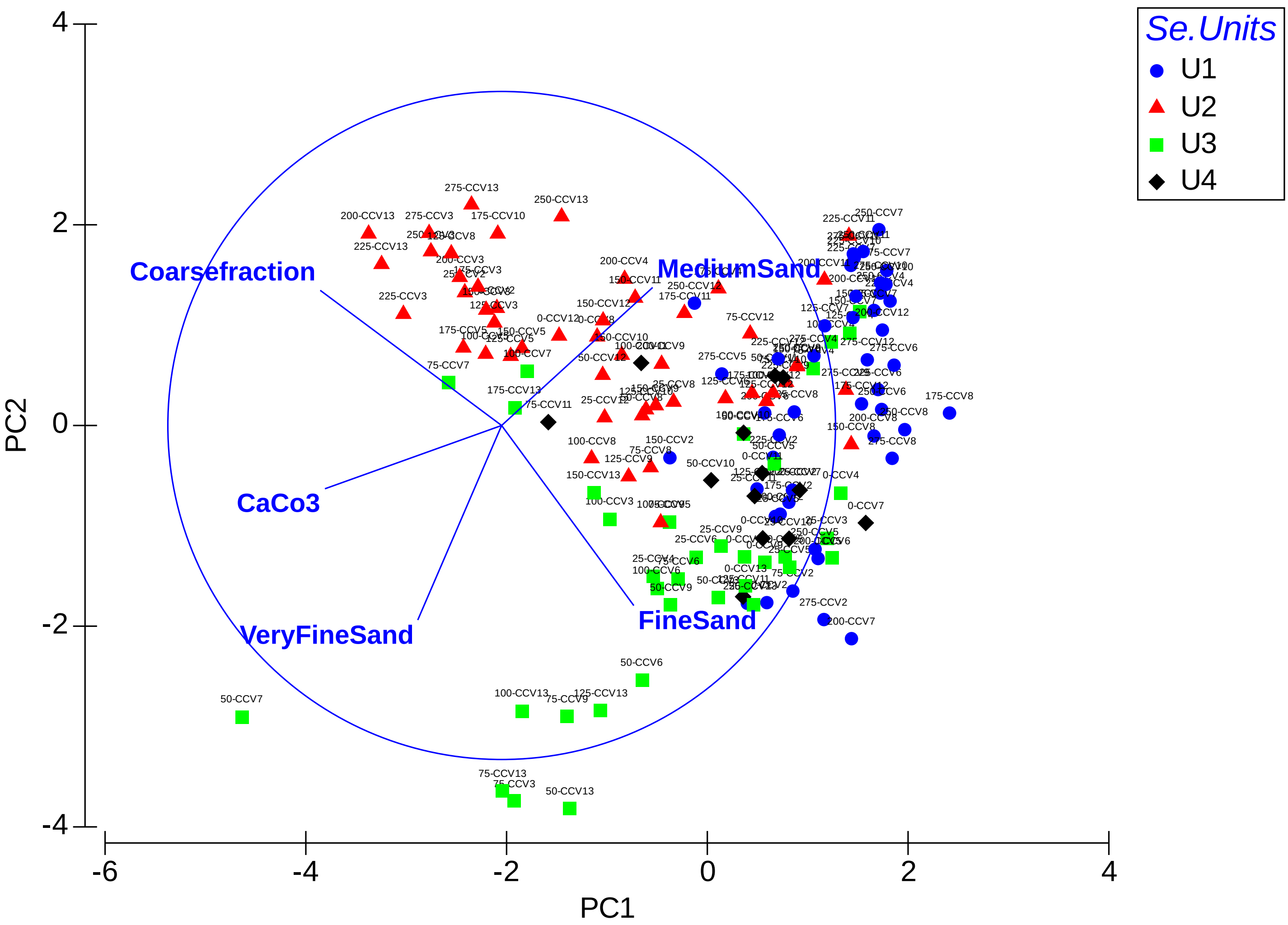

Figure 24: Principle components analysis (PCA) results, axis 1 and 2 are illustrated. Blue circles represent sedimentary unit 1, red triangles represent the sedimentary unit 2, green squares represent sedimentary unit 3 and purple diamond sedimentary unit 4.

4.4 Correlation of sedimentary units

The sedimentary units identified in the Costa da Caparica borrow area present a varying pattern of thickness and depth location along the different cores. An attempt of correlation of the sedimentary units is presented in the Figure 25, Figure 26, Figure 27 and Figure 28.

For the correlation, the cores were organized following an orientation West-East, and divided into 4 different transects.

The transect 1 (T1) is represented by cores CCV9, CCV10, CCV11 and CCV12 (Figure 25). In this transect, Unit 1 correlates between cores CCV10, CCV11 and CCV12, although at different depths. In all of these three cores, Unit 1 starts at the core base, but presents a different thickness, being thicker in core CCV12 and thinner in the core CCV11. Unit 2 appears in all the cores along T1. However, in core CCV9 this unit appears at the core base whereas in core CCV12 it is at the top of the sedimentary sequence. In cores CCV10 and CCV11, Unit 2 is in between Units 1 and 4, the latter being present on the top of the sedimentary sequence of those two cores. For this transect, the only core that presents Unit 3 is core CCV9 and this unit is observed on the top of the sedimentary sequence.

In transect 2 (T2), which includes cores CCV6, CCV7 and CCV8 (Figure 26), Unit 1 takes place on the base of the sedimentary sequence, though varying in thickness, being thicker in core CCV7 and thinner in core CCV6. Unit 2 does not appear in core CCV7 and takes place on the top of the sedimentary sequence in core CCV8 and appears in the core CCV6 in between Units 1 and 3. Unit 3 is at the top of the sequence of core CCV6 and in core CCV7 Unit 3 is in between Units 2 and 4. Unit 4 is just observed in core CCV7 being at the top of the sedimentary sequence.

Transect 3 (T3) is represented by the cores CCV3, CCV4 and CCV5 (Figure 27). Unit 2 is at the base of the sedimentary sequence in the first core and Unit 1 in the other two cores of this transect. However, Unit 2 is present in all the three cores and all of them have Unit 3 at the top of the sedimentary sequence. Although, the thicknesses of Units 2 and 3 vary in the transect, Unit 2 is thicker in core CCV3 and Unit 3 in core CCV4.

Lastly, transect 4 (T4) is represented by cores CCV13 and CCV2 (Figure 28). The only common unit in both cores is Unit 2. However this Unit is thicker and at the base of the sedimentary sequence in core CCV13 whereas it is at the top in core CCV2. Furthermore, core CCV13 has Unit 3 at the top of the sedimentary sequence while core CCV2 has Unit 1 at the base of the sequence.

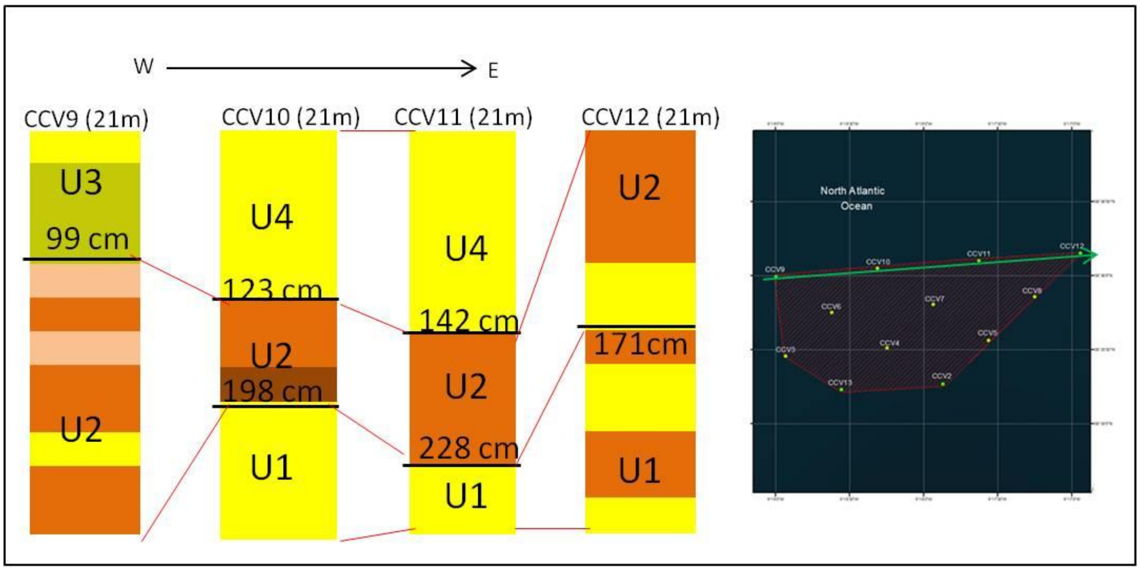

Figure 25: Correlation of the sedimentary units observed in the cores CCV9, CCV10, CCV11 and CCV12 and in brackets the water depth which each core is placed. The transect follows the direction West-East in the transect 1 (T1).

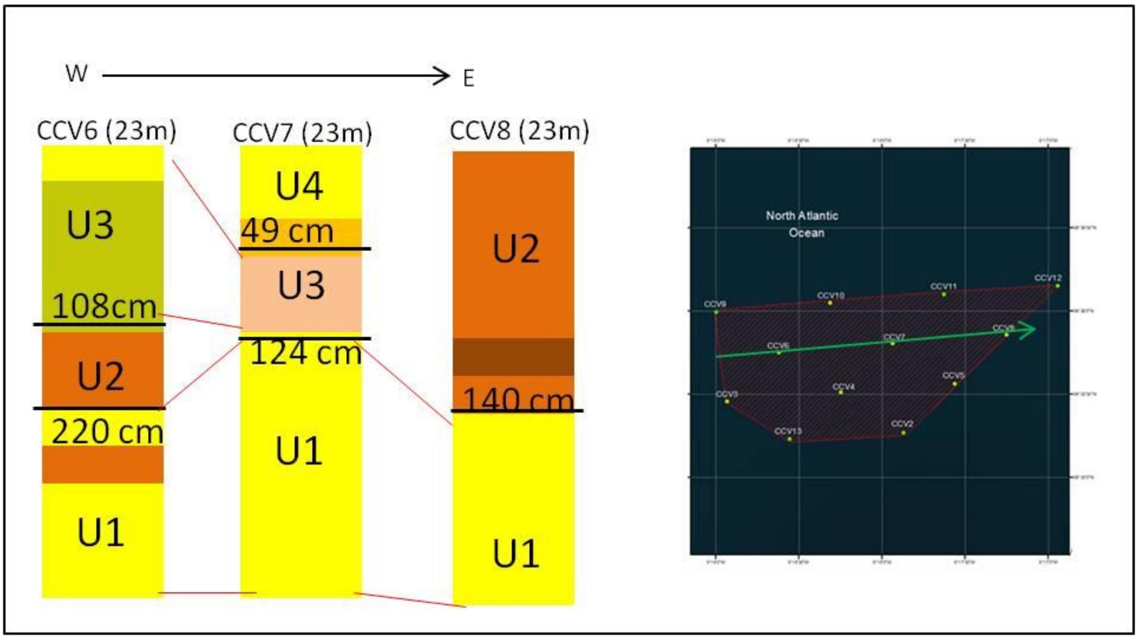

Figure 26: Correlation of the sedimentary units observed in the cores CCV6, CCV7 and CCV8 and in brackets the water depth which each core is placed. The transect follows the direction West-East in the transect 2 (T2).

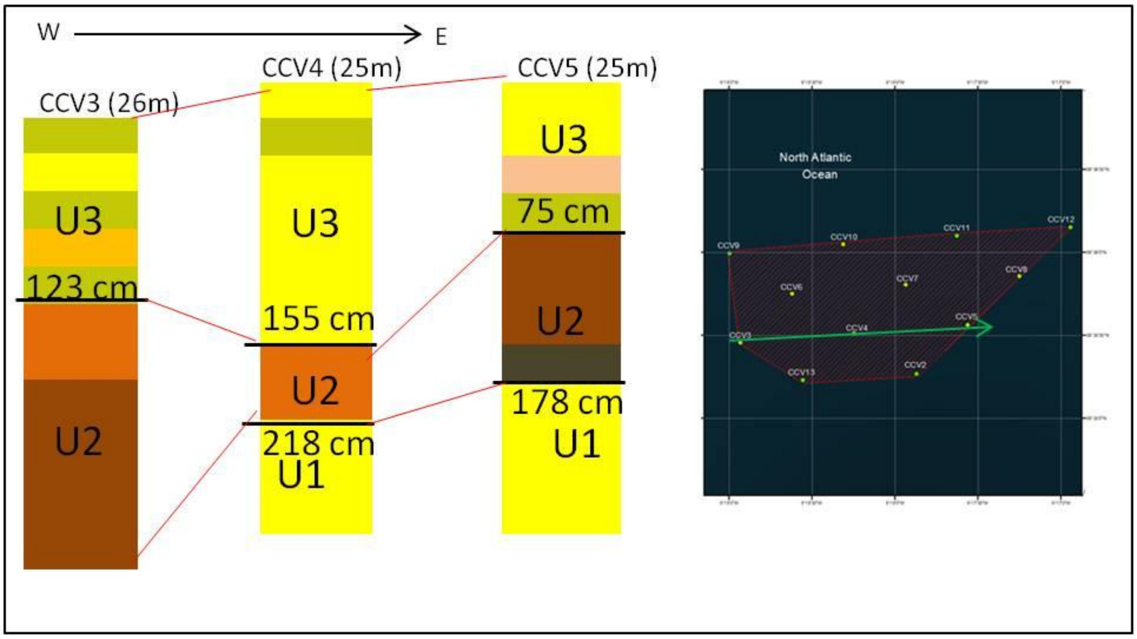

Figure 27: Correlation of the sedimentary units observed in the cores CCV3, CCV4 and CCV5 and in brackets the water depth which each core is placed. The transect follows the direction West-East in the transect 3 (T3).

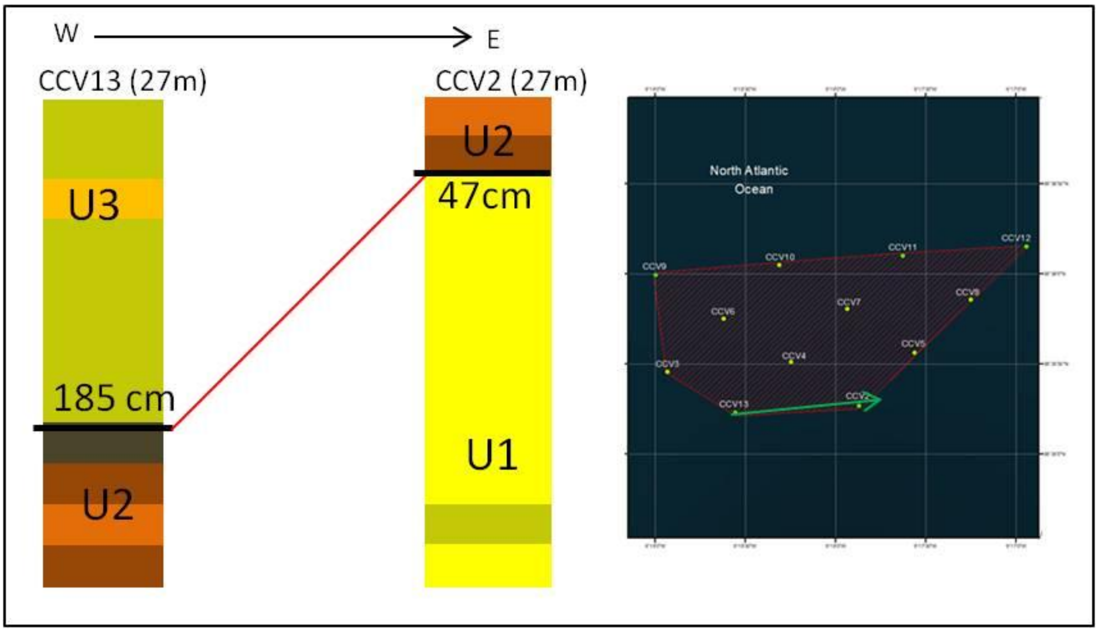

Figure 28: Correlation of the sedimentary units observed in the cores CCV13 and CCV2 and in brackets the water depth which each core is placed. The transect follows direction West-East in the transect 4 (T4).

Based on the different transect, the spatial distribution of the sedimentary units appears to follow a pattern. Most of the cores located in the westernmost part of the studied area have Unit 3 at the top of the sedimentary sequence and Unit 2 at the base, an exception being core CCV6 which has Unit 1 at the core base.

For the cores located in the easternmost part, the top of the sedimentary sequences is represented by Unit 2, an exception being core CCV5 which has the top sequence represented by Unit 3. The base of the sedimentary sequences for all the cores located in this area is represented by Unit 1.

For all the cores located in the middle of the borrow area, Unit 1 is observed at the base of the sedimentary sequence. Furthermore, for most of the cores the top of the sedimentary sequence is represented by Unit 4, with an exception being core CCV4 which has Unit 3 at the top. Additionally, all the cores located in the middle of the borrow area are represented by three different units and for most of them Unit 2 is in between the other two units previously mentioned. An exception of this is core CCV7 which has Unit 3 in between (Figure 26).

5 DISCUSSION

Comprehensive evaluation of sedimentary units plays an important role in characterizing sedimentary deposits. Moreover, the knowledge about the characteristics of the sediments and in which depths they are located in the borrow area is fundamental for achieving success in a beach nourishment project.

In the present study three of the four identified units that could be useful for the nourishment project in Costa da Caparica as discussed the sections hereafter.

5.1 Sedimentary units: possible sediment sources and variations

The Costa da Caparica borrow area is situated in a narrow (25 km length) portion of the Portuguese continental shelf and has water depths (relative to the hydrographic zero) ranging from 21 m to 27 m. In this area the sediment supply originates from the Meso-Cenozoic sedimentary rocks from the Lower Tejo Basin. The textural sources of the sediment available in the borrow area is mainly sand from the Tejo ebb delta, the cliff erosion between Lagoa de Albufeira and Bicas beach (until 20 m water depth) and carbonate sands of marine origin (> 20 m water depth) (Martins *et al.,* 2012; Taborda and Andrade, 2014; Taborda *et al.,* 2009).

The sediments in the area are transported to the inner-shelf through the hydrographic draining basin of Costa do Sol and the wind corridor Guincho/Guia (0,1 10^5 m^3/year), Tagus River (1-5 x 10^6 tones) and the north long-shore drift (in the order of 10^5 m^3/year). These sedimentary dynamics in the area are complex due the interaction of the river ebb delta, long-shore drift, waves and tides (Burdloff *et al*., 2008; Silva *et al*., 2013; Taborda and Andrade, 2014).

Observing the studied borrow area, Unit 1 (medium and fine sand) correspond to the basal unit of almost all the cores, although cores CCV3, CCV9 and CCV13 stand as exceptions with their basal unit represented by Unit 2 (medium and coarse sand).

Cores CCV3, CCV9 and CCV13, in which Unit 2 correspond to the basal unit, are located in the western portion of the borrow area in water depths of 26 m, 21 m and 27 m, respectively. Two hypotheses can be raised to explain this pattern. The first one could be that Unit 1 did not deposited in the portion where these cores are, being the deposited restricted just to areas where the cores which has Unit 1 as the basal unit are. Following the direction of West-East, the last cores which present Unit 1 are CCV6, CCV4 and CCV2 which could be marking the horizontal spatial limit of this unit inside the studied area. The second hypothesis could be that, at CCV3, CCV9 and CCV13 locations, Unit 1 is deeper not being retrieved with the 3 m long corer, thus not appearing in these samples.

The general characteristics of the Units are defined by the textural composition of the sands. Observing the core water depths and the information in the literature about the sediments' dynamics in the west Portuguese coast, the studied borrow site corroborate the previously cited studies (see sub-section 1.2).

The finer grain content and silt content in Unit 3 could be related to the Tejo fluvial runoff. For instance, Burdloff *et al*. (2008) points out that Tejo River is responsible for an expressive source of fine sediments. Thus, it could be a hypothesis that the provenance of sediments of Unit 3 could be from the Tejo River.

Furthermore, the sand distribution pattern found is in concordance with the main sand sources for the region. The provenance of the sand for the area could be from draining basin of Costa do Sol and the wind corridor Guincho/Guia and long-shore drift (Taborda and Andrade, 2014).

The variations in the sediment characteristics found within the same sedimentary unit but in different cores could be attempted to be explained by the benthic macrofauna action, such as bioturbation and natural digenesis of the sediments.

Bioturbation is a process where the macro-benthic organisms transport particles and water between sedimentary layers. This process alters chemical profiles, changes chemical reactions and modifies sediment physical properties, changing the grain size, porosity and permeability (Shull, 2009).

In addition, the biological activity can contribute to the variations found in the sediment proprieties. Shell fragments were found in some samples, which could be presumed to explain the variations in grain size, calibration and carbonate contents found between the samples in the same sedimentary unit.

5.2 Multivariate Statistical approach for identifying the sedimentary units

The multivariate statistical approach appears to play a fundamental role in defining the sedimentary units. Some characteristics using the visual subjective interpretation of the graphics appear to be insufficient to define correctly the units.

For instance, as it was possible to observe in the present study, the visual graphical differentiation between Units 4 and 3 was not supported by the results of PERMANOVA and Pairwise tests. These units being sequential in deposition and this in time, might therefore be just one and unique unit with some small lateral sedimentary variations. On the other hand, although Unit 1 appears to have no significant differences with the Unit 4, they represent different deposition moments, with units 2 and 3 in between, hence the former is found at the base of the sedimentary sequence and the latter at the top.

Thus, when analyzing Units 3 and 4, both have coarse sand, medium sand and $CaCO_3$ as variables contributing to the average similarities. However, in Unit 3 the contribution of very fine sand and very coarse silt is higher than in Unit 4, being represented by finer sediments. This pattern is also observed in the PCA in which some samples of Unit 3 are more highly correlated with the fine sediments when compared to Unit 4. However, some samples of Unit 3 appear in the same group as samples of Unit 4.

When taking this into consideration, 3 different hypotheses can be raised. The first one is that Unit 3 and 4 are not different and Unit 3 is just a transitional phase between Units 2 and 4. The second is that Unit 3 is different and what is making that significant difference do not appear is the fact that both have similar variables contributing for the similarity between them. The third hypothesis is that some samples considered as part of Unit 3 are in fact belonging to Unit 4, and thus the limit between Units should be redefined.

This mixing pattern of some samples between Units 3 and 4, is also observed in the MDS and in the Cluster analysis. However, a few samples of Unit 3 in both analyses are isolated from all the others of the same unit. Suggesting that these are the only samples that do not have any similarity with samples of Unit 4, reinforcing the hypothesis that some samples considered visually as Unit 3 can actually belong to Unit 4.

The respective cores and depths of samples of Unit 3 which are shown isolated from the others are: CCV3 75 cm; CCV6 50 cm; CCV7 50 cm; CCV9 75 cm and CCV13 50 cm, 75 cm, 100 cm and 125 cm. The PCA shows that these samples correlated with finer grains (fine sand and very fine sand). When analyzing the graphics it is also possible to observe that the content of coarse silt in these samples is 9 %, 3 %, 15 %, 4 %, 7 %, 4% and 5%, respectively. These samples show the highest content of coarse silt of all the analyzed cores in the present study. This provides one more indication that they are indeed a different unit, and the other samples previously considered as Unit 3 are actually part of Unit 4 as it is shown in the similarities' analysis and PCA.

Previous studies used multivariate analyses to characterize sedimentary deposits. For instance, Martins *et al*. (2012) used this approach for the sedimentary characterization of the Portuguese continental shelf together with identifying the provenance of the sediments. This tool was decisive for classifying different groups of sediments and to link with the accurate provenance of them. This allowed the authors to find the different sediment sources of as fluvial input, natural or anthropogenic, shelf-morphology, hydro-dynamism and biological activity.

Multivariate analyses were also used by Rosa *et al*. (2013), whom used this approach to identify the influence of coastal processes on the inner shelf sediment distribution. This tool allowed the authors to make detailed sediment distribution maps and to verify that these maps can serve as a tool for management of coastal and marine resources.

Kendemir (2016) used the multivariate analyses in drilling cores to understand the spatial distribution of coal deposits, having seen that the cluster analysis was decisive to support similarities between the boreholes and identifying the coal deposits. Zaitouny *et al.* (2020) used as well the multivariate approach for fast detection of geological boundaries between different lithological layers. The authors concluded that the multivariate method demonstrated to be accurate, efficient and cheap to identify and to distinguish rocks' physical property and detecting transitions in mineral exploration boreholes.

In conclusion, we can reinforce the usefulness of multivariate statistical techniques to distinguish the sedimentary units.

5.3 Costa da Caparica borrow area sand for beach nourishment projects

The grain sizes most available in the present studied borrow area have been determined as medium sand (Unit 1, 2 and 4), coarse sand (Unit 2) and fine sand (Unit 3 and 4). Costa da Caparica's beaches are represented by medium sand with a mean grain size of 300 µm (Freire *et al*., 2006). Hence, it would be recommended to perform a thorough sand fill using Units 1, 2 and 4, with respectively mean grain size of 284 µm, 490 µm and 233 µm which would allow to preserve the natural characteristics and morphology.

However, the coast of Costa da Caparica could be described as a coastal zone which is exposed to strong longshore currents and high wave energy (Franz *et al*., 2017). Therefore, using fine sand from Unit 3 for the Costa da Caparica nourishment project could be problematic. Indeed, Veloso-Gomes *et al*. (2009) reported an amount of 500 000 m^3 of medium and fine sand being used in the 2007 nourishment project.

The use of fine sediments for nourishments on beaches which the natural sediments are coarser can be problematic. Cases in point to mention are the

Mediterranean coast of Israel (Bitan *et al.,* 2020) and Praia de Piçarras, Santa Catarina, Brazil (Araujo *et al*., 2009) where constantly ongoing, costly and never-ending maintenance is required.

Another example from Poland, more specifically in the Hel Peninsula, occurred. during the construction of the Wladyslawowo port, when a strong erosion state was uncovered in the region. To contain the erosion problems a nourishment project was performed using a total volume of 9.8 m^3 of sand. However, the sand used in the nourishment, dredged from Puck Bay, was much finer than the original one. Consequently, erosion problems continued and most of the sediment disposed was dragged away through the littoral drift (Hanley *et al*., 2014).

It is already known that sediment losses occur and that they can be expected after the nourishment in Costa da Caparica. Indeed, during the period of 2001 – 2007, Veloso-Gomes, *et al*. (2009) and Silva *et al.* (2013) reported that the sand losses after monitoring programs were approximately 2 000 000 m^3 in total and of about 290 000 m^3/year.

Hence, after the nourishment, if sediments from the CC borrow area were used and if the environmental conditions were to remain the same as the current ones, sediment losses of the same volume could be expected. Although, if Unit 3 was used, the losses would probably be higher than 290 000 m^3/year reported by Veloso-Gomes, *et al*. (2009), being a non-durable nourishment.

In addition, Veloso-Gomes *et al*. (2009) recommended in a pessimistic scenario a re-nourishment every 5 years. However, if the finer sediments available were used, a necessary re-nourishment in the CC could be expected sooner than in the pessimistic scenario proposed by these Authors.

Nevertheless, the CHIMERA Project (Mil-Homens *et al*., 2020) estimated that the volume of “useful material” for nourishment beach of this area is circa 14 000 000 m^3. This volume is considerably high and would be enough for mitigate the annual losses with small nourishments along the years and also to perform a big nourishment project if necessary.

On the other hand, if medium or coarse sand, or even both (bimodal sediment) are utilized, it is possible to reach a good and a durable result preserving the natural characteristics of the beach and reaching the objectives of the project.

Another case study is the nourishment project that took place in Copacabana, Brazil, as reported by Vera-Cruz (1972) where a durable and a successful nourishment project was confirmed. Another example being a project which took place in the Gold Coast of Australia (Boak *et al*., 2001). Even in Liguria, Italy, Vacchi *et al*. (2020) conducted a study using and investigating bimodal river sediments and ultimately concluding that the grain size is important but the place in which the borrow sand is placed in, is just as relevant of a factor to achieve success in a sand fill project.

Although, if only the coarse fraction is used, it could result in changes in the beach profile. The grain size plays a fundamental role on sandy beaches. The grain size together with the shoreline morphology, tide amplitude and the wave climate are variables which define the beach morphology (Short, 1999; 1996; Short and Wrigth, 1983). Each one of the variables is responsible for different beach types. Sandy beaches can have a dissipative, intermediate or a reflective morphology.

The use of the coarse fraction could result in a durable sand fill which could lead to a more stable beach state. However, as cited before, it would change the beach profile and result probably in a reflective beach morphology, which is characterized to have a steep slope and an absent or a short surf zone (Short and Wrigth, 1983). The change in the beach profile could result in a less favorable beach for bathing and surfing.

However, Costa da Caparica is not just a touristic area but also a well-known surf spot, and in light of this, the possible changes in the surfability and quality of waves should be considered when planning the nourishment. Albada *et al.,* (2006) evaluated the effect of beach nourishment on surfing in St. Johns County, Florida, before, during and after the sand fill and concluded that after the fill there was a temporary improvement in the waves' quality over pre-fill conditions. However, 4 months after the sand fill the waves' quality decreased, which again emphasizes the idea that surfing aspects must be taken into consideration as a benefit in a nourishment project.

6 CONCLUSIONS

By analyzing the characteristics of twelve sedimentary cores from the continental shelf, it is possible to conclude that the studied borrow area of Costa da Caparica have a sedimentological texture mainly composed of medium sand. However, it also presents considerable quantities of fine and coarse sand.

Four different sedimentary units were identified. Unit 1 characterized mainly by medium and fine sand, Unit 2 mainly by coarse sand, Unit 3 mainly by fine sand and Unit 4 mainly by fine and medium sand. Unit 2 was the most abundant unit, followed by units 1, 3 and 4. The maximum carbonate content (29,3 %) is present in Unit 3. Unit 4 is the unit which presents the second highest maximum carbonate content (17,1 %) followed by Unit 2 (13,9 %) and Unit 1 (9,9 %). According to the Blott and Pye (2012) classification the sediment in Unit 1 is sand. very slightly gravelly sand, slightly gravelly sand, sand and very slightly muddy sand. In Unit 2 are gravelly sand, slightly gravelly sand and very slightly gravelly sand. In Unit 3 are very slightly muddy sand, slightly muddy sand, very slightly gravelly very slightly muddy sand and sand. Finally, in Unit 4 the sediment is classified as sand.

The multivariate statistical analyses confirmed the hypothesis that the sedimentary units defined by the visual analysis of the graphics are different. The PERMANOVA test showed significant difference ($p < 0,05$) between the sedimentary units. The Post-Hoc Pairwise test showed that only Units 1 and 4; and Unit 3 and 4 were not significantly different ($p > 0,05$). The similarity analysis shows a pattern that corroborate with the PERMANOVA results, showing the units in which the difference appears isolated from the others and the units which are not significantly different are grouped. The PCA shows correlation of medium and coarse sand with Units 1, 2 and 4 and a correlation of fine sand with Unit 3. Although, some samples of Unit 3 are also correlated with medium sand.

Of these four defined sedimentary units, only Unit 3 is not a good option for nourishment of Costa da Caparica beaches. Even though Unit 3 has finer sediments than the medium grain size sands of Costa da Caparica it could be used, although higher sand losses exceeding the current volume of 290 000 m^3/year can be expected.

Units 1 and 4 appear to be the best option to guarantee similar aspects to the actual beach. Unit 2 could be a good option for the durability of the nourishment and beach stability; however it could change the beach profile, resulting in a beach less favorable for bathing and surfing.

To summarize the main conclusions: I) Four sedimentary units were identified and three out of four appear to be a good option for nourishment projects in Costa da Caparica beaches. II) A multivariate statistical approach can be an effective tool to define the sedimentary units. III) The type of sediment has to be chosen carefully in order to achieve a successful beach nourishment project. IV) The recreational activities, increase in tourism and surfability can be considered as a potential driver of economic and welfare gains through the beach nourishment of Costa da Caparica. V) Small-scale beach nourishments appear to be an eco-sustainable approach to combat beach erosion which minimizes the negative impact on the fauna and flora of sandy beaches.

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