



Multidisciplinary study of the quaternary deposits of the Vila Nova de Gaia, NW Portugal, and its climate significance

H. Ribeiro^{1,2} · A. Pinto de Jesus^{1,2} · J. Sanjurjo³ · I. Abreu^{1,4} · J. R. Vidal Romani³ · F. Noronha^{1,2}

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Abstract

Palynological, geochronological, and sedimentological analyses were conducted on samples from different depositional units of well-preserved marine, fluvial and palustrine sedimentary deposits from Vila Nova de Gaia located at the northwestern Portuguese coast. The studied deposits occur on two terraces: Terrace A—Lavadores (18 m to 33 m) and Terrace B—Canidelo (50 m). Chronological and sedimentological features allowed to date the deposits to the Upper Pleistocene until the last glacial period, being observed an evolution from a depositional setting in a marine intertidal zone, passing to a fluvial environment and ending in a palustrine/lagunar environment with possible periglacial influence. Pollen assemblages collected in the fluvial sedimentary horizons also suggested changes in the environmental conditions. A pollen content with good representation of arboreal species (*Quercus*, *Pinus*, *Castanea*, *Fraxinus*, *Salix*, *Betula* and *Corylus*), changed to a vegetation environment dominated by non-arboreal species, such as Poaceae, *Plantago* and Asteraceae. The top horizons, corresponding to a palustrine/lagunar environment, presented a pollen profile completely dominated by non-arboreal species, with minimal tree representation (*Prunus*, *Quercus*, *Pinus* and *Castanea*) which, combined with sedimentological characteristics may point to a more dry and cold climate than nowadays.

Keywords Quaternary · OSL · Sedimentary record · Pollen

Resumen

En este estudio, se realizaron análisis palinológicos, geocronológicos y sedimentológicos en muestras de diferentes unidades de depósitos sedimentarios marinos, fluviales y palustres bien conservados de Vila Nova de Gaia, ubicados en el margen portugués del Atlántico norte. Los depósitos estudiados se sitúan en dos terrazas: Terraza A - Lavadores (de 8 a 33 m) y Terraza B - Canidelo (50 m). Las características cronológicas y sedimentológicas permitieron datar los depósitos desde el Pleistoceno superior hasta el último período glacial, observándose una evolución desde un entorno de deposición en una zona intermareal marina, pasando a un entorno fluvial y terminando en un entorno palustre/lagunar en un área con posible influencia periglacial. Los datos de polen recolectados de los horizontes sedimentarios fluviales también sugirieron cambios en las condiciones ambientales. Un contenido de polen con una buena representación del estrato arbóreo (*Quercus*, *Pinus*, *Castanea*, *Fraxinus*, *Salix*, *Betula* y *Corylus*), a cambiado a un entorno de vegetación dominado por especies no arbóreas, tales como Poaceae, *Plantago* y Asteraceae, y con mínima representación de árboles. Los horizontes superiores, correspondientes a un entorno palustre/lagunar, presentaron un perfil de polen completamente dominado por especies no arbóreas, indicando un entorno de vegetación abierta con una representación mínima de árboles (*Prunus*, *Quercus*, *Pinus* y *Castanea*) lo que, combinado con las características sedimentológicas, puede apuntar un clima más seco y frío que hoy en día.

Palabras clave Pleistoceno · OSL · Registro sedimentario · Polen

✉ H. Ribeiro
helena.ribeiro@fc.up.pt

¹ Institute of Earth Sciences, Porto-Pole Portugal, R. Campo Alegre 687, 4169-007 Porto, Portugal

² Department of Geosciences, Environment and Spatial Planning, University of Porto, R. Campo Alegre 687, 4169-007 Porto, Portugal

³ Instituto Universitario de Xeoloxía Isidro Parga Pondal, Universidade da Coruña, A Coruña, Spain

⁴ Biology Department, Faculty of Sciences, University of Porto, R. Campo Alegre 687, 4169-007 Porto, Portugal

1 Introduction

The Quaternary (ca. 2.58 Ma—present) represents a time of dramatic climate and sea-level change. The coastlines found above and below present sea level can present relict features from past environments when the sea stood higher or lower, or when the climate was warmer or colder, wetter or drier, or stormier or calmer than present (Bird 2008). Several studies have been conducted on deep ocean cores, elevated ancient shorelines, marine and fluvial terraces aiming to compile information on Quaternary sea level fluctuations over time and its relationship with changes in the volume of the oceans (eustatic movements), in ocean temperature and salinity, current patterns, sedimentation, and tectonic movements (El Kadiri et al. 2010; Litchfield et al. 2010; Margari et al. 2010; White et al. 2010; Zazo et al. 2010; Viveen et al. 2012a,b).

Due to its position in Europe facing the Atlantic Ocean and being one of the westernmost zones of this continent, the Portuguese coast holds a good archive of different types of palaeoenvironments and of sea-level fluctuations impacts on ecosystems. Concerning the northwestern Atlantic Portuguese coastal segment it can be observed a complex serie of coastal depositional systems. They include relict marine terraces, river terraces, ancient forest soils, dune fields, peat bogs, wetlands and lagoons, which reflect the existence of different environments influenced by the variety of changes that occurred during the Quaternary (Granja and De Groot 1996; Granja 1999; Cabral et al. 2006; Soares de Carvalho et al. 2006; García-Amorena et al. 2007; Naughton et al. 2007; Granja et al. 2010; Carvalhido et al. 2014). These systems have been the subject of several studies along the years aiming to understand and explain how past climate and the sea level changes affected ecosystems dynamics. However, well-constrained geochronological data beyond the ^{14}C -range and palaeobotanical data for this Portuguese segment are scarce (Soares de Carvalho et al. 2006; Viveen et al. 2012b). This has hindered a comprehensive interpretation about the depositional settings and the prevailing conditions during vegetation establishment for the most ancient deposits.

Our study was performed in well-established Quaternary depositional units located at the northwestern Atlantic Portuguese coast, in Vila Nova de Gaia near the Douro River mouth. It aims to perform palynological analysis of several levels from these deposits and establish the absolute chronology of the deposits by means of OSL dating and characterize its sedimentology. This would contribute to the knowledge of the coastal evolution in the north Atlantic Portuguese margin.

2 Geological setting

2.1 Regional lithology

In the study area, the most represented lithologies are those of magmatic rocks, mainly Variscan granites, metamorphic rocks from an ante-Ordovician complex mainly constituted by metapelites, metaconglomerates, micaschists and gneisses and Quaternary sediments represented by siliciclastic fluvial, colluvial, aeolian, estuarine and beach sedimentary deposits (Costa and Teixeira 1957; Teixeira et al. 1962).

These deposits are part of the designated “littoral platform”, a flatter surface identified in the Northwestern Portuguese coastal line, organized in several steps observed at different altitudes (no more than 150 m height) and that is limited from the inland by a straight relief (Araújo et al. 2003).

Studies have identified the “littoral platform” steps as old marine levels that had its origin only related to the Quaternary eustatic changes (Ribeiro et al. 1943; Zbyszewski and Teixeira 1949). Most recently, sedimentological studies showed that many of these deposits have a continental origin containing fluvial or alluvial fan facies (Araújo et al. 2003).

In the surrounding area of the Douro River mouth, the “littoral platform” presents several Plio-Pleistocene deposits being divided into three major groups by Araújo et al. (2003): (i) above the 130 m classified as occurring in the marginal relief; (ii) between 130 and 50 m considered as continental deposits, with fluvial facies and (iii) below 50 m where marine deposits can be observed.

2.2 Regional tectonics

During the upper Neogene and the Quaternary, the western Iberian margin underwent compressive deformation referred with a maximum tension from WNW-ESE to E-W in the margins and NNW-SSE at inner areas (Cabral and Ribeiro 1988; Cabral 1993, 1995).

The analyses of aerial photography complemented with field data from the area suggests several probable tectonic lineaments, representing two main systems: ENE–WSW and NNW–SSE to N–S. The same systems can be observed in the northern of Douro river namely at Porto area where a NNW–SSE fault cut a Quaternary deposit (Noronha 2003). In Minho region, northern of Neiva river, the same systems occur and present an inverse fault striking N10°W with a dip of 60°W (Gandra fault) and reject fluvial deposits considered lower Quaternary in age (Carvalhido et al. 2014) (Fig. 1).

3 Materials and methods

3.1 Sampling

The study site was located in Vila Nova de Gaia at the northern Atlantic Portuguese margin near the Douro mouth. Sampling was performed in two terraces at different distances from the present shoreline: Terrace A located in Lavadores and Terrace B located in Canidelo. This kind of terraces are described as Quaternary marine, fluvial-marine and fluvial sedimentary deposits (Costa and Teixeira 1957) (Fig. 1).

It was studied in Terrace A (Lavadores) two depositional units, named as DU_A (Pedras Amarelas) and DU_B (Rua da Bélgica I), and in Terrace B (Canidelo) one depositional unit, named as DU_C (Rua da Bélgica II) (Fig. 1). These two terraces are located respectively between 18 m to 30 m and 50 m above the present sea level and all at less 1000 m from the sea line (Fig. 1).

A total of fourteen samples were collected: nine samples in site DU-A (LAV1, LAV2, LAV4, PA2, PA3, PA16, PA17, PA18 and PA20); three samples in site DU-B (PA12, PA13 and PA14) and two samples in site DU-C (PA15 and MO13).

Samples LAV1, PA13, PA14, PA16, PA17, PA18 and PA15 were used for OSL dating, sedimentary and palynological analyses. Additional seven samples (LAV2, LAV4, PA2, PA20, PA3; PA12 and MO3) were used only for pollen analyses.

3.2 Palynology

Samples used for pollen analyses were collected in situ, after cleaning the surface layer, placed into disposable plastic bags, sealed, identified and taken to the laboratory.

Sub-sample fractions of 5 cm³ were used for pollen content studies and subject to dissolution, leaching and acetolysis according to the methodology proposed in Faegri and Iversen (1989). The obtained residue was stored in phenolated glycerine.

For pollen identification and quantification, slides were mounted and observed at a transmitted light microscope ($\times 400$ and $\times 630$) along full lengthwise traverses. At least 300 pollen grains were counted per each slide. Pollen counts for each type identified were then converted into percentages of the total pollen counts. Pollen grains were classified by morphological characteristics and identified by comparison with bibliographic material (Reille 1992, 1995, 1998).

3.3 Geochronology

The chronological study was performed by optical stimulated luminescence (OSL) in the 180–250 μm fraction of quartz-rich sandy-gravelly sediments at the Luminescence Laboratory of the Instituto Universitario de Geología “Isidro Parga Pondal” of the University of A Coruña (Spain). For this, samples were collected at variable depth by inserting stainless steel tubes of around 40 cm long and 10 cm in diameter in the layers after cleaning its surface in order to avoid contamination.

An acid wash was used to remove carbonates and organic matter. Feldspars and heavy minerals were removed by density separation, using sodium polytungstate solutions. The remnant quartz grains were treated with HF to etch the surface of quartz grains (to eliminate the alpha contribution). Measurements were made in a Riso DA-15 automated TL/OSL reader system equipped with a 0.120 ± 0.003 Gys-1 ⁹⁰Sr/⁹⁰Y beta-source and a 9235QA photomultiplier tube (PMT), using an optical Hoya U-340 filter (to measure the UV range emission) after optical stimulation with blue diodes. The single aliquot regenerative dose (SAR) protocol (Murray and Wintle 2000) was used to estimate the equivalent dose, performing OSL at 125 °C during 40 s after preheating at 220 °C for 10 s. The natural dose-rate was estimated using a Canberra XTRA gamma detector (Ge Intrinsic) during 46–68 h counting time (Hossain et al. 2002; Poreba and Fedorowicz 2005). The factors of Guerin and Mercier (2011) were considered to calculate dose-rates conversion. The cosmic dose rates were calculated according to Prescott and Hutton (1994).

3.4 Sedimentology

On the outcrops, work field consisted of delimiting stratigraphic boundaries of the beds, regarding lithology and sedimentary internal structures, as well as the bedding shape and geometry and sampling.

Lab work consisted mainly of grain size analyses. After manual disintegration of the samples, dry mechanical shake sieving was done using sieves ranging from 8 mm to 63 μm .

Analyses on the roundness and sphericity of the clasts was made using a magnifying glass and the microscope and values were estimated by the silhouette method (after Shepard and Young 1961).

The statistical treatment on the grain size distribution was made regarding Folk and Ward (1957) parameters.

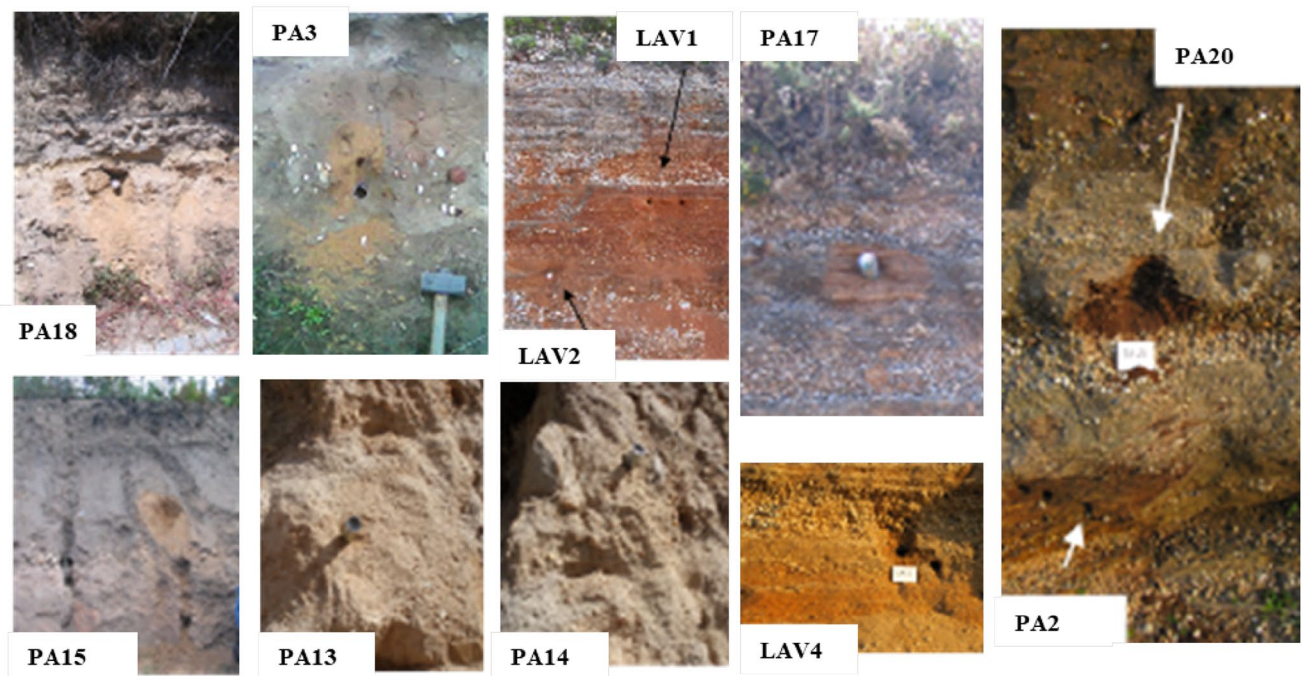
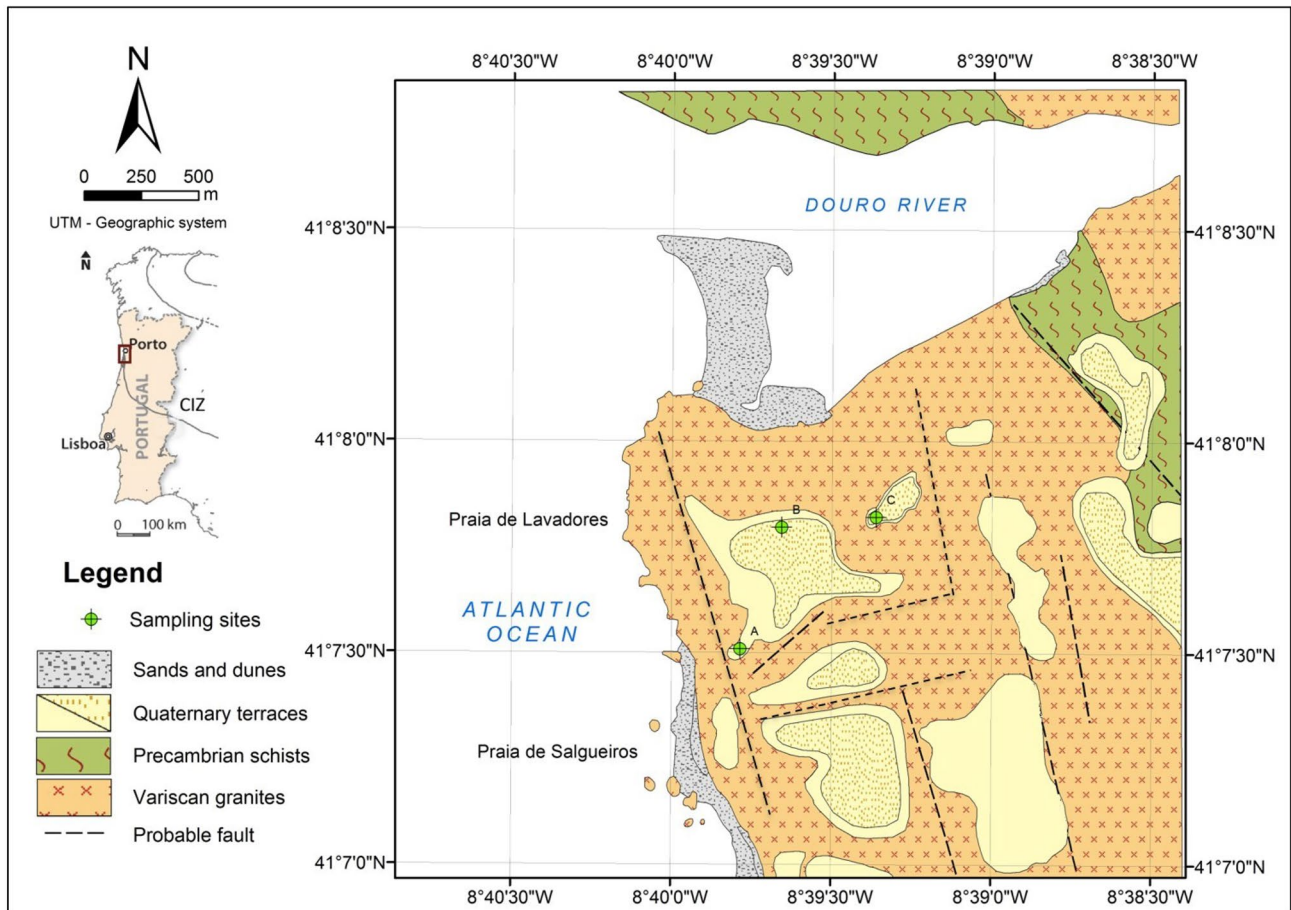


Fig. 1 Map with the location of the studied depositional units in Vila Nova de Gaia (Lavadores Terrace A: DU_A; DU_B and Canidelo Terrace B: DU_C), situated between 18 and 50 m above sea level,

adapted from Costa and Teixeira (1957). Images of the different sampling levels located in the Terraces A (Lavadores) and B (Canidelo)

4 Results and discussion

4.1 Sedimentological and palynological studies

4.1.1 Terrace A (Lavadores)

In Terrace A two depositional units were studied, site DU_A: Pedras Amarelas and site DU_B: Rua da Bélgica I.

At site DU_A, from the sedimentological point of view, three main horizons can be recognized. From the bottom to the top:

- Two conglomeratic and sandy beds, each one almost 1 m thick, with yellowish brown color (Fig. 2). Texturally, is clast- to sandy matrix-supported. Graphic mean size ranges between 6.4 mm for the coarser levels and 0.9 mm for the finest ones (PA 16). Graphic standard deviation results indicates a poor sorting, a marine intertidal sub-environment is well defined with the presence of rounded to sub-rounded elongated pebbles with a two-way imbrication and evidencing palaeocurrents from East to West.
- Three main sandy-conglomeratic yellowish brown beds (LAV 1 and PA 17), ranging from 0.3 m to 0.7 m in thickness. With normal graded bedding, texture tends to be clast-supported in the base (lag), and gradually passing to matrix-supported to the top of each bed. Sample PA 17 grain size distribution is poorly sorted, fine-skewed

and mesokurtic in good relation with an environment not too selective. Concerning roundness and sphericity, the coarser clasts (pebbles and granules) tend to be sub-rounded and sub-spherical, and the finer ones (sand and silt) have lower roundness values (sub-angular to angular) and a not well defined sphericity. The described characteristics suggest a main fluvial system as depositional environment.

- One pelitic bed with pebbles, greenish gray in color, with less than 0.5 m in thickness. It presents a muddy matrix-supported texture in which sub-rounded and elongated pebbles are positioned with the long axis vertically. From this clastic content results a grain size distribution (PA 18) very poorly sorted, very coarse-skewed, and platikurtic. The sedimentological characteristics and the geometric position of the long axis of the pebbles, related with sorted polygons, suggest periglacial freeze–thaw cycles. This pelitic bed corresponds to the “Formação Areno-Pelítica” from Costa and Teixeira (1957), Teixeira et al. (1962) and studied by Ribeiro et al. (2014).

The data above and the sequence of this bed seems like to be deposited in an area with periglacial influence, maybe in relation with a glacial stage (cf. Einsele 2000, pp 19–28).

Regarding statistical sedimentary grain size parameters, from bottom to the top, sorting becomes poorer, skewness is coarser, and kurtosis passes to a platikurtic distribution,

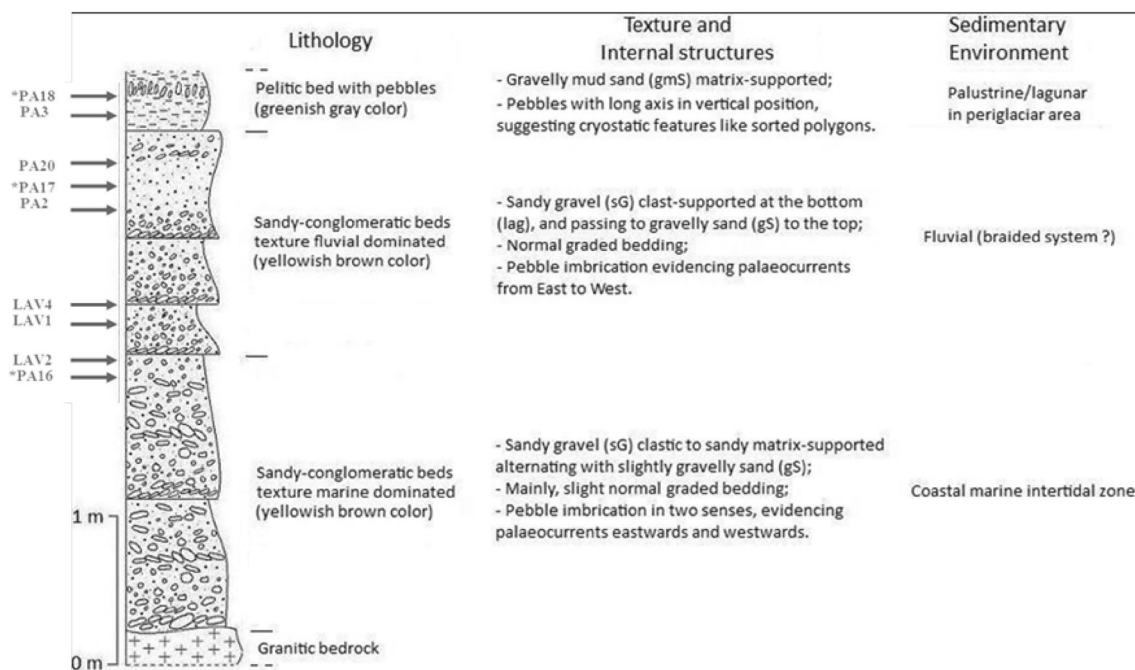


Fig. 2 Samples position, sedimentary record and summarized conclusions for the DU_A site (Pedras Amarelas) in Terrace A (Lavadores). Codes for textural terminology after Folk and Ward (1957), asterisk represent dated samples

suggesting sedimentary supply from a continental area (Table 1).

Overall, this site is interpreted as representative of a regression because we found an environmental migration from a marine intertidal passing to a fluvial environment, and ending in a palustrine/lagunar environment in a periglacial zone. Araújo et al. 2003 describe the site DU_A as corresponding to a marine deposit (below 50 m) topped by a sandy-pelitic layer (assign to Würm) although they didn't describe the existence of a fluvial depositional environment.

At the site DU_B the outcrop presents one pelitic bed with pebbles, with greenish gray color, and 1 m in thickness (Fig. 3). Consists of a muddy matrix-supported texture and near the bottom sedimentary characteristics are very similar to the top of the DU_A, where sub-rounded and elongated pebbles are positioned with the long axis vertically.

Pollen analyses conducted on site DU_A showed that the pollen profile is dominated by non-arboreal taxa, with minimal tree representation in all levels studied (Fig. 5). Samples collected at the sedimentary units from marine

origin present almost null pollen content (PA16 and LAV2) as well as the sample LAV4. On the profile top samples, corresponding to palustrine/lagunar layers, the pollen assemblages indicate a landscape dominated by Asteraceae mainly *Carduus*-type (from 60% up to 80%) and other, with grasses and the presence of some herbs such Brassicaceae, *Plantago* and Umbeliferae. Although in low percentages, it was also observed the co-existence of woody taxa such as *Prunus*, *Quercus*, *Alnus*, Ericaceae and *Pinus*.

On site DU_B pollen analyses was conducted on 2 samples (PA15 and MO3), corresponding to an age of around 67 ± 4.9 ka. The pollen profile is dominated by steppe species such Poaceae, *Plantago* and Asteraceae (Liguliflorae and Tubuliflorae). Contrary to the previous unit, in this section the presence of pollen from Asteraceae *Carduus*-type is residual. Also, it was observed the presence of pollen-types from Ericaceae, Umbeliferae, Brassicaceae and Isoetes spores. The arboreal species have a residual representation (2%) being observed *Prunus*, *Quercus*, *Alnus*, *Pinus* and *Castanea* pollen (Fig. 5).

Table 1 Results of the statistical sedimentary grain size parameters for the samples of the three studied sites, DU_A (Pedras Amarelas) and DU_B (R. Bélgica I) in Terrace A (Lavadores); DU_C (R. Bélgica II) located in Terrace B (Canidelo)

Site	Sample	Graphic mean (mm)	Inclusive graphic		Graphic Kurtosis
			Standard deviation	Skewness	
Terrace A Lavadores					
DU_A	PA18	0.37	Very poorly sorted (3.27)	Very coarse-skewed (-0.57)	Platykurtic (0.54)
Pedras Amarelas	PA17	2.5	Poorly sorted (1.10)	Fine-skewed (0.18)	Mesokurtic (0.94)
	PA16	0.9	Poorly sorted (1.18)	Near-symmetrical (-0.03)	Very leptokurtic (1.80)
	LAV1	6.4	Poorly sorted (1.90)	Very fine-skewed (0.41)	Platykurtic (0.68)
DU_B	PA15	1.54	Poorly sorted (1.62)	Fine-skewed (0.19)	Leptokurtic (1.27)
Terrace B Canidelo					
DU_C	PA13	0.26	Poorly sorted (1.25)	Very coarse-skewed (-0.58)	Mesokurtic (0.98)
R. Bélgica II	PA14	0.24	Poorly sorted (1.80)	Coarse-skewed (-0.22)	Leptokurtic (1.19)

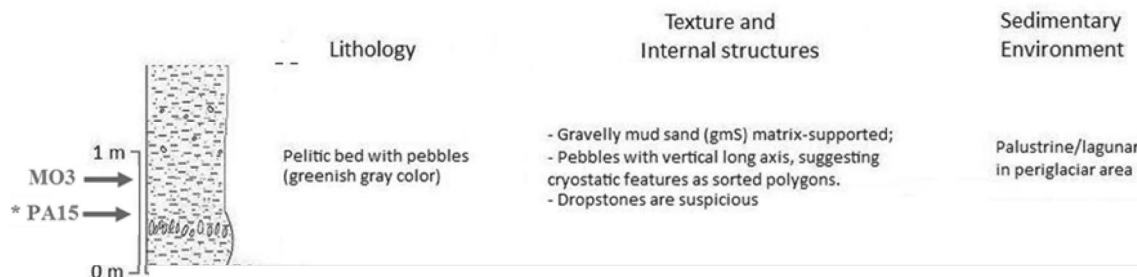


Fig. 3 Samples position, sedimentary record and summarized conclusions for the DU_B site (R. Bélgica I) in Terrace A (Lavadores). Codes for textural terminology after Folk and Ward (1957), asterisk represent dated samples

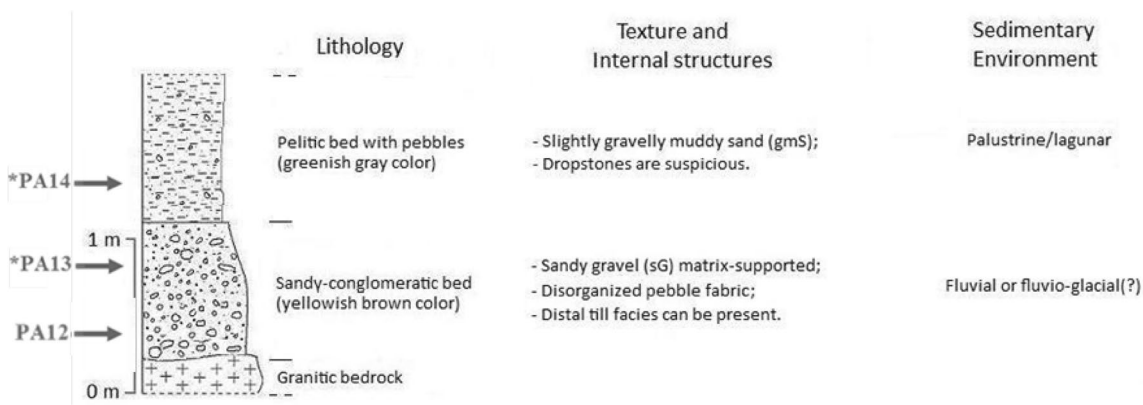


Fig. 4 Samples position, sedimentary record and summarized conclusions for the DU_C site (R. Béglica II) in Terrace B (Canidelo). Codes for textural terminology after Folk and Ward (1957), asterisk represent dated samples

Table 2 Optical luminescence age determination and measurement informations for the samples collected in the three sites DU_A, DU_B and DU_C sites located in Lavadores, Vila Nova de Gaia

	Site	Sample	Dose-rate (Ga/ka)	Equivalent Dose (Ga)	Age (ka)
Terrace A Lavadores	DU_A (Pedras Amarelas)	PA16	1.47 ± 0.21	247.75 ± 23.12	168.27 ± 28.48
		PA17	1.44 ± 0.09	239.05 ± 18.24	166.05 ± 17.79
		PA18	4.00 ± 0.21	269.37 ± 13.96	67.40 ± 4.94
Terrace B Canidelo	DU_B (R. Béglica I)	PA15	3.97 ± 0.21	269.37 ± 13.96	67.82 ± 4.99
		DU_C (R. Béglica II)	PA13	1.80 ± 0.09	168.12 ± 11.61
		PA14	4.08 ± 0.21	229.52 ± 13.40	56.25 ± 4.37

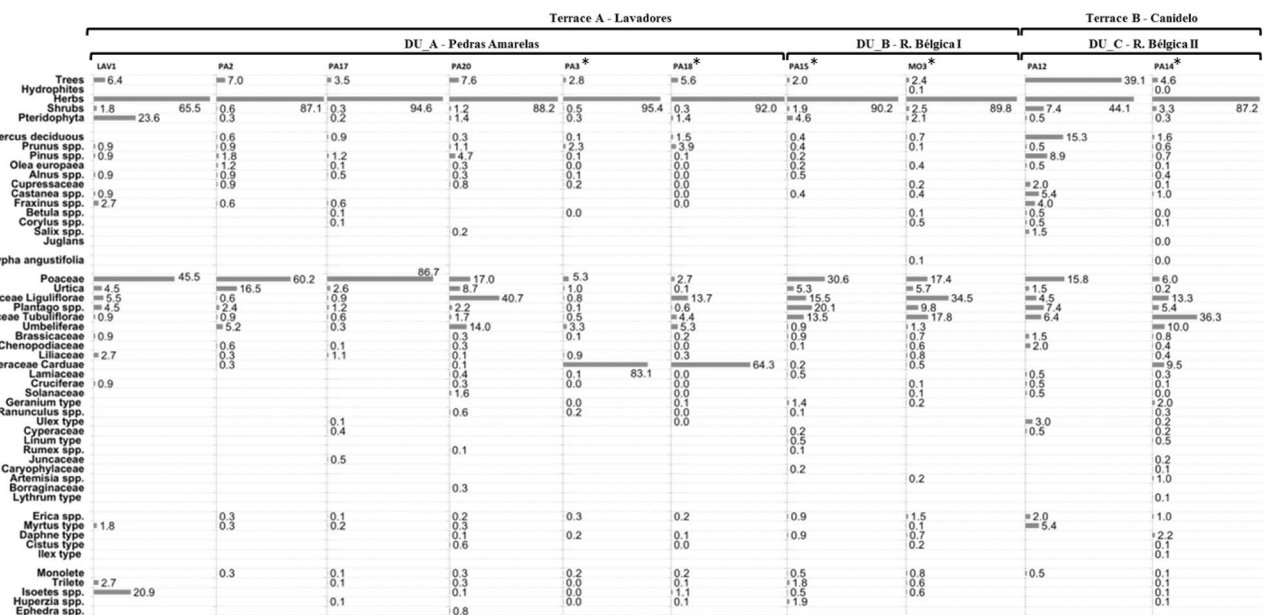


Fig. 5 Pollen spectra of the samples collected in the three depositional units, DU_A and DU_B located in the Terrace A: Lavadores and DU_C located in the Terrace B: Canidelo (asterisk results from Ribeiro et al. 2014)

4.1.2 Terrace B (Canidelo)

In Terrace B one depositional unit was studied, site DU_C: Rua da Bélgica II.

For this site, two main horizons were recognized (Fig. 4). From the bottom to the top:

- One sandy-conglomeratic yellowish brown bed, with sandy texture matrix-supported and sedimentary disorganized. Further, sedimentary grain size parameters (PA13) points to a poorly sorted, very coarse-skewed, and mesokurtic distribution. Nevertheless some sub-rounded pebbles were observed and all size grains tend to be sub-angular to angular without defined sphericity.
- One pelitic bed with pebbles, with greenish gray color, and presenting 0.8 m in thickness. Consists of a muddy matrix-supported texture in which sub rounded pebbles and granules are disseminated. From this clastic content (PA14) results a grain size distribution poorly sorted, coarse-skewed, and leptokurtic (for the strong content in fine sand, and silt) (Table 2).

Concerning the pollen content, the bottom sample (PA12) presented a pollen assemblage with the highest representation of the arboreal level (39%), dominated by *Quercus*, *Pinus*, *Castanea*, *Fraxinus*, *Salix*, *Betula* and *Corylus*, and of shrubs (7%). This pollen assemblage points to the existence of open forested environment dominated by temperate and Mediterranean trees, opposing to the observed in the DU_A samples collected from the fluvial sedimentary environment.

Sample PA13 was sterile in pollen, suggesting a change in the environmental conditions. The top sample (PA14), presented high pollen content mostly from non-arboreal species particularly Asteraceae (Liguliflora and Tubuliflora) and Umbeliferae. Pollen types from Poaceae, Asteraceae *Carduus*-type, *Plantago* and *Erica* were present. Arboreal species were residually represented (4%) by *Prunus*, *Quercus*, *Pinus* and *Castanea* (Fig. 5).

4.2 Geochronological results

In the Table 2 are presented the optical luminescence age determination and measurement informations for the three sampled sites.

Several time stages can be identified:

- Period around 168.27 ± 28.48 and 166.05 ± 17.79 ka represented in DU_A site in samples PA16 and PA17;
- Period around 92.58 ± 8.07 ka represented in site DU_C in sample PA13;
- Period between 67.82 ± 4.94 and 56.25 ± 4.37 ka represented in the top sample PA18 from DU_A; PA14 from DU_C and PA15 from site DU_B.

4.3 Correlation between the different sites

The combination of chronological, sedimentary and palynological analyses performed in our study for the surrounding area of the Douro River mouth, in the “littoral platform” supports the previous interpretation of Araújo et al. (2003) reporting the presence of marine and continental deposits below the 50 m.

The dates obtained at the site DU_A in Terrace A has shown values ranging from 180 ka, taken at the top of the sedimentary layers from marine origin (Pinto de Jesus et al. 2008), up to 166.05 ± 17.79 ka on the fluvial origin sedimentary layers. Concerning the palynological study, they are characterized by an initially sterile or low pollen content followed by a continued increase in the pollen quantity and diversity, always dominated by non-arboreal species, mainly Poaceae. These environments correspond to an Upper Pleistocene period suggesting its formation during MIS6 (Margarit et al. 2010) and agree with the occurrence of a glacial/interglacial cycle (Martínez-Carreño and García-Gil 2017) causing a marine regression and transition to a fluvial sedimentary environment. This indicates that at this height in the Portugal coast the last sea level withdrawal can be correlated to the transition between MIS7 and MIS6 of the global glacioeustatic curve. According to the pollen records, during the first stages of the regression the exposed land was colonized by Poaceae and herbs such as Asteraceae. The initial presence of *Isoetes* spores in relevant amount indicates the existence of a wet environment and reflects the fluvial water supply changes due to the nature of sedimentation observed. At the arboreal strata marginal levels of *Quercus* and *Pinus* pollen indicate the presence of these species in the nearby area.

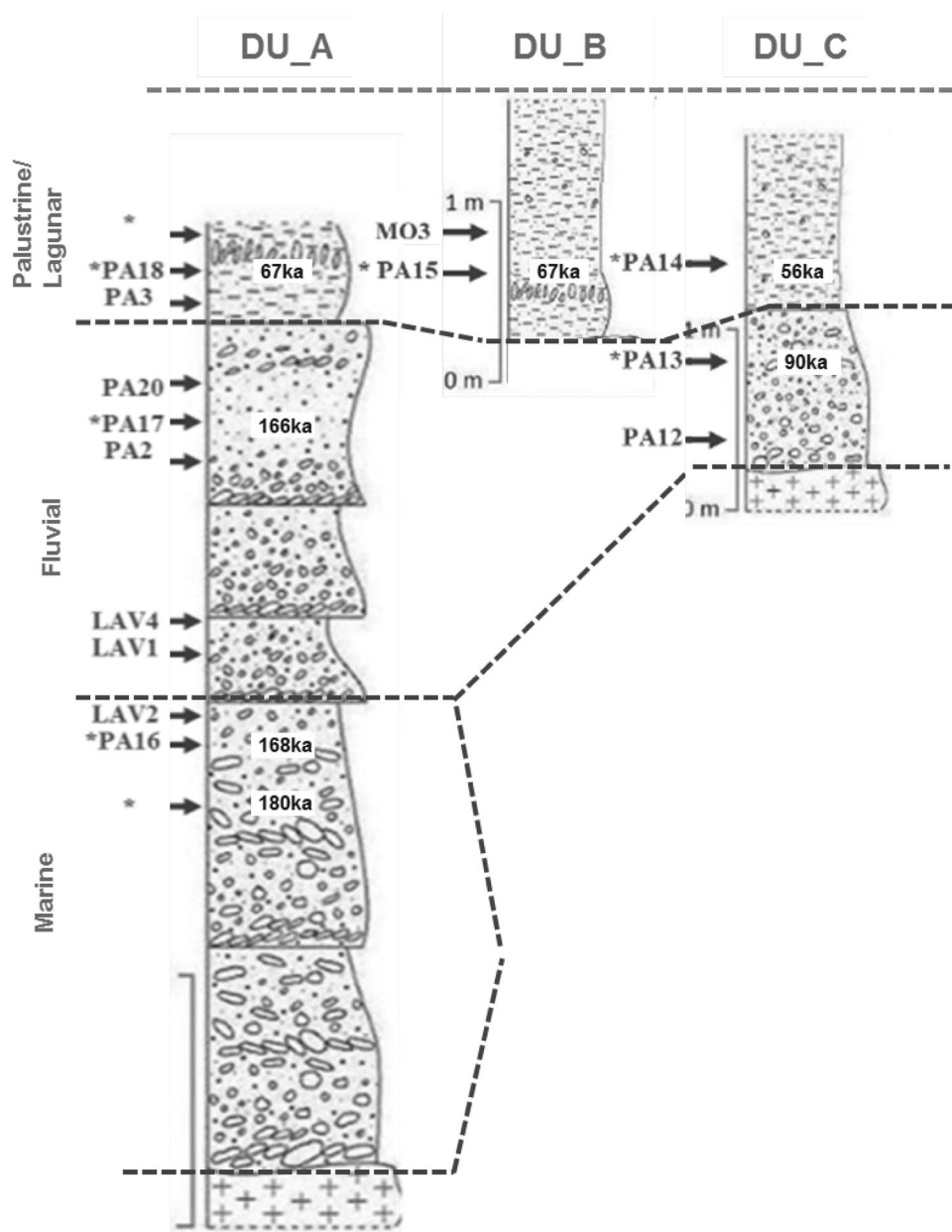
The date obtained for the DU_C (92.58 ± 8.07 ka) at the sedimentary layer from fluvial origin was more recent than the ones at DU_A. At DU_C, the two samples taken for pollen analysis presented distinct assemblages. The dated sample presented no pollen content while the pollen spectrum of the sample located below had a good representation of the pollen from the arboreal level (*Quercus*, *Pinus*, *Castanea*, *Fraxinus*, *Salix*, *Betula* and *Corylus*). The development of *Quercus* forest associated with *Corylus* and *Betula* in north-western Iberia has been reported from 126 to 122 ka and associated with warm-temperate conditions (Sanchez-Goñi et al. 2005). Pollen studies at an organic Quaternary deposit at the Portuguese Atlantic coast, few kilometers north of Lisbon, also showed an increase in woodland species, with a peak in *Quercus* pollen at approximately 114 ka and a period between 104 and 109 ka marked by forest maturation from *Betula*, *Corylus*, *Quercus*, *Olea*, *Salix*, *Fagus* and *Cornus* (Minckley et al. 2015). These observations correlate with our pollen results and can place the sample PA12 within this period.

For the same time period covered by the DU_C (MIS5 to MIS3), in the nearby Galician coast there was also reported changes in the environmental conditions, namely sea level falls that occurred during MIS 5d (110 ka), MIS 5b (90 ka) and MIS 4 (60–70 ka) (Gómez-Orellana et al. 2007; Martínez-Carreño and García-Gil 2017; Muñoz Sobrino et al. 2018,) that influenced the vegetation development dynamic and also pollen preservation conditions (García-Moreiras et al. 2015).

The top layers of all the three studied sites represent a time period between 67.82 ± 4.99 and 56.25 ± 4.37 ka (Fig. 6), suggesting its formation during MIS3. In all of them, a similar pollen spectrum was observed with high representation of non-arboreal pollen (between 95 and 98%),

particularly of Poaceae, Asteraceae, Ericaceae, Umbeliferae, *Isoetes*. These assemblages show some correlation to the pollen diagram for the Portuguese offshore MD95-2039 site reported by Roucoux et al. (2005) where Poaceae dominated, followed by Ericaceae and Asteraceae (Liguliflorae and Tubuliflorae), being also recorded the presence of *Isoetes*, Brassicaceae, *Plantago* and Umbeliferae. As well, the arboreal pollen remained low, close to the percentages observed in our study. The pollen types identified are indicative of a dry and cold climate and it was suggested that 60.5 ka corresponds to a period of increased climatic severity (colder and drier conditions) (Roucoux et al. 2005). This also corroborates the interpretation made in our study that the top layers of the DU_A (Pedras Amarelas in Terrace A) were

Fig. 6 Correlation between the DU_A, DU_B and DU_C sites located in Lavadores, Vila Nova de Gaia suggesting the presence of three depositional units with different characteristics. Asterisk represent dated samples



influenced by a periglacial deposition leading to the vertical position of the longitudinal axis of the pebbles.

Studies performed in the nearby estuarine system of Ría de Vigo showed the existence of MIS-3 period (57.0–38.8 cal ka BP) sedimentary sequences (García-Moreiras et al. 2019, Muñoz Sobrino et al. 2018). but not quite similar to the ones in our study. The authors report the dominance of tree pollen from deciduous *Quercus*, *Alnus*, *Betula*, *Carpinus betulus*, *Corylus* and *Pinus*. The presence of Ericaceae and Poaceae were also observed (García-Moreiras et al. 2019). These results are similar to the pollen spectrum obtained in sample PA12 at DU_C, with probable age $> 92.58 \pm 8.07$ ka.

5 Conclusions

The Portuguese northwestern “littoral platform” has been widely studied along the years and with this investigation was possible to obtain chronological data for some deposits located in ancient terraces found in Vila Nova de Gaia, Northwest of Portugal, near the Douro River mouth. Chronological and sedimentological features allowed assigning the deposits from the Upper Pleistocene (MIS7–MIS6c) until the last glacial period, being observed an evolution from a depositional setting in a marine intertidal zone, passing to a fluvial environment and ending in a palustrine/lagunar environment.

Vegetation was dominated by non-arboreal species, indicating an environment of open vegetation. A good representation of the arboreal level was observed in the fluvial sedimentary environment pointing to the existence of open forested environment dominated by trees from temperate and Mediterranean areas. On the palustrine/lagunar layers, the pollen assemblages indicate the co-existence of woody taxa, in a landscape dominated by grasses and other herbaceous plants.

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