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Characterization and dating of coastal deposits of NW Portugal (Minho–Neiva area): A record of climate, eustasy and crustal uplift during the Quaternary

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ABSTRACT

This study presents the characterization and numerical dating of Quaternary coastal deposits of NW Portugal, located between the mouths of the Minho and Neiva rivers. They record continental (small alluvial fans and streams) and transitional (aeolian dunes, interdune ponds, estuary, sandy and gravelly beaches) paleoenvironments. Quartz and K-feldspar optically stimulated luminescence (OSL) dating is employed as well as AMS ^{14}C dating. A staircase of coastal terraces (abrasion shore platforms) was identified (altimetry, a.s.l.) and ascribed to the following probable Marine Isotope Stages (MIS): T1 – 20-18 m (MIS11); T2 – ca. 13 m (MIS9); T3 – 9.3–7.3 m (MIS7); T4 – 5.5–4.5 m (MIS5); T5 – 3.5–2.0 m (MIS5). The terraces have some preserved sedimentary facies that includes coeval beach sediments on the lowest four. A late Pleistocene to Holocene sedimentary cover comprises four sub-units: a) the lower sub-unit, corresponding to ferruginous stream deposits and aeolian dunes dated ca. 67–61 ka (MIS4), probably related with sub-humid to arid mid-cold conditions; b) on the slopes, the lower sub-unit is overlapped by sandy-silty colluvium and sandy alluvial deposits dated ca. 56–28 ka (MIS3) and probably reflecting cold/mid-cold and wet/dry climate conditions; c) this sub-unit is topped by soliflucted lobes and sandy-silty/silty deposits recording cold and dry climate dated 20–13 ka (MIS2), and d) a top sub-unit dated to 16–18th century, recording Little Ice Age events, consisting of fluvial sediments coeval with temperate climate evolving to aeolian dunes from the Maunder Minimum (cold windy dry conditions).

1. Introduction

The interpretation of coastal terrace staircases in relation to causal mechanisms (eustasy, tectonics and climate) is still a subject of discussion (e.g. Benedetti et al., 2009; Ristuccia et al., 2013). Within Iberia, the coastal terrace staircases located near the mouths of rivers draining to the Atlantic Ocean could provide suitable archives to interpret the roles played by these mechanisms.

The interest in the Quaternary evolution of Minho coast, northwestern Portugal, began with the study of river and marine terraces by Choffat (1894), Pinto (1932), Berthois (1949), and Zbyszewski (1958). Later, other studies were carried out by Alves (1989, 1995, 1996) and Meireles (1992). In the adjacent coastal areas of Galicia and Neiva-Aveiro, several studies on the Pleistocene and Holocene deposits were also made: Granja (1990), Granja and Carvalho (1991, 1992, 1993, 1995), Carvalho et al. (1995, 2006), Granja and Groot (1996), Granja et al. (1996, 1999, 2008, 2010), Carvalho and Granja (1997, 2003), Groot and Granja (1998), Pérez-Alberti et al. (1998, 2009), Alonso and Pagés (2000, 2007), Blanco-Chao et al. (2002, 2003, 2007), Fábregas Valcarce et al. (2003), Araújo (2001, 2004, 2005, 2008), Araújo et al. (2003), Garcia-Amorena et al. (2007), Thomas et al. (2008), Araújo and Gomes (2009) and Ribeiro et al. (2010, 2011).

This paper focuses on the geomorphological and sedimentological characteristics of a Pleistocene coastal terrace staircase of

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NW Portugal, covered by extensive late Pleistocene to Holocene sedimentary units. The study area is located between the Minho River mouth (N41°51′54.22″; W8°51′44.02″) and the Neiva River mouth (N41°36′45.77″; W8°48′37.72″) (Fig. 1). The main purpose of this study of the Pleistocene–Holocene record is to: 1) give some of the first numerical ages for Pleistocene sequences in NW Portugal; 2) contribute to the understanding of the evolution of coastal processes and coeval sedimentary and geomorphic controls, 3) identify the main climatic stages and 4) clarify the tectonic evolution of the Minho region.

2. Geological setting

2.1. Regional lithology

In the study area, the most represented lithologies are those belonging to the metamorphic (mainly metapsamopelites, quartzites, metaconglomerates and micaschists) and magmatic basements (mainly granitoids). Pleistocene and Holocene sedimentary units are represented by siliciclastic fluvial, colluvial, aeolian, estuarine and beach deposits.

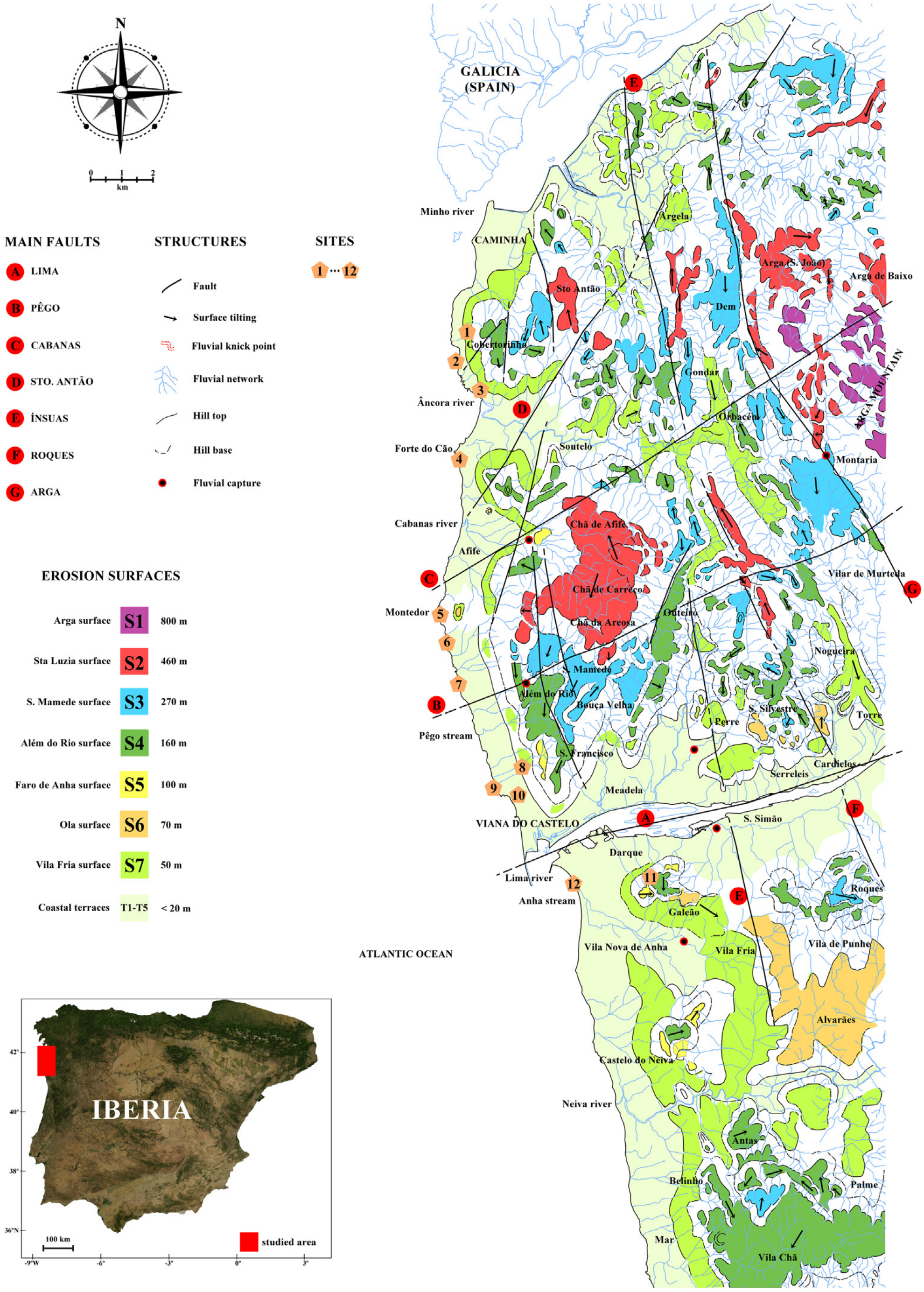

Fig. 1. Geomorphological map of NW Portugal coast, with location of the studied sites (adapted from Carvalhido, 2012). Sites: 1) Estrada Real; 2) S. Domingos – Moledo; 3) St. Isidoro – Âncora; 4) Forte do Cão/Gelfa; 5) Alcantilado de Montedor; 6) Cambôa do Marinheiro - Montedor; 7) Canto Marinho; 8) S. Sebastião – Areosa; 9) Rego de Fontes; 10) Ribeira de Portela – Areosa; 11) Galeão; 12) Ribeira de Anha – Cabedelo.

2.2. Regional tectonics

Teixeira (1944) discussed the possibility that NW Portugal may comprise three main fault blocks, the Galician, Minho and Douro blocks. During the Pliocene and the Quaternary, the western Iberian margin underwent compressive deformation that changed from NW–SE to WNW–ESE (Rodrigues et al., 1992; Ribeiro et al., 1996; Andeweg, 2002; De Vicente et al., 2011). Cabral and Ribeiro (1988) and Cabral (1993, 1995) referred to a Quaternary *Shmax* at the western Iberian margin from WNW-ESE to E–W and NNW–SSE at inner areas. The regional late Variscan fault network has been reactivated during the Alpine cycle as shown by the Gandra Fault (S. Pedro da Torre, Valença) (Pereira, 1989; Granja, 1990; Cabral, 1993, 1995; Granja et al., 1999), oriented N10°W. This fault dips 60°W and exhibits inverse movement. The Palaeozoic gneiss-granite overlies a fluvial deposit (50 m a.s.l.) considered as Pleistocene. Cabral (1995) suggested this structure is the south extension of the Tui-Caldas de Reyes Fault, controlling regional structures such as the Porriño basin and Louro valley. Santanach (1994) and De Vicente and Vegas (2009) referred to the Tui-Caldas de Reyes as a sinistral strike-slip fault which has the same movement as the NNE-SSW system Vilariça and Verín-Penacova faults, that control several tectonic basins (Pereira et al., 2000).

The analysis of aerial photography, DEM and related hill shade models, complemented with field data also suggests several probable tectonic lineaments, representing two main systems: ENE–WSW/E–W and NNW–SSE/N–S/NNE-SSW. These faults were involved in several geomorphological details of landscape, as surface tilting and dropping, fluvial captures and knickpoints, tectonic scarps, and river incision control (Carvalhido, 2012) (Fig. 1).

3. Geomorphological setting

The region shows a diversity of landforms that resulted from the action of coastal, fluvial and continental processes, but also lithological and tectonic controls. The relief rises more than 100 m above mean sea level (a.s.l.) (Araújo, 2004) and is organised into nuclei. These are more dispersed south of the Lima River (granite massifs of Galeão, Roques and S. Romão) and are more concentrated to the north. The tops of these massifs consist typically of planation surface remains: Arga surface (S1) 800–720 m; Sta. Luzia surface (S2) 470–330 m; S. Mamede surface (S3) ~270 m; Além do Rio surface (S4) ~160 m and Faro de Anha surface (S5) ~100 m a.s.l. (Fig. 1).

Developed at lower elevations, ~70–75 m a.s.l., the Ola surface (S6) is distinguished from the Marginal Relief by a well-marked cliff, especially north of the Lima River where the Viana do Castelo massif rises abruptly at an elevation of 60 m a.s.l., with slopes above 30% that in exceptional cases can reach 60%. South of Lima River, the main cliff of Galeão (slopes > 30%) also appears above 60 m a.s.l., and faces the Lima valley. At S. Romão massif, the main cliff is an innermost orographic element, appearing usually between 80 and 100 m a.s.l., rarely at lower elevations. At an elevation of ~50 m a.s.l., the Vila Fria planation surface (S7) can be identified.

Despite the extensive outcrops across the study area, spreading over more than 30 km of coastline, there are only a few deposits that record the Quaternary evolution of this Atlantic margin. Given the geographical location of these deposits, it is assumed that the recent landscape evolution, particularly during the Little Ice Age (LIA), leading to the development of an extensive aeolian dune cover, contributed to the preservation of previous formations. However, the recent erosive evolution of the coast exposed an important part of the sedimentary record.

Meireles (1992) and Meireles and Texier (2000) identified ten marine terraces, not considering any duplication by active faults, as follows (elevations a.s.l): M1 (100–140 m), M2 (80–88 m), M3 (63–67 m), M4 (48–54 m), M5 (41–45 m), M6 (31–36 m), M7 (25–27 m), M8 (18–22 m), M9 (8–14 m) and M10 (3–5 m). These authors assigned the lower terraces M10 and M9b to the MIS5 and MIS7, respectively, and identified on the cover unit several colluvial intercalations (CA, CR1, CR2, CR3 and CR4), as well as lagoon and dune deposits.

In the study area, the cover unit is very extensive and is sandy-silty. It was firstly termed as "Sandy-silty Cover Fm." by Berthois (1949) and Costa and Teixeira (1957), and subsequently referred in several other sheets of the 1/50,000 geological maps of Portugal (Teixeira et al., 1962; Teixeira and Assunção, 1963; Teixeira and Medeiros, 1965). This terminology had a wide acceptance among the scientific community (e.g. Carvalho, 1983, 1985; Alves, 1989, 1996; Granja, 1990; Carvalho and Granja, 2003). Some authors as Carvalho and Granja (2003) and Araújo (2008) recognised that this formation has not been the subject of extensive study, and that the grain-size terminology used have contributed to errors in the genetic and age interpretations of distinct continental sub-units.

To date, there is very limited numerical age information for Pleistocene sedimentary deposits in NW Portugal. Carvalho and Granja (1997) presented ^{14}C ages of fluvial sands (13860 ± 440 BP, Afife site) and from siliciclastic deposits (Montedor site) (>42370 BP). Ribeiro et al. (2011) recognised a thin layer of organic-rich mudstone dated 5880 ± 60 BP, recording a continental character that never had a direct connection to the sea.

4. Methods

The information presented here is derived from geomorphological, stratigraphical, sedimentological, and chronological data using a standard approach: a geomorphological study of the region complemented by local detailed investigations and the generation of detailed maps using GIS; field descriptions and stratigraphic correlation of the sedimentary units; sedimentological characterization of the deposits and numerical dating (OSL and ^{14}C dating). Mapping of geomorphological features was undertaken in three stages: (1) field mapping onto topographical (1/25,000) and geological (1/50,000) base maps; (2) analysis of 1/25,000 black/white aerial photographs and of a digital elevation model (DEM) based upon a 1/25,000 topographic database to improve the resolution of the field mapping; (3) ground truthing in the field to refine the geomorphological map produced from remote sensing.

The geomorphological studies were done taking into account that neotectonic activity was responsible for terrace genesis. The tectonic features in the area were identified by aerial photographs, DEM models and related hill shade models, and GIS lab work (geomorphic indexes). Field survey was focused on detailed altitude studies of local coastal platforms (w/DGPS) and fracture evolvement (e.g. slickensides traces).

The sites investigated consist of littoral outcrops but also quarries and excavations on beaches, coastal cliffs and hillsides. The outcrops were mainly located between the Lima River mouth and the Minho River mouth, exposing the following terraces (always with abrasion shore platforms): T2 (ca. 13 m) – sites 4 and 8; T3 (7.3–9.3 m) – sites 1, 5 and 10; T5 (2.0–3.5 m) – sites 2, 3, 6, 7, 9 and 12 (Fig. 1). Three outcrops were also studied at the Além do Rio surface (160 m), Faro de Anha surface (100 m) and Vila Fria surface (50 m) (Fig. 1), mainly consisting of sands on the top of those planation surfaces.

Field work included stratigraphic logging and sedimentological characterization of the sedimentary deposits in order to obtain data such as depositional architecture, bedding, depositional facies, sediment colour, texture, maximum particle size, clast lithology and fossil content (diatoms, dinoflagellates and macrofossils). Clast macrofabrics were taken to provide palaeocurrent data inferred from the direction of the maximum dip angle of quartzite cobbles or to give a periglacial flow indicator by measuring the major axis direction of boulders (Trueba, 2006). Sediment samples were collected from the sections described here and from modern depositional environments for detailed particle analysis using either sieving at 2 Phi intervals (for sands) or a Sedigraph 5100 (for muddy samples). Particle size parameters were calculated using the Gradistat program (Blott and Pye, 2001). The mineral composition of the sand fraction was evaluated by observation with a binocular microscope. Age determination of the Pleistocene sections was achieved by optically-stimulated luminescence (OSL) and AMS radiocarbon methods.

Where they were encountered, samples of charcoal were analysed by accelerator mass spectrometry (AMS) by Beta Analytic laboratories (FL, USA). The charcoal samples were collected from sediment by manual picking with tweezers, labelled and saved on aluminium foil avoiding ^{14}C cross contamination between samples and with packaging material. As the samples were encrusted in clayed sediments, we pursued the matrix removal by physical pretreatment using flotation on ultra-purified water and manual humid sieving with a 180 μm ASTM sieve. The samples were packaged in the aluminium foil, making a small airtight pouch labelled with the sample code number. The results reported are conventional radiocarbon ages (1 sigma). The calibrated date ranges have been calculated by the maximum intercept method (Stuiver and Reimer 1986), using the IntCal13 data set and Calib V7.0 program provided by the University of Washington Quaternary Isotope Lab (Reimer et al., 2013).

The radiocarbon dating method has significant upper and lower limits because the decay rate is logarithmic. It is not very accurate for recent deposits where little decay has occurred, and the error factor may be larger than the date obtained (Ramsey, 2008). The practical upper limit, about 43,500 BP, is achieved when the activity of the material is statistically the same as the background, hence this age should be reported as minimum.

OSL samples were collected by inserting opaque tubes into the walls of sampling exposures that were excavated at least 1 m back from the face of the outcrop. Sands, preferably without ferruginisation and at a minimum distance of 50 cm from the substrate or boulders were selected (Fig. 2). When the insertion of sampling tubes was not possible (e.g. units accessed by digging – Sites 5, 6 and 7, Fig. 1), direct sampling was taken at night using dim red light (Fig. 2).

For OSL, sample preparation for luminescence analyses was done in darkroom conditions involving wet-sieving to separate the 180–250 μm grain size fraction followed by HCl (10%) and H_2O_2 (10%) treatments to remove carbonates and organic matter, respectively. The K-feldspar-rich fraction was floated off using a heavy liquid solution of sodium polytungstate ($\rho = 2.58$ g/cm^3). The quartz fraction was obtained by etching another portion with concentrated HF (40%). The K-feldspar fraction was treated with 10% HF for 40 min to remove the outer alpha-irradiated layer and to clean the grains. After etching, both the quartz and K-feldspar fractions were treated with HCl (10%) to dissolve any remaining fluorides. Quartz purity was confirmed by the absence of a significant infrared-stimulated luminescence (IRSL) signal. Environmental dose rates were calculated from the radionuclide concentrations of the sediment, measured by high-resolution gamma spectrometry (Murray et al., 1987). Equivalent doses (D_e) were measured on Risø TL/OSL DA- 20 readers. Quartz 8 mm aliquots were mounted on stainless steel discs and K-feldspar 2 mm aliquots mounted on stainless steel cups.

Quartz dose estimates were made using a standard SAR protocol using blue light stimulation at 125 °C for 40 s with a 240 °C preheat for 10 s, a 200 °C cut heat and an elevated temperature (280 °C) blue-light stimulated clean-out step (Murray and Wintle, 2000, 2003). The OSL signal was detected through a U-340 filter. All samples have a strong fast component. The net OSL signal was calculated from the initial 0.0–0.8 s of stimulation and an early background between 0.8 and 1.6 s.

The K-feldspar D_e values were measured using a post-IR IRSL SAR protocol using a blue filter combination (Thomsen et al., 2008; Buylaert et al., 2012). After a pre-heat of 320 °C for 60 s the aliquots were first IR bleached at 50 °C for 200 s and subsequently stimulated again with IR-light at 290 °C for 200 s. It has been shown by Buylaert et al. (2012) that the post-IR IRSL signal measured at 290 °C gives accurate results without the need to correct for signal instability. For all calculations, the initial 2 s of the luminescence decay curve less a background derived from the last 50 s was used.

5. Results

5.1. Terrace staircase

A staircase of coastal terraces is also represented at the following elevations (a.s.l.) (Fig. 3): T1 – 20–18 m, consists of an abrasion shore platform with a residual sedimentary cover; T2 – ca. 13 m, with a sedimentary infill (<4.50 m); T3 – 9.3–7.3 m, with a sedimentary infill (<4.0 m); T4 – 5.5–4.5 m, with sedimentary infill (<2.0 m); T5 – 3.5–2.0 m, with a sedimentary infill (<2.5 m). At the

Fig. 2. Sampling for OSL dating: A) Galeão (site 11, cf. Fig. 1) and B) Sto Isidoro (site 3, cf. Fig. 1).

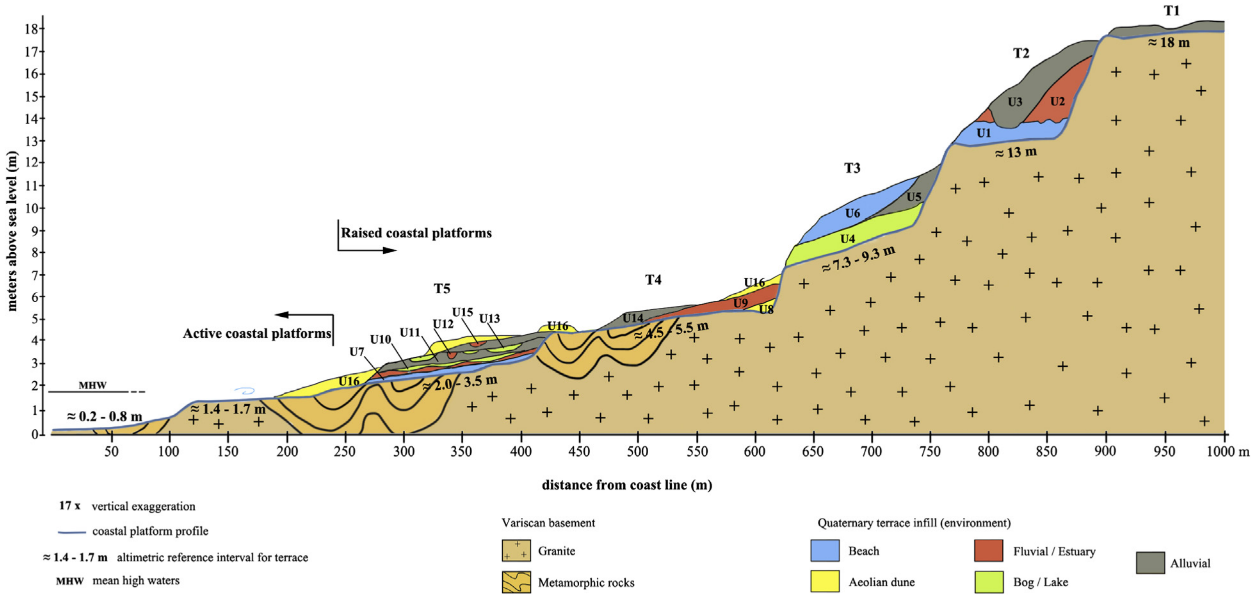

Fig. 3. This profile documents the coastal terrace staircase identified at the Minho - Neiva area; topography based on DGPS studies on Montedor, Rego de Fontes and Cabedelo sites. The relative width of the terraces reflects the inequality of its spatial development, which is larger on the lowest ones. The horizontal scale is indicative only and was calibrated from the terrace 2.0–3.5 m in order to calculate the vertical exaggeration of the profile (25 ×) (adapted from Carvalhido, 2012).

coastline, two lower platforms can also be identified at 1.7–1.4 m and 0.8–0.2 m. The terraces are essentially modelled in a granite substratum. Exceptions are the T4 and T5, well preserved all over the littoral, whose substratum also includes schist and quartzite.

T1 is preserved at Montedor, with colluvium infill and intense bioturbation (Table 1).

T2 is preserved at Gelfa, Montedor and S. Sebastião sites. At Gelfa consists in a 1.5 m thick sequence, comprising well-sorted and imbricated clast-supported gravels covered by poorly sorted compact reddish sands. At S. Sebastião, the sequence is thicker (3 m) and comprises: yellow sands with good sorting, a middle layer of brown sandy-silty, both partly eroded by compact reddish

Table 1

Summary of key geological attributes for the Minho–Neiva staircase of coastal terraces (NW Portugal). Terrace altitude refers to the base (asl). *Sedimentary units that appear on other terraces.

Terrace	Sedimentary unit	Sedimentology	Paleocurrent direction
T1 20–18 m	–	Residual sedimentary cover that shows intense bioturbation.	–
T2 13 m	U3	Massive reddish poorly sorted subarkosic sand; channel filling at the base (channel width <50 cm) and massive at the top.	N338° (channel axis)
	U2	Brown to mottled reddish sandy-silt with flaser-bedding.	N70° (flaser-bedding)
	U1	Clast-supported gravels, well sorted, imbricated (maximum particle size, MPS = 16 cm); yellow sand with good sorting, reddish mottled sand with wave ripples.	N125° and N293° (gravels imbrication) N62° (wave ripples)
T3 9.3–7.3 m	U6	Clast-supported conglomerate (ferruginous cement), well sorted, with imbrication.	N104° and N130° (imbrication)
	U5	Massive matrix-supported gravels with rounded granite boulders (MPS = 90 cm).	–
	U4	Massive brownish very poorly sorted sandy-silt layer, with iron oxi-hydroxides (base) and charcoal (top).	–
T4 5.5–4.5 m	–	Rare sedimentary infill by U8, U9, U14 and/or U16.	–
T5 3.5–2.0 m	U16*	Well sorted greyish quartz sand with planar cross-bedding.	N65° (cross-bedding)
	U15*	Well sorted greyish quartz sand with current ripples.	N245° (current ripples)
	U14*	Very poorly sorted unit that alternates between darkish-greyish to reddish and silty-sand to matrix-supported gravels with boulders (MPS = 350 cm). Intense bioturbation.	N–S to N22° (boulders major axis)
	U13	Massive dark brownish very poorly sorted silty layer.	–
	U12*	Subarkosic coarse yellowish to reddish sand, poorly sorted, low angle planar cross-bedding.	–
	U11	Very poorly sorted unit, finning upward; layer alternates between coarse sand channel-filling and horizontal bedding, and massive fine sediments.	–
	U10	Very poorly to poorly sorted greyish quartz sand with charcoal to massive dark arkosic sandy-silt.	–
	U9*	Reddish to reddish mottled coarse subarkose (ferruginous cement), moderately to poorly sorted, trough cross-bedding.	–

Table 1 (*continued*)

Terrace	Sedimentary unit	Sedimentology	Paleocurrent direction
	U8*	Massive very well sorted yellow quartzarenite (ferruginous cement).	–
	U7	Clast-supported conglomerate (carbonate cement), well sorted, imbricated; massive very well sorted coarse subarkosic greyish sand.	N76°, N148°, N211° and N315° (gravels imbrication)

poorly sorted sands. At Montedor, the terrace does not preserve a sedimentary infill (Table 1).

T3 is observed at Moledo and Montedor sites. At Moledo the terrace is composed, from base to top, by a brownish very poorly sorted sandy-silty layer partly eroded by a matrix-supported gravels where rounded granite boulders occur (Maximum Particle Size, MPS = 90 cm). This level is partly eroded by a clast-supported cemented gravel, well-sorted and with imbrication. At Montedor, the terrace has no sedimentary infill (Table 1).

T4 is well exposed at Gelfa (granite basement) and Montedor (a basement of granite, schist and quartzite). Despite the absence of beach sedimentary remains, the preservation of notches confirms the marine origin of the terrace (Table 1).

T5 is observed at Gelfa (granite basement), Montedor (granite, schist and quartzite basement), Rego de Fontes (schist basement) and Cabedelo (granite basement). This terrace has evidence of littoral geoforms, sea-urchin alveoli (*Paracentrotus lividus* - infra-littoral habitat), and notches. The best outcrop was found at the Moledo site, preserving well-sorted coarse sands, covered with well-sorted yellow sands. These layers are topped by poorly sorted greyish sands with charcoal, by a dark sandy-silty layer, and by a very poorly sorted unit that alternates between coarse and fine

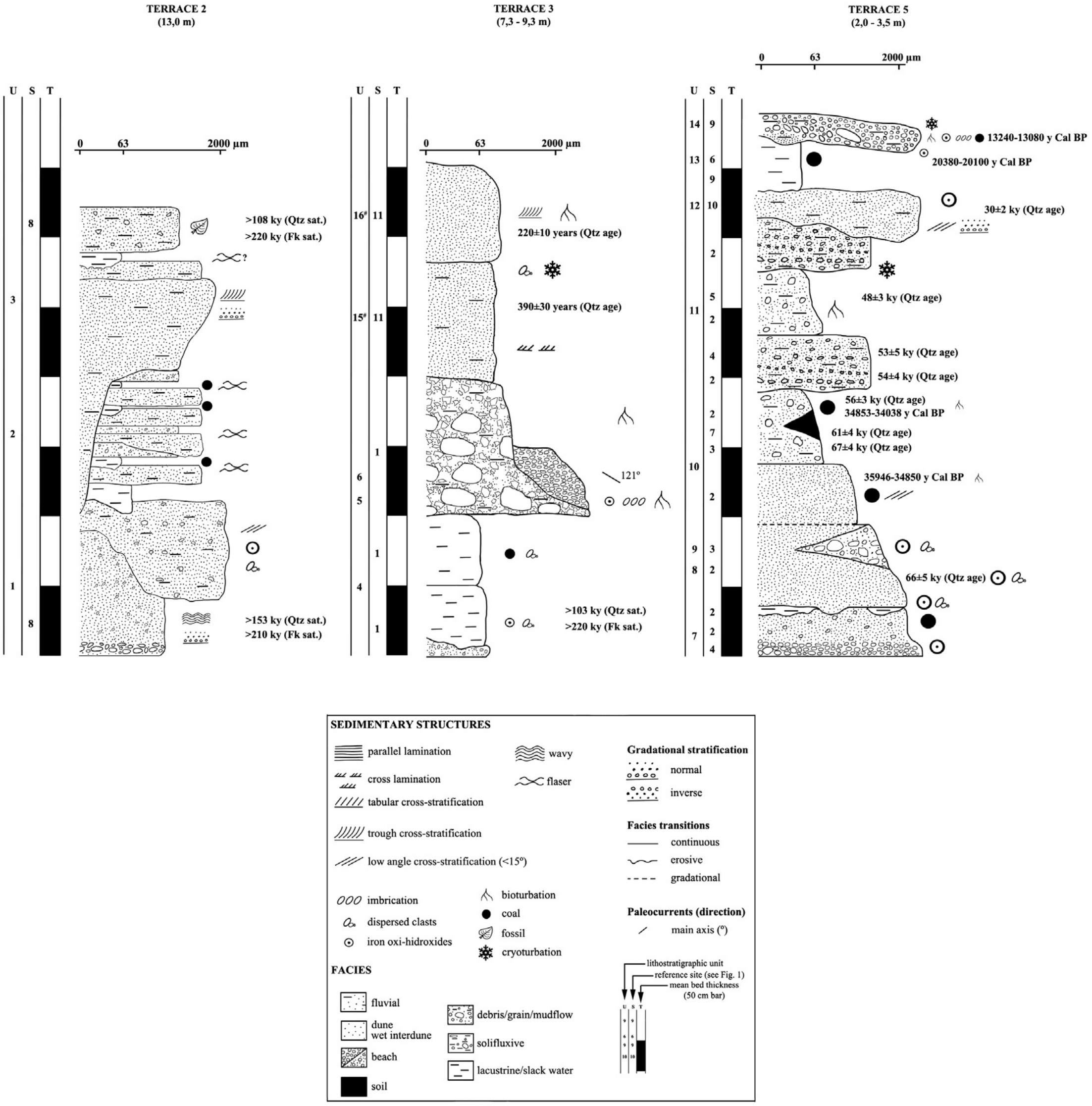

Fig. 4. Main synthetic stratigraphic columns of the study area. The most relevant ages obtained are indicated (^{14}C, quartz-OSL and pIRIR). Legend partially adapted from Tucker (2003).

sediments. Rego de Fontes and Montedor display the uppermost unit, a dark brownish very poorly sorted sandy-silty layer (Table 1).

A summary of the stratigraphy and sedimentary data of the studied deposits is given by three main synthetic stratigraphic columns (Fig. 4). The thicknesses of the sedimentary units vary considerably, from 0.2–0.3 m to 1.5–2.0 m.

5.2. *Numerical dating*

For luminescence dating, fifteen sediment samples were collected: (i) two samples from the T2 terrace, from the base (code PC5251) and top (code PC5252) of the terrace deposits (at the S. Sebastião site); (ii) one sample (code PC5253) from the T3 terrace (at the Estrada Real site); (ii) eight samples from the late Pleistocene–Holocene cover unit (codes 102208, PC5243, PC5246, PC5247, PC5248, PC5249, PC5250 and PC5254), collected at several sites; (iii) two samples from a historic fluvial-aeolian unit (codes PC5244, PC5245); (iv) two modern samples (codes 102209 and 102210). The luminescence dating results are presented in Tables 2–4.

There is some evidence that quartz OSL gives accurate results up to 150–200 Gy (e.g. Murray and Funder, 2003; Murray et al., 2007). Beyond this dose limit the reliability of quartz equivalent doses is questionable. The samples with quartz De values >>200 Gy were dated using the pIRIR290 SAR protocol. However, the pIRIR290 signal was also very close to saturation. Hence, we estimated the dose at 86% of the saturation level of the dose response curve and the resulting ages are considered minimum values (>220 ka).

The subunits identified on the late Pleistocene–Holocene cover unit (covering basement slopes and the T4 and T5 terraces) were dated (quartz-OSL ages and AMS ^{14}C ages from charcoal samples – Table 5): stream deposits and aeolian dune sands dated ca. 67–61 ka; sandy-silt to silty colluvium deposits were dated to 56–13 ka. Samples from Galeão (site 10, Fig. 1) with ages 0.22 ± 0.01 ka and 0.39 ± 0.03 ka, refer to historic fluvio-aeolian sediments that correlate with the Little Ice Age climatic event. These sediments were sampled at Vila Fria Surface (~50 m a.s.l.) and Faro de Anha Surface (~100 m a.s.l.) but the sub-unit can also be found at higher and lower altitudes.

Table 2
Burial depth, radionuclide concentrations and water content used for dose rate calculation of the luminescence samples.

Sampling site & number (Fig. 1)	Field code	Lab code	Burial depth (cm)	^{238}U (Bq kg^{-1})	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	Water content (field, saturation) (%)
Estrada Real 1	MB2.1SES	PC5253	330	96 ± 9	85 ± 1	64 ± 1	841 ± 16	13 (13, 30)
S. Domingos 2	MOL 0	PC5249	245	137 ± 8	49 ± 1	21 ± 1	549 ± 12	16 (16, 24)
	MOL 170	PC5248	110	56 ± 9	39 ± 1	33 ± 1	1126 ± 22	13 (13, 32)
Sto. Isidoro 3	VPA 2	PC5246	70	43 ± 7	34 ± 1	23 ± 1	811 ± 18	12 (11, 28)
Forte do Cão 4	GELFA 1.2	102208	100	37 ± 6	44 ± 1	64 ± 1	391 ± 10	12 (12, 44)
Alcantilado de Montedor 5	MALC52	PC5250	50	93 ± 9	65 ± 1	73 ± 1	652 ± 15	10 (6, 26)
Cambôa do Marinheiro 6	MD-50	PC5247	50	44 ± 7	50 ± 1	55 ± 1	544 ± 13	10 (10, 27)
Canto Marinho 7	CM105	PC5243	100	40 ± 7	35 ± 1	47 ± 1	640 ± 16	8 (6, 25)
S. Sebastião 8	CP1	PC5251	400	45 ± 6	40 ± 1	37 ± 1	620 ± 14	25 (37, 42)
	CP5	PC5252	280	75 ± 10	67 ± 1	52 ± 1	672 ± 15	13 (13, 25)
Rego de Fontes 9	PNB1	PC5254	140	51 ± 7	36 ± 1	37 ± 1	917 ± 18	5 (3, 22)
Galeão 10	GAL50.1	PC5245	350	37 ± 8	38 ± 1	45 ± 1	512 ± 12	6 (6, 27)
	GAL100	PC5244	50	28 ± 8	21 ± 1	25 ± 1	562 ± 14	6 (6, 24)
Cabedelo 11	RIC-PRAIA	102209	30	34 ± 6	29 ± 1	37 ± 1	558 ± 11	10 (4, 25)
	RIC-DUNA	102210	30	32 ± 6	36 ± 1	51 ± 1	603 ± 11	8 (4, 28)

Table 3
Summary of quartz optically stimulated luminescence. *Natural signals were in saturation (i.e. >86% of the saturation level of the dose response curve).

Sampling site & number (Fig. 1)	Field code	Lab code	Geographic coordinates	Sedimentary facies	Platform altitude (m)	Terrace top altitude (m)	Sample altitude (m)	Quartz dose rate (Gy/ky)	Quartz equivalent dose (Gy)	Quartz age (ky)	Probable MIS age
Estrada Real 1	MB2.1SES	PC5253	41°50′30.75″N 8°52′15.49″W	Silty sand, palustrine	8.4	12.3	9.0	4.72 ± 0.21	485 ± 114*	>103 ± 25	7 (?)
S. Domingos 2	MOL 0	PC5249	41°50′1.42″N	Aeolian sand	3.0	3.75	6.2	2.95 ± 0.13	194 ± 10	66 ± 5	4
	MOL 170	PC5248	8°52′30.32″W	Silty sand, fluvial	3.0	6.2	5.1	4.45 ± 0.19	239 ± 12	54 ± 4	3
Sto. Isidoro 3	VPA 2	PC5246	41°49′42.33″N 8°52′30.87″W	Sandy silt, wet interdune	2.0	3.4	2.7	3.37 ± 0.14	226 ± 9	67 ± 4	4
Forte do Cão 4	GELFA 1.2	102208	41°47′47.25″N 8°52′15.26″W	Sandy silt, fluvial	13	14.5	13.5	3.06 ± 0.13	163 ± 13	53 ± 5	3
Alcantilado de Montedor 5	MALC52	PC5250	41°44′58.82″N 8°52′46.74″W	Sandy silt, palustrine	2.7	4.5	4.0	4.34 ± 0.19	209 ± 10	48 ± 3	3
Cambôa do Marinheiro 6	MD-50	PC5247	41°44′44.95″N 8°52′37.20″W	Wet interdune sand	2.6	3.9	3.4	3.39 ± 0.15	190 ± 4	56 ± 3	3
	CM105	PC5243		Muddy sand, fluvial	2.0	3.2	2.2	3.49 ± 0.15	212 ± 8	61 ± 4	3/4

Table 3 (*continued*)

Sampling site & number (Fig. 1)	Field code	Lab code	Geographic coordinates	Sedimentary facies	Platform altitude (m)	Terrace top altitude (m)	Sample altitude (m)	Quartz dose rate (Gy/ky)	Quartz equivalent dose (Gy)	Quartz age (ky)	Probable MIS age
Canto Marinho			41°44′15.27″N								
7			8°52′28.60″W								
S. Sebastião	CP1	PC5251	41°42′37.29″N	Beach sand	13.2	17.8	13.8	2.71 ± 0.11	415 ± 18*	>153 ± 9	9 (?)
8	CP5	PC5252	8°51′7.73″W	Fluvial sand	13.2	17.8	15.0	3.83 ± 0.17	415 ± 37*	>108 ± 11	9 (?)
Rego de Fontes	PNB1	PC5254	41°41′59.78″N	Fluvial sand	7.5	9.4	8.0	4.17 ± 0.19	126 ± 4	30 ± 2	3
9			8°50′55.17″W								
Galeão	GAL50.1	PC5245	41°40′45.17″N	Fluvial sand	50.0	54.0	50.5	3.05 ± 0.14	1.19 ± 0.06	0.39 ± 0.03	1
10			8°48′0.47″W								
	GAL100	PC5244	41°40′27.13″N	Aeolian sand	100	101	100.5	2.67 ± 0.12	0.58 ± 0.01	0.22 ± 0.01	1
			8°48′6.80″W								
Cabedelo	RIC-PRAIA	102209	41°40′42.55″N	Beach (berm) sand	–	3	2.7	–	–	–	1
11	RIC-DUNA	102210	8°49′51.02″W	Sand dune	–	5	4.7	–	–	–	1

Table 4
Summary of K-feldspar post-IR IRSL290 dating (pIRIR$_{290}$). *Natural signals were in saturation on the dose response curve (i.e. >86% of the saturation level of the dose response curve). The quoted dose corresponds to a signal at 86% of saturation and is considered a minimum value.

Sampling site & number (Fig. 1)	Field code	Lab code	Geographic coordinates	Sedimentary facies	Platform altitude (m)	Terrace top altitude (m)	Sample altitude (m)	Burial depth (cm)	Water content (field, saturation) (%)	Kf dose rate (Gy/ky)	Kf Equiv. Dose (Gy)	pIRIR age (ky)	Probable MIS age
Estrada Real	MB2.1SES	PC5253	41°50′30.75″N	Silty sand,	8.4	12.3	9.0	330	13 (13, 30)	5.53 ± 0.21	1011 ± 67*	>220	7 (?)
1			8°52′15.49″W	palustrine									
S. Sebastião	CP1	PC5251	41°42′37.29″N	Beach sand	13.2	17.8	13.8	400	25 (37, 42)	3.52 ± 0.11	753 ± 46*	>210	9 (?)
8	CP5	PC5252	8°51′7.73″W	Fluvial sand	13.2	17.8	15.0	280	13 (13, 25)	4.64 ± 0.17	1031 ± 95*	>220	9 (?)

Table 5
AMS ^{14}C age results. The radiocarbon dates were calibrated (Cal BP 2 sigma statistics) using the IntCal13 Radiocarbon Age Calibration Curves (Reimer et al., 2013).

Sampling site & number (report Fig. 1)	Field code	Lab code	Geographic coordinates	Sedimentary facies	Sample altitude (m)	Conventional age^{14}C (yr BP) (1 sigma)	Calibrated age^{14}C (yr Cal BP) (2 sigma)	^{13}C/^{12}C (‰)	Probable MIS age
S. Domingos	MOL150	Beta-269979	41°50′1.42″N	Wet interdune sand (soil?)	3.80	30490 ± 220	34853–34038	−24.5	MIS3
2	MOL65	Beta-268463	8°52′30.32″W	Wet interdune sand	3.50	31500 ± 240	35946–34850	−23.7	MIS3
Cambôa do Marinheiro	MD29	Beta - 275841	41°44′44.95″N	Silt, palustrine	2.55	17120 ± 70	20885–20447	−25.1	MIS1
6			8°52′37.20″W						
Rego de Fontes	PN23	Beta 277233	41°41′59.78″N	Sandy silt, proximal flow	3.60	11260 ± 50	13234–13043	−25.2	MIS1
9			8°50′55.17″W						

The OSL and ^{14}C ages obtained for the cover unit are according to stratigraphy (Fig. 6) and there is no evidence that the ages systematically vary between different sites with similar stratigraphic successions. However an exception was the ^{14}C dating results from the S. Domingos site, which returned ages younger than those obtained by quartz-OSL, probably related to root penetration.

6. Paleoenvironments and ages of the sedimentary units

The T1 terrace (at 20-18 m a.s.l.), only locally represented, consists of an abrasion shore platform with a residual sedimentary cover (Table 1) and should be considered a marine terrace.

The T2 terrace (at ~13 m a.s.l.) occurs at Forte do Cão (site 4, Fig. 1) and S. Sebastião (site 8, Fig. 1), displaying three sedimentary units (Figs. 3, 4 and 6, Table 1). At Forte do Cão, the basal unit (U1) is a high energy beach (pebbly), a lateral equivalent of S. Sebastião base unit pebble beach record which evolves to moderate energy beach (sandy beach – reddish mottled sands with wave ripples). The OSL measurements carried out on samples of this sandy layer (Tables 2–4) retrieved the quartz and K-feldspar signal in saturation (age >220 ka). The top of U1 is overlain by estuarine facies (flaser bedding preserved) – U2 – suggesting a Lima paleoestuary at about 3 km to the north of present location. The continental character is definitely established at the top of the sedimentary sequence – U3 – by channel-fill facies reflecting an episodic fluvial regime and alluvial fan deposits (reddish sands) in which a fossilized underground stem of *Pteridium aquilinum* was identified. The quartz and K-feldspar OSL signals of the samples collected in U1 and U3 are in saturation (age >220 ka). At Estrada Real (site 1, Fig. 1), the transition between the T3 and T2 terraces can be observed with no evidence of tectonic contact.

The T3 terrace (~8 m a.s.l.) was observed at Estrada Real (site 1, Fig. 1). Three lithostratigraphic units (U4, U5 and U6; Figs. 3 and 6, Table 1) were identified above an erosive surface on granite, showing morphological evidences of marine occupation (e.g. potholes). U4 was interpreted as a quiet aquatic environment, progressively confined (charcoal content increases to the top, iron oxides disappear – anoxia conditions?), with fresh-water (diatom *Rhizosolenia morphotype*) - predictably a lacustrine/bog. The sample collected from the middle part of U4 gave a minimum age of 220 ka. The top of U4 is an erosional surface followed upwards by debris-flow deposits (U5), transitional laterally to well rounded, ferruginous-imbricated gravels (U6) interpreted as a beach deposit (9 m a.s.l.).

The T4 and T5 have a continental and transition sedimentary infill (Table 1), and coastal geoforms (T5 – notches and sea-urchin alveoli; T4 – only notches). Beach sediments found at T5 (Forte do Cão Gravels and Sands, U7), aren't suitable for OSL dating (reduced distance to the granite basement and coarse sediments).

The youngest deposits (unit U9 to U16) cover mostly the T5 but rarely the T4 terrace platforms. Most dated layers cover the T5 terrace and provide ages between 67 ± 4 ka (OSL) (MIS4) and 13 ka Cal BP (^{14}C) (MIS2). The deposits that cover the T4 terrace are mainly gravity-dependent, such as aeolian dune deposits (Ronca de Montedor Sands, U8) and alluvial deposits (S. Domingos Upper Sands, U11):

a) The Ronca de Montedor Sands (U8) and the Sto Isidoro Sands (U9) are ferruginous-cemented sands indicating warm sub-humid to arid environments that could have a probable age of ca. 70–65 ka (possibly recording warm pulses observed during MIS4; see NGRIP, 2004 or Desprat et al., 2005), consistent with aeolian dunes (U8) and fluvial (U9) environments;
b) The S. Domingos Sands and Silts (U10), the S. Domingos Upper Sands (U11) and the Ribeira de Portela Sands (U12) provided ages between 67 ± 4 and 30 ± 2 ka (MIS3). These units show a progressive reduction of indirect marine influence – wet interdune/interdune ponds (U10), grain-flow/mud-flows (cyclic) (U11) and fluvial deposits (U12). Depositional conditions are marked by the availability of water, with increased energy towards the upper units. The S. Domingos Sands and Silts (U10) and the Ribeira de Portela Sands (U12) reveal climatic conditions favourable to edaphogenesis (U10) and fluvial drainage reestablishment (U12), which may have occurred between ≈ 32 and ≈ 28 ka. This evidence agrees with Granja et al. (2008), who reported successions of small fluvial systems progressively covered by wet aeolian accumulations during the first half of MIS 3. Pérez-Alberti et al. (2009) described paleosols on the Galician coast, dated between ≈ 32 and ≈ 25 ka. The radiocarbon dating on U10 was performed on charcoal samples (circular section, diameter up to 20 mm) retrieving younger ages than those provided by OSL dating obtained from the top layer sequence (U11). Considering that U12 has a similar age and presents fluvial facies, we suggest the possibility that the charcoal is a plant rootlet intrusion related to an edaphogenesis phase (Dansgaard–Oeschger event 7) prior to the onset of Heinrich Event 3 (H3) (c.f. Fig. 5a/5f);
c) Cambôa do Marinheiro Silts (U13) has been radiocarbon dated between 20 and 13 ka cal BP (14C) (MIS2), indicating sedimentary processes depending on liquid water scarcity drainage. These processes relates to the installation and progression of cold conditions arising from the last glaciation. The diffuse drainage conditions installed could have contributed to the formation of highly confined lacustrine bodies, with marshy or boggy character, in shallow coastal depressions of the Littoral Platform;
d) Rego de Fontes Gravels and Sands (U14) dated <13 ka cal BP (MIS2 and MIS1), match depositional paleoenvironments showing some facies variability linked to fluctuation of water availability, responsible for poorly sorted deposits that varies between coarser - torrential regimes (grain-flow to debris-flow deposits) and fine grained - solifluction processes.

The historic units, Ribeira de Areia Sands (U15) and Galeão Sands (U16), have been dated from the late XVI century and the end of the XVIII century. Based on the σ^{18}O signal, these layers are assigned to the Little Ice Age climate crisis:

a) The U15 dated between 1590 and 1650 records the water availability typical of climate conditions that immediately preceded the Maunder Minimum (Little Ice Age), matching fluvial sedimentation on the Ribeira da Areia stream. The top of this unit shows evidence of cryoturbation, overlain by dune sands (U16). The cryoturbation was diagnosed by identification of involuted 3A layers, interpreted as seasonally frozen ground or permafrost (Vandenberghe classification – Vandenberghe, 1988, 1992), with granite cryoclasts;
b) U16 records the Little Ice Age, matching cool and dry weather conditions reflected in intense aeolian dynamics. This unit is assigned to a coastal aeolian dune environment during the Dalton Minimum, between the early XVII century and the late XIX century (≈between 1780 and 1800) that promoted the deposition of aeolian sands covering coastal terraces (Abreu, 1987), Vila Fria Surface (~50 m a.s.l.), Faro de Anha Surface (~100 m a.s.l.) and Além do Rio Surface (~160 m a.s.l.).

Due to the fact that the beach unit (U7) that covers the T5 terrace is not suitable for OSL dating and because the OSL samples collected at the T3 and T2 marine terraces only provided a minimum age of 220 ka, precise numerical dating of the studied marine terraces was not achieved. Correlation between the marine terraces and Marine Isotopic Stages requires further substantiation, presented in the following paragraphs.

The T5 and T4 shore platforms (at 2.0 - 3.5 m and 4.5–5.5 m a.s.l., respectively) correspond to MIS5 due to the geomorphic position directly above the modern littoral and the presence of a gravelly beach unit (U7) covered by aeolian dune deposits (U8) dated ca. 67 ka. The two platforms could represent a similar situation as with contemporaneous shore platforms (mesotidal exposed Atlantic coast - inter-tidal platform at 0.2–0.8 m and high-tide platform at 1.4–1.7 m a.s.l.).

The T3 terrace might be ascribed to MIS7 because the shore platform could correlate with the high sea-level during 245–230 ka. The above lacustrine/bog unit (U4) could represent some sea level lower conditions during 230–220 ka (OSL minimum age of 220 ka) and the upper beach unit (U6) as recording the high sea-level during 220–190 ka. This matches the peculiarity of MIS7 that has two climatic optimums, MIS7.5 and MIS7.3, with similar interstadial conditions. Between these optimums, climate degradation is observed (stadial conditions – MIS7.4), matching the bog (U4) and debris-flow (U5) deposits.

Based on the previous interpretations, the T2 and T1 marine terraces could correspond to MIS9 and MIS11 respectively, which have high sea level stands at ca. 325 ka and 400 ka, respectively. The geomorphic data available show no evidence of tectonic displacement between coastal platforms. The sedimentary units of the northern littoral of Portugal allowed insight about the Pleistocene paleoenvironments (Fig. 6).

7. Neotectonics

The staircase of coastal terraces (shore platforms and sediments preserved) show no significant differences in the associated paleoenvironments and vertical deformation since MIS5 (Eemian) in the NW Iberian coast, between the Minho–Neiva sector (this study) and the Minho-Cape Silleiro (Galicia, Spain) sector. Alonso and Pagés (2000, 2007) noted four formations at the Galician coast: Castro de Fazouro Fm. (MIS5), interpreted as beach deposits resting on an abrasion shore platform 2–3 m (a.s.l.); Arnela Fm. and Nóis Fm. (MIS4–MIS3), correspond to classical slope deposits (soliflucted lobes, debris flows and soils, but also peat and swamp deposits); and Moreiras Fm. (MIS2) that represents environments from at least the Last Glacial Maximum and the beginning of deglaciation.

For the same time interval, the paleoenvironmental data available at the southern adjacent coastal sector (Neiva-Aveiro sector) (e.g. Granja, 1990; Granja and Carvalho, 1991, 1992, 1993, 1995;

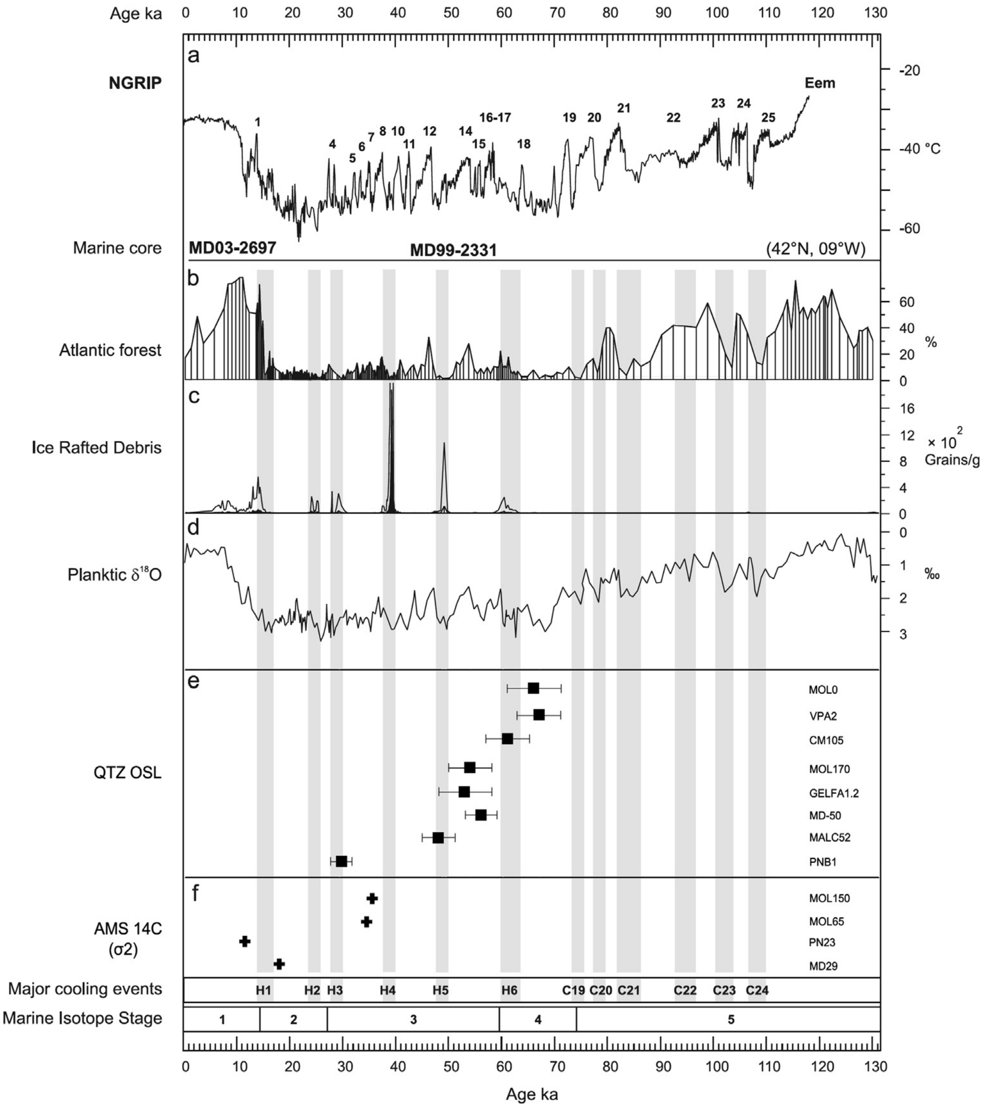

Fig. 5. Consistency between OSL ages, related sedimentary facies (middle Pleistocene to Holocene coastal units) and high-resolution stable isotope records from deep-sea core of Northwestern Iberia Margin, at Galician latitude (adapted from Desprat et al., 2005). For reference sample (e and f) see Tables 3–5. Radiocarbon ages are calibrated (Cal BP) using the IntCal13 Radiocarbon Age Calibration Curves (Reimer et al., 2013). All radiocarbon ages were converted in order to be comparable with OSL ages.

Carvalho et al., 1995; Granja and Groot, 1996; Granja et al., 1996, 2008; Groot and Granja, 1998; Thomas et al., 2008) show important differences. Three litostratigraphic units preserved in the higher shore platform (20–55 m a.s.l.) are described as beach environments (MIS5) – Pinhote Conglomerate, Outeiro Conglomerate and Gatinheira-Góis Sands; and two formations in the lower shore platform (2–10 m a.s.l.) – Cepães Fm. (MIS3) described as beach/fluvial deposits, and the Aguçadoura Fm. as dune, beach and lagoon deposits (MIS1).

Based on the similarities found on paleoenviroments assigned to each coastal terrace at Galicia and Minho, we propose that the Baiona-Minho (Galicia) and the Minho–Neiva coastal areas acted as one tectonic block (Baiona-Neiva block), showing coeval neotectonic behaviour at least since MIS5. The remarkable differences found to southern adjacent area concerning the paleoenvironments and topography, in relation to the southern adjacent area, suggest different neotectonics.

Using as geomorphic references the old planation surfaces, it is suggested that the S2 and S3 blocks were uplifted, controlled by NW–SE/NNW–SSE faults and a broad relief raising since the genesis of S4 modelling (Carvalhido, 2012; Fig. 1). The geomorphological, stratigraphical, and dating data clarified the relive evolution of the coastal terrace staircase from Middle Pleistocene to Holocene. Assuming the proposed correlation between the marine terraces and MIS (T4 and T5 – MIS5; T3 – MIS7; T2 – MIS9; T1 – MIS11?), the average rate of vertical deformation has been calculated as ca. +0.05 mm/y (linear regression method, R^2 >95%) for the last 400 ka. This agrees with Cabral (1995) who estimated Piacenzian-Quaternary maximum vertical deformation to this sector of Portuguese littoral, as between 0.03 and 0.05 mm/y. The partial vertical deformation has been determined for each coastal platform modelling (matching technique – Lajoie, 1986), ranging between −0.15 mm/y (MIS9 – MIS7.5) and +0.26 mm/y (MIS6–MIS5e) (Carvalhido, 2012).

8. Conclusions

On the coastal zone of northern Portugal, a staircase of five terraces (abrasion shore platforms) was identified at the heights

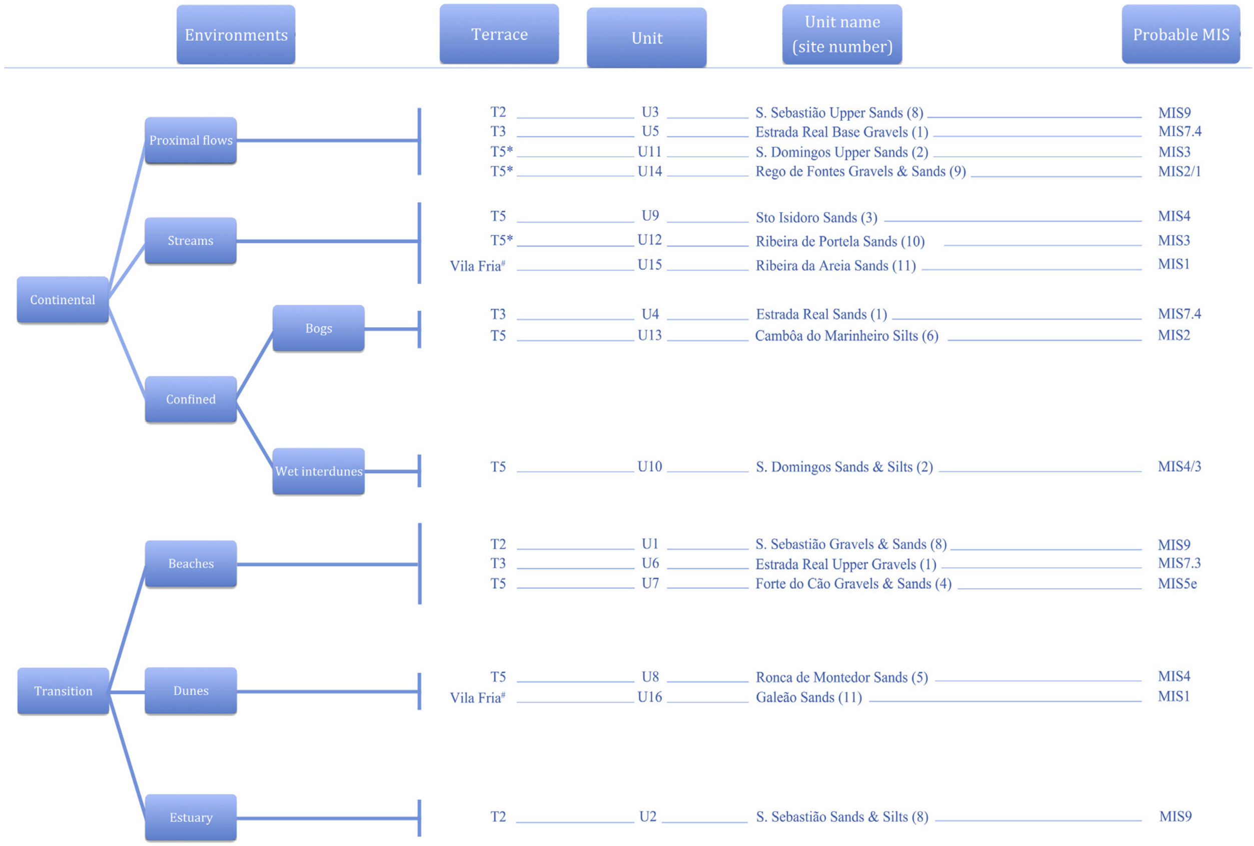

Fig. 6. Sedimentary units of the northern littoral of Portugal, interpreted paleoenvironments and proposed correlation with MIS, based on high-resolution stable ^{18}O isotope records from deep-sea Galician margin composite core (MD01-2447, MD99-2331 and MD03-2697). Units marked with * can occur at other terrace than those presented. (#) Vila Fria Surface is presented as a terrace, but no detailed geomorphological studies are yet available. For site number, please refer to Fig. 1.

(a.s.l.) of: T1 – 20–18 m; T2 – ca. 13 m; T3 – 9.3–7.3 m; T4 – 5.5–4.5 m; T5 – 3.5–2.0 m. The lower coastal terraces (T2, T3 and T5) have a beach sedimentary infill and were ascribed to the following Marine Isotope Stages: T2 (MIS9), T3 (MIS7), T4 and T5 (MIS5).

Sixteen lithostratigraphic units, representing the Pleistocene and Holocene, were characterized. The lithostratigraphy was based on geomorphology, stratigraphy, sedimentology, fossil content and dating (luminescence and AMS ^{14}C). The study of the sedimentary units allowed the identification of several Pleistocene depositional environments: a) continental - gravity flows (debris-flow, grain-flow and mud-flow), fluvial and palustrine systems (boggy) and b) transition - aeolian dune fields with interdune ponds, estuary, sandy and pebbly beaches.

The sedimentary cover unit provides detailed information regarding the climate evolution since the late Pleistocene: a) ferruginous stream deposits and aeolian dune sands dated ca. 67–61 ka (MIS4), probably related with sub-humid to arid mid-cold conditions; b) sandy-silty colluvium and sandy small alluvial fan deposits dated ca. 56–28 ka (MIS3), probably reflecting installation of mid-cold/cold and wet/dry climate conditions; c) soliflucted lobes and sandy-silty/silty deposits formed by diffuse drainage on liquid water scarcity, recording cold and dry climate dated ca. 20–13 ka (MIS2) and d) a later period of historic temperate climate (fluvial sediments) with a peak of aeolian dynamics during the Little Ice Age (cold windy dry conditions), episodes dated from 1590–1780.

The most probable correlation of the several abrasion shore platforms to the MIS provided an estimate of +0.05 mm/y for the average crustal uplift in the study area during the late Quaternary (MIS11 – MIS1), similar to the Galician coast (northern area) and contrasting evidence recorded at southern area (Neiva-Aveiro), especially with the presence of Late Holocene lagoon environments in this area. It is proposed that the Baiona-Minho (Galicia) and the Minho–Neiva coastal areas acted as one tectonic block (Baiona-Neiva block), showing coeval neotectonic behaviour, at least since MIS5.

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