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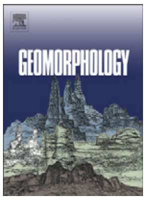

Dating the Tejo river lower terraces in the Ródão area (Portugal) to assess the role of tectonics and uplift

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ABSTRACT

The Tejo river is one of the major drainages in Iberian Peninsula; it is a long-lived system (ca. 3.4 Ma) and provides an archive of long-term landscape development and environmental change controlled by tectonics, climate and eustasy. The most upstream Portuguese reach of the Tejo river, ~200 km from the Atlantic coast, shows evidence for five fluvial terraces (T1 to T5) with elevations reaching more than 120 m above the modern river bed. A chronological framework for these terraces is established here by integrating geomorphological, stratigraphical and archaeological information with ages from luminescence dating. Optically stimulated luminescence dating of K-feldspar, (involving the correction for anomalous fading of the luminescence signal), indicates that the younger terraces have a probable age range of: T5 — 31 to 40 ka; and T4 — 100 to ~280 ka. We deduce that the related major fluvial changes are likely to have been as follows: ~10 m of aggradation from ~280 to 100 ka (0.06 m/ka); 14 m of incision from 100 to 40 ka (0.23 m/ka); 8 m of aggradation from 40 to 31 ka (0.89 m/ka); 16 m of incision during the last 31 ka (0.52 m/ka). These values indicate that the duration and rate of both aggradation and river downcutting episodes were variable. There is widespread evidence for neotectonic activity in this intraplate region. Neither eustatic nor climatic changes during the Quaternary provide clear trends that might explain the observed pattern of valley incision, thus we conclude that this tectonic activity is the most likely driving mechanism. In the study area, the probable age of the Tejo river sediments deposited before the beginning of valley incision allows the calculation of a time-averaged incision rate of ~0.07 to 0.10 m/ka over the last ~2.6 Ma. This long-term incision was probably determined by an increase in the relative uplift rate, resulting from the intensification of intraplate compressive stress. During the late Cenozoic fluvial incision stage, the Ródão depression underwent less uplift than the adjacent areas along the river, in which the Tejo has incised a narrow valley into basement rock, with almost no terrace development. Terrace formation was also promoted by soft bedrock (Tertiary arkoses) and by impoundment of alluvium behind resistant barriers crossed by the river. Geomorphological evidence for terrace tectonic offset was also supported by luminescence dating.

1. Introduction

The Tejo, called Tajo in Spain, is the longest (1007 km) and one of the largest rivers of the Iberian Peninsula (catchment size of 78,463 km^2), draining to the Atlantic Ocean (Fig. 1). Is a perennial fluvial system with a present average flow of ~9 km^3 yr^{-1} (1952–1982) in the study area (~200 km upstream of the Atlantic coast). Before dam construction, erosion affected most of the catchment and deposition was localized to the lower reaches (Portuguese reaches IV and V) and on the adjacent Atlantic margin.

The Tejo river has a varying number of fluvial terraces along its course, up to five in the Portuguese transect. In Spain, up to 12 terrace levels can be observed between Talavera de la Reina and Malpica (in the "Campo Arañuelo area, in the western part of the Madrid Tertiary Basin). In the Spanish sector, the terraces are stepped between 8 m and 195 m above the present-day alluvial plain (Pérez-González, 1994; Silva et al., 1997; Silva, 2003). There the river incision began on a surface (the "*piedmont*" of Valdelaosa, altitude 623 m) much higher than that in the Portuguese Ródão area, where the incision started at an altitude of ~300–350 m (top of the Falagueira Formation; these altitudes refer to present elevation above sea level). Some recent geomorphological studies of the Tejo terraces have been made in the Spanish sector (e.g. Pérez-González, 1994; Gutiérrez-Elorza et al., 2002) and in the Portuguese sector (Martins, 1999; Cunha et al., 2005). However, only few, relatively young terrace ages have been published;

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for the Portuguese sector twelve ages are known (four U-series and eight thermoluminescence ages; Raposo, 1995a; Raposo and Cardoso, 1998), all in the range 27 to >127 ka.

Using the Tejo river as an example, we set out here to establish an absolute chronology for part of this large, long-lived fluvial system, where incision is considered to be driven primarily by tectonics (Cunha et al., 2005). The main aim of the present study is to use luminescence ages for the fluvial terraces to assess the main control on drainage development and to attempt to quantify changes in the incision rate during the Quaternary.

The study region lies in an intraplate moderate compressional continental setting resulting from the convergence between Africa and Iberia along the Azores–Gibraltar Fracture Zone and Atlantic ridge-push forces (e.g. Srivastava et al., 1990; Ribeiro et al., 1996). Ongoing intraplate deformation of Iberia is typically manifested by earthquake activity concentrated on the Pyrenees, Betic Orogen and Atlantic domain. Iberia is characterized by a consistent horizontal compressional stress field that is dominated by northwest-directed stress trajectories fanning out in Portugal into a more westerly direction and in northeastern Spain into a northerly direction (Andeweg et al., 1999). The magnitude of Plio-Pleistocene vertical motions suggests that process controlling topography development are still ongoing and exert a first-order control on the present topographic configuration of Iberia, characterized by a succession of highs and lows that trend normal to the present-day intraplate compressional stress trajectories (Cloetingh et al., 2005).

Studies of uplift-driven valley incision and river terrace formation over Quaternary time-scales have proposed extrinsic controls such as eustasy, climate or tectonics as driving mechanisms. However, neither eustatic nor climatic changes during the Quaternary (Shackleton and Opdyke, 1973) provide clear trends that might explain the patterns of valley incision recognised across Europe (Maddy, 1997). Tectonic controls on terrace formation have been widely reported in Europe, for example, in the Middle Rhine area (Brunnacker and Boenigk, 1983), Maas valley (Van den Berg, 1996) and England (Maddy, 1997; Bonnet et al., 2000). The elevation and estimated ages of the river gravel deposits of the Upper Thames Valley have been used by Maddy (1997) and Maddy et al. (2000) to calculate uplift rates by using a simple linear model. However, to determine the driving mechanisms for bedrock river incision more quantitative age constraints are required. New geochronological techniques, such as optically stimulated luminescence (OSL), and cosmogenic nuclide dating, are being used to obtain chronological frameworks in systems that were previously only poorly known.

Geomorphological and stratigraphical approaches, based on spatial relationships, allow the establishment of a relative chronological sequence of the geomorphological or sedimentary records and of the geological events they represent. However, it is often difficult to correlate terraces on adjacent reaches of the same river; similar depositional facies can exist at different terrace levels and significant vertical displacements of the same surface can be produced by active tectonics (Burbank and Anderson, 2001). By dating fluvial terraces

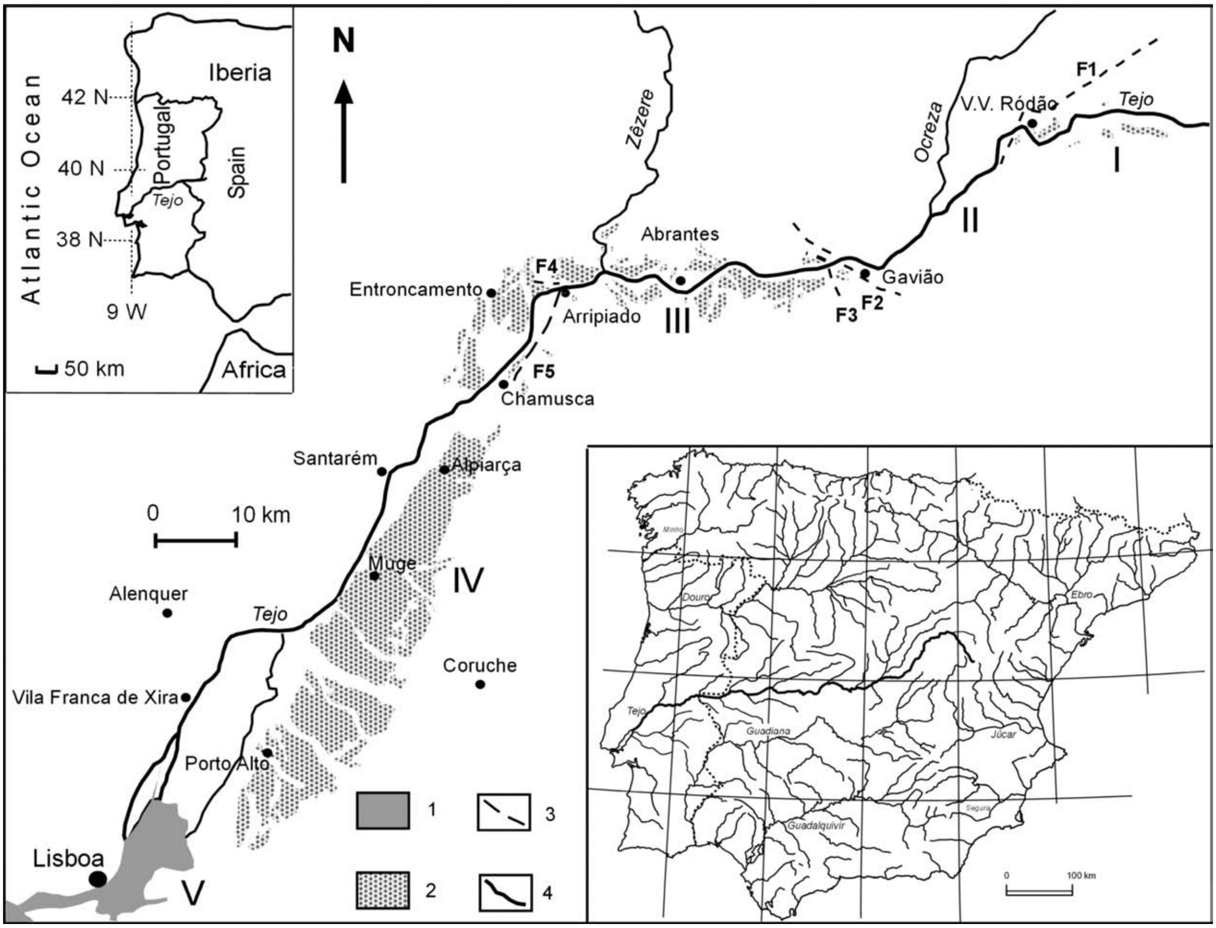

Fig. 1. Division of the Tejo river into the main Portuguese reaches (Lower Tejo Basin): I — from the Spanish border to the Ponsul–Arneiro fault (a general E–W trend, mainly consisting of polygonal segments); II — from the Ponsul–Arneiro fault to Gavião (NE–SW); III — from Gavião to Arripiado (E–W); IV — from Arripiado to Vila Franca de Xira; V — from Vila Franca de Xira to the Atlantic shoreline. The faults that define the limits of these reaches are indicated as F1, F2, F3, F4 and F5. 1 — estuary; 2 — terraces; 3 — faults; 4 — Tejo main channel. The main Iberian drainage basins are also represented.

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such geomorphic markers can better be used to track deformation associated with active faults.

Integration of different types of dating, such as (1) relative, provided by geomorphological, stratigraphical and archaeological approaches, and (2) quantitative, resulting from the measurement of physical processes (absolute dating techniques), improves the temporal control of the main evolutionary stages of the landscape. This also helps us to understand controls on the long-term dynamics of a fluvial system, by assessing the interplay of tectonics, climate and eustasy.

A fluvial deposit may contain fossils (useful for biostratigraphy or paleoenvironmental reconstruction) and datable material which can be used to establish an independent geochronology; datable material can include: organics for radiocarbon age estimation; bone, travertine and other calcareous precipitates for U-series methods; and quartz or feldspar minerals extracted from the sediments for luminescence methods (e.g. Pederson et al., 2006). However, it is common that for a particular suite of terraces only some quantitative dating methods can be used. Luminescence dating offers a reliable and widely-applicable approach to the dating of fluvial sequences (Huntley and Lian, 1999; Wallinga, 2002). OSL dating of quartz has given well constrained chronologies for sediments with ages of a few decades to >100 ka (Murray and Olley, 2002). K-feldspar may also be used in OSL, but its accuracy is limited by a phenomenon known as anomalous fading (Aitken, 1998: Appendix D). Recently, Pedoja et al. (2006) successfully applied OSL from feldspar in conjunction with U/Th of corals to establish a chronology for marine terraces, with sediments as young as the marine isotopic stage (MIS) 5e (~130 ka) to as old as MIS 9 (~330 ka). Unfortunately, the unusually high dose rates of our studied sediments (4.1 to 7.0 Gy/ka) prevented the routine application of quartz OSL and so we have investigated the use of feldspar as an alternative for dating these terraces. The main aim of this study is to use K-feldspar infrared stimulated luminescence (IRSL) and TL dating to establish the terrace chronology.

2. Geological and geomorphological setting

2.1. Geology

In the study area, the basement consists of intensely folded Pre-Cambrian to Lower Cambrian slates and metagreywackes, Ordovician quartzites and slates that occur in synclines, and alkaline plutons. The Tertiary sediments are divided into the Beira Baixa Group (Paleogene to Upper Miocene) and the Murracha Group (probable upper Tortonian to Piacenzian) (Cunha, 1992, 1996). The older group, mainly made up of arkoses, was deposited by an extensive fluvial drainage system in the Lower Tejo Tertiary basin. The younger group, predominantly consisting of coarse siliciclastic deposits, represents the sedimentary response to uplift phases of the Portuguese Central Cordillera. During the late Tortonian to Zanclean, the Lower Tejo basin was endorheic and alluvial fan sedimentation was present along tectonic scarps. An exorheic drainage system was only developed at the transition to the more humid conditions of the Piacenzian, when the ancestral Tejo river became a gravelly braided river with abundant bed load (Cunha et al., 1993). The Falagueira Formation, the last sedimentary episode of the Murracha Group, represents the beginning of an Atlantic fluvial system that captured the drainage network of the Madrid Tertiary Basin (Cunha et al., 1993; Pérez-González, 1994). In the study area, the Falagueira Formation is about 10 m-thick and indicates that the ancestral Tejo river flowed over an extensive alluvial plain, up to 12 km wide. The unit is made up of quartz arenites and clast-supported conglomerates of quartzite (ca. 80%) and quartz, with an average of the largest 10 clasts (MPS) of 25 cm. Intense

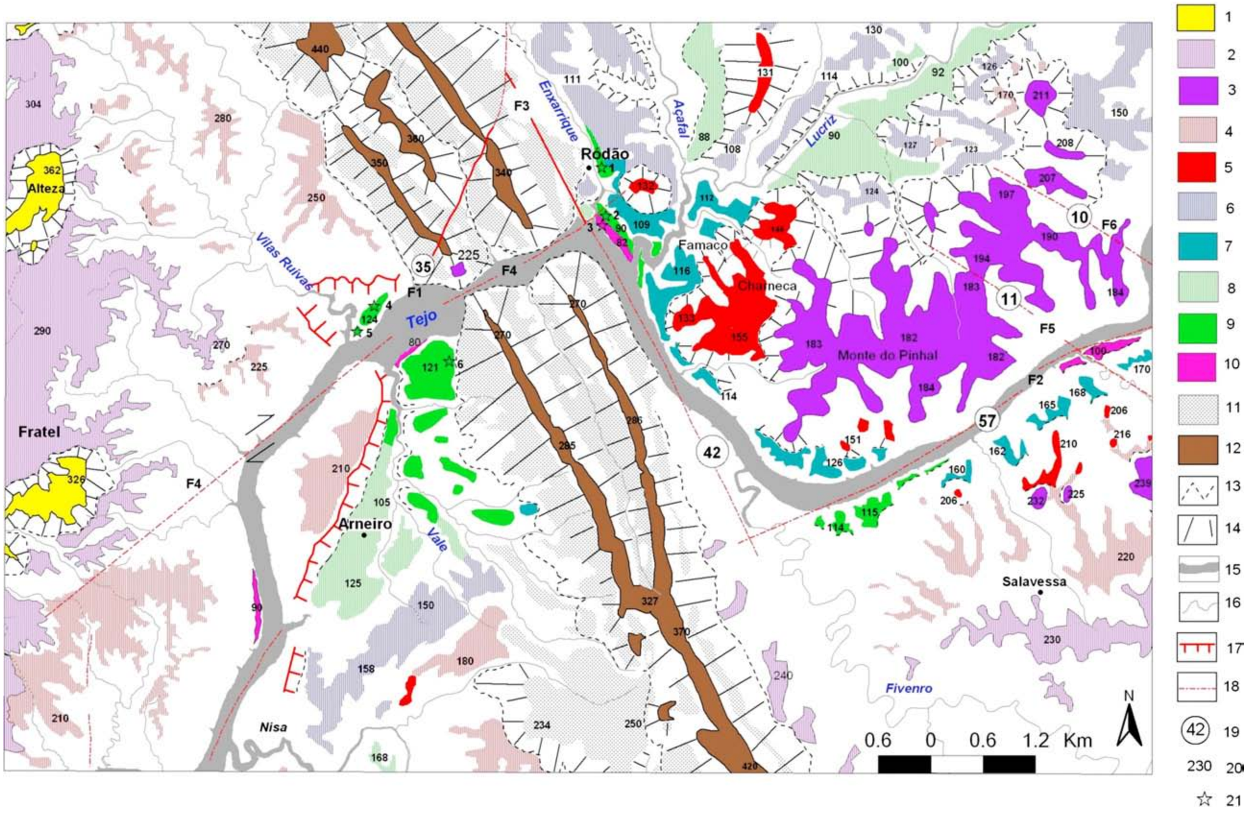

Fig. 2. Geomorphological map of the study area. 1 — residual relief (surface of the Falagueira Formation); 2 — N1 surface; 3 — T1 terrace; 4 — N2 surface; 5 — T2 terrace; 6 — N3 surface; 7 — T3 terrace; 8 — N4 surface; 9 — T4 terrace; 10 — T5 terrace; 11 — scree or alluvial fan deposits; 12 — quartzite ridge; 13 — slope base; 14 — steep slope; 15 — Tejo river; 16 — stream; 17 — fault; 18 — probable fault; 19 — estimated vertical displacement (m) affecting the T1 or the N1; 20 — altitude (m a.s.l.); 21 — location of the OSL samples (1 — T4 at Rodense Bolaria; 2 — T4 at the Enxarrique stream mouth; 3 — T5 at the Enxarrique stream mouth; 4 — T4 at Vilas Ruivas; 5 — T4 at the Vilas Ruivas stream mouth; 6 — T4 at Arneiro).

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kaolinization and hydromorphism are typical, reflecting a humid and hot climate and important drainage. During the following incision stage, deep valleys were excavated and, in tectonic depressions such as the Ródão graben, terrace staircases have developed.

2.2. Tectonic structures

The area is located in the Hesperian Massif, a strongly fractured morpho-structural unit of the Iberian Peninsula. Late-Variscan NNE–SSW, NE–SW, NW–SE and N–S trending faults were reactivated during the late Cenozoic by a maximum horizontal compressive stress trending NW–SE to WNW–ESE (Ribeiro et al., 1996). The main regional structure is the Ponsul fault, trending NE–SW, with a total length of 120 km and a maximum left lateral offset of around 1.5 km. This structure was strongly reactivated during the late Tortonian to early Pliocene (Cunha, 1996; Sequeira et al., 1997) but evidence of some Plio-Quaternary reactivation was found at several places (Dias and Cabral, 1989). The fault gave rise to a large scarp, well exposed at the north and northwest sides of the Ródão graben. The actual morphological expression of the scarp (ca. 170 m) results from partial exhumation by erosion of the Tertiary sediments. This can be inferred by the transverse drainage of one reach of the Ponsul river, a 7 km stretch of which sits on the uplifted block near Idanha-à-Nova (Ribeiro, 1939, 1943a) and by the transverse drainage of the Tejo river, also superimposed onto the Ponsul–Arneiro hanging fault wall (Ribeiro, 1943b) (F1 fault on Fig. 2). In the study area, some active faults were described by Cunha et al. (2005): a) the SW–NE Tejo reach fault (F2); the SSE–NNW Tejo reach fault (F3) and the Tejo gorge fault, trending NE–SW (F4; Fig. 2). Vertical displacements along these faults, affecting the drainage and the incision, will be described later.

2.3. Relief

The regional relief is dominated by elongate NW–SE resistant quartzite ridges (inselbergs), with altitudes of more than 500 m, crossed by the Tejo river in a gorge "Portas do Ródão". Below the quartzite ridges, an extensive but fragmented Paleogene planation surface is developed at an altitude of ca. 300 m in the areas of metagreywackes/slates or granites. Within the Ródão depression this surface remains buried by Tertiary sediments.

The altitude of the lower segments of the quartzite ridges (270 m) and the altitude of the Falagueira Formation remnants (300 to 362 m) indicates that the ancestral Tejo river overlay these ridges and the hanging wall of the Ponsul fault (Ribeiro, 1943b).

The highest and oldest terrace (T1) and a planation surface (Fratel Level — N1) developed onto the basement are incised by between 35 and 50 m below the top of the Falagueira Formation and are extensively represented in the area (Cunha and Martins, 2000). The younger terraces and coeval erosion surfaces are incised by between 14 and 51 m below the previous terrace, and they will be described below.

3. The Tejo river terraces in the Portuguese reach I

Along the Tejo valley in the Portuguese reach I (Fig. 1), from the Spanish border to the Ponsul fault, four terrace levels have been previously identified and mapped (Cunha et al., 2005). However, more detailed field-work and dating have since shown that the lower and younger terrace may locally be made up of two levels, the upper one of which is a narrow strip. In the following paragraphs, the main characteristics of the terraces in the Monte do Pinhal–Enxarrique (Table 1) and in the Vilas Ruivas–Arneiro areas will be described (Figs. 2, 3, 4 and 5) in order to provide a context for the dating results.

The *Monte do Pinhal terrace* (T1) forms an extensive plateau at 183 m above sea level (a.s.l.; 117 m above the modern river bed — m.r.b.). T1 is ~13 m m-thick, and is made up of massive clast-supported gravel–boulder conglomerates, with poor to moderate sorting. The clasts are sub-rounded to rounded, with MPS=32 cm, of quartzite (90%) and white quartz, showing a red patina (iron oxides).

The *Monte da Charneca terrace* (T2), developed at 155 m a.s.l. (89 m above m.r.b.) but with a lower surface at 133 m a.s.l., seems to be a complex terrace on the right side of the Tejo river. This terrace is ~23 m-thick, consisting of massive clast-supported gravel–boulder conglomerates with some 0.5 m-thick coarse sandstones lenses. The sorting is poor to very poor, due to the presence of a red sandy–silty matrix. The clasts are sub-rounded to rounded, with MPS=24 cm, of quartzite (78%) and white quartz.

The *Monte do Famaco terrace* (T3), at 116 m a.s.l. (50 m above m.r.b.) can be readily identified close the Açafal stream mouth, and followed upstream as a narrow strip along the Tejo right bank. More upstream, on the left bank, it is identified by the remains of a strath (160–170 m a.s.l.). The T3 terrace is made up of a 1 m-thick clast-supported gravel–boulder conglomerate, with poor sorting. The clasts are sub-rounded, with MPS=32 cm, of quartzite (75%), white quartz and rare slates/metagreywackes. At the Monte do Famaco site, thirty-four rolled

Table 1
Summary of key geological and geomorphological attributes for the Monte do Pinhal–Enxarrique terrace staircase

Level	Typology	Previous incision episode	Thickness	Altitude	Sedimentology	Lithic industries *in situ*
T1 *Monte do Pinhal*	Terrace	73 m (24 –170 m), below the Falgueira Fm.	13 m	183 m a.s.l. (117 m a.r.b)	– Massive clast-supported gravel–boulder conglomerates; poor to moderate sorting; – Sub-rounded to rounded clasts of quartzite (90%) and quartz; MPS=32 cm.	–
T2 *Monte da Charneca*	Terrace	51 m (18 –132 m)	23 m	155 m a.s.l. (89 m a.r.b)	– Massive clast-sup. gravel–boulder congl., with 0.5 m-thick coarse sandstone lenses; poor sorting; – Sub-rounded to rounded clasts of quartzite (78%) and quartz; MPS=24 cm.	–
T3 *Monte do Famaco*	Terrace and strath	47 m (15 –108 m)	1 m	109 m a.s.l. (43 m a.r.b)	– Massive clast-sup. gravel–boulder congl.; poor sorting; – Sub-rounded clasts of quartzite (75%), quartz and rare slates/metagreywackes; MPS=32 cm.	Middle Acheulian (Lower Palaeolithic)
T4 *Capela da Senhora da Alagada*	Terrace	27 m (1 9–82 m)	8 m	90 m a.s.l. (24 m a.r.b)	– Fine sandstones with pedogenic calcareous concretions (probable conglomeratic base not exposed).	Mousterian (Middle Palaeolithic) at the top
T5 *Foz do Enxarrique*	Terrace	14 m (90–76 m)	6 m	82 m a.s.l. (16 m a.r.b)	– A basal 0.5 m-thick massive, clast-sup. boulder congl.; – Upper 5 m of very fine sandstones with calcareous concretions; – Sub-rounded clasts of quartzite and slates/metagreywackes; MPS=31 cm;	Late Mousterian (late Middle Palaeolithic)
Modern river bed	Alluvium and rocky bed	16 m (2–66 m)	0–4 m	66 m	– Pebbly to boulder gravel	

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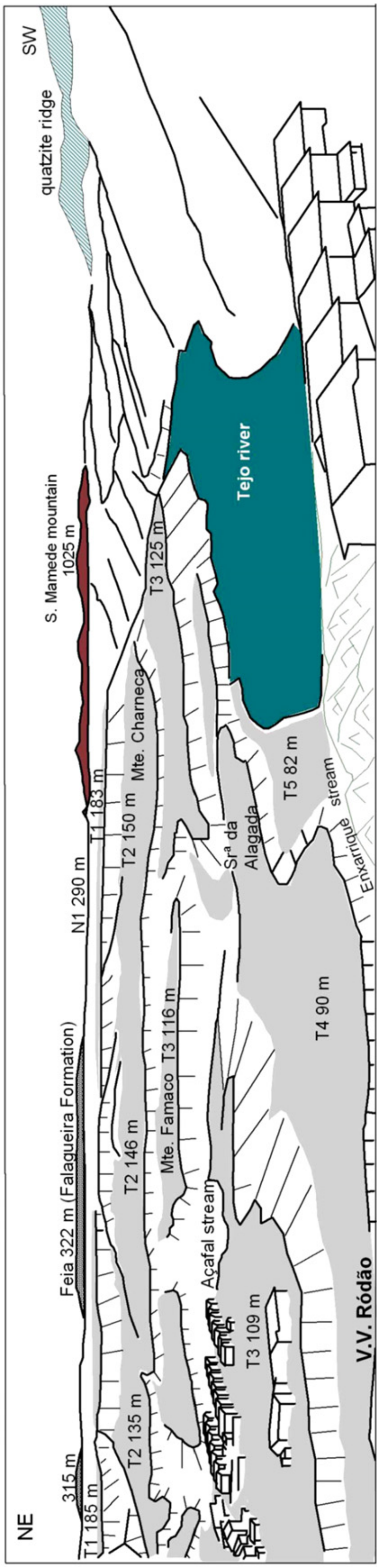

Fig. 3. Panoramic drawing, view towards southeast, of the Enxarrique–Monte do Pinhal terrace staircase.

quartzite artifacts have been found in the conglomerate and attributed to the early middle Acheulian (Lower Palaeolithic) (Raposo, 1987). In a colluvium at the top of the terrace, ~1500 middle Acheulian quartzite artifacts – bifaces, cleavers, scrapers, etc. – have been collected, some showing evidence of wind abrasion but none indicating later fluvial transport.

The *Capela da Senhora da Alagada terrace* (T4), forms a very narrow constructional bench at ca. 90 m a.s.l. (24 m above m.r.b.) on the Tejo right bank, between the mouths of the Açafal and Enxarrique streams. The upper 4 m consists of fine sandstones (rich in quartz and muscovite), with thin levels of pedogenic calcareous concretions interpreted as fossil riparian root horizons. The lower part of T4 is covered by T5 deposits. In T4 and in a related colluvium, Mousterian artifacts (Middle Palaeolithic) have been found *in situ*. Immediately downstream of the quartzite gorge, the terrace is located at 124 m a.s.l. (59 m above m.r.b) on the right bank (near the Vilas Ruivas stream mouth) and at 121 m a.s.l. on the left bank (Arneiro). On the right bank, the T4 sedimentary sequence is made up of (Fig. 6): a) a 2 to 0.5 m-thick clast-supported boulder conglomerate (MPS = 42 cm); b) 2–2.5 m of a pebbly medium sandstone with some planar cross stratifications and cobble channel pavements; this has yielded six rolled Acheulian type artifacts (Raposo and Silva, 1981; Raposo, 1987); c) a 1 to 0.5 m-thick siltite bed containing Mousterian artifacts (Raposo, 1995a), and; d) an upper ~4 m-thick clast-supported boulder conglomerate, massive and with MPS = 27 cm. On the left bank (Arneiro), the sequence is thicker (~15 m) and consists of 2 m of a basal sandy conglomerate, 4–10 m of massive coarse sandstones and an upper 0.2 to 8 m-thick clast-supported gravel–boulder conglomerate (MPS = 40 cm).

The *Foz do Enxarrique terrace* — T5 forms a constructional bench at 82 m a.s.l. (16 m above m.r.b.) on the Tejo right bank, between the mouths of the Açafal and Enxarrique streams. The T5 terrace is 6 m m-thick. The base is a massive, clast-supported boulder conglomerate, 0.5 to 1 m-thick and containing sub-rounded clasts, with MPS = 31 cm, of quartzite, white quartz and metagreywackes/slates. The upper 5 m are white brown massive very fine sandstones (rich in quartz and muscovite) and coarse siltites, with some thin levels of pedogenic calcareous concretions. A 5 to 20 cm-thick level at the base of the fine sandstones provided a rich *in situ* late Mousterian industry (Raposo, 2000, 2002) – some ten thousand artifacts of quartzite — 67%, quartz — 23%, and some flint – in association with abundant (~800) fossils of mammals (*Cervus elaphus* — 27% of the total number of fossil remains, *Equus caballus* — 18%, *Bos primigenius* — 1.2%, *Oryctolagus* sp. — 2%, *Elephas antiquus* — 0.7% and *Vulpes vulpes* — 0.1%), birds and fish (Raposo et al., 1985; Raposo, 1987; Brugal and Raposo, 1999).

The present Tejo valley floor is at an altitude of 66 m.a.s.l. and the alluvium consists of some pebbly to boulder gravel.

The resistant quartzite ridges have promoted aggradation upstream of the gorge, where the river was easily able to enlarge the valley into the soft Tertiary sediments. The coarse-grained nature and poor sorting of the T1, T2 and T3 sediments suggest transport as bed load with a high sediment to water ratio within a high-energy fluvial system. The downcutting into the Paleozoic basement explains the generally small representation of the T4 and T5. The terraces are restricted mainly to the confluences of the Açafal and Enxarrique streams where they enter against the flow of the Tejo river, leading to the local predominance of overbank fines.

The large Tejo valley between the quartzite gorge and the Ponsul–Arneiro hanging wall fault, cut into the soft Tertiary arkoses, was also favourable for T4 aggradation.

4. Fluvial control by local tectonics

Geomorphological evidence for local tectonic control of drainage arises from interpretation of asymmetric valley and drainage patterns, fault scarps, tectonic lineaments, fracture-controlled valleys, and vertical displacement of planation surfaces and terraces (Cunha

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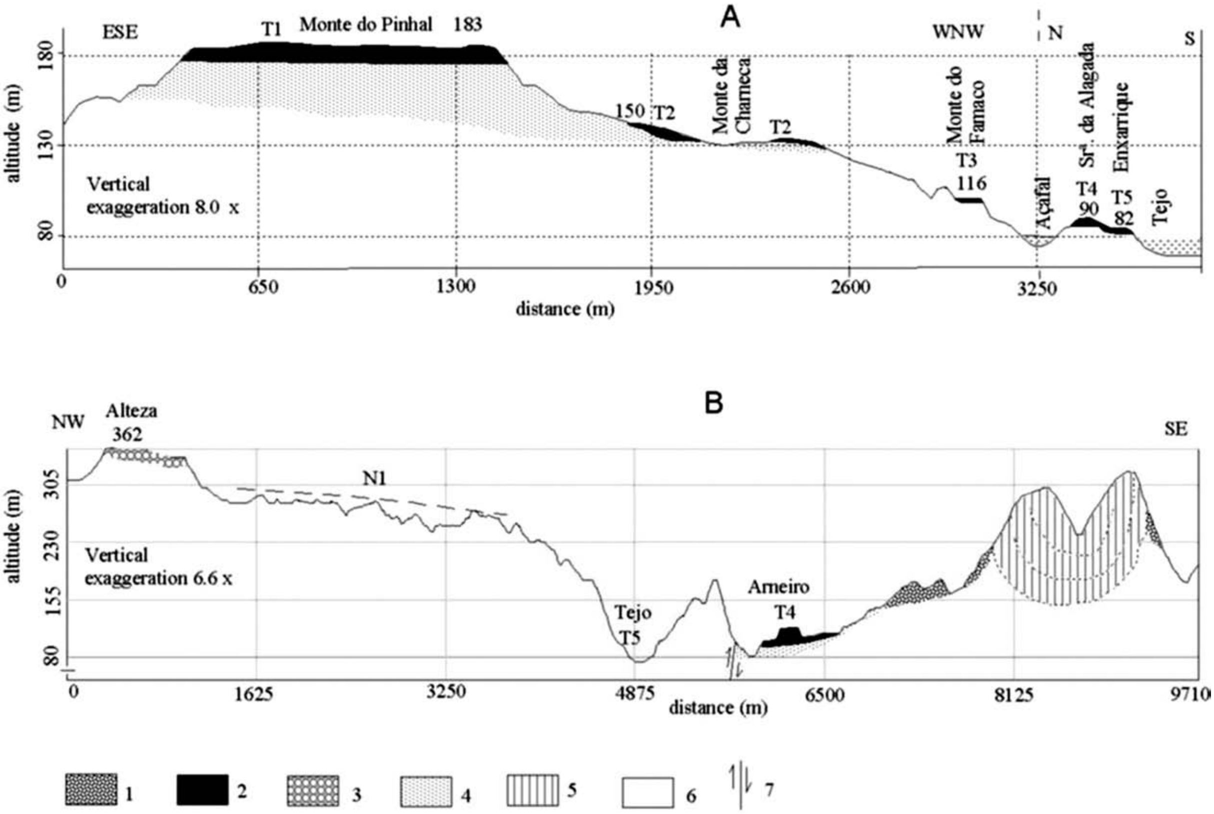

Fig. 4. Transverse profiles in the Monte do Pinhal–Enxarrique area (A) and between Alteza and the quartzite ridges, crossing the Arneiro graben (B) (see Fig. 2 for location). 1 — colluvium and alluvial fan deposits; 2 — terraces; 3 — Falagueira Formation (quartz arenites and clast-supported conglomerates; Piacenzian); 4 — Beira Baixa Group (arkoses; Paleogene); 5 — quartzites and slates (Ordovician); 6 — slates and metagreywackes (Late Precambrian and Cambrian); 7 — fault.

et al., 2005). In the study area, the main faults actively controlling the Tejo drainage are considered to be (Fig. 2):

- The Ponsul–Arneiro fault (F1), trending NNE–SSW, providing relatively greater uplift of the western block (vertical displacement: N1 — 35 m; N2 — 30 m; T5 — ca. 10 m). The T5 displacement was measured between the strath terrace (90 m) on the convex bank of the Tejo, southwest of Arneiro, and the narrow fill terrace (80 m) on the opposite bank, north of Arneiro.
- A probable fault (F2) controlling the valley of the local SW–NE Tejo reach. This fault displaces all the terraces (the southern block is uplifted; vertical displacement: T1 — 57 m; T2 — 55 m; T3 — 34 m; T4 — ca. 24 m; T5 — ca. 18 m).
- A probable SSE–NNW fault (F3), following the line of the Tejo valley until the entrance to the quartzite gorge (Dias and Cabral, 1989; Cunha et al., 2005). The alignment of this fault should correspond to the N20°W, 45°SW reverse fault observed in a recent excavation inside the small town of Vila Velha de Ródão (Fig. 7). The outcrop shows the metamorphic basement thrust over the Cenozoic, here composed of angular to sub-rounded blocks of quartzite (not weathered) and beds of green siltite. This fault may be responsible for the vertical displacement of ca. 42 m of the T1

Fig. 5. General view of the Tejo terraces at the Enxarrique confluence. T2 — *Monte da Charneca terrace*, at 132 m a.s.l.; T3 — *Monte do Famaco terrace*, at 109 m a.s.l.; T4 — *Capela da Senhora da Alagada terrace*, at 90 m a.s.l.; T5 — *Foz do Enxarrique terrace*, at 82 m a.s.l.. Samples 052204/LTA8 (88.5 m a.s.l.) and 052247 (87 m a.s.l.) were collected in the T4 terrace, samples 062201 (81 m a.s.l.), 052202 (76.5 m a.s.l.) and 052201 (76.3 m a.s.l.) were collected in the base of T5 (Enxarrique archaeological site). The excavated scarp of the Ponsul fault can be seen in the upper left corner.

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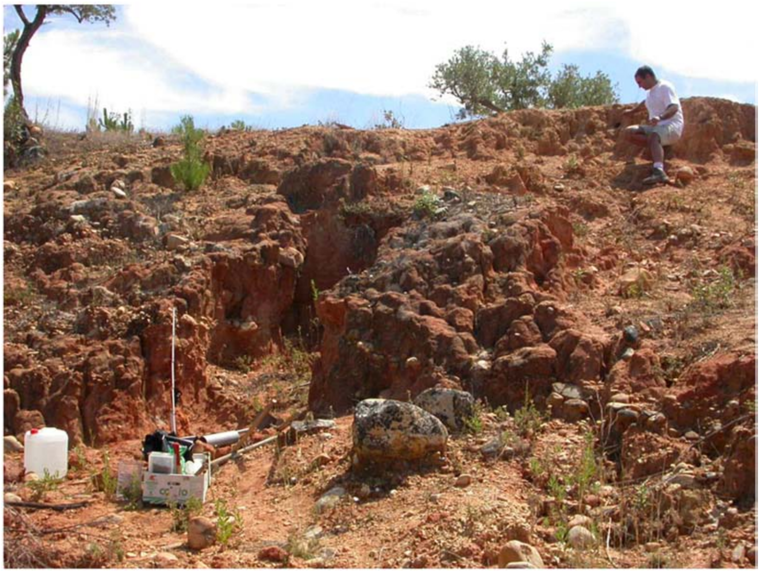

Fig. 6. View of the lower part of the Vilas Ruivas terrace sequence. The boulders belong to the 0.5 m-thick boulder conglomerate that overlies the metamorphic basement. Sample 052246 was collected near the base of the pebbly coarse sandstone bed, with cobble pavements, as indicated by the black plastic close to the 1 m long-ruler. Sample 052207 was removed from the 1–0.5 m-thick siltite bed, at the upper position indicated by the person; sample 052253 was collected about 20 m more to east, in the same bed and at the same location as samples VRU1 and VRU2. This photograph does not show the upper part of the terrace sequence, a 4 m-thick conglomerate.

terrace (at 225 m a.s.l on the right bank of the quartzite gorge and at 183 m a.s.l. at Monte do Pinhal) and the 31 m displacement of T4 (at 90 m a.s.l. near the Enxarrique stream, upstream, and 121 m at Arneiro, downstream).

- The suspected NE–SW strike-slip fault (F4), along the asymmetric valley of the Lucriz stream, passing along the quartzitic gorge. This fault is probably represented in the outcrop located in the eastern sector of Vila Velha de Ródão (Senhora da Alagada urbanization). The fault plane (N42°E, 85°NW) appears to displace Tertiary sediments and exhibit slickensides with a 28° SW pitch. This indicates a right-lateral oblique strike-slip fault, probably activated by a maximum compression along WNW–ESE (Cunha et al., 2005).

In summary, the complexity of these small fault-bounded blocks has resulted in unequal tectonic vertical movements in several sectors (Fig. 2) and accounts for the considerable differences in altitude of the several terrace levels in adjacent reaches. These differences are greatest in the oldest terraces, suggesting cumulative fault displacement. The faults referred to above are also responsible for the different altitudes of the same terrace on opposite banks of the Tejo river. This is particularly evident when comparing the Salavessa and Monte do Pinhal sectors (Fig. 2).

5. Dating methods

5.1. Field techniques

The geomorphological characterization of the Ródão area made use of 1:24,000 aerial orthophotos and a digital elevation model (DEM) based on a 1:25,000 topographic database, followed by detailed field surveying, mapping and outcrop description (Cunha et al., 2005). For the present study, complementary field-work was undertaken and sediment samples were collected for luminescence dating. The sampling strategy was to collect from the base and top of each terrace deposit, but only the two lower terraces provided lithologies (sandstones and siltites) suitable for luminescence dating. Each sample was collected in a light-safe tube, together with some additional material in a waterproof plastic bag for later laboratory analysis of water content, grain size and composition.

5.2. Geochronological techniques and approaches

Thermoluminescence (TL) dating and its counterpart, optically stimulated luminescence (OSL), are techniques for measuring the time

Fig. 7. Outcrop oriented E–W, at Vila Velha de Ródão, showing the metamorphic basement thrusting the Cenozoic. The hammer indicates the fault plane.

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Table 2
Summary of thermoluminescence dating results

Laboratory code	Site name	Altitude (m)	Terrace level	Grain size	Dose rate (Gy/ka)	D_e (Gy)	Corrected age (ka)
LTA8	Enxarrique stream mouth	88.5	T4 — top	Very fine sand	4.26±0.19	500±20	93 +20/−13
VRU1	Vilas Ruivas (Tejo river right bank)	118	T4 — middle	Silt	6.81	500±200	70 +40/−30
VRU2	Vilas Ruivas (Tejo river right bank)	118	T4 — middle	Silt	6.53	350±90	51 +13/−12

elapsed since sedimentary grains of quartz or feldspars were last exposed to daylight (Duller, 2004). The main difference which distinguishes the two methods is the mean of stimulating the signal from the sediment: TL uses heat (up to 500 °C) and OSL employs intense narrow-band light from e.g. a light emitting diode array.

For TL dating, a portable gamma spectrometer was used in the field to estimate the sediment dose rate and thick source alpha counting was used to measure the alpha contribution (Table 2). Carbonates were removed with dilute HCl and the 2–10 µm grains were mounted on a ~10 mm diameter planchet. TL was measured in the UV through a Schott UG11 filter. The signals were integrated between 280 and 300 °C. Equivalent doses were obtained by a multiple aliquots regenerative protocol (Wintle, 1997). A second glow measurement was employed to normalise the luminescence response of every aliquot.

For OSL dating, radionuclide concentrations were measured by high-resolution gamma spectrometry (Murray et al., 1987; Olley et al., 1996); the results are summarised in Table 3. To determine the internal dose rate from ^{40}K and ^{87}Rb (in K-feldspar) we assumed a conservative estimate of 12.0±0.5% and 400±100 ppm, respectively, following the recommendation of Huntley and Baril (1997) and Huntley and Hancock (2001). All further processing took place under subdued red light. Wet sieving was used to separate the 180–250 µm grain size, which was then acid treated using HCl (10%) and H_2O_2 (10%) to remove carbonates and organic matter, respectively. K-feldspar (<2.58 g/cm^3) was separated using a heavy liquid solution of sodium polytungstate. The outer layer of K-feldspar grains was etched with diluted HF (10%, 40 min), to minimise any contribution from external alpha particles to the dose rate. Finally, HCl (10%) was again used to dissolve any remaining soluble fluorides.

OSL measurements were performed on a Risø TL/DA-15 reader (Bøtter-Jensen et al., 2003). Luminescence was filtered by a combination of Schott BG39, Corning 7-59 and Schott GG400. The single-aliquot regenerative-dose (SAR) procedure was applied to measure the equivalent dose, D_e (Murray and Wintle, 2000). Identical heat treatments (250 °C for 60 s) for both dose and test dose (Auclair et al., 2003; Huot and Lamothe, 2003) were employed. Optical stimulation was with infrared diodes (880 nm) for 100 s at 50 °C. Further technical details and observations are provided when using the SAR protocol (Murray and Wintle, 2000; Murray and Olley 2002).

6. Results of the luminescence dating

Thermoluminescence ages derived in the manner used here are known to underestimate the event of interest, due to a non-thermal mechanism with a mean life of approximately 100 ka, and have been corrected to compensate for this phenomenon (Debenham, 1985) (Table 2).

Infrared stimulated luminescence dating of K-feldspar was performed on 13 terrace samples. On each sample the OSL measurements were made on 8–24 aliquots, each containing about 100 grains. The natural luminescence was well below the saturation level allowing us to precisely measure the equivalent dose from all of our samples. Recycling ratios were close to unity, indicating that the test doses successfully monitored changes in luminescence sensitivity throughout the measurement sequence. Dose recovery tests (Wintle and Murray, 2006) were also successful (mean ratio of measured to given dose of 0.98±0.02; n=84), thus suggesting our SAR protocol is able to accurately determine doses given in the laboratory before any heating of the sample.

OSL ages, derived by dividing the equivalent doses (D_e) by the total dose rates, are summarised in Table 4. It is likely that the OSL ages from K-feldspars underestimate the burial age because of anomalous fading (Huntley and Lamothe, 2001; Huntley and Lian, 2006). In anomalous fading, some trapped electrons leak out of traps (in particular those that give rise to the OSL signal) while the sediment is buried. Laboratory induced luminescence does not have the time to decay by the same relative amount as does the natural luminescence. Because D_e is measured essentially by taking the ratio of natural luminescence to that regenerated by a laboratory beta dose, measurements of equivalent doses are expected to underestimate the true burial dose. Our measurements of the rate of this anomalous fading also used the same SAR procedure as outlined above. Time delays were inserted after the heat treatment of the dose (Lx) and before the corresponding luminescence measurement (Auclair et al., 2003). An average value of "g" (a measure of the fading rate) of 3.15±0.04%/decade (n=143) was observed. This rate was used for fading corrections using the dose rate correction (DRC) of Lamothe et al. (2003) (Table 4). We are sceptical of the precision in our ages obtained from sediments with uncorrected D_e values >500 Gy. In these cases the DRC model puts the natural signals close to luminescence saturation, giving a minimum corrected D_e of about 1000 Gy.

7. Discussion of the luminescence dating results

The OSL ages confirm the chronological sequence of terrace formations and agree with the age interpretation of the archaeological materials found *in situ* in the terraces: T5 — late Mousterian (late Middle Palaeolithic); T4 — Acheulian (Lower Palaeolithic) and Mousterian (Middle Palaeolithic) at the top; and T3 — middle Acheulian.

Taking into account the position in the sedimentary sequences of the corrected K-feldspar ages it is probable that the younger terraces have an age range of (Table 4 and Fig. 8): T5 — 31 to 40 ka; T4 — 100 to ~280 ka; and T3 — >300 ka.

Sample 052202 gave an uncorrected age of 25.4±1.0 ka, clearly showing an age underestimation when compared with the U-series performed on three teeth from the same stratigraphic level (isochron plot resulting in an age of 33.6±0.5 ka) (Raposo, 1995b). The corrected age of 34.8±1.3 ka is much closer to this value and helps to give confidence in the fading correction approach.

Table 3
Summary of radionuclide activities, water content and corresponding dose rates

Laboratory code	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	Water content (%)	Dose rate (Gy/ka)
052208	19±6	28±0.6	30±0.6	902±17	25	3.91±0.12
052247	44±4	49±0.6	75±0.7	765±8	15	4.87±0.17
052204	52±4	52±0.5	76±0.7	715±9	15	4.81±0.17
052201	108±6	109±1	191±2	784±19	25	6.97±0.24
052202	89±6	77±0.8	98±0.9	727±10	25	4.95±0.17
062201	64±7	68±0.9	92±1	764±14	10	5.68±0.21
052246	27±4	23±0.4	28±0.5	843±12	10	4.21±0.15
052207	63±11	70±2	109±2	621±33	13	5.38±0.21
052253	69±8	61±0.8	96±1	536±10	10	5.00±0.19
062216	43±6	36±0.6	59±0.8	734±12	12	4.55±0.16
062217	45±5	42±0.6	67±0.7	625±8	18	4.23±0.14
062202	25±5	28±0.5	22±0.5	843±14	10	4.10±0.15
062203	18±5	25±0.5	27±0.5	995±12	8	4.64±0.17

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Table 4
Summary of optically stimulated luminescence from K-feldspars

Field code	NLL laboratory code	Site name	Altitude (m)	Terrace level	Grain size	Dose recovery (measured/applied)[a]	D_e (Gy)	n	Dose rate (Gy/ka)	OSL age (ka)[b]	Corrected age (ka)
PC9	052208	Rodense Bolaria (Enxarrique stream)	101	T4 — base	Silt	1.01 ± 0.02	624 ± 11	12	4.1 ± 0.1	151 ± 7	–
ENXAR1	052247	Enxarrique stream mouth	87	T4 — middle	Very fine sand	1.05 ± 0.01	371 ± 8	17	4.9 ± 0.2	76 ± 3	125 ± 7
PC4	052204	Enxarrique stream mouth	88.5	T4 —top	Very fine sand	0.95 ± 0.01	346 ± 13	8	4.8 ± 0.2	71 ± 4	136 ± 10
PC1	052201	Enxarrique stream mouth	76.3	T5 — base	Very fine sand	0.93 ± 0.01	184.7 ± 3.3	12	7.0 ± 0.2	26.5 ± 1.2	38.5 ± 1.6
PC2	052202	Enxarrique stream mouth	76.5	T5 — base	Very fine sand	–	125.9 ± 0.9	10	5.0 ± 0.2	25.4 ± 1.0	34.8 ± 1.3
ENXAR2	062201	Enxarrique stream mouth	81	T5 — top	Very fine sand	1.06 ± 0.01	120.7 ± 1.3	24	5.7 ± 0.2	21.3 ± 0.9	31.6 ± 1.3
VRU5	052246	Vilas Ruivas (right bank)	116	T4 — base	Coarse sand	0.99 ± 0.02	636 ± 21	13	4.2 ± 0.1	151 ± 8	277 ± 17
PC8	052207	Vilas Ruivas (right bank)	118	T4 — middle	Silt	0.98 ± 0.02	349 ± 13	12	5.4 ± 0.2	65 ± 4	105 ± 5
VRU3	052253	Vilas Ruivas (right bank)	118	T4 — middle	Silt	0.96 ± 0.01	351 ± 9	12	5.0 ± 0.2	70 ± 3	113 ± 6
FVR1	062216	Vilas Ruivas stream mouth	90	T4	Muddy sand	1.03 ± 0.01	396 ± 6	20	4.5 ± 0.2	87 ± 4	151 ± 6
FVR2	062217	Vilas Ruivas stream mouth	88	T4	Silt	1.03 ± 0.01	463 ± 11	12	4.2 ± 0.1	109 ± 5	–
PARN1	062202	Arneiro (left bank)	105	T4 — near base	Medium sand	0.99 ± 0.00	479 ± 13	12	4.1 ± 0.2	117 ± 6	209 ± 11
PARN2	062203	Arneiro (left bank)	128	T4 — top	Medium sand	0.99 ± 0.01	371 ± 12	12	4.6 ± 0.2	80 ± 4	129 ± 8

[a] Represents the average of 10–12 aliquots.

[b] Ages are considered as minimum estimates; see text for additional details.

Despite possible limitations in accuracy arising from the presence of anomalous fading, we suggest that any systematic error in age should be similar from one sample to another, since all mineral samples derive from the same drainage catchment. The sediment should contain a homogeneous mixture of K-feldspars, originating from the same geological source or mixture of sources. Hence, the associated effects of anomalous fading should be similar between samples, implying that sediment of the same age should provide comparable ages, whether uncorrected or corrected. There is evidence to support such a conclusion (e.g. Wolfe et al., 2002).

As it was stated before, D_e values >500 Gy, as measured in samples 052208 and 052246, probably underestimate the true age, and we regard them here as only >300 ka.

The fading corrected OSL ages have a tendency to be older than the corrected TL ages and have much higher precision. The discrepancy between the two sets of ages may reflect differences in the correction models employed by these two methods. For instance, the same 1–0.5 m m-thick siltite bed, at the middle part of the Vilas Ruivas terrace sequence, gave TL ages of 51 +13/−12 ka and 70 +40/−30 ka (samples VRU1 and VRU2), and OSL corrected feldspar ages of 105 ± 5 ka and 113 ± 6 ka (samples 052207 and 052253). Also, the same stratigraphic level at the Senhora da Alagada terrace (T4) provided a TL age of 93 +20/−13 ka (sample LTA8) and an OSL corrected feldspar age of 136 ± 10 ka (sample 052204); the corrected age of sample 052247, located 1.5 m below, is 125 ± 7 ka.

Due to its altitude (121 to 124 m a.s.l.), the terrace at the Vilas Ruivas–Arneiro area was previously correlated with the T3 (116 m a.s.l., Monte do Famaco). However, recent geomorphological mapping indicates that the Monte do Pinhal–Enxarrique area is less uplifted and the luminescence dating (Fig. 8) supports correlation with the T4 (90 m a.s.l.). If this is true, the vertical displacement of the T4 between these two areas is ~30 m.

8. Estimation of aggradation and incision rates, and the interpretation of uplift

The corrected OSL K-feldspar ages of the T4 and T5 indicate the following broad fluvial episodes: ~10 m of aggradation from ~280 to

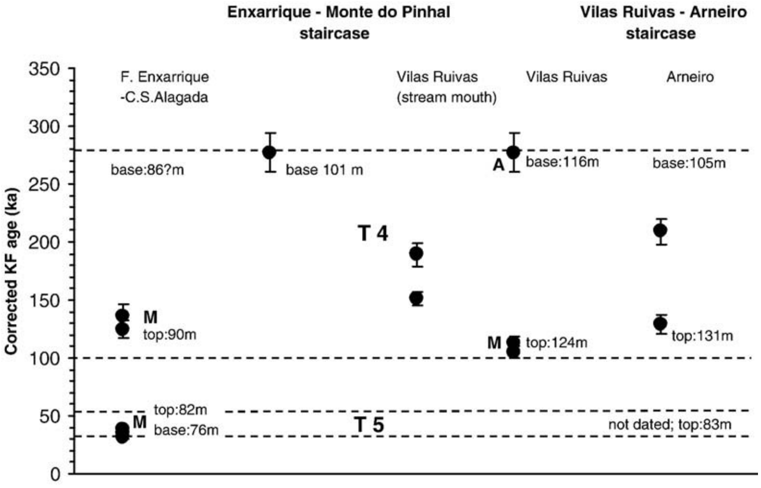

Fig. 8. Corrected OSL ages, with the stratigraphic location of each sample in relation to the terrace base and top (altitude in m a.s.l.), for each section. The ages confirm the geomorphological interpretation of the terrace levels and lateral correlation of the two adjacent staircases. Occurrences of lithic industries are also identified in each section: M — Mousterian; A — Acheulian.

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100 ka (0.06 m/ka); 14 m of incision from 100 to 40 ka (0.23 m/ka); 8 m of aggradation from 40 to 31 ka (0.89 m/ka); 16 m of incision during the last 31 ka (0.52 m/ka).

According to Burbank and Anderson (2001), fluvial terraces etched into bedrock (strath terraces) record previous positions of an actively incising river; using the height of a strath above the modern river, if it is assumed that the strath resulted from erosion at or near the low point of the river channel, and if the elapsed time since the abandonment of the strath by the incision river is known, then long-term rates of bedrock incision can be calculated (e.g. Maddy, 1997; Maddy et al., 2000). These incision rates are, in turn, used as a proxy for rock-uplift rates (Merritts et al., 1994). For the Enxarrique–Monte do Pinhal staircase, time-averaged incision rates can be estimated using the following references: a) the ~66 m a.s.l. surface corresponding to the modern Tejo bed; b) the T5 terrace surface, at 82 m a.s.l., 16 m above the river bed (a.r.b.), dated at ~31 ka; c) the T4 terrace surface at 90 m a.s.l. (24 m a.r.b.), dated at ~100 ka; and d) the probable position of the Falagueira Formation surface, at about 243 m a.s.l. (177 m a.r.b.), for which the probable age is estimated at ~2.6 Ma, suggested by dating in the more distal sediments of this Atlantic sedimentary system (Cunha et al., 1993). Using these values, several time-averaged incision rates can be calculated: a) 0.52 m/ka over the last 31 ka (16 m/31 ka); b) 0.24 m/ka over the last 100 ka (24 m/100 ka); c) ~0.07 m/ka estimated for the last 2.6 Ma (177 m/2600 ka) (Fig. 9). The decrease in the time-averaged incision rate is not surprising, since pulses of uplift, which can be significant over short time-scales, average out over longer time-scales with periods of quiescence. An estimate for the burial ages of the T3, T2 and T1 deposits was obtained by fitting a curve using the available age controls and the respective height of terrace surfaces above river bed: T3 at ~470 ka, T2 at ~1.2 Ma and T1 at ~1.6 Ma.

A similar approach can be made in the Vilas Ruivas–Arneiro area, downstream of the quartzitic gorge, using the following reference levels: a) the ~65 m a.s.l. corresponding to the modern Tejo bed; b) the T4 surface at 124 m a.s.l., dated at ~100 ka; c) the top of the Falagueira Formation, at 290 m a.s.l. (~2.6 Ma). The corresponding time-averaged incision rates are: a) 0.56 m/ka over the last 100 ka (56 m/100 ka); b) ~0.09 m/ka estimated for the last 2.6 Ma (225 m/2600 ka).

Just downstream of the Ponsul–Arneiro fault (beginning of reach II), in the hanging wall, the Falagueira Formation surface is at 326 m a.s.l., the N1 surface at about 270 m a.s.l., the N2 surface at 225–210 m a.s.l., a small strath at 90 m a.s.l. (T5), and the river bed at ~60 m a.s.l. A long-term incision rate of about 0.10 m/ka is estimated for the last 2.6 Ma (266 m/2.6 Ma).

The above estimates of time-averaged incision rates for the adjacent tectonic blocks crossed by the Tejo river are greater than those corresponding to the Enxarrique–Monte do Pinhal area because the equivalent fluvial geomorphic records are at higher altitude, thus indicating more uplift.

The long-term incision rates calculated for the Tejo reach I are similar to previous estimates (Cabral, 1995) for uplift in Central Portugal that reach rates of ca. 0.1 m/ka for the last 3.5 Ma and 0.2 m/ka for the last 1.6 Ma near the coast and rather more in the upland areas (ca. 0.1 and 0.3 m/ka, respectively). A geodynamic model of activation of the Portuguese passive margin by horizontal compressive stress seems to be compatible with rates of this magnitude (Ribeiro et al., 1996).

Cloetingh et al. (1990) suggested that the increase in the Quaternary uplift rates of areas located around the edges of the North Atlantic basin is the result of major reorganization of spreading direction and rate. This occurred during the Pliocene along the Atlantic spreading system, leading to an increase in the intraplate tectonic stress.

Studies in lowland Europe, for example on the Thames, Rhine–Meuse (Maas), Loire–Allier and others (e.g. Van den Berg, 1996; Bridgland, 2000; Westaway et al., 2002, 2003; Brocard et al., 2003; Westaway, 2004; Wallinga et al., 2004) also used river terraces to calculate incision rate and infer uplift. As noted by Lancaster (2005), those studies indicate an average regional incision/uplift rate of 0.1 to 0.2 m/ka during the Pleistocene, but the values vary significantly both geographically and temporally. For example, incision rates of the Rhine–Meuse system were interpreted to have increased since the late Pliocene from 0.03 m/ka to 0.61 m/ka (Bridgland, 2000).

For the genesis of the terraces examined here, Cunha et al. (2005) proposed a regional uplift event controlling one period of incision, followed by a period of valley enlargement and aggradation. Based on the obtained OSL dating, the intervals of incision can be estimated as: ~470 (?) to ~280 ka; ~100 to ~40 ka; and the last 31 ka. The youngest incision interval could also have been induced by a sea-level lowering (35 to 16 ka, oxygen isotope stage (OIS) 2; Pillans et al., 1998) but the previous period (~100 to ~40 ka) was presumably determined by uplift; it does not correspond to any known low sea-level stand. It is also interesting to note that the age range obtained for the T4 terrace (~280 to 100 ka) indicates a long aggradation period (~180 ka), with no indication of the OIS 6 low sea-level stand, during which sea level was about −120 m (at ~140 ka). Climatic changes during the Quaternary (Shackleton and Opdyke, 1973) do not provide clear trends that might

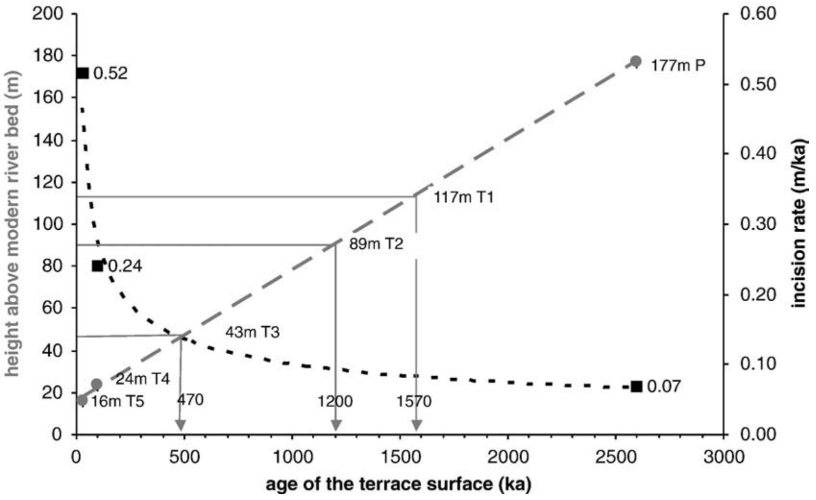

Fig. 9. For the Enxarrique–Monte do Pinhal staircase, ages of T5, T4 and Falagueira Formation top (*P*; probable age) plotted against height above the modern river bed (circles). The plot allows estimation of the probable age of the older terraces: T3 at ~470 ka, T2 at ~1.2 Ma and T1 at ~1.6 Ma. The long-term rates of bedrock incision (squares) were calculated based on the height of the terrace above the modern river bed and the respective age.

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explain the formation of these terraces. Blum and Törnqvist (2000) have argued that one of the main difficulties in correlating terrace genesis with a climate control arises from the complexity of the climate change during the glacial–interglacial cycles; climate changes on temporal scales of 10^3 and 10^4 yr are superimposed on the 100 ka cycles. The debate between climate and tectonic models is also conditioned by the resolution of the existing dating methods and obtained ages.

9. Conclusions

Of the terrace levels distinguished in the more upstream Portuguese reach of the Tejo river, only the two lower levels were found to be suitable for OSL dating. The older terraces give ages beyond the range of our present luminescence dating methods. They need to be dated by other techniques, such as cosmogenic radionuclide profiling.

The high dose rates of the sediments (4.1 to 7.0 Gy/ka) prevented the use of OSL from quartz for all samples. However, infrared stimulated luminescence dating of K-feldspar (with anomalous fading correction) has provided important support for the geomorphological correlation of the terraces and interpretation of tectonic displacements. Taking into account the position of the corrected K-feldspar ages in the sedimentary sequences, it is probable that the younger terraces have an age range of: T5 — 31 to 40 ka; T4 — 100 to ~280 ka; and T3 — >300 ka. These ages provide an important contribution to the age interpretation of the archaeological materials found *in situ* in the terraces: T5 — late Mousterian (late Middle Palaeolithic); T4 — Acheulian (Lower Palaeolithic) at the base and Mousterian (Middle Palaeolithic) at the top; and T3 — middle Acheulian.

Intervals of strath cutting occurred between: 0 to 31 ka; ~40 to ~100 ka; and ~280 to ?470 ka. These cannot readily be related to climate changes; although the youngest interval might have been induced by sea-level lowering (35 to 16 ka), the previous interval appears to have been controlled mainly by an episode of crustal uplift.

Fluvial terraces can be used to record the response of the river to differential uplift across faults. The time-averaged incision rate from the Rodão graben (~0.07 m/ka over the last ~2.6 Ma) is smaller than those derived from the adjacent reaches (e.g. reach II, ~0.10 m/ka). In those reaches, the Tejo has a narrow valley incised in the Variscan basement, partly because of the presence of resistant bedrock. The long-term incision rate calculated for the study area as a whole is similar to previous estimates for uplift in central Portugal and in lowland Europe.

The intensification of tectonically driven regional uplift has provided a steady forcing function causing overall incision of the Tejo river over the past ~2.6 Ma. Higher frequency tectonic clustering, possibly coupled with climatically modulated variations in sediment flux and river discharge, are superimposed on this forcing function and have led to the creation of terraces. However, a full interpretation of the relative importance of climate or eustasy *versus* tectonics in terrace formation needs the development of a more detailed chronology for the fluvial and marine terraces associated with the Tejo river.

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