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Geomorphological and Geochronological Analysis Applied to the Quaternary Landscape Evolution of the Yeltes River (Salamanca, Spain)

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Abstract: This paper aims to study the Quaternary geomorphological evolution of the Yeltes river-valley (Duero Basin, Central Spain) primarily based on the study of the Late Neogene piedmont dissected by the river and its Quaternary terrace sequence, since fluvial terraces are excellent archives to study the landscape and climate evolution during this period. Detailed geomorphological mapping implemented in GIS-based digital elevation models was used to the further applications of existing fluvial chronofunctions (relative terrace height-age transfer functions) to establish a numerical geochronology to the sequence of fluvial terraces in the zone. The obtained theoretical ages points to an onset of fluvial incision in the zone after 2.0–2.5 Myr ago, with the dissection of the “Raña surface” (a Gelasian alluvial piedmont widely developed in Central Spain). The obtained terrace ages coincide, in most cases, with warm isotopic stages (MIS) or mainly with the transit of cold to warm MIS. Additionally, this study suggests that the full connectivity of the Yeltes drainage (Ciudad Rodrigo Basin) with the Atlantic drainage was not completely effective until MIS 9 (c. 0.29 Myr). The new reported data allows for the exploration of the timing and processes involved in the capture of inland sedimentary basins (Ciudad Rodrigo, Duero basins) by the Atlantic drainage during the early Quaternary.

Keywords: fluvial terraces; chronology; quaternary landscape; Yeltes river; Duero basin (Spain)

1. Introduction

During the last million years, the Cenozoic basins in the center of the Iberian Peninsula opened to the Atlantic, produced the so-called Atlantic Capture [1]. This process represented the present drainage network development and this region’s landscape modeling, through the dissection of the Plio-Quaternary alluvial piedmont known as the “Raña surface” in central Spain [2–7]. Fluvial dissection into the Raña surface allowed us to analyze the development of river valleys and their correlative terrace sequences in central Spain, as well as their relationships with the Quaternary climate changes.

The river terraces are excellent archives on the relationships of landscape evolution and climate during the Quaternary [8–10]. They record low-frequency climatic changes of astronomical origin, but also climatic fluctuations correlated with marine isotopic stratigraphy [11]. Valley aggradation occur during glacial periods (cold periods) and dissection during the end of interglacial periods (warm periods) [12]. However, river-response to climate change is complex, in terms of aggradation and incision periods and in the morpho-climatic characteristics of each area, which require specific studies [13]. Consequently, this work deals with the geomorphological analysis and evolution of the

Yeltes river-valley (Duero Basin, Central Spain; Figure 1) pondering all the geomorphological processes that shape the relief.

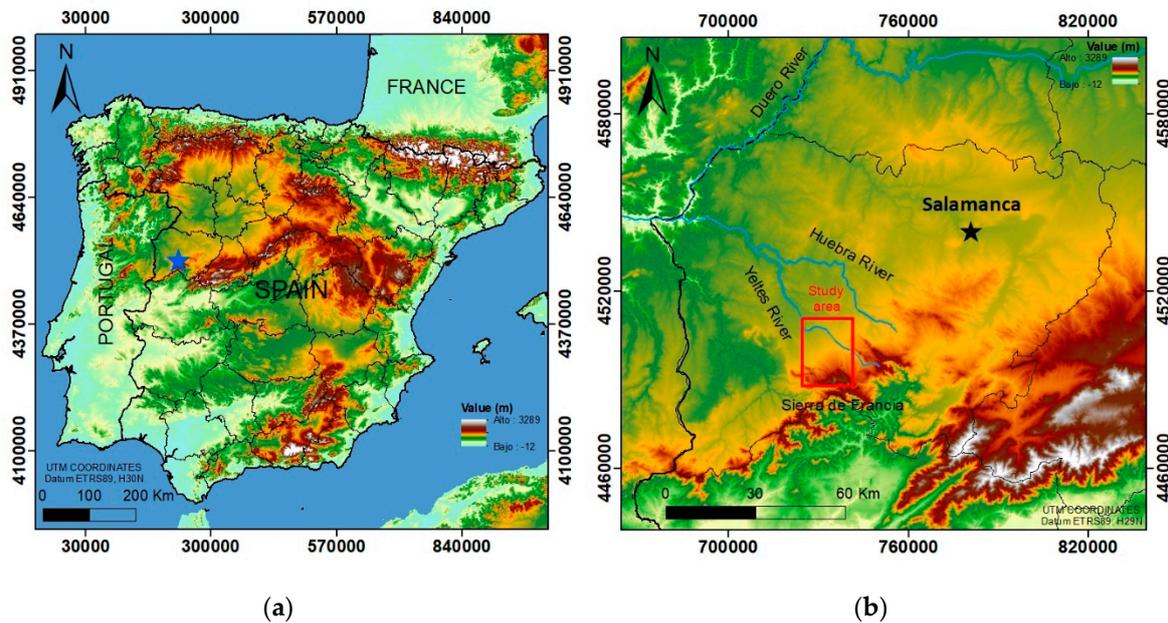


Figure 1. Location of the study area in the (a) Iberian Peninsula and the (b) Salamanca province.

This work is focused on a detailed geomorphological mapping of the Yeltes river basin, and more specifically of the sequence of existing fluvial terraces. These will be used as the main elements to set the temporal sequence of sedimentation-erosion processes behind valley development, but also to infer the timing of the Atlantic capture of the drainage in this southern zone of the Duero basin. The theoretical timing of the geomorphological evolution will be explored by the application of fluvial chronofunctions developed for the Atlantic river basins of the Iberian Peninsula, which calculate theoretical terrace ages from the relative height of fluvial terraces. Once established, the theoretical geochronology of valley development, the geomorphological, tectonics, and climatic factors operating in the area during the Quaternary will be explored, making it possible to advance a more accurate interpretation of the evolution of physical environment and the landscape of the Yeltes river valley.

2. Geology and Geography of the Study Area

The Yeltes River area is located in the central-western part of the Iberian Peninsula in the province of Salamanca (Castilla y León, Spain; Figure 1), occupying an area of 387 km². The southern part has reliefs belonging to the Sierra de Francia, a range-hill of the Spanish Central System, with a W-E orientation, and elevations around 1700 m. To the north of these landforms, there is a large plain that constitutes the “Raña” piedmont, where the altitude decreases from 1000 m in the range front to 753 m, which is the lowest elevation of the study area. The average altitude of the piedmont is about ± 800–900 m. All the drainage network of the area belongs to the Duero drainage-basin, which eventually flows into the Atlantic Ocean (Figure 1). The Yeltes river is the main drainage system in the area and the main objective of study for this work. The Yeltes originates in the Quilamas mountain range and flows into the Huebra river to then flow into the Duero river at the end of the “Arribes Canyon.” When crossing the study area, the Yeltes river carves an important escarpment on its right bank and presents a well-developed terrace system on its left bank, which is an essential part of the analysis done in this work.

The study area is within the Paleozoic Iberian Massif of Central Spain and more specifically of the Central-Iberian Zone [14]. This is an ancient geological zone occupying the western part of the Iberian Peninsula and constitutes a large outcrop of the old European Variscan Chain. This zone is

featured by the notable extension of Ordovician and Precambrian metamorphic outcrops (Schists, Shales, and Quartzites) as well as subsidiary late Palaeozoic granitic intrusions [15,16] (Figure 2). The oldest rock successions belong to the Precambrian being part of Neoproterozoic “Complejo Esquisto-Grauváquico” (Schist–Greywacke Complex) and Ordovician materials are constituted by the Armorican Quartzites, both typical of the European Variscan units [14]. These metamorphic units are verticalized and strongly folded featuring old structural units of the Tamames-Ahigal Syncline and the Sierra de Francia-Torralba Syncline [15,16]. Quarzite crests are the main landforms within the Sierra de Francia Range featuring the main intermontane water-divides (Figure 2). These folded units also display important fault systems, the dominant ones being those oriented at N40–55E y N10–20E with reverse and sinistral kinematics, otherwise typical of the Spanish Iberian Massif [17]. To the north, all these metamorphic and subsidiary granitic rocks are buried by Paleogene, Neogene, and Quaternary detrital deposits linked to the sedimentary infilling of the Ciudad Rodrigo Basin (Figure 2). This basin is a sub-basin of the largest Duero Basin, one of the more important Cenozoic basins within the Iberian Peninsula (Figure 1).

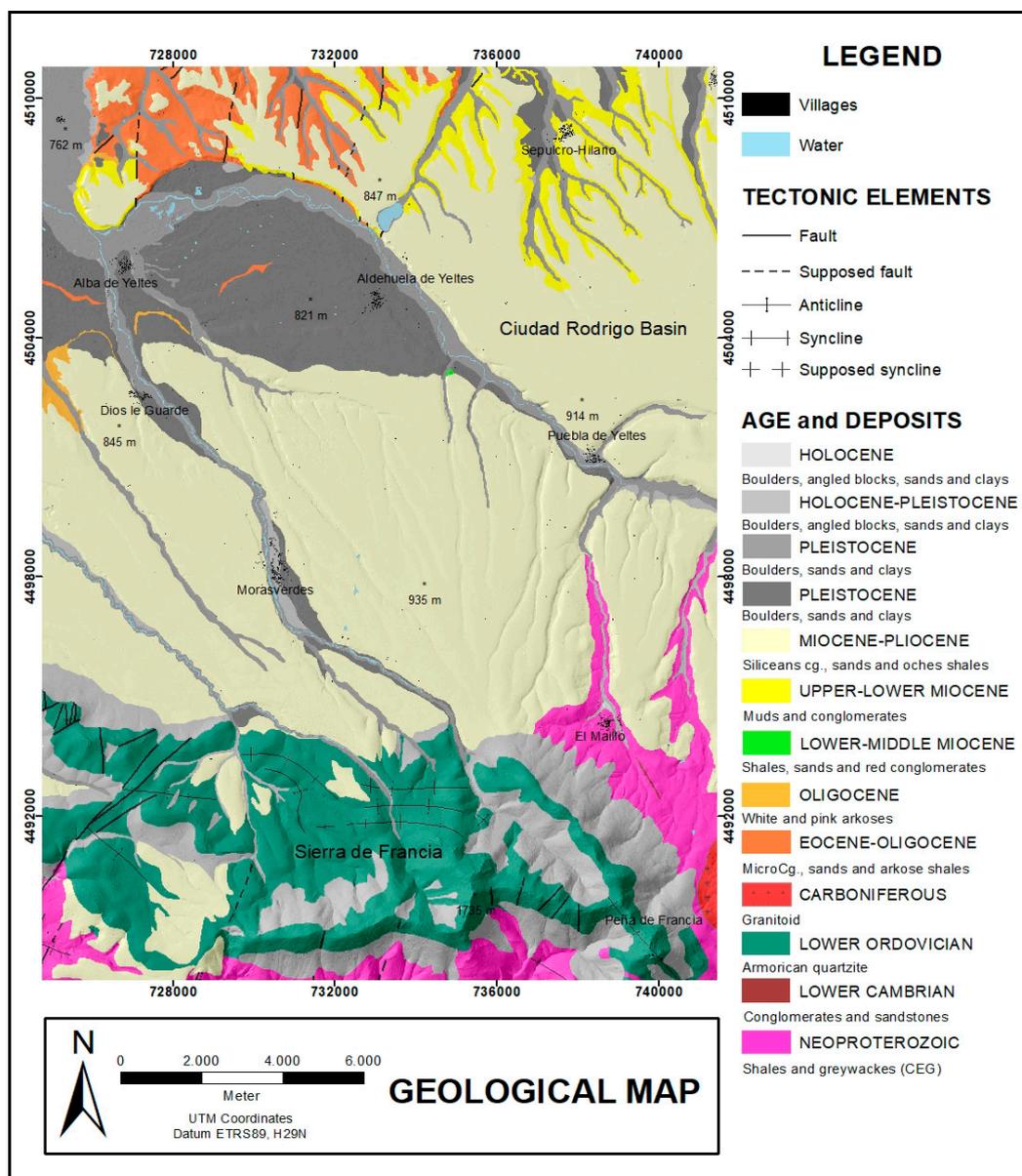


Figure 2. Geological map of the study area.

Ciudad Rodrigo Basin formation occurred during the Alpine orogeny and their sedimentary infilling records different phases linked to different tectonic pulses [18,19]. The first sedimentary phase occurred during the Paleogene (Eocene-Oligocene) and was featured by coarse-grained fluvial systems generating the so-called “arkosic filling” [18]. The second phase was dominated by the deposit of large alluvial fans fed by the relief of the Sierra de Francia (Figure 2), constituting the so-called post-arkosic Neogene sedimentary filling of the basin [18]. Faulting occurred during the last stages of the Variscan orogeny and had a great impact on the later Alpine evolution of the zone. These old fault systems conditioned the structure and geometry of basins as well as ranges throughout the entire Paleozoic Massif and were reactivated as normal or reverse faults from the Paleogene [19,20]. Therefore, the Ciudad Rodrigo Basin has a tectonic origin and has an asymmetrical structure with a greater sediment thickness at their southern zone [19,21].

3. Materials and Methods

A multidisciplinary methodology has been used, based mainly on field research and mapping, the compilation of existing geological information, remote sensing, geomatics, and statistics. We use field research and Geographic Information System (GIS)-based geomorphological mapping to perform a detailed geomorphological analysis (Section 3.1) and develop a theoretical geochronological approach (Section 3.2) to the age of the different fluvial terraces within the Yeltes river-valley. For this last issue, we used the existing fluvial chronofunctions proposed for the Atlantic river basins of the Iberian Peninsula [22], the models of fluvial evolution of the zone [23,24], as well as more recent papers on fluvial valley evolution for the Duero and Tagus river basins in Portugal [1] and Spain [25,26] containing modern geochronological data (Optically Stimulated Luminescence -OSL and Cosmogenic data) for the corresponding terrace systems.

3.1. Geomorphological Mapping

Geomorphological analysis was performed considering all the existing cartographic information for the studied area. Moreover, complementary photointerpretation and a fieldwork checking were accomplished. The geological cartographic information from the Spanish Geological Survey 1:50.000 maps [15–17,19–21] covering the studied area were digitized to obtain a geological map (Figure 2) as the previous background for the geomorphological analysis. All the cartographic information was homogenized, scaled, and implemented in a Geographic Information System (GIS) using the software ArcGIS v10.5. The processed digital information was: (1) topographic maps; (2) orthophotos of the Program PNOA 2017; (3) air-photos of the 1956–57 American flight; (4) 1977–78 Interministerial orthophotos; and (5) the geological cartography of the Spanish Geological Survey. In addition, a Digital Terrain Model (DTM) with 5 m/pixel resolution was generated to obtain the hillshade and slope DTMs. For the detailed geomorphological analysis, a higher resolution DTM (1 m/pixel) was generated from a LIDAR (Light Detection and Ranging or Laser Imaging Detection and Ranging) point cloud in LAS format.

The image generated from the 1 m/pixel DTM-LIDAR in hillshade model provided valuable geo-spatial information to produce a detailed photointerpretation capable to differentiate geomorphological units and individual landforms. Both were classified according to their morphogenetic origin following previous classifications for the zone [27] based on modern issues on geospatial digital geomorphological mapping [28,29]. An initial legend was prepared based on previous morphogenetic classifications for the zone [23] following classical guidelines differentiating landforms according to their endogenic (i.e., structural landforms) or exogenic origin (i.e., landforms generated by surface processes) [28]. A description of each landform starts from the morphogenetic classification and is summarized in Table 1. This description is based on the characteristics of its morphology (shape), genetics (process), composition, structure (background geology), and relative chronology. The exogenic landforms are mainly depositional elements whereas endogenic landforms are mainly erosional features or old elements inherited from the tectonic evolution of the area. The geomorphological classification

(Table 1) and mapping (Figure 3) follow the overall guidelines proposed for digital geomorphological mapping [29], previously applied to different sectors of the Duero basin [23,24,27,30] or to other zones all over the globe [31]. Once the overall geomorphology of the zone and individual landforms were checked and validated on the field, photointerpretation was revised, and the final geomorphological map was produced by the use of various manual and digital cartographic techniques [28]. The obtained digital map (Figure 3) constitutes a key-tool to accomplish the geomorphological analysis of the zone and reconstruct the temporal process-sequence behind the landscape evolution of the Yeltes river-valley.

Table 1. Summary of the morphogenetic system (M.S.), domains, and landforms of the Yeltes river-basin.

M. S.	Domain	Landforms	Description	Age
M. S. Structural	Structural Landforms	Fault	Fractures on materials that condition the structural reliefs and drainage orientations	Carboniferous (Variscan orogeny)
		Suspect fault	Probable fractures from photointerpretation not verified in the field	Carboniferous (Variscan orogeny)
		Crest	Narrow ridges (hogback-type) mainly developed on resistant quartzites	Paleogene-Neogene (Alpine orogeny)
		Summits	Water-divides within the mountain area, usually coincides with quartzite crests	Paleogene-Neogene (Alpine orogeny)
M. S. Fluvial	Fluvial-Alluvial Landforms	Drainage network	Present set of river and stream channels allowing water erosion and sediment transport	Holocene
		Flood plain	Alluvial surface adjacent to a river subject to periodic/episodic flooding	Holocene
		Terrace scarp	Topographic steps (slope-ruptures) between the different terrace levels	Holocene-Pleistocene
		Fluvial Terrace	Ancient floodplains hang up several meters above the present river thalweg, resulting from consecutive cycles of river downcutting and sedimentation	Holocene-Pleistocene
		Fluvial escarpments	Slope ruptures generated by the erosive action of the rivers	Holocene-Pleistocene
		Alluvial fan	Fan-shaped alluvial sedimentary bodies generated at the toe of large escarpments which extends radially downslope	Holocene-Pleistocene
		Erosional landforms	Areas excavated and shaped by river action in Neogene sediments	Holocene-Pleistocene
M. S. Lacustrine	Endorheic Landforms	Small lakes, ponds	Endorheic lakes of hydro-eolian origin favored by differential erosion along structural elements	Pleistocene
M.S. Gravitational	Slope Landforms	Talus cones	Debris accumulations related to gully erosion and escarpments retreat	Holocene
		Hillslopes	Steep slopes in a mountainous area, where various gravitational processes occur	Holocene-Upper Pleistocene
		Terrace wash-slopes	Accumulations developed with the erosion of the terrace escarpments	Holocene-Pleistocene
M. S. Periglacial	Periglacial Landforms	Talus-scrree (Canchales)	Talus-slope accumulations of angular clasts in elevated zones at the foot of large quartzite crests and rock walls	Holocene-Upper Pleistocene
M.S. Polygenic	Polygenic surfaces and Landforms	Glacis	Glacis-type deposits coming from the reworking of raña deposits composed of relatively angular clasts. It could be considered as the first terrace	Lower Pleistocene
		Raña surface (Piedmont)	Extensive alluvial sedimentary platforms and deposits unconformably placed on top of the Neogene sedimentary filling of the basin	Pliocene-Pleistocene
		Pediment	Exhumed relic rocky surface free of the older overlaying weathering profile (removed by erosion)	Pliocene
M. S. Anthropogenic	Anthropogenic Elements	Roads	Main road network	Modern
		Quarry	Aggregate extraction quarries (Gravelly)	Modern
		Villages	Localities (sites)	Historic

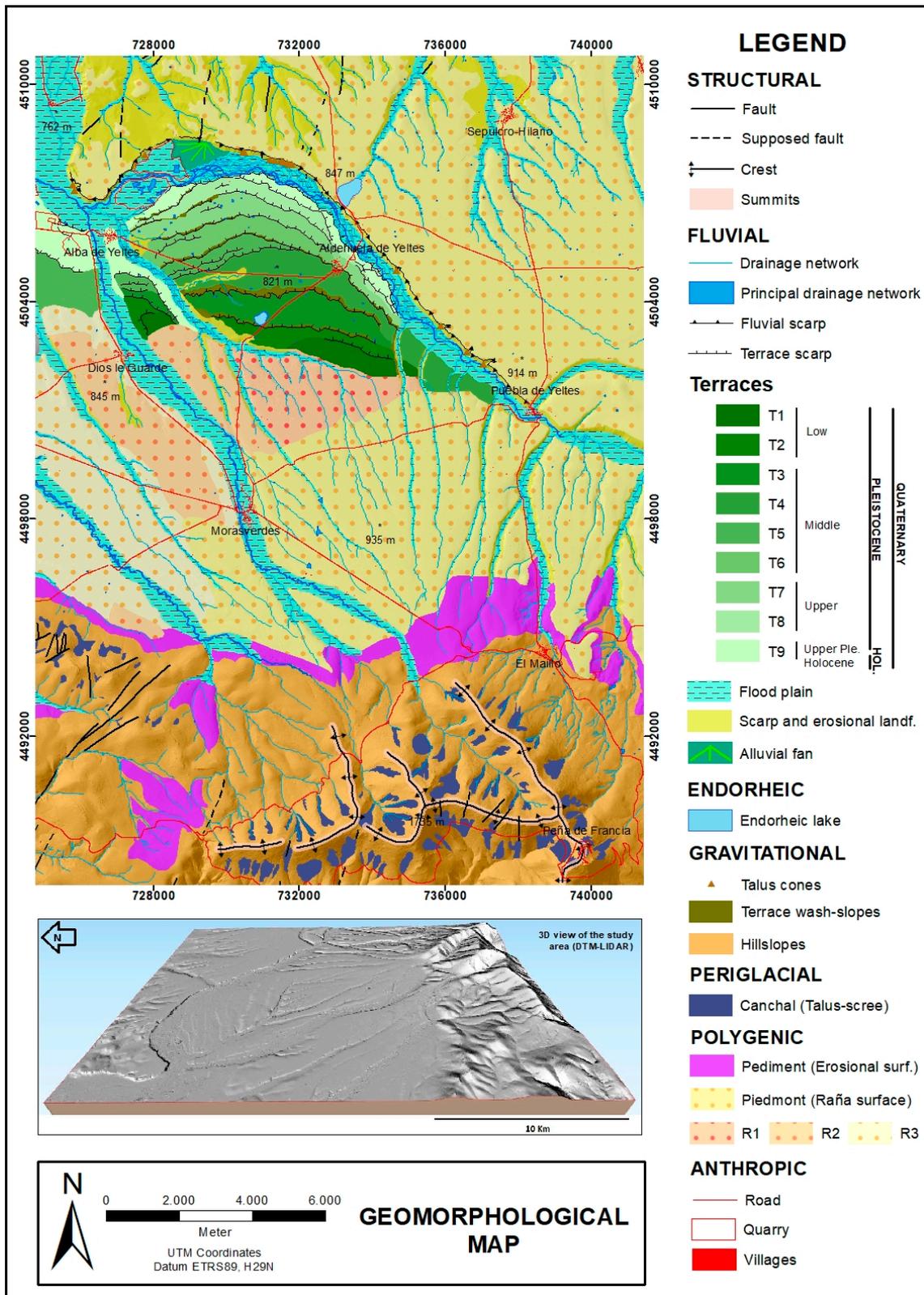


Figure 3. Geomorphological map of the study area.

3.2. Geochronological Analysis

In the geochronology section, theoretical ages were calculated and discussed for the fluvial terraces of the river Yeltes by the applications of the height-age transfer chronofunctions developed

for the Atlantic river basins of Central Spain [22]. The used chronofunctions are based on the existing published dataset of numerical dates, coming from different dating methods: (^{14}C -, Thermoluminescence -TL-, OSL, Thorium/Uranio -Th/U-, Electron Spin Resonance -ESR-, AminoAcids Racemization -AAR-, and Paleomagnetic determinations), for the Duero and Tagus basin till the year 2017 [22]. These equations describe the river incision and terrace development during the Quaternary from the large battery of numerical ages existing for these two Atlantic river-basins. This method offers a statistical approach to calculate the theoretical ages of the terraces in the Atlantic side of Iberia, suitable to be applied to the Yeltes river-basin, located nearly in the limit of the Duero and Tagus basins. The mathematical approach is based on multiple power and polynomial correlations between the relative height of the terraces with respect to the river thalwegs and the numerical ages obtained by different numerical dating methods (Table 2) [22]. These numerical models relate terrace relative height to age, transforming relative heights into numerical ages with correlation coefficients (R^2) above 0.92 (Table 2). The application of the four chronofunctions listed in Table 2 indicate that the two second order polynomial chronofunctions [a, d] are the best-fit for the study area [23]. These chronofunctions will provide us with the general numerical age (y) of the different terrace levels as a function of their relative height above the thalweg (x). As we will see, the obtained terrace ages fit quite well with recent geochronological studies in the Duero [25] and Tagus basins [26]. These chronofunctions are of use and applicable to the Atlantic river basins of the Iberian Peninsula, which underwent a similar geological history and sea-level changes; for other areas (i.e., Northern Europe, Mediterranean, etc.) similar equations have to be developed from local data [22]. For a deep discussion on the development and application of the listed fluvial chronofunctions, consult the work of Silva et al. [22].

Table 2. Best-fitted fluvial chronofunctions for Central Spain applied to the study area [22]. The parameter [x] represents the relative height of the terrace with respect to the present river thalweg, and the parameter [y] is the resulting theoretical numerical age for the terrace deposit. R^2 represents the correlation coefficient for each equation.

Chronofunction name	Equation (R^2)
2nd Order polynomial function (Duero Basin) [a]	$y = 0.098x^2 + 8.057x - 16.38$ (R^2 0.96)
Power Function for Arlanzón valley (Duero Basin) [b]	$y = 2.942x^{1.37}$ (R^2 0.92)
3rd Order polynomial function (Duero + Tagus Basin) [c]	$y = -0.001x^3 + 0.199x^2 + 4.38x - 21.16$ (R^2 0.98)
2nd Order polynomial function (Duero + Tagus Basin) [d]	$y = 0.085x^2 + 8.05x - 38.59$ (R^2 0.96)

4. Results and Discussion

The geomorphology section (Section 4.1) shows the resulting digital map, the classification of all the landforms and deposits in both morphogenetic systems, and domains summarized in Table 1. The distinguished terrace sequence is explained and discussed in Section 4.2 in relation to large polygenetic landforms (raña surfaces) developed before the fluvial dissection of the zone. The geochronology section (Section 4.3) is focused on the theoretical determination of the ages for the fluvial terraces of the river Yeltes by the application of the height-age transfer equations listed in Table 2. Finally, Section 4.4 presents the geomorphological analysis of all the information focused on the geomorphological evolution of the mapped area and its relationships with other nearby river basins around the Spanish Central System.

4.1. Geomorphology

The Yeltes River is located on the border between the northern plateau (Meseta norte) and the beginning of the mountainous relief of the Central System, linking the relief of the Sierra de Francia range with the Paleogene and Neogene filling of the Ciudad Rodrigo Basin. This results in a transition from a mountainous relief in the south to an almost flat area in the north, passing through an interesting piedmont made up of Neogene alluvial fan deposits. The uplift of the Central System and

the subsequent incision of the drainage triggered the fluvial dissection of the piedmont, generating an important set of landforms and deposits of mainly fluvial origin (Figure 3 and Table 2) [23,25].

The main geomorphological and structural elements within the southern mountain ranges are the faults, crests, and summits. These last elements usually constitute the water-divides within the range and usually follow the outcrops of the resistant Armorican Quartzite. The orientation of valleys, drainage, and summits is strongly conditioned by the folded structure of the quartzites and by the fracture systems originated during the Variscan. In other words, the subjacent Variscan structure strongly controls the present landscape within the mountain range area.

Within this southern mountain area are also typical geomorphological elements generated by periglacial processes during the Late Pleistocene. Periglacial landforms are restricted to several colluvial deposits of the talus-scrée type, called “canchal” in Spanish. These occur in the most elevated areas, linked to the steep slopes flanking the crests of Armorican Quartzite within the Sierra de Francia and Sierra de Valdefuentes ranges (Figure 3). As in other zones of the Spanish Central System, cryoclastic activity and gelifraction were important processes during the Last Glacial Cycle, generating important talus-scrée formations [30].

The polygenic landforms correspond to those generated by the participation of different erosive and/or depositional morphogenetic processes (e.g., fluvial-aeolian; fluvial-alluvial, etc.) or those for which the main morphogenetic process is doubtful. Within this category of landforms, erosive pediments, sedimentary piedmonts, and complex large escarpments occur in the Yeltes River (Table 1). The pediment is located at the foot of the southern ranges constituting a narrow fringe around the reliefs. It constitutes a relic rocky surface that has been exhumed and is free of sediments. In the study area, it corresponds to a pre-paleogene etchplain-type surface constituting the ancient substrate of old and thick weathering profiles [19]. These weathered materials were removed by differential erosion during the process of denudation and exhumation of the zone before the deposit of the extensive piedmont of the “Raña surface” [4,5].

The “Raña” is the main polygenic landform featuring the piedmont areas around Central Spain and have been subject of numerous studies [2–6]. These are extensive sedimentary gravelly formations placed in unconformity on top of the old Neogene alluvial sediments within the Ciudad Rodrigo Basin [19]. The “rañas” constitute broad alluvial piedmonts composed of quartzite gravels pasted by a reddish clayey matrix coming from the torrential erosion of the weathered metamorphic materials (quartzites, schists, and shales) within the southern mountain areas. These formations do not display evident stratigraphic structures (mainly massive) but support well developed fersialithic red-soils testifying old near-tropical climates dominating Central Spain during the end of the Neogene [2–4]. All around the Spanish Central System, the raña formations mark the transit between the old Neogene endorheic conditions of the Duero and Tagus basins and their Quaternary fluvial dissection, that is, the onset of the present fluvial network [4]. They have been traditionally considered to have a generic Plio-Quaternary age before the incision of the present the fluvial valleys [2–4]. In the mapped area, the “raña” formation is found north and south of the Yeltes river-valley [23], which axially dissect this ancient piedmont (Figure 3). On the northern bank of the valley, the Yeltes river carved a prominent scarp on the raña deposits about 12 km length and 60–50 m high (Figure 3), being one of the more prominent polygenic landforms of the zone.

A last polygenic element in the area is the set of gentle slope accumulation glaciais zones connecting the raña surface with the terrace system of the Yeltes river (Figure 3). These sedimentary features are constituted by sub-angular quartzite clasts embedded in a reddish clayey matrix, clearly derived from the erosion the raña deposits with no clear sedimentary structures [23]. The detailed mapping performed in this work allowed us to recognize that the surface of this accumulation glaciais is gently stepped, similarly to the raña surfaces in Tagus basin [2]. Consequently, three stepped surfaces have been newly differentiated (R1, R2, and R3; Figure 3) connecting the Plio-Pleistocene piedmont (Raña surface) with the Quaternary terrace system. The “raña surface” is at +134–138 m above the river thalweg, and the stepped surfaces at +118–122 m (R1), +100–105 m (R2), and +89–92 m (R3) (Figure 4).

These deposits would be considered as the product of the early dissection episodes of the raña surface, with a similar meaning that the “rañizo terraces” dissecting the raña formations in the Tagus basin [22], that is, fanhead trench terraces indicating the early stage of dissection of the raña surface soon before the “Atlantic Capture” of the zone.

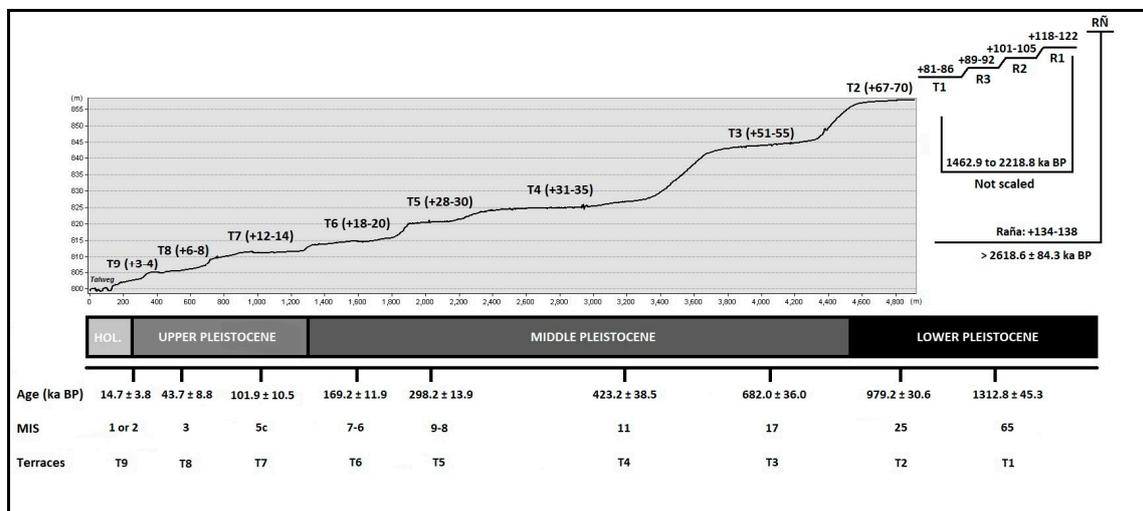


Figure 4. Topographic Profile of Yeltes river terraces between T2 and T9. T1 and stepped piedmont surfaces (R1 to R3) are indicated out of the profile. The horizontal time-bar is not scaled and theoretical terrace ages (kyr = 1000 years) and corresponding warm isotopic stages (MIS) are shown (See explanation in Section 4.3).

Fluvial landforms and deposits are the main geomorphological elements in the zone, mainly featured by the terrace system of the Yeltes river, constituted by nine staircased levels developed between +82–86 m (T1) and +3–4 m (T9) above the present river thalweg (Figure 3). As aforementioned, this terrace sequence is inset on the stepped piedmont of the raña surface and rañizo terraces between +134 and +89 m (Figure 4). The terrace levels T1 to T5 are terraces with a thickness of 2–3 m, whilst the younger terraces (T6–T9) are cut and fill terraces but with no relevant thickness (<5 m). Terrace deposits are specially developed in the southern slope of the valley and are constituted by sub-rounded quartzite and quartz clasts with a sandy matrix (Figure 5). This features the Yeltes valley as an asymmetric river valley with large terrace surfaces on the left bank, while the present flood plain and river-bed are located in the northern bank at the toe of the previously mentioned large escarpment carved in the raña deposits. Erosion is still an active process operating in this large escarpment, leading the development of gullies, slope deposits (colluvial slopes and small talus cones), and alluvial fans along their toe (Figure 3). The main alluvial fan occurs in the NW corner of the mapped zone (1 km long and 1.5 km wide), but is subject to anthropic modification by mining operations for the extraction of aggregates [23]. The largest floodplain in the Yeltes river develops a clear braided system with multiple channels (abandoned and active) and many sand and gravel bars in between. This floodplain can reach near 1.5 km wide in the NW corner of the mapped area (Sancti-Spiritus plain). The main tributaries of the Yeltes river, like the Morasverdes and Tenebron rivers, also display well-developed braided systems (Figure 3). These braided systems present a torrential activity, the flash floods within the floodplain being a common hazardous process [32]. The last important flooding occurred just this same year on 31st May 2020, affecting to the locality of Martín de Yeltes downstream the mapped area. These main rivers and most of the secondary drainage network seems to be adapted to NW-SE and N-S fault systems. These fractures clearly affect Neogene and Paleogene materials, but no fault offset has been observed in the more modern raña and fluvial deposits.

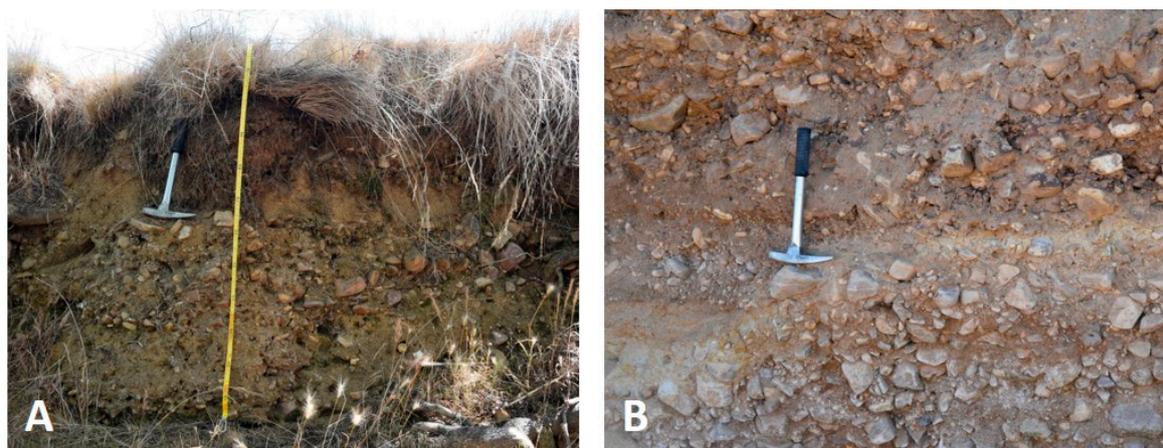


Figure 5. Stratigraphic profiles of the Yeltes river terraces. (A) Interbedded silt-sandy and gravel levels (T3). (B) Detail showing the poor classification and sub-angular nature of quartzite clasts.

The endorheic lacustrine elements are represented by two small lakes (ponds) on the T3 terrace surfaces near the village of Aldehuela de Yeltes. The Largest pond occurs just above the escarpment of the Yeltes river on the raña flat surface (El Cristo Lake). The development of small lakes or ponds in the raña surface is a common geomorphological element in the zone. These ponds have an eolian origin, since they are located in small depressions originated by the wind action in zones subject to strong deflation during the Late Pleistocene. Therefore, these endorheic elements can be labelled as hydro-eolian landforms [23,27] originated under arid to semi-arid climate with dominant NE-SW wind directions and favored by structural elements (faults, fractures) with similar orientations [33]. These climatic conditions were characteristic during the end of the last glacial period in the whole northern piedmont of the Spanish Central System, where dune fields and deflation actions occurred in the absence of water (retained in the glacier systems of the ranges) [34].

The gravitational morphogenetic system is mainly featured by talus slope deposits located in the southern mountain area of the mapped zone, previously featured as periglacial talus scree. Within the basin, the small talus cones developed along the toe of the mentioned Yeltes escarpment are also characteristic gravitational landforms (Figure 3). In this escarpment, minor earth-slides and creeping, out of the resolution of the map scale, also occur, evidencing that gravitational processes are still active along this landform, controlling its evolution. Within the terrace system, small wash-slope debris-slope deposits develop at the toe of the terrace scarps, especially in the older terraces up to +35 m (>T4). They are also included in this morphogenetic system (Figure 3).

The anthropogenic elements are summarized in Table 2. It is only necessary to highlight the morphological modifications of the ground surface generated by the intense quarrying of gravels and sand (aggregates) in the floodplain and lower terrace levels (Figure 3).

4.2. Fluvial Terrace Sequence of the Yeltes River

Fluvial terraces represent the ancient floodplains of a river-valley presently hanged several meters above the river thalweg because of pulses of river incision and sedimentation during the Quaternary [35]. Climatic sea-level changes, tectonics, or uplift cause relative drops of the river base-level, allowing the downcutting of river channels in their active floodplains, leaving these abandoned and hanging above the new incised river bed, constituting successive terrace levels [36]. The alternation of aggradation and incision processes occurred during warm and cold stages along the Quaternary produced terrace sequences in fluvial valleys, providing a record of river flow changes, sediment supply fluctuations, and base-level variations over the period of valley development [35]. A recent analysis in Central Spain indicates that terrace sedimentation mainly occurs during the transit of cold to warm Oxygen Isotopic Stages (OIS) [37]. Floodplains stabilized during warm OIS, where soil development starts and form the

end of warm OIS (odd-numbered OISs) and the complete subsequent cold OIS (even-numbered OISs) river downcutting dominates in response to glacier sea-level drops [37,38]. Consequently, the set of terraces in a fluvial valley represent a chronological sequence of incision, stabilization, soil formation, and sedimentation within the river basin, allowing the study the geomorphological and climatic evolution of the area [38,39].

Within the mapped area, the terrace sequence of the Yeltes river displays a geometry of asymmetrical fan-splay incised in the raña surface giving place to a kind of asymmetrical valley [39]. The entire terrace system only develops on the southern bank of the river, creating a very large flat but gently stepped area of about 75 km² (Figure 3). In this sector, the terraces appear as cartographically narrow and elongated bands from WNW (T1) to N-S (T9) orientation, displaying a gentle slope towards NNW [27]. This particular “fan-splay” geometry of the terrace system indicates a progressive displacement towards the NNE of the river channel during the Quaternary downcutting of the valley. This fact, together with the N-S asymmetrical filling of the basin [39], strongly suggests continuous uplift of the Spanish Central System and correlative northwards tilting of the Plio-Pleistocene piedmont (raña surface) during the fluvial dissection of the zone.

Usually, it is difficult to find the scarps among the different terraces, since many times the topographic steps have a small height (1–2 m) and are normally very degraded. In many times, terrace scarps are nearly buried by the occurrence of wash-slope and debris-slope accumulations adjacent to the scarps. In basis to the texture and grain size of detritic materials incorporated in the fluvial terraces, it is possible to assess that the Yeltes river has sustained a braided fluvial system from its initial stages of development. The stratigraphy of the upper terraces displays numerous interbedded levels of floodplain facies (sands and silts) and gravel bars (quartzite clasts) (Figure 5A). In other outcrops, these braided gravels were originated by a large amount of matrix-less quartzite clasts, within river channels with insufficient capacity of transport, as presently occurs in the present braidplain of the river. This is one of the main reasons for the poor classification and sub-rounded nature of the gravels (Figure 5B) of almost the whole terrace sequence.

As aforementioned, the terrace system of the Yeltes river presents nine terrace levels (T1–T9). These have been discriminated by means of GIS and photointerpretation using the 1 m/pixel DTM created for this study [23]. Terrace 1 (T1) is the oldest fluvial level at +82–86 m above the river thalweg and T9 is the most modern one at +3–4 m, just above the present floodplain (braidplain) of the river, which is the younger fluvial landform of the mapped area (Figure 3). As already indicated, the glacia-deposits morphologically connecting the raña surface with the terrace sequence was identified as a unique polygenic unit in previous studies [23]. Detailed mapping allowed to differentiate a stepped piedmont with three distinct surfaces (R1, R2, and R3) inset within the raña surface. These pre-fluvial surfaces developed between +89 to +122 m inset in the raña surface which stands at a mean relative altitude of +134–138 m above the present thalweg of the Yeltes river. These relative elevation values fit well with the relative elevation of the highest fluvial terrace of the Duero river (+144 m), indicating the Atlantic Capture of the Duero Basin [22,25]. However, more recent studies place the final development of the raña until the Gelasian Period previous to the Olduvai normal paleomagnetic subchron prior to 2.0–1.9 Myr [22]. From this period on started the true fluvial dissection (i.e., the Atlantic Capture) of the Duero and Tagus basins [22]. More recent studies based on OSL and Cosmogenic dating profiles (e.g., ¹⁰Be–²⁶Al) suggest that the endhoreic-exorheic transition in the Tagus and Duero basins occurred between 2.42 and 2.36 Myr [25,26].

The relative heights of the different terrace levels and raña surfaces were measured in a perpendicular NW-SE section from the locality of El Maillo to near the village of Alba de Yeltes (Figure 3). Despite T9 (+3–4 m) being elevated above the present floodplain, it is presently subject to active flooding during episodic strong storms in the zone [32]. The partial terrace profile (T2–T9) obtained by means GIS tools on the 1 m/pixel MDT is displayed in Figure 4.

4.3. Geochronology

This section is focused on the geochronological analysis of the terrace sequence based on the chronofunctions proposed for Central Spain [22] listed in Table 2. As mentioned in the methodological Section 3.2, the proposed equations are based on multiple correlations between the relative altimetry of fluvial terraces in the Tagus and Duero basins and the numerical ages obtained by different dating methods. Consequently, this supposes a statistical approach to assess the theoretical numerical ages of the terrace sequence for the Yeltes river-valley. Additionally, the same chronofunctions have been applied to the early incision surfaces (R1 to R3) inset in the raña and to the raña surface itself (Table 3). The obtained values for this last alluvial piedmont surface indicate the age in between its eventual deposition and its early dissection. As indicated for the Tagus basin, the early dissection of the raña surface are not properly linked to the Atlantic Capture of the zone, but to intrinsic controls common to the late evolution of alluvial fan systems (i.e., proximal to distal trenching) [22]. The Atlantic Capture occurred after an important degree of intrabasinal dissection of the old Neogene basins of Central Spain, which favored intensive soil development (raña red soils), as well as their eventual endorheic-exoreic transition [2]. Modern cosmogenic and relative dating of raña and rañizo surfaces [1,25,26] indicate that this transition was not a synchronous process in Central Spain as traditionally considered [4].

Table 3. Age-values for fluvial terraces and stepped piedmont (raña and rañizo surfaces) obtained from different chronofunctions [a, b, c, d] for fluvial terraces in Central Spain [22] listed in Table 2.

Terraces	Relative Height (m)	[a] 2nd Order Polynomial Duero (ky)	[b] Power Function Arlanzón Valley (ky)	[c] 3rd Order Polynomial Duero + Tagus (ky)	[d] 2nd Order Polynomial Duero + Tagus (ky)
T9	+3–4	13.04	16.45	−3.39	−9.35
T8	+6–8	44.92	42.53	19.09	22.01
T7	+12–14	105.02	98.95	67.37	80.51
T6	+18–20	172.18	166.28	127.18	145.13
T5	+28–30	299.79	296.66	248.94	266.43
T4	+31–35	424.18	422.24	370.74	383.35
T3	+51–55	686.32	677.73	627.17	627.17
T2	+67–70	995.59	962.92	891.19	911.87
T1	+82–86	1352.29	1273.41	1157.99	1237.71
R3	+89–92	1515.64	1410.20	1263.71	1386.30
R2	+100–105	1839.69	1672.63	1440.97	1680.10
R1	+118–122	2362.05	2075.64	1641.40	2151.75
Raña	+134–138	2822.95	2414.22	2822.95	2822.95

The analysis of the values obtained by means of the four chronofunctions proposed for Central Spain [22] offers very similar values to each other (Table 3). However, the data resulting from the 3rd Order [c] and 2nd Order polynomial [d] functions for the complete data set (Duero + Tagus basins) offer slightly lower values for the whole data set and even negative values for the lowest terrace (T9). This is due to the inclusion of palaeomagnetic data in these functions, which introduce great uncertainties in the computed values [22]. On the contrary, the values coming from 2nd Order polynomial function for the Duero basin [a] and the power function for the Arlanzón valley [b] (Table 3) offer more congruent and similar values and have been selected for this study. Their results are best suited to the geographical area of the Duero Basin [22]. To homogenize the theoretical chronologies of the terraces, we present the average ages resulting from the age values obtained by the two equations [a, b]. Table 4 displays the obtained average ages (kyr) but also the age uncertainties (\pm kyr) resulting to calculate the age of the maximum and minimum relative height for each terrace level; this is the difference between maximum and minimum calculated age “per case.” The same methodology was applied to calculate average ages and errors for the stepped piedmont surfaces of the Raña and the Raña surface itself (Table 4). In this way, it is important to note the mean age obtained for the Raña surface (2.62 ± 0.84 Myr) will correspond to the youngest possible age for their deposition, since it is a pre-incision surface not truly related to the theoretical fluvial downcutting described by the equations.

Table 4. Average ages and errors (\pm ky) of the fluvial terraces and raña surfaces (stepped piedmont) for the Yeltes river valley. Numerical ages and errors obtained was obtained from mean values of the best-fit polynomial [a] and power [b] equations listed in Table 3.

Terraces	Relative Height (m)	Numerical Age (ky)	Error (\pm ky)	Epoch/Subepoch	MIS
T9	+3–4	14.75	3.8	Holocene-Upper Pleist.	2–1
T8	+6–8	43.72	8.8	Upper Pleistocene	3
T7	+12–14	101.98	10.5	Upper Pleistocene	5
T6	+18–20	169.23	11.9	Chibanian (Mid. Pleist)	7–6
T5	+28–30	298.22	13.9	Chibanian (Mid. Pleist)	9–8
T4	+31–35	423.21	38.5	Chibanian (Mid. Pleist)	11
T3	+51–55	682.02	36.0	Chibanian (Mid. Pleist)	17
T2	+67–70	979.25	30.6	Calabrian (Low. Pleist)	25
T1	+82–86	1312.85	45.3	Calabrian (Low. Pleist)	43
R3	+89–92	1462.92	35.4	Calabrian (Low. Pleist)	51
R2	+100–105	1756.16	63.1	Gelasian (Low. Pleist)	65
R1	+118–122	2218.84	55.3	Gelasian (Low. Pleist)	89
Raña	+134–138	2618.58	84.3	Late Pliocene	> 103

The obtained theoretical terrace ages are similar to those recently proposed for comparable tributary valleys of the Spanish Upper Duero Basin (i.e., Tormes valley) [24] and more recently for the terrace sequence of the Duero river between +117 m and +13 m [25]. However, the obtained values are slightly older than OSL-ESR ages obtained for terrace levels down to +30 m in the Lower Duero Basin near Barca d’Alva in Portugal [1]. As noted by these authors [25] the apparent difference of ages between the upper (Spain) and the lower (Portugal) sectors of the Duero basin can probably be linked to the important step of the longitudinal profile of the river introduced by “Los Arribes Canyon” (c. 200 m) between these two zones. All the tributary basins in Spain are located upstream of “Los Arribes Step,” whilst the still scarce set of age determinations in Portugal are downstream it [1]. Similar age discrepancies occur with the Portuguese and Spanish sectors of the Tagus river basin, where a more robust set of numerical age determinations are available [22]. The obtained ages are listed in Table 4 and illustrated in the topographic section of Figure 4. As can be seen, all the fluvial sequence (stepped piedmont and terrace system) entirely develop during the Quaternary. The rañizo terraces (R1 to R3) developed during the Lower Pleistocene and the Lower-Middle Pleistocene transit occurs between the deposit of the T2 and T3 terraces (Table 4). The numerical approach suggests that an effective climatic sensitivity in terrace development occurs from the isotopic stage MIS 11 (T4) and specially from the MIS 9 (T5). In this sense, the obtained ages (Table 4) indicate in most of the cases terrace sedimentation mainly occurred during warm isotopic stages (odd MIS), and in many cases close or during the transit between cold to warm isotopic stages (i.e., glacier terminations). As indicated by other studies in the Iberian Peninsula [22,25,37], river downcutting occurs during cold stages (even MIS) in response to long-lasting sea-level drops, but sedimentation preferably took place during the transit between glacier-interglacial periods when the melting of the mountain glaciers promotes important sedimentation rates. The subsequent step progresses during the second half of warm stages (odd MIS), when terrace surfaces stabilized being dominant soil formation processes [37], before fluvial downcutting re-start again.

4.4. Discussion: Quaternary Landscape Evolution of Yeltes River

The onset of the present landscape evolution in the zone was promoted by the alpine tectonics, which disrupted the old peneplain imprinted on the Palaeozoic materials of the Iberian Massif. Alpine tectonics promoted the uplift of marginal reliefs around Spanish Central System (e.g., Sierra de Francia) and generated new sedimentary basins (e.g., Ciudad Rodrigo Basin) from the end of the Paleogene period. In many cases, basin formation was controlled by the reactivation of the old variscan faults cutting the Paleozoic massif. Cenozoic sedimentation was defined by the so-called arkosic (Paleogene) and post-arkosic (Neogene) cycles defined for this area, constituted by materials derived from the erosion of granitic materials of the southern reliefs [18]. These two cycles

record a transit from fluvial (arkosic) to alluvial fan (post-arkosic) sedimentation indicating accelerated uplift of the Central System ranges and a replacement of source areas from granitic to metamorphic materials [18]. During the Neogene cycle, the superposition of large alluvial fans coming from the southern ranges generated a large piedmont system along the southern zone of the Ciudad Rodrigo Basin. Neogene sedimentation culminates with the deposit of the “raña” materials giving place to an extensive alluvial piedmont, which is a characteristic Plio-Quaternary landform around the Spanish Central System [2–4].

As traditionally considered, the deposit of the “raña” occurred as a time-transgressive event coupled to the endorheic-exoreic transition of the old Neogene basins in central Spain [4]. The Raña deposit constitutes the last sedimentary episode in endorheic conditions before the incision of the present fluvial system and the eventual “Atlantic Capture” of the Neogene basins [1,22]. This process occurred during and elapsed time of several thousands of years from the Late Pliocene to the Lower Pleistocene, but mainly during the recently recognized early stage of the Quaternary (i.e., Gelasian: c. 2.5–2.0 Myr ago), previously assigned to the Late Pliocene [22,40]. The “raña” deposit is formed by quartzite cobbles and pebbles embedded in a reddish clayey matrix (normally 2.5 YR in Munssel code [2]) coming from the reworking of Neogene weathering profiles in the Paleozoic metamorphic rocks within the ranges. They were deposited under a relatively humid climate, as testified by the red soils developed on top [1,2,22], but subject to torrential rainfall events favoring the mobilization of weathered materials downslope [3,27]. The increased intra-plate compression, the overall westward tilting of the Iberian Peninsula, and the important climate changes preceding the beginning of the Quaternary around the African-Eurasian plate boundary facilitated the so-called “Atlantic Capture” [1,6,7]. The high topography of the Iberian Massif peneplain in the western sector of the Iberian Peninsula allowed the isolation from the Atlantic base-level of the old sedimentary basin during the Neogene [41]. However, the climate deterioration (cooling) and sea-level fall occurred from the onset of the Quaternary produced a relevant base-level drop triggering the fluvial capture of the ancient sedimentary basins in central Spain [1,25,40]. Recent geomorphological approaches to this process in the Duero Basin points that the endorheic to exorheic transition in western Iberia started from about 3.7 Myr ago, testified by the development of a series of erosion surfaces inset in the Iberian massif peneplain [1]. However, fluvial dissection in the upper Tagus and Duero Late Neogene basins only occurs from c. 2.5–2.6 Myr [22,24,25].

The detailed geomorphological analysis carried out in this work allowed to characterize the raña surface in the studied area as a stepped piedmont, as already noticed in the southern slope of this Spanish Central System [2]. In this way, R1, R2, and R3 surfaces have been mapped inset in the raña piedmont in relation to its early incision stages (Figure 3). These stepped surfaces develop between +122 m and +89 m above the present river thalwegs and can be comparable to the upper rañizo terraces described in the Tagus basin [22,25,40]. In other words, large fan-ahead trench-like terraces linked to the intrinsic dissection of alluvial systems before the onset of proper fluvial downcutting by headward erosion linked to the “Atlantic Capture” [40].

The application of the fluvial chronofunctions (Table 4) to the stepped piedmont surfaces of the raña (+132 to +89 m) identified in this study indicates that the early dissection of the area occurred from c. 2.6 to 1.4 Myr (Figure 5). From this time starts the true fluvial incision and fluvial terrace development (T1, T2, T3) preserved upstream of Los Arribes Canyon (c. 1.3–0.68 Myr; Table 4). Climatic sensitivity to terrace development is clear from the isotopic stage MIS 11 (T4), from which fluvial sedimentation are clearly linked to the early phases of warm isotopic stages or to the transit of cold to warm stages (Table 4). This fact can be related to drainage connectivity problems between the lower and upper sectors of the Duero drainage basin due to the existence of important internal steps of the base-level. These internal steps would prevent the upstream propagation of headward erosion. In the study area, these steps are nicely represented by “Los Arribes Canyon” in the axial fluvial valley, but also by the series of gorges developed in all the tributaries in the eastern slope of the Canyon [36], as is the case of the Huebra river along which the Yeltes flows to the Duero (Figure 1). This hypothesis indicates

that base-level induced headward erosion was limited in the Duero Basin before the development of the T4 (+31–35 m; Figure 5). Fluvial downcutting linked to the youngest terraces (<MIS 11) appears climatically controlled as internal thresholds theoretically disappeared. This hypothesis should be properly analyzed in further studies when the set of available numerical ages for the upper (Spain) and lower (Portugal) sectors of the Duero basin will be more robust than today.

Figure 6 illustrates terrace development of the Yeltes river-valley in relation to the 41 ka and 100 ka worlds defined by the Milankovitch orbital cycles and the so-called “Middle Pleistocene Transition” (MPT) [22,42]. The main curve describes terrace development for central Spain as described by the 3rd Order polynomial curve corresponding to the equation [c] listed in Table 2. In our case, is clear that the oldest rañizo surface (R1) and the raña surface itself show an important deviation from this general chronofunction curve (Figure 6). Since the calculation of these chronofunctions [22] only considered the rañizo terraces described in the Tagus basin, the observed deviation will indicate a younger evolution of the Duero basin in relation to the Tagus one, and therefore a more recent “Atlantic Capture” for the Duero as already suggested by previous authors [22,41]. On the other hand, it seems clear that the climatic control of fluvial terrace development occurs after the MPT, during the 100 ka world (Figure 6). T3 roughly coincides with the end of the MPT and the subsequent development of T4. T5 to T9 is clearly linked to climatic pulses (Figure 6), indicating that from T3 (c. 0.68 Myr) the Atlantic base-level changes could freely propagate upstream Los Arribes and the Huebra canyons towards the studied area. The extreme glaciations and base-level drops (c. ±120 m) depicting the 100 ka world [42] could largely help to eliminate probable internal thresholds working in the past.

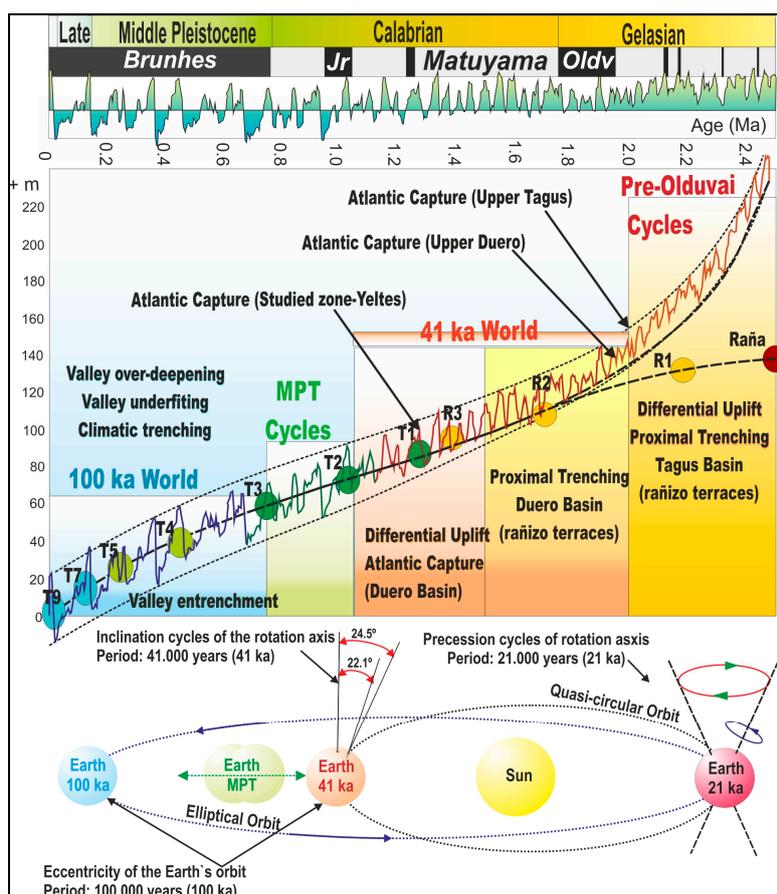


Figure 6. Theoretical behavior of the river under conditions of dynamic equilibrium in the readjustment of the classical MIS curve to the 3rd order polynomial function describing terrace development in Central Spain [c] in relation to the Milankovitch cycles. The circles mark the terrace age-data obtained for the Yeltes River. Modified and adapted from [22].

After terrace development, the subsequent significant impact on the landscape of the zone occurred during the last glacial cycle. The development of the ephemeral lakes of el Cristo and La Cervera on the highest terrace levels and the widespread development of “canchales” (talus-scree) in the southern mountain zone (Sierra de Francia) are related to periglacial conditions from the end of the Pleistocene to the present. These formations of matrix-less angular rock debris generate an important water reservoir within the mountain area, forming a quaternary type aquifer with numerous springs [25].

5. Conclusions

The geomorphological evolution of the studied zone began with the Alpine orogeny that triggered the uplift of the Spanish Central System and the generation of piedmont basins. One of these basins is the Ciudad Rodrigo basin filled by Paleogene and Neogene detritic materials of fluvial and alluvial origin. The final filling of the basin is featured by the alluvial deposit of the raña as occurs in most of the old Neogene basins in central Spain sourced by quartzite-schist metamorphic reliefs [2,3]. The performed geomorphological analysis has been largely supported and improved by the implementation of LIDAR data in high-resolution digital elevation models (1 m/pixel DTMs) allowing a detailed photointerpretation and facilitating fieldwork. The elaboration of a detailed geomorphological map (Figure 3) allowed the establishment of the spatial and temporal distribution of the different geomorphological units and systems operating in the area. Seven morphogenetic systems have been identified (Table 2): Structural (tectonic structure), Fluvial, Alluvial, Gravitational (slope processes), Periglacial, Polygenetic, and Anthropogenic (human activity). All these systems have been classified in the map legend differentiating among erosive and depositional landforms (Figure 3). The detailed geomorphological analysis developed in this work allowed to differentiate nine terrace Levels (T1 and T9), between +82–86 m and +3–4 m above the present river thalweg, but also three higher stepped piedmont surfaces (R1, R2, R3) between +89 and +122 m inset in the piedmont of the raña surface (+134–138 m). For the first time a stepped raña piedmont in the northern slope of the Spanish Central System is described, which make possible for the comparison of these newly reported surfaces with the rañizo terraces described in the Tagus basin [2,22,26].

Chronological analysis has been implemented by means of the application of fluvial chronofunctions developed for central Spain (Table 1). The obtained theoretical ages indicate that the entire fluvial and alluvial terraces and surfaces inset in the raña piedmont entirely developed during the Quaternary (≤ 2.2 Myr). The raña deposit results older than c. 2.6 Myr with a Late Pliocene age and its early dissection (R1–R3) during the Gelasian (Table 4), being these ages comparable to those obtained by cosmogenic dating for similar surfaces in central Spain (2.42–2.36 Myr) [26]. The Atlantic capture of the Ciudad Rodrigo (T1) basin occurs about 1.4–1.3 Myr. during the end stages of the Calabrian, but complete drainage connectivity does not seem to happen until the development of terrace T4 during the isotopic stage MIS 11 (c. 0.42 M.a). It seems that base-level changes did not freely propagate upstream in the Duero basin for a period of about one million years, by the occurrence of internal thresholds (steps) in the river profile along the “Los Arribes Canyon” and the Huebra river gorges. These constitute transverse drainage systems [25,41] connecting the lower (Portugal) and upper (Spain) sectors of the Duero drainage basins, inducing a step of c. 200 m in the river profiles. Fluvial terrace development seems clearly climatically controlled from MIS 11 when terrace deposits mainly occur during the initial phases of warm isotopic stages or closely related to cold-warm stage transitions. The large sea-level drop linked to the extreme glaciations of the 100 ka world (Figure 6) seems to facilitate the removal of the probable internal thresholds existing within the Duero basin during the Middle and Lower Pleistocene. The obtained chronological scenario for the Yeltes river-valley provides an estimate for the timing of terrace formation due to river incision that seem to be in agreement with recent proposals based on cosmogenic dating for the Duero river upstream Los Arribes Canyon [25], especially for terraces down to +40–35 m. The chronology of the other landforms (Table 1) existing in the zone was assigned in function to their position in relation to the terrace chronology.

The landscape of the area links polygenic piedmont fossil landforms prior to 2.5 M.a., dissected by much younger fluvial landforms (terraces) of Quaternary age. These last dominate the geomorphological evolution of the area during the last 1.4 M.a., but especially since the isotopic stage MIS 11 (C. 420 ka).

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