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First chronostratigraphic framework of fluvial terrace systems in the eastern Cantabrian margin (Bay of Biscay, Spain)

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ABSTRACT

Reported here is the first chronostratigraphic study of the Quaternary fluvial terrace deposits of three different valleys (Deba, Nerbioi, Oiartzun) located in the eastern Cantabrian margin (northern Spain), designed to understand long-term fluvial dynamics of this region. Fourteen samples were collected for numerical dating purpose, in the lowest terrace levels from 5 m to 63 m above current river channel. Optically Stimulated Luminescence dating was performed using the SAR protocol. For samples from terraces > 20 m above the current river channel, over 20% of measured aliquots were above saturation of the OSL signal. Consequently, only minimum ages could be estimated. Five samples also underwent Electron Spin Resonance (ESR) dating following the Multiple Centre approach. The ESR signals of the Aluminium and Titanium (Ti-Li and Ti-H) centres were systematically measured in each sample. In particular, the ESR signal of the Ti-H centre was strong enough to derive reliable and meaningful dose estimates. Obtained age results range between ~140 and ~400 ka for the terrace levels from +10 to +25 m. They suggest phases of aggradation during MIS 6, MIS 8 and MIS 10, for terrace levels T+10m, T+20m and T+25m, respectively.

1. Introduction

In contrast with many fluvial systems of Western Europe (Bridgland and Westaway, 2014) or even within the Iberian Peninsula (Santisteban and Schulte, 2007; Silva et al., 2017), the Quaternary evolution of the valleys in the eastern Cantabrian margin has been barely studied so far. Very little is known about the timing of the changes in the fluvial dynamics of this area, and the absence of numerical ages to constrain the chronology of the fluvial deposits is quite striking.

The lack of systematic and exhaustive scientific projects focused on the Quaternary evolution of these fluvial valleys may be explained by a series of factors. The poor preservation of the fluvial features in the landscape significantly complicates any fluvial studies in this area. Landslide processes are very active due to very high rainfall rates (~1200–~2400 mm/a) in combination with the presence of very steep slopes and short torrential rivers, producing thus very high hillside erosion rates (denudation rates of 3.3–5.2cm/ka over the last 1.5 Ma; Fernández et al., 2010, 2012). Furthermore, extensive urban and industrial areas occupy a large surface of the territory, especially on the flat areas, making it difficult to find and access the fluvial deposit outcrops.

To overcome the current lack of numerical age results in the valleys of the eastern Cantabrian margin, 14 fluvial sediment samples were initially collected for Optically Stimulated Luminescence (OSL) dating. Many of these samples were found in first instance unsuitable for OSL dating. Therefore, five of those samples were then selected to be tentatively dated using Electron Spin Resonance (ESR). The OSL and ESR age results obtained here enable to propose a preliminary

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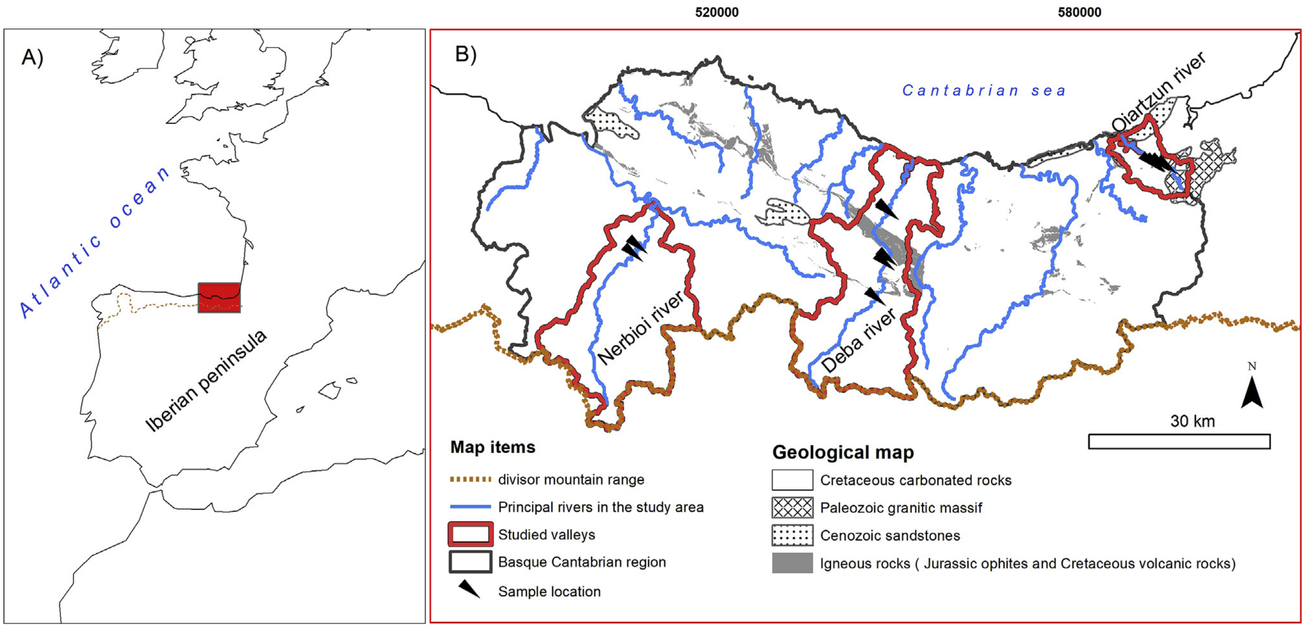

Fig. 1. Geographical location (A) and simplified geologic map (B) of the studied area including from west to east, Nerbioi, Deba and Oiartzun river valleys.

chronostratigraphic framework for the Quaternary fluvial deposits of the Deba, Oiartzun and Nerbioi valleys.

2. Geographical and geological setting

The eastern Cantabrian margin, Northern Spain, is located on the north side of a watershed south of which feeds the rest of the Iberian Peninsula, in the Atlantic climatic region (Fig. 1). The mountains forming the watershed are located at a maximum of 70 km from the coast line, with highest summits at an altitude of around 1500 m above sea level. Cretaceous carbonated rocks that emerged in response to the Alpine orogeny extend over more than the 70% area (Aranburu et al., 2015), but punctual presence of metamorphic rocks, sandstones and igneous rocks has been identified as well, suggesting different origins for the quartz grains dated by numerical methods. The uplift of the Cantabrian margin has remained very slow (maximum of 0.07–0.15 mm/a) for at least the last 1 million years (Alvarez-Marrón et al., 2008). The drainage system is formed by short and torrential rivers roughly flowing in a South-North direction. The combination of high level of precipitation with very steep slopes result in very active landslide processes.

The sampling for OSL/ESR dating purpose has been focused on three different valleys (Deba, Oiartzun and Nerbioi) of the studied area. The Deba River system comprises of 8 levels of fluvial terraces (Arriolabengoa, 2015), which are distributed as follows: TD1 (+120m above the current river channel), TD2 (+85m), TD3 (+64m), TD4 (+50m) TD5 (+35-29m) TD6 (+20m) TD7 (+10m) and TD8 (+4–8m). In comparison, 10 terrace levels have been identified in the Oiartzun valley: TO1 (+100m), TO2 (+75 m), TO3 (+60m), TO4 (+50m), TO5 (+35m), TO6 (+25m), TO7 (+20m), TO8 (+15m), TO9 (+10m) and TO10 (+5m) (del Val et al., 2015a). Finally, 9 terraces have been identified in the Nerbioi river system: TN1 (+120m), TN2 (+100m), TN3 (+60m), TN4 (+50m), TN5 (+30m), TN6 (+20m), TN7 (+15m), TN8 (+10m) and TN9 (+5m) (del Val et al., 2015b). The repetition of several terrace levels at similar altitudes in the different valleys could suggest a similar geological evolution, or at least a similar response to the external factors as climatic or tectonic control, which drove the evolution of these fluvial valleys. A simplified terrace staircase stratigraphy for the three different valleys is presented in Fig. 2.

3. Material and methods

Aware of the specific context of the eastern Cantabrian margin and of the basic requirements and limitations of the ESR and OSL dating methods, the sampling strategy has been adjusted accordingly. For example, the highest terraces rarely preserve sandy material suitable for dating, so only the lowest terraces (from +5 m above river channel to +25 m) were sampled. The presence of landslide processes frequently overlay the fluvial deposits. It is not always possible to see the erosional bedrock surface. Additionally, the alluvial cover is usually thin, around 2–3 m for the lower terraces and 1 m for higher terraces. The alluvium consists of a simple sequence: a channel facies bed, formed by decimetric or centimetric fluvial pebbles, sometimes overlain by a silty floodplain facies. If present, the latter usually appears reworked by colluvial processes or affected by soil development, and the presence of datable sandy deposits is very rare.

We identified several outcrops potentially suitable for sampling: a total of 14 sediment samples were collected for dating purpose (Fig. 1 and Supplementary Information, Figures S1, S2 and S3 and Table S1): six from different terrace levels of the Deba valley (CANT15127 to CANT15132), two in the Nerbioi valley (CANT15133 and CANT15134) and six in the Oiartzun river valley (CANT15135 to CANT15140). Their position within the simplified terrace staircase stratigraphy is shown in Fig. 2.

Sampling was performed following the standard procedure in OSL dating, by hammering a light-tight PVC tube into the section. Sample preparation was performed in accordance with the method proposed by Bateman and Catt (1996) and Bateman and Herrero (1999). OSL and ESR dose evaluations were carried out on the same purified quartz extracts using a multi-grain single-aliquot regenerative-dose protocol (SAR) (Murray and Wintle, 2000) (Table S2) and Multiple Centre approach (MC) based on a multi-grain multi-aliquot additive (MAA) dose procedure as proposed in Duval et al. (2015), respectively. Dose rate values were obtained from a combination of *in situ* and laboratory analyses. Full details about the methodology employed may be found in Supplementary Information.

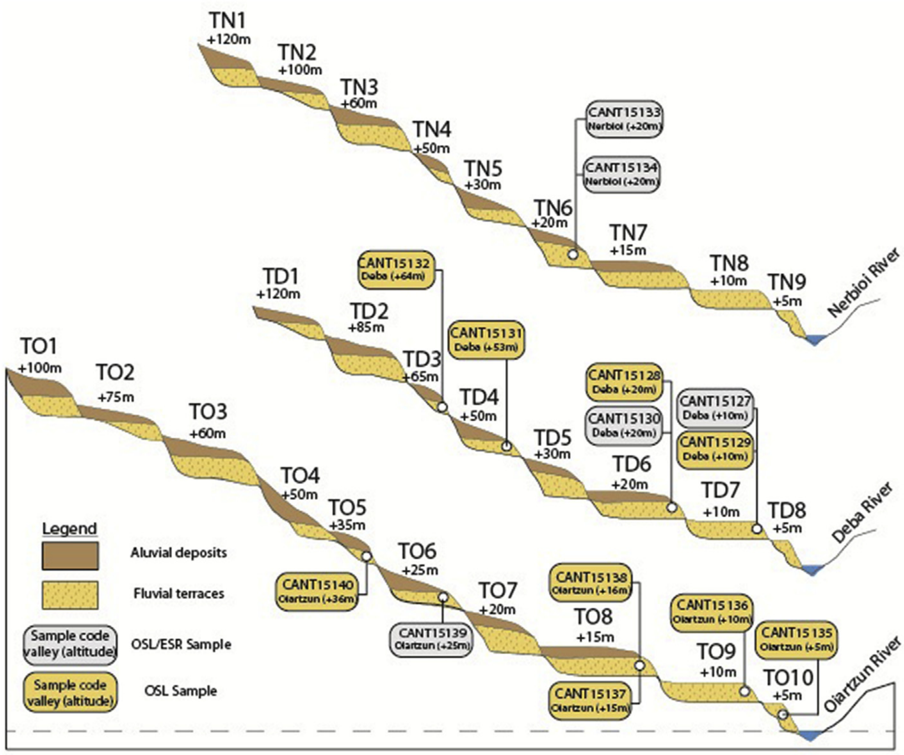

Fig. 2. Stratigraphic position of the OSL and ESR samples within the simplified terrace sequence of each valley. Relative altitudes of the terrace levels are evaluated from the surface of the terrace to the present-day water level. Because of a limited preservation of the outcrops, the contact of the deposits with the bedrock is not visible. However, the sedimentary sequences in these terrace deposits display a limited thickness (3 m approx.), minimizing thus the existing uncertainty on the relative altitudes.

4. Results and discussion

4.1. OSL data

A dose recovery preheat-plateau test with increasing temperatures between 160 and 260 °C (held for 10 s) was performed on samples CANT15130 (TD6 +20m), CANT15133 (TN6 +20m) and CANT15139 (TO6 +25m) (2 multi-grain aliquots per temperature step). A preheat temperature of 260 °C for 10 s prior to OSL measurement was considered the most appropriate. Feldspar contamination was tested using IR simulation and no detectable IRSL signal was observed. Initial measurements showed that 3 samples (CANT15132 (TD3 +64m), CANT15135 (TO10 +5m) and CANT15140 (TO5 +36m)) derived equivalent dose (De) values centred around 0 Gy. These results suggest that these samples were contaminated with recently bleached material, most likely related to the presence of plant roots or anthropogenic mixing processes. This is not surprising, as the three of them have been collected near the ground surface (sampling depths ≤ 1 m). Our field observations initially showed that the sedimentary context was probably not ideal for sampling (see Fig. S2 and S3 and Table S1), although an attempt was made given the lack of accessible outcrops in the area. Consequently, these three samples were discarded from the study as they were simply not suitable for providing useful information on the formation of the terraces. The number of aliquots passing the rejection criteria (specified in SI) for the other eleven samples varies between 25% and 83% (Table 1).

Measurements show that the OSL signal of the accepted aliquots is dominated by the fast component (Fig. S4). Dose distributions of the samples can be categorised into two groups (Figure S5). The first group is made of samples CANT15128 (TD6 +20m), CANT15131 (TD4 +50m), CANT15136 (TO9 +10m), CANT15137 (TO8 +15m) and CANT15138 (TO8 +16m). These samples showed highly scattered dose distributions, and over dispersion (OD) values up to 82%. Focusing on sample CANT15128 (TD6 +20m), the 38% of the saturated aliquots indicate a very old component, but at the same time, the lowest D_e values are close to 0, indicating a very young component. This is interpreted as the occurrence of post-depositional mixing processes. As a result, for these samples the Central Age Model (CAM) was considered inappropriate so a finite mixture model (FMM, as in Bateman et al., 2007) was applied in an attempt to provide a final D_e closer to true D_e values.

The second group includes samples CANT15127 (TD7 +10m), CANT15129 (TD7 +10m), CANT15130 (TD6 +20m), CANT15133 (TN6 +20m), CANT15134 (TN6 +20m) and CANT15139 (TO6 +25m). In this group > 25% of the measured aliquots were close to or above the saturation limit of the dose response curve. As a result, ages derived for these samples (irrespective of whether FMM or CAM was applied) should be considered as minimums of sediment deposition.

Interestingly, the OSL results are consistent with previous field observations. The two groups of samples strongly correlate with the initial description of the sedimentary context (see Table S1). The samples from Group 1 showing some post-depositional mixing processes were collected in somewhat unclear sedimentary environments. In contrast, those from the group 2 were obtained from outcrops in which sandy layers suitable for dating analyses could be easily identified in first instance.

4.2. ESR data

Five samples (CANT15127 (TD7 +10m), CANT15130 (TD6 +20m), CANT15133 (TN6 +20m), CANT15134 (TN6 +20m) and CANT15139 (TO6 +25m)) belonging to the second group of OSL samples were subsequently measured by ESR following the MC approach.

4.2.1. Al centre

Repeated measurements of the Al centre over different days show an acceptable D_e variability of between 2.5% and 13.1% (Table S10). Therefore, the final D_e values for each sample were calculated based on the average ESR intensity values. The relative bleaching component values vary within a narrow range (around 55–60%), suggesting similar bleaching conditions for all samples from this area. This is consistent

Table 1
Summary of the OSL data obtained for the 11 samples. Key: OD = over-dispersion of the resulting dose distribution; CAM = Central Age model; FMM = Finite mixture model.

Sample	Terrace level	number of aliq. measured	Saturated aliquots (%)	% of aliq. accepted	OD (%)	Method	D_e	error
CANT15127	TD7 +10m	48	25	38	49	CAM	91.71	10.96
CANT15128	TD6 +20m	42	38	40	80	FMM	95.48	5.89
CANT15129	TD7 +10m	36	50	67	25	CAM	88.98	5.09
CANT15130	TD6 +20m	36	53	58	38	CAM	88.97	8.35
CANT15131	TD4 +50m	26	0	81	28	FMM	14.75	0.66
CANT15133	TN6 +20m	46	61	30	15	CAM	131.32	8.03
CANT15134	TN6 +20m	48	88	46	30	CAM	69.30	5.02
CANT15136	TO9 +10m	28	0	64	23	FMM	75.63	4.70
CANT15137	TO8 +15m	38	0	34	36	FMM	23.85	0.77
CANT15138	TO8 +15m	18	0	83	82	FMM	7.31	0.35
CANT15139	TO6 +25m	24	100	25	15	CAM	121.32	10.25

Table 2
Summary of the ESR data collected for the 5 samples. Detailed fitting results for Al, Ti-Li and Ti-H centres are available in Supplementary information (Tables S10, S11 and S12, respectively). (*) unlike the other samples, CANT15134 was measured only twice.

Sample	Al centre		Ti-Li centre (option D)		Ti-H centre (option C)		D_e ratio	
	Adjusted r^2	D_e (Gy)	Adjusted r^2	D_e (Gy)	Adjusted r^2	D_e (Gy)	Ti-Li:Al	Ti-H:Ti-Li
CANT15127	0.993	771 ± 132	0.993	466 ± 64	0.992	367 ± 38	0.60	0.79
CANT15130	0.999	1130 ± 50	0.998	694 ± 42	0.994	515 ± 51	0.61	0.74
CANT15133	0.993	1144 ± 192	0.991	1090 ± 138	0.983	539 ± 74	0.95	0.49
CANT15134*	0.989	836 ± 177	0.984	745 ± 91	0.984	464 ± 70	0.89	0.62
CANT15139	0.997	2013 ± 271	0.997	1824 ± 164	0.986	1511 ± 222	0.91	0.83

with previous observations (see examples in Voinchet et al., 2007, Duval, 2008 and Tissoux et al., 2012). Goodness-of-fit is overall good for all samples, with adjusted r^2 values of > 0.99, the only exception being sample CANT15134 (TN6 +20m) with $r^2 = 0.989$.

4.2.2. Ti-Li centre

According to the recommendations by Duval et al. (2015) ESR intensities of the Ti-Li centre were measured following different options, namely A, D and E (Figure S6). All numerical results may be found in Supplementary information. D_e values calculated from option A, are systematically and significantly higher than those values calculated for option D (by a factor of up to almost 2), with the exception of sample CANT15139 (TO6 +25m) for which they are roughly within error. These differences are due to the peak at $g = 1.979$ (option E), which taken alone provides the highest D_e estimates of the data sets, although these values should be considered with extreme caution given the poor goodness-of-fit achieved. This pattern is similar to previous observations made on fluvial sediment samples from Cuesta de la Bajada site, Spain (Duval et al., 2017), where option D was found to be the most reliable option for the Ti-Li signal. The best fitting for the studied samples was also achieved with option D. For these reasons, option D was preferred for age calculation purposes. D_e repeatability shows acceptable values for most of the samples (< 15%), except for CAN15134 (TN6 +20m) (34%) that could be measured only twice (Table S11). This sample also shows the lowest adjusted r^2 value compared to the other samples, < 0.99, suggesting that the reliability of the ESR data collected for this sample should be considered with caution.

4.2.3. Ti-H centre

This centre offers a very interesting potential for dating late Middle Pleistocene deposits (see Duval et al., 2017), although the weak ESR intensity observed in most of the samples makes it extremely complicated to measure (e.g. Méndez-Quintas et al., 2018). The signal intensity of the Ti-H signal appears to be strong enough to derive reliable values despite being 43% and 52% lower than that of option A (except sample CANT15139 (TO6 +25m) in which it was 20%). Additionally, the goodness-of-fit is acceptable, with r^2 systematically > 0.98.

4.2.4. D_e comparison

Ti-Li option D provides equivalent dose estimates that are systematically lower compared to those obtained for the Al centre (−21% on average). This difference is significant for samples CANT15127 (TD7 +10m) and CANT15130 (TD6 +20m) with −40% and - 39% respectively. In contrast, for samples CANT15133 (TN6 +20m), CANT15134 (TN6 +20m) and CANT15139 (TO6 +25m) the De estimates from the two centres are within error (between −5% and −11%). Interestingly, this pattern displays a strong apparent correlation with the origin of the samples: samples CANT15127 and CANT15130 both come from the Deba valley, while the other samples were collected in the Nerbioi and Oiartzun valleys. This might suggest different transport and bleaching conditions for the three valleys.

Ti-H centre provides D_e estimates that are systematically lower than those from the Ti-Li centre (−30% on average), although one may notice that results are within error for sample CANT15139 (TO6 +25m) (Table 2). According to the principles of the MC approach, this may be interpreted in first instance as an evidence of incomplete reset of the Al and Ti-Li ESR signals during sediment transport (Toyoda et al., 2000). Consequently, we consider that the Ti-H results are the best estimates of the true burial dose of the samples, except for sample CANT15139 (TO6 +25m). The D_e values derived from the three centres for this sample exceed 1000 Gy and are about 2–3 times higher than those obtained for the other four samples. The Ti-H signal is known to saturate earlier than that of the Al and Ti-Li centres, and it is presently still unclear whether it can provide reliable dose estimates for D_e values > 1000 Gy (Duval and Guilarte, 2015). Although we cannot exclude here that the difference in the D_e values between Ti-Li and Ti-H centres might be due to an incomplete bleaching of the Ti-Li signal, we consider there is a series of evidence suggesting that it is rather most likely due to a saturation of the Ti-H signal. This hypothesis is supported by the extremely high dose rate value measured for this sample (see section 4.3.). In summary, we consider that the Ti-Li D_e estimate is more reliable for CANT15139. This value is in any case 1 sigma consistent with both Al and Ti-H D_e values.

Table 3
OSL and ESR age results. Key: CAM = Central Age model; FMM = Finite mixture model; (*) Samples showing > 20% of measured doses above saturation: the corresponding OSL age results should be interpreted as a minimum age estimate; (**) ESR-Al ages should be interpreted as maximum age estimates. An internal dose rate of 0.05 ± 0.03 Gy/ka was assumed for all samples. Dose rates were calculated using DRAC (Durcan et al., 2015). In bold, the OSL and ESR ages considered for the discussion.

Sample	Terrace level	External β dose rate (Gy/ka)	External γ dose rate (Gy/ka)	Cosmic dose rate (Gy/ka)	Environmental dose Rate (Gy/ka)	OSL		ESR		
						Model	Age (ka)	Al centre Age (ka)**	Ti-Li centre option D Age (ka)	Ti-H centre option C Age (ka)
CANT15127	TD7 +10m	1.4 ± 0.1	0.9 ± 0.1	0.3 ± 0.0	2.7 ± 0.1	CAM	**34.4 ± 4.4***	289.9 ± 51.7	175.2 ± 25.6	**138.0 ± 15.8**
CANT15128	TD6 +20m	1.5 ± 0.1	1.1 ± 0.1	0.3 ± 0.0	2.9 ± 0.1	FMM	**32.1 ± 2.4***			
CANT15129	TD7 +10m	1.9 ± 0.1	1.1 ± 0.1	0.3 ± 0.0	3.3 ± 0.2	CAM	**26.4 ± 2.0***			
CANT15130	TD6 +20m	1.5 ± 0.1	0.8 ± 0.1	0.3 ± 0.0	2.6 ± 0.1	CAM	**33.0 ± 3.5***	421.2 ± 26.9	258.7 ± 19.7	**192.0 ± 21.0**
CANT15131	TD4 +50m	1.7 ± 0.1	1.1 ± 0.1	0.3 ± 0.0	3.1 ± 0.2	FMM	**4.8 ± 0.3**			
CANT15133	TN6 +20m	0.9 ± 0.1	0.5 ± 0.0	0.3 ± 0.0	1.7 ± 0.1	CAM	**171.8 ± 6.0***	628.0 ± 111.2	598.3 ± 82.9	**296.3 ± 43.8**
CANT15134	TN6 +20m	1.2 ± 0.1	0.9 ± 0.1	0.3 ± 0.0	2.4 ± 0.1	CAM	**28.4 ± 2.5***	344.7 ± 75.2	307.2 ± 40.8	**191.3 ± 30.5**
CANT15136	TO9 +10m	2.1 ± 0.1	1.1 ± 0.1	0.3 ± 0.0	3.5 ± 0.2	FMM	**20.9 ± 1.6**			
CANT15137	TO8 +15m	1.8 ± 0.1	1.1 ± 0.1	0.3 ± 0.0	3.2 ± 0.2	FMM	**7.5 ± 0.4**			
CANT15138	TO8 +15m	1.7 ± 0.1	1.0 ± 0.1	0.3 ± 0.0	3.0 ± 0.1	FMM	**2.4 ± 0.2**			
CANT15139	TO6 +25m	2.5 ± 0.2	1.7 ± 0.1	0.3 ± 0.0	4.5 ± 0.2	CAM	**26.7 ± 2.6***	445.3 ± 63.2	**403.5 ± 40.5**	334.3 ± 51.6

4.3. Environmental dose rate evaluation

The gamma dose rates derived from *in situ* gamma measurements are on average lower by about 9% (Table S14) than those derived from the ICP-MS analyses (Table S13). Although one cannot exclude that part of this difference might be due to some slight disequilibrium in the U-238 decay chain (which cannot be assessed with ICP-MS analyses), this is most likely the result of the highly heterogeneous sedimentary environment in the vicinity of the samples (See Fig. S1, S2 and S3).

Interestingly, total environmental dose rate values (Table 3) differ slightly from one valley to another, with increasing values from West to East. Samples from Nerbioi valley, where the river flows mostly through Cretaceous carbonated and marly rocks, show the lowest values, between 1.8 and 2.4 Gy/ka. In comparison, the sediments from Deba valley, where Jurassic ophites and Cretaceous volcanic rocks locally outcrop, has values between 2.7 and 3.4 Gy/ka. In comparison, samples from Oiartzun valley, where the granitic massif outcrops in the upper basin, provide the highest total dose rates of up to 4.5 Gy/ka.

4.4. Age results

Final age estimates were calculated using D_e values derived from OSL and ESR measurements, while environmental dose rate are based on alpha and beta dose rates derived from ICP-MS analyses and gamma dose rates from *in situ* measurements.

As mentioned earlier, most samples exceeded the limits for OSL and only minimum ages could be calculated. Of the remainder, ages obtained for samples CANT15128 (TD6 +20m), CANT15131 (TD4 +50m), CANT15136 (TO9 +10m), CANT15137 (TO8 +15m) and CANT15138 (TO8 +16m) should be considered with caution, as OD suggest that sediment may had suffered post-depositional mixing affecting the correctness of the resulting De values. Samples CANT15127 (TD7 +10m), CANT15129 (TD7 +10m), CANT15130 (TD6 +20m), CANT15133 (TN6 +20m), CANT15134 (TN6 +20m) and CANT15139 (TO6 +25m) show a high proportion of saturated luminescence signals, and the resulting OSL ages should therefore be considered as minimum estimates.

The OSL chronology obtained for the different terrace levels may be summarized as follows: in Nerbioi River valley, terrace level TN6 +20m is > 72 ka (CANT15133); In the Deba River valley, the age of terrace level TD7 +10m is > 34 ka (CANT15127), while terrace level TD6 +20m is > 32–33 ka (CANT15128, CANT15130). Finally, terrace level TO6 +25m in the Oiartzun River valley yields a minimum age of 27 ka (CANT15139) (Table 3).

In comparison, the five samples (CANT15127 (TD7 +10m), CANT15130 (TD6 +20m), CANT15133 (TN6 +20m), CANT15134 (TN6 +20m) and CANT15139 (TO6 +25m)) also dated by ESR return much older age estimates. Similar to previous works based on the MC approach (Duval et al., 2015, 2017), the Al centre systematically provides the oldest ages, whilst Ti-H centre yields the youngest results for ESR signals (around 50% lower than Al centre, with exception of sample CANT15139 which is 25% lower). This suggests and incomplete bleaching of the Al signal, most likely as the result of its slow bleaching kinetics (Duval et al., 2017). With the exception of sample CANT15133 (TN6 +20m), the Al centre ESR age estimates are in apparent stratigraphic order and range from 289 ± 51 (T10m) to 445.3 ± 63 ka (T25m). These ages should be considered as maximum possible estimates for the sediment deposition. Due to the relatively fast bleaching rates of the Ti-H centre compared with the other centres, and the relatively robust ESR data obtained in the present work, we consider the Ti-H chronology as providing the best estimate for the sediment deposition, with the exception of sample CANT15139 (TO6 +25m). For this sample, the 3 centres provide age results within error, but the highly radioactive environment (the highest of the data set, see Table 3) and the magnitude of the resulting D_e values (> 1000 Gy) suggest that the Ti-H age result may be underestimated. Consequently, the age derived from the Ti-Li (404 ± 41 ka) is likely to be a better estimate for T25m.

Results obtained for T20m are scattered, with samples CANT15130 (TD6 +20m) and CANT15134 (TN6 +20m) providing very close results around 190 ka while CANT15133 (TN6 +20m) gives an age older by 100 ka. In first instance the age difference seems to be due to the environmental dose rate, which is > 25% lower for CANT15133 (TN6 +20m) in comparison with the other samples. However, laboratory and measured gamma dose rates yield similar values (0.7 and 0.6 Gy/ka respectively, Table S14), showing the homogeneity of the surrounding environment. Therefore, we do not have any explanations for this age scattering and have no reason to consider this age as being unreliable. A weighted mean age of 205.9 ± 16.1 ka (n = 3) may be thus derived for T20m.

4.5. Geomorphological implications

It is now widely accepted that the terrace staircases formation responds to climatic cycles and/or tectonic pulses (Antoine, 1994; Bridgland and Westaway, 2008, 2014; Vandenberghe, 2015). Glacial and interglacial cycles have an effect on glacier growth, sea level changes, precipitation rates and the development of the vegetation, which together, determine the fluvial dynamics and the development of aggradation and erosion phases. Nevertheless, the terrace development within a climatic cycle (glacial-interglacial) and their response to the external factors is still under debate (Bridgland and Westaway, 2008; Vandenberghe, 2015; Blum and Törnqvist, 2000; Blum, 2007; Viveen et al., 2014).

According to Álvarez-Marrón et al. (2008), tectonic uplift has remained stable for the last 1–2 Ma in the Cantabrian margin, where an uplift rate of 0.07–0.15 mm/a has been calculated. The absence of glacial development in the highest summits of this sector of the Cantabrian mountain range (Rodríguez-Rodríguez et al., 2015) discards glacial input in the supply of sediments in the fluvial system. As a result, terrace aggradation and incision cycles may have been controlled by sea level changes, driven by climatic changes, and sediment supply from landslide activity, which varies with precipitation and presence of vegetation, closely related to climatic changes as well. Some evidences on karst environments from the studied fluvial valleys (Aranburu et al., 2015; Arriolabengoa, 2015) point towards a climatic control of multi-level karst development. Nevertheless, the response of these river systems to the external factors has been barely studied in this area. The ages obtained in the present study shed some light on this topic. Calculated ages suggest aggradational phases during MIS 6, MIS 7 and MIS 11, respectively for terrace levels TD7 +10m, TD6 +20m, TN6 +20m and TO6 +25m, in correspondence to a 100 ka climatic cycle. An average incision rate of 0.06 ± 0.01 m·a^{-1} may be derived from the ESR age results obtained for TO25 to current river channel. This result is in good agreement with those estimated in other surrounding areas, such as the maximum incision rate of 0.07–0.09 m·a^{-1} proposed by Viveen et al. (2012) in the western Cantabrian range.

5. Conclusion

This work presents the first numerical dating results ever obtained on the Quaternary fluvial deposits of the Eastern Cantabrian valleys. They enable to establish a preliminary chronostratigraphic framework for the fluvial terrace staircases of three different valleys of the area. The results show that the lower terrace levels from 10 to 25 m above the current river channel have developed since the Middle Pleistocene, from ~400 ka to ~140 ka.

The OSL dating study showed the difficulty to apply the standard dating procedures to the quartz samples, most of the samples showing either a high proportion of saturated aliquots or a significant OD values. Given the characteristics of the samples from this area, other approaches such as single grain dating or the use of K-feldspars will be tested in the near future, as they have demonstrated to be especially useful in relatively high dose rate environments to reach older chronologies (e.g. Arnold et al., 2015). In any case, these OSL results enabled to identify the most suitable sedimentary contexts and outcrops for future dating study in this area.

The initial ESR dating results obtained from five samples have shown the great potential of the Ti-H signal to date those Middle Pleistocene terraces. This is not so frequent, as in most cases it is very difficult to derive any meaningful result for this signal given its weak signal (e.g. Mendez-Quintas et al., 2018). Overall, those very promising dating results demonstrate the interest of using a multi-technique dating approach.

This preliminary work enables to better define the applicability of the OSL and ESR dating methods in the Eastern Cantabrian valleys. The difficulty to find new and suitable outcrops is probably one of the main limiting factors for any future dating study, but the conclusions derived from this work will undoubtedly ensure future successful Luminescence and ESR dating applications in this area. Moreover, the ongoing palynological study of the fluvial deposits and their correlation with the karst levels identified nearby (Arriolabengoa, 2015) should enable to improve the preliminary chronostratigraphic framework established in the present study.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quageo.2018.07.001.

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