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 purposes, 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 hillslope erosion rates (denudation rates of 3.3–5.2 cm/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...
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.

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.
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 (\(D_e\)) 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 \(\leq 1\) 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 +20m), CANT15130 (TD6 +20m), CANT15135 (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
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 CANT15134 (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 $D_e$ 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 Guilarate, 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-H 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 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.

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

### 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.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Al centre</th>
<th>Ti-Li centre (option D)</th>
<th>Ti-H centre (option C)</th>
<th>$D_e$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Adjusted $r^2$</td>
<td>$D_e$ (Gy)</td>
<td>Adjusted $r^2$</td>
<td>$D_e$ (Gy)</td>
</tr>
<tr>
<td>CANT15127</td>
<td>0.993</td>
<td>771 ± 132</td>
<td>0.993</td>
<td>466 ± 64</td>
</tr>
<tr>
<td>CANT15130</td>
<td>0.999</td>
<td>1130 ± 50</td>
<td>0.998</td>
<td>694 ± 42</td>
</tr>
<tr>
<td>CANT15133</td>
<td>0.993</td>
<td>1144 ± 192</td>
<td>0.991</td>
<td>1090 ± 138</td>
</tr>
<tr>
<td>CANT15134</td>
<td>0.989</td>
<td>836 ± 177</td>
<td>0.984</td>
<td>745 ± 91</td>
</tr>
<tr>
<td>CANT15139</td>
<td>0.997</td>
<td>2013 ± 271</td>
<td>0.997</td>
<td>1824 ± 164</td>
</tr>
</tbody>
</table>
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 (Duran et al., 2015). In bold, the OSL and ESR ages considered for the discussion.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Terrace level</th>
<th>External β dose rate (Gy/ka)</th>
<th>External γ dose rate (Gy/ka)</th>
<th>Cosmic dose rate (Gy/ka)</th>
<th>Environmental dose rate (Gy/ka)</th>
<th>Model</th>
<th>Age (ka)</th>
<th>Al centre Age (ka)</th>
<th>Ti-Li centre option D Age (ka)</th>
<th>Ti-H centre option C Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANT15127</td>
<td>T27 +13m</td>
<td>1.4 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>2.7 ± 0.1</td>
<td>CAM</td>
<td>34.4 ± 4.4</td>
<td>289.9 ± 51.7</td>
<td>175.2 ± 25.6</td>
<td>138.0 ± 15.8</td>
</tr>
<tr>
<td>CANT15128</td>
<td>T26 +20m</td>
<td>1.5 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>2.9 ± 0.1</td>
<td>FMM</td>
<td>32.1 ± 2.4</td>
<td>264.9 ± 20.9</td>
<td>123.2 ± 15.1</td>
<td>92.0 ± 15.2</td>
</tr>
<tr>
<td>CANT15129</td>
<td>T27 +10m</td>
<td>1.0 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.3 ± 0.2</td>
<td>FMM</td>
<td>26.4 ± 2.0</td>
<td>328.3 ± 20.4</td>
<td>171.2 ± 15.1</td>
<td>121.0 ± 15.2</td>
</tr>
<tr>
<td>CANT15130</td>
<td>T26 +20m</td>
<td>1.5 ± 0.1</td>
<td>0.8 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>2.6 ± 0.1</td>
<td>FMM</td>
<td>33.0 ± 3.5</td>
<td>421.2 ± 26.9</td>
<td>258.7 ± 19.2</td>
<td>192.0 ± 21.0</td>
</tr>
<tr>
<td>CANT15131</td>
<td>T24 +50m</td>
<td>1.7 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.1 ± 0.2</td>
<td>CAM</td>
<td>4.8 ± 0.3</td>
<td>628.0 ± 111.2</td>
<td>589.3 ± 82.9</td>
<td>296.3 ± 43.8</td>
</tr>
<tr>
<td>CANT15133</td>
<td>T11 +20m</td>
<td>0.9 ± 0.1</td>
<td>0.5 ± 0.0</td>
<td>0.3 ± 0.0</td>
<td>1.7 ± 0.1</td>
<td>FMM</td>
<td>17.8 ± 6.0</td>
<td>344.7 ± 75.2</td>
<td>307.2 ± 40.8</td>
<td>191.3 ± 30.5</td>
</tr>
<tr>
<td>CANT15134</td>
<td>T25 +20m</td>
<td>1.2 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>2.4 ± 0.1</td>
<td>FMM</td>
<td>28.4 ± 2.5</td>
<td>445.3 ± 63.6</td>
<td>403.5 ± 40.5</td>
<td>334.3 ± 51.6</td>
</tr>
<tr>
<td>CANT15136</td>
<td>T29 +10m</td>
<td>2.1 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.5 ± 0.2</td>
<td>FMM</td>
<td>20.9 ± 1.6</td>
<td>344.0 ± 75.2</td>
<td>307.2 ± 40.8</td>
<td>191.3 ± 30.5</td>
</tr>
<tr>
<td>CANT15137</td>
<td>T28 +15m</td>
<td>1.8 ± 0.1</td>
<td>1.1 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.2 ± 0.2</td>
<td>FMM</td>
<td>7.5 ± 0.4</td>
<td>445.3 ± 63.6</td>
<td>403.5 ± 40.5</td>
<td>334.3 ± 51.6</td>
</tr>
<tr>
<td>CANT15138</td>
<td>T26 +50m</td>
<td>1.7 ± 0.1</td>
<td>1.0 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.0 ± 0.1</td>
<td>CAM</td>
<td>26.7 ± 2.6</td>
<td>445.3 ± 63.6</td>
<td>403.5 ± 40.5</td>
<td>334.3 ± 51.6</td>
</tr>
</tbody>
</table>

4.4. Age results

Final age estimates were calculated using D0 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 (T26 +20m), CANT15131 (T27 +10m), CANT15136 (T29 +10m), CANT15137 (T28 +15m) and CANT15138 (T26 +50m) should be considered with caution, as OD suggest that sediment may have suffered post-depositional mixing affecting the correctness of the resulting D0 values. Samples CANT15127 (T27 +10m), CANT15129 (T26 +20m), CANT15130 (T26 +20m), CANT15133 (T26 +20m), CANT15134 (T26 +20m) and CANT15139 (T26 +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 T26 +20m is > 72 ka (CANT15133); in the Deba River valley, the age of terrace level T27 +10m is > 34 ka (CANT15127), while terrace level T26 +20m is > 32-33 ka (CANT15128, CANT15130). Finally, terrace level T26 +25m in the Oiartzun River valley yields a minimum age of 27 ka (CANT15139) (Table 3).

In comparison, the five samples (CANT15127 (T27 +10m), CANT15130 (T26 +20m), CANT15133 (T26 +20m), CANT15134 (T26 +20m) and CANT15139 (T26 +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 (T26 +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 (T26 +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 D0 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 (T26 +20m) and CANT15134 (T26 +20m) providing very close results around 190 ka while CANT15133 (T26 +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 (T26 +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; Vandenberghé, 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-Rodriguez 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 8, respectively for terrace levels Td7 + 10m, Td6 + 20m, Td6 + 20m and Td6 + 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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