Moraine crest or slope: an analysis of the effects of boulder position on cosmogenic exposure age

**Matt D. Tomkins1,2, Jason M. Dortch3, Philip D. Hughes1,2, Jonny J. Huck1, Raimon Pallàs4, Ángel Rodés5, James L. Allard1,2, Andrew G. Stimson1, Didier Bourlès6, Vincent Rinterknecht7,8, Vincent Jomelli8, Laura Rodríguez-Rodríguez 9, Ramon Copons10, Iestyn D. Barr11,2, Chris M. Darvill1,2, Thomas Bishop1**

1Department of Geography, University of Manchester, Manchester, M13 9PL, UK

2Cryosphere Research at Manchester, Manchester, UK

3Kentucky Geological Survey, University of Kentucky, Lexington, USA

4Departament de Dinàmica de la Terra i de l’Oceà, Universitat de Barcelona, 08028 Barcelona, Spain

5Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride G75 0QF, UK

6Aix-Marseille Univ., CNRS, IRD, INRA, Coll France, UM 34 CEREGE, Technopôle de l’Environnement Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France

7Department of Earth and Environmental Sciences, University of St Andrews, Fife KY16 9AL, UK

8Université Paris 1 Panthéon-Sorbonne, CNRS Laboratoire de Géographie Physique, 92195 Meudon, France

9Dpto. Geología, Universidad de Oviedo, Arias de Velasco s/n, 33005 Oviedo, Spain

10Snow and Mountain Research Centre of Andorra (CENMA), Andorran Research Institute (IEA), Sant Julià de Lòria, Andorra

11School of Science and the Environment, Manchester Metropolitan University, Manchester, UK

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**Abstract**

Terrestrial cosmogenic nuclide dating of ice-marginal moraines can provide unique insights into Quaternary glacial history. However, pre- and post-depositional modification of moraine boulders can introduce geomorphic uncertainty to estimates of moraine ages. To avoid geomorphic outliers, boulders are typically selected based on their depositional context and individual characteristics but while these criteria have good qualitative reasoning, many have not been tested quantitatively. Of these, boulder location is critical, as boulders located on moraine crests are prioritised, while those on moraine slopes are rejected. This study provides the first quantitative assessment of the relative utility of moraine crest and moraine slope sampling using new and published 10Be and 36Cl ages (*n* = 19) and Schmidt hammer sampling (SH; *n* = 635 moraine boulders, ~19,050 SH R-values) in the Pyrenees mountains, France/Spain. These data show that for many of the studied moraines, the spatial distribution of “good” boulders is effectively random, with no consistent clustering on moraine crests, ice-proximal or -distal slopes. In turn, and in contrast to prior work, there is no clear penalty to either moraine crest or moraine slope sampling. Instead, we argue that landform stability exerts a greater influence on TCN age distributions than the characteristics of individual boulders. In this study, moraine degradation was widespread for matrix-rich unconsolidated moraines deposited at the Last Glacial Maximum, while boulder-rich, matrix-poor moraines stabilised rapidly after deposition. While this pattern is unlikely to hold true in all settings, these data indicate that differences between landforms are often far more significant than differences at the intra-landform scale. As ad hoc assessment of landform stability is extremely challenging based on geomorphic evidence alone, preliminary SH sampling, as utilised here, may be a useful method to assess the temporal distribution of boulder exposure ages and to prioritise individual boulders for analysis.

**1. Introduction**

Ice-marginal moraines are classic features of glaciated mountain ranges and are prominent terrestrial records of glacial history (Hallet and Putkonen, 1994). By constraining the timing of moraine deposition, it is possible to reconstruct the growth and decay of glaciers and ice sheets through the Quaternary and the palaeoclimatic drivers of glacial cycles (Broecker and Denton, 1990). Recent developments in terrestrial cosmogenic nuclide (TCN) dating have transformed our understanding of Quaternary glaciations by permitting direct analysis of the fragmentary glacial stratigraphic record (Gibbons et al., 1984; Zreda and Phillips, 1995). Despite this progress, TCN dating can be complicated by geomorphic processes which result in pre- or post-depositional exposure of rock surfaces and which account for apparent TCN ages that pre- or post-date the assumed age of the landform (Applegate et al., 2010). While prior exposure is possible, post-depositional erosion, exhumation and shielding have been shown to profoundly influence TCN age distributions (Briner et al., 2005; Zech et al., 2005; Heyman et al., 2011; Murari et al., 2014).

To avoid geomorphic outliers, researchers select samples based on the depositional context and characteristics of individual surfaces (Palacios et al., 2019). While these criteria have good qualitative reasoning, many have not been tested quantitatively. Previous studies have advocated sampling:

* boulders on moraine crests or on flat, stable surfaces (Gosse et al., 1995),
* the tallest boulders, to minimise the likelihood of post-depositional shielding (Heyman et al., 2016),
* the largest boulders (Akçar et al., 2011) or boulders embedded in the moraine matrix (Ivy-Ochs et al., 2007), to minimise the likelihood of post-depositional instability,
* well-rounded boulders which preserve evidence of glacial transport (Darvill et al., 2015a), to minimise the likelihood of pre-depositional exposure.

Of these, boulder location is critical, as boulders on moraine crests are prioritised, while those on moraine slopes are typically rejected, irrespective of their individual characteristics. However, there is a paucity of quantitative research correlating these factors with tightly clustered TCN datasets (e.g. ). In turn, further work is required to test existing criteria for sample selection and to develop quantitative methods which minimise the effects of geomorphic processes (Dortch et al., 2020). These developments have the potential to significantly improve the robustness of TCN datasets and the chronological utility of the moraine record (Applegate et al., 2008; 2012).

This paper focuses on a fundamental component of TCN sample selection; the effect of moraine crest sampling on boulder exposure age. Early numerical models of moraine evolution predicted the greatest ground-lowering at moraine crests (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003) with a period of maximum instability as glaciers retreat and as oversteepened ice-proximal slopes erode and stabilise (Porter and Swanson, 2008). However, moraines continue to degrade through time as a function of moraine height and sedimentology (Putkonen and Swanson, 2003; Putkonen et al., 2008; Schaller et al., 2009), as slope diffusion removes fine-grained material from moraine crests and deposits material at the base of moraine slopes (Applegate et al., 2010). Over time, these processes drive exhumation of boulders which have been shielded from cosmogenic exposure. In turn, the age distribution of moraine crest boulders may primarily reflect an initial stabilisation phase (~1 ka; Briner et al., 2005; Dortch et al., 2010), modified by the ongoing process of moraine degradation, rather than the timing of initial moraine deposition (Putkonen and O’Neil, 2006). In contrast, slope diffusion models and lichenometric methods predict relative stability on moraine slopes (Hallet and Putkonen, 1994; Putkonen and O’Neil, 2006), but these are rarely sampled for TCN, in part due to the perceived risk that boulders may rotate, shift or roll throughout the lifetime of the moraine. This dichotomy between model predictions and sampling procedures raises a fundamental and currently unanswered question: should moraine crests or moraine slopes be prioritised in TCN sample selection?

To address this uncertainty, this paper utilises new and published 10Be and 36Cl TCN ages (*n* = 19) and Schmidt hammer sampling (SH; *n* = 635 moraine boulders, ~19,050 SH *R*-values) of ice-marginal moraines in the Pyrenees mountains, France/Spain, to assess the relative utility of moraine crest and moraine slope sampling.

**2. Methods**

**2.1. Moraine selection**

Six moraines of varying age and geomorphology were selected in the Pyrenees (Fig. 1); a mountain range which was extensively glaciated during Quaternary glacial stages (*see* Fig. 1F; Calvet et al., 2011; Oliva et al., 2019) but is now on the verge of total deglaciation (Chueca et al., 2007). Moraines were selected to encompass the primary deglaciation phases of the Pyrenees since the global Last Glacial Maximum (gLGM) and all feature large populations of quartz-rich granitic moraine boulders which are suitable for 10Be dating. While this focused approach does not comprise all moraine types or depositional settings (Barr and Lovell, 2014), these sites do encompass a range of moraine types commonly found in cirque and valley landsystems and which are often priority targets for TCN dating (i.e. ≤ gLGM). In contrast, for moraines with complex post-depositional histories, alternative techniques are often more appropriate, although TCN dating has proved invaluable at sites where long-term moraine denudation is minimal (e.g. Owen et al., 2006; Morgan et al., 2011; Balter et al., 2020).

Selected moraines include both left and right latero-frontal moraines in the Arànser catchment, Cerdanya (Fig. 2A). These moraines are matrix-rich, steep-sided (~30 - 40°), heavily forested, and record the maximum ice extent (MIE) of the Arànser glacier during the Würmian glacial stage (11.7 - 110 ka; Calvet et al., 2011). The right latero-frontal moraine has previously been dated using 36Cl (*n* = 2; Palacios et al., 2015). Here, we present the results from a further 10 10Be dated boulders (Table 1). On the north side of the Pyrenees, two lateral moraines were selected in the Gave de Pau catchment (Fig. 2B). At least two proximal (~60 m) but distinct lateral moraine ridges have been identified (Soum d’Ech moraines; Fig. 1D), with the outer moraine previously dated using 10Be (*n* = 4; Rodés, 2008). As at Arànser, these moraines likely correspond to the Würmian MIE but their distinctive morphologies (multiple nested ridges *vs*. a single large moraine) likely reflects a topographic control on moraine deposition (open topography *vs*. confined valley; Palacios et al., 2015).

On the south side of the Pyrenees, and in the Val de Molières catchment of the Noguera Rigaborçana, sampled sites include the boulder-rich, matrix-poor Outer Pleta Naua terminal moraine (Fig. 3B, 1B), previously assigned to the Younger Dryas chronozone based on 10Be (*n* = 3; Pallàs et al., 2006), and the Tallada cirque moraine (Fig. 3A, 1A), which consists of a single sharp-crested, arcuate terminal moraine with two minor ice-proximal ridges. Although undated, the Tallada moraine is assumed to be late-Holocene in age based on its elevation (~2400 m), topographic setting (small enclosed cirque; ~0.16 km2), aspect (NNE) and the presence of a permanent snowfield (~0.03 km2; Pallàs et al., 2006).

**2.2. Sampling approach**

To investigate the depositional and post-depositional histories of these moraines, glacial boulders were selected to cover the entire moraine surface, including the moraine crest (C), the inner ice-proximal slope (IS) and the outer ice-distal slope (OS), while the number of selected boulders varied as a function of moraine size (*n* = 60 - 275). In turn, boulder selection was primarily motivated by spatial location and the construction of a dense matrix of sampling points, rather than individual boulder characteristics. Each boulder was sampled using the Schmidt hammer (SH) to assess the relative degree of weathering following the sampling approach of Tomkins et al. (2018a). All boulders were of sufficient size (Sumner and Nel, 2002) and sampled areas were free of surface discontinuities (Williams and Robinson, 1983) and lichen (Matthews and Owen, 2008). SH *R*-values were recorded perpendicular to the tested surface to reduce the risk of frictional sliding of the plunger tip (Viles et al., 2011), with single impacts separated by at least a plunger width (Aydin and Basu, 2005). 30 *R*-values were recorded for each boulder by a single operator (MT) and no outliers were removed following Niedzielski et al. (2009). Schmidt hammer functioning was assessed regularly using the Proceq test anvil (Aydin and Basu, 2005), with instrument and age calibration performed following the guidelines of Dortch et al. (2016) and Tomkins et al. (2018a). In total, 635 moraine boulders were sampled and ~19,050 SH *R*-values were generated.

Schmidt hammer *R*-values were analysed based on the assumption that the degree of weathering is inversely correlated with the exposure age of the rock surface (Goudie, 2006). However, this assumption is only valid in the absence of lithological variation between tested rock surfaces (McCarroll, 1989; 1991). Crucially, however, intra-landform variability in rock type is absent, as all sampled boulders share a common source area. Moreover, inter-landform variability in rock type is likely minimal, as all sampled boulders were coarse- to medium-grained granites and granodiorites sourced from the Hercynian Axial Zone (Crest et al., 2017). As granitic lithologies have proved particularly effective for calibrated-relative age dating (*see* Engel et al., 2007; 2011; Tomkins et al., 2016; 2018a, 2018b; Wilson et al., 2019; Zasadni et al., 2020), SH *R*-values are used here as a proxy for exposure age based on a 10Be-SH calibration dataset developed by Tomkins et al. (2018b). This dataset comprises 52 10Be ages obtained from granite and granodiorite glacial boulders and glacially-sculpted bedrock from across the central and eastern Pyrenees (Pallàs et al., 2006; 2010; Delmas et al., 2008; Crest et al., 2017) and their corresponding SH *R*-values (Fig. 5A; Tomkins et al., 2018b). This dataset has been updated to include two additional 10Be dated surfaces from the Val de Molières (MUL01 and MUL03; Pallàs et al., 2006; *see* Supplementary Table 1).

However, surface weathering is not only a function of exposure age and lithology, as the rate and style of weathering may be modified by climate (Small et al., 1997; Riebe et al., 2001; 2004; Kuhlemann et al., 2008; 2009; Portenga and Bierman, 2011; Marrero et al., 2018). Importantly, however, intra-landform variability in climate is absent as all boulders on an individual landform share a common climatic regime. While variability at the inter-landform scale is evident, for example between the Atlantic and Mediterranean-influenced climates of the northern and southern Pyrenees respectively, the strong correlation between exposure ages and *R*-values for the calibration dataset (Fig. 4A; R2 = 0.96, *p* < 0.01; Tomkins et al., 2018b), indicates that regional climate variability modulates rather than obscures the signal of varying exposure age.

**2.3. Calculating calibrated boulder exposure ages**

To utilise this existing correlation, 10Be ages analysed by Tomkins et al. (2018b), in addition to the two new samples described above, were normalised using the CRONUS Earth Web Calculator (Version 2.0; Marrero et al., 2016, available at: <http://cronus.cosmogenicnuclides.rocks/2.0/>), the latest production rates (Borchers et al., 2016), the time-dependent Lm scaling scheme (Lal, 1991; Stone, 2000) and assuming 0 mm ka-1 erosion. No corrections were made for snow shielding or glacio-isostatic adjustment. To ensure consistency, all 10Be and 36Cl TCN ages discussed in this paper have been recalibrated using these input parameters (full sample details used for exposure age calculation are provided in the Supplementary Information). In turn, a 10Be-SH calibration curve was constructed using logarithmic orthogonal distance regression (ODR, Boggs and Rogers, 1990a; 1990b) which minimises orthogonal residuals to account for measurement uncertainties in both the independent and dependent variables. We utilise Monte Carlo simulations to explicitly incorporate measurement errors; an approach which is preferable to a weighted ODR which requires unnecessary assumptions regarding weighting constants and is biased by TCN age-uncertainty collinearity (*as* age ↗, uncertainty ↗; Ivy-Ochs et al., 2007; Dortch et al., 2020). Our analytical procedure, which returns prediction estimates (1σ) of ± 2.0 - 2.3 ka, is described fully in the Supplementary Information and has been implemented on SHED-Earth (<http://shed.earth>), an online calculator developed to enable wider and more consistent application of our approach (Tomkins et al., 2018a).

Based on this calibration curve, mean *R*-values from the 635 sampled boulders were converted into “calibrated exposure ages” through interpolation. While uncertainty estimates for individual calibrated exposure ages are larger than typical uncertainties associated with individual TCN exposure ages, landform age estimates can be of comparable precision to established techniques when derived from large SH datasets (e.g. *n* boulders ≥ 30; Tomkins et al., 2018b; 2018c) and when appropriate statistical approaches for outlier identification and error propagation are employed (Applegate et al., 2012; Dortch et al., 2013; 2020).

**2.4. Calculating landform ages**

To determine the timing of moraine deposition at each site, we analysed the distribution of calibrated boulder exposure ages using the Probabilistic Cosmogenic Age Analysis Tool (P-CAAT Version 1.0; Dortch et al. 2020). This method utilises non-linear curve fitting and a Monte Carlo style approach to isolate component Gaussian distributions to account for positive (prior exposure) and negative skew (incomplete exposure) of age datasets (*see* Dortch et al. 2020 for full details). The results of this analysis are presented in Fig. 5 and Table 2. To assess the validity of these landform ages, we compared these data to previously published 10Be and 36Cl ages (*n* = 9; Pallàs et al., 2006; Rodés, 2008; Palacios et al., 2015) and present 10 new 10Be ages from the Arànser catchment (Table 1).

Based on landform age analysis, individual boulders were sorted into “good” and “bad” groups, which include interpolated boulder ages which are within or outside the 2σ (95%) age boundaries of the landform age respectively. Selection of a broad 2σ threshold is appropriate given the uncertainties associated with SH sampling (Aydin and Basu, 2005; Viles et al., 2011), in addition to the systematic (Jull et al., 2015; Borchers et al., 2016) and geologic uncertainties (Hallet and Putkonen, 1994) inherited from TCN dating. Logistic analysis is used to distinguish boulders which correspond to the timing of moraine deposition or initial stabilisation (“good”) from those which are likely compromised by pre- or post-depositional exposure (“bad”).

**2.5. Spatial analysis**

Finally, the spatial distribution of “good” and “bad” boulders was analysed using global and local Moran’s *I* spatial autocorrelation (Moran, 1950; Table 3). At the global level, Moran’s *I* was used to assess whether the overall clustering of the data was significantly different from a random distribution. For datasets that are non-random (*p* < 0.05), local Moran’s *I* was used to identify the location of statistically significant boulder clusters (Fig. 6). Current sampling approaches are based on the qualitatively-sound but quantitatively-untested assumptions that (i) the distribution of “good” boulders is non-random and that (ii) “good” clusters are more likely on moraine crests. These assumptions can be explicitly tested for the studied moraines using global and local Moran’s *I* respectively.

**2.6. Sensitivity Analysis**

The above analyses provide important information on the relative occurrence and spatial clustering of “good” and “bad” boulders for moraines of varying age and geomorphology. However, this logistic classification is ultimately dependent on the calculated landform age, which will vary depending on the choice of numeric bandwidth estimator and the size and clustering of the input dataset (Dortch et al., 2020).

To evaluate the reproducibility of our results, sensitivity testing was performed to evaluate the number of samples required to reproduce the estimated landform age based on 1σ and 2σ thresholds. The full analytical approach is described in the Supplementary Information and the results are presented in Fig. 7B.

**3. Results**

**3.1. Calibrated boulder exposure ages**

There is a very strong correlation between recalibrated 10Be ages and SH *R*-values, based on a large calibration dataset (Fig. 4; *n* = 54). Of the 19 36Cl and 10Be samples from the studied moraines, 15 were located and re-sampled with the SH. Of these, the vast majority closely match the existing calibration dataset (*n* = 13). These observations indicate that when lithological variation is minimised, and when a consistent sampling approach is adopted, the relative degree of rock surface weathering can be used as a proxy for surface exposure age.

The exceptions to this are samples ECH-03 (17.2 ± 3.5 ka) and ECH-04 (16.8 ± 3.3 ka) from the Soum d’Ech moraines (Rodés, 2008) which are significantly more weathered (~38 R) than their corresponding 10Be ages would predict (~47 R). This difference likely reflects sub-surface weathering prior to boulder exhumation. However, the scale of this influence is unlikely to be universal given the close correspondence between sample ECH-01 (19.7 ± 3.6 ka) and the existing calibration dataset (*see* Fig. 4). While sub-surface weathering of boulders under thin soil cover (~25 cm) can occur (Allen, 2002; Darmody et al., 2005; 2008), boulders are often protected from weathering by sediment burial, as evidenced by the emergence of unweathered boulders from glacial tills (Birkeland, 1999) and alluvium (Ehlmann et al. 2008). In turn, as calibrated exposure ages from the Soum d’Ech moraines may well incorporate the effects of both sub-aerial and sub-surface weathering, these data can be considered maximum-limiting ages for surface exposure.

**3.2. Landform ages**

Landform ages calculated using P-CAAT and relevant model parameters are reported in Table 2 (Dortch et al. 2020). Based on this approach, latero-frontal moraines in the Arànser catchment were deposited at 23.3 ± 1.1 ka (left) and 22.3 ± 0.9 ka (right). As these estimates are consistent within measurement uncertainties, and given the comparable stratigraphic positions of these deposits (Fig. 2A), we consider moraine deposition to be contemporaneous. No independent dating evidence is available for the left lateral moraine, but 12 TCN ages are now available for the right lateral moraine (36Cl, *n* = 2; 10Be, *n* = 10). Using P-CAAT, and selecting the oldest component Gaussian distribution that contains ≥ 3 ages to represent the age of the landform (*see* Fig. 3 in Dortch et al. 2013), these data return a landform age of 21.5 ± 2.2 ka (Mean bandwidth estimator; Numeric bandwidth = 0.8108, R2 = 0.9997, *p* < 0.01), while the oldest sample is 22.4 ± 1.8 ka (SAL-10). Both of these estimates are consistent within measurement uncertainties with the SH-derived landform ages and are based on standard procedures for interpreting moraine ages as minimum limiting ages (Putkonen and Swanson, 2003; Briner et al., 2005).

In the Gave de Pau catchment, calibrated exposure ages from the proximal Soum d’Ech lateral moraines return landform ages of 26.2 ± 2.5 ka (outer, *n* = 61) and 26.1 ± 1.7 ka (inner, *n* = 39). While these moraines are stratigraphically distinct, they cannot be statistically distinguished. In turn, it is possible that moraine deposition occurred within the resolution of our sampling approach, or that differences in moraine age have been masked by moraine stabilisation, degradation or sub-surface boulder weathering. As the temporal distribution of calibrated exposure ages is near identical (Table 2), we assign these deposits a landform age of 27.3 ± 1.8 ka based on P-CAAT (*n* = 100; STD / IQR bandwidth estimator; Numeric bandwidth = 0.9877, R2 = 0.9989, *p* < 0.01), and perform subsequent analyses on the combined dataset for computational ease.

While it must be noted that this estimate is significantly older than the corresponding 10Be ages (*n* = 3; Rodés, 2008), limiting 14C ages obtained from a proximal palaeolake sediment sequence at Lac de Lourdes appear consistent with an older age for moraine deposition. While the oldest radiometric 14C ages from this over-deepened glacial basin are now considered suspect due to contamination from mineral carbon *(*Reille and Andrieu, 1995; Pallàs et al., 2006), a younger AMS 14C age from glaciolacustrine clays suggests initial ice-free conditions by 24.1 ± 0.4 ka cal. BP, as calculated using IntCal 13 (Reimer et al., 2013) and OxCal 4.3 (Bronk Ramsey, 2009), while an AMS 14C age from overlying gyttja indicates the culmination of glaciolacustrine sedimentation and deglaciation of the lower Gave de Pau by 18.8 ± 0.3 ka cal. BP (Reille and Andrieu, 1995). Based on these data, the younger ages from Soum d’Ech can be considered suspect. While the oldest sample (ECH-01; 19.7 ± 3.6 ka) is closer to the assumed age of deglaciation, continued glacial occupation of the Soum d’Ech site until ~19.7 ka is unlikely given initial deglaciation of low ground by ~24.1 ka. Instead, it appears likely that this exposure age is representative of final moraine stabilisation, rather than initial deposition.

In the Val de Molières catchment of the Noguera Rigaborçana, recalibrated 10Be ages on the Outer Pleta Naua moraine range from 12.6 ± 1.5 ka to 13.2 ± 1.6 ka (*n* = 3; Pallàs et al., 2006). These estimates are consistent with the calibrated exposure ages, which range from 11.8 ± 2.0 ka to 13.1 ± 2.0 ka (*n* = 60). As these data conform to a normal distribution (Fig. 5B; Shapiro-Wilk test*, W* = 0.96, *p* = 0.07), are extremely well-clustered (IQR = 0.6 ka), and return an excellent P-CAAT model fit with a single component Gaussian (R2 = 1, *p* < 0.01), we use the arithmetic mean () to represent the age of the landform and estimate the total uncertainty (*t*) following Dortch et al. (2020) as follows:

where systematic uncertainty (*SU*) incorporates measurement errors:

and where geologic uncertainty (*GU)* incorporates the clustering of the dataset, which is typically interpreted as the effects of pre- and post-depositional processes that modify cosmogenic nuclide concentrations:

In turn, the Outer Pleta Naua moraine was likely deposited at 12.5 ± 0.4 ka. Applying the same analytical approach () to the corresponding 10Be ages produces 12.9 ± 1.0 ka, which overlaps within measurement uncertainties. Moreover, these estimates are stratigraphically consistent with independent landform ages in the Val de Molières catchment (Pallàs et al., 2006), with maximum and minimum limiting ages for moraine deposition provided by samples from the Molières (MUL01 = 14.9 ± 2.6 ka, MUL03 = 14.9 ± 1.9 ka) and Inner Pleta Naua moraines respectively (Fig. 3B; IPN01 = 6.3 ± 0.9 ka; Pallàs et al., 2006).

Finally, the Tallada cirque moraine returned a landform age of 3.4 ± 0.7 ka. While this estimate cannot be independently verified, the limited weathering of the moraine boulders (SH *R* ≥ 60), in combination with the topographic setting of the Tallada cirque, appears consistent with a late-Holocene origin. This estimate should probably be regarded as a maximum age for cirque deglaciation at this site as glacier re-growth or expansion during the Little Ice Age is possible (Hughes, 2018).

**3.3. Temporal results**

While estimated landform ages are generally consistent with independent TCN ages, the age distribution of calibrated exposure ages varies significantly between the sampled moraines (Fig. 5). The Arànser and Soum d’Ech moraines exhibit strong negative skew (Table 2), in line with exhumation models (Applegate et al., 2012), while Tallada is normally distributed with a slight positive skew (Shapiro-Wilk test, *W* = 0.98, *p* = 0.56); a trend which may reflect prior exposure or reworking of glacial material (Applegate et al., 2010).

In light of these trends, the proportion of “good” and “bad” boulders, as defined by the 2σ age boundaries of the corresponding landform age, varies between the sampled moraines. The proportion of “good” boulders is highest on the Outer Pleta Naua moraine (100%) and lowest on the Arànser left (56%) and Arànser right moraines (49%). For moraines corresponding to the ~gLGM, most “bad” boulders are younger than the assumed age of deglaciation (Table 2), while the Holocene Tallada moraine contains a small but significant component of boulders which are older than the assumed age of deglaciation (14%).

**3.4. Spatial results**

Summary statistics for spatial analysis are presented in Table 3. This approach reveals marked inter-landform variation, with statistically significant spatial clustering absent from the Tallada, Outer Pleta Naua and Arànser right moraines (simulated *p* > 0.05). In turn, the spatial distribution of “good” and “bad” boulders for these moraines is effectively random.

One exception to this rule is the Arànser left moraine where statistically significant clustering is evident (simulated *p* < 0.05) and where clusters identified using local Moran’s *I* have plausible geomorphological explanations (Fig. 6A). Clusters of “young” boulders occur:

1. at the moraine terminus,
2. where the moraine crest has been cross-cut and incised by a minor stream and,
3. where boulders have accumulated at the base of the moraine slope.

Clusters (i) and (ii) are likely fluvial in origin, with the former explained by incision of the terminal deposits, which may have led to degradation of the lateral flanks and exhumation of moraine boulders. This pattern of post-depositional degradation matches the spatial clustering of 36Cl ages on a comparable gLGM moraine deposited in the nearby Duran valley (*see* Fig. 11 in Palacios et al., 2015). The second cluster may be partially explained by meltwater erosion, given the proximity of the incised area to the former terminus of the Setut glacier (Fig. 2A). The origins of the final “young” cluster are less clear, but this ultimately reflects instability of the ice-proximal slope, although it is not yet clear whether this was driven by autogenic moraine stabilisation or external factors (e.g. subsequent glacial advance, fluvial erosion). Clusters of “good” boulders were also identified on the Arànser left moraine but these are distributed across moraine crests and ice-proximal and -distal slopes and follow no clear spatial pattern. Finally, local Moran’s *I* identified a single “young” cluster on the outer Soum d’Ech moraine (Fig. 6B) but there is no clear geomorphological evidence for its presence.

Linked to this, while the proportion of “good” boulders varies markedly between the studied moraines, this overall trend is relatively consistent across boulder groups (C, IS, OS) at the intra-landform scale (Fig. 7A). While there are clear differences between boulder groups at the Arànser left and right moraines, there are no consistent trends at the inter-landform scale and no single boulder group performs optimally across all landforms.

**3.5. Sensitivity results**

Based on the sensitivity analysis described in Section 2.6, there are clear differences in the number of samples required to reproduce the results obtained here (Fig 7B). The Outer Pleta Naua landform age requires only three samples at both 1σ and 2σ. Landform ages for both the Arànser left and right moraines can be reproduced with relatively few samples at both 1σ (*n* ≤ 26) and 2σ (*n* = ≤ 16), while both the Soum d’Ech and Tallada moraines require ≥ 40 samples to reproduce the landform age at 1σ.

These trends are largely explained by the degree of overlap between component Gaussian distributions (*see* Fig. 5). Both the Tallada (Fig. 5A) and Soum d’Ech moraines (Fig. 5E) feature lower probability component Gaussians, centred on 4.7 ± 0.9 ka and 24.4 ± 1.7 ka respectively, which overlap with the highest probability component Gaussian. In contrast, there is minimal overlap between component Gaussians for the Arànser left moraine (Fig. 5C), despite the high degree of dataset skew and the large number of “bad” boulders (44%). The Arànser right moraine is intermediate in character (Fig. 5D), with clear unidirectional skew but a greater degree of overlap between the highest probability Gaussian (22.3 ± 0.9 ka) and younger lower probability component Gaussians (17.6 ± 2.9 ka; 20.9 ± 0.9 ka). This distribution explains the larger number of samples required at both 1σ and 2σ relative to the Arànser left moraine. Ultimately, as the degree of overlap between component Gaussians increases, more samples are required isolate the highest probability component Gaussian and eliminate PDE skew. Despite this, all landform ages could be reproduced with relatively few samples at both 1σ (n ≤ 40) and 2σ (n ≤ 26).

**4. Discussion**

Accurate dating of ice-marginal moraines is critical to our understanding of Quaternary glacial history and the climatic drivers of glacial cycles. Within this context, efforts to minimise geomorphic bias of moraine TCN datasets may significantly improve the utility of the moraine record. However, while careful geomorphological assessment of individual boulders is necessary to isolate those influenced by pre- or post-depositional processes (Akçar et al., 2011; Palacios et al., 2019), many criteria for TCN sample selection have not been tested quantitatively. Of these, boulder location is critical, as moraine crest boulders are prioritised due to perceived stability (e.g. Gosse et al., 1995; Hallet and Putkonen, 1994), while those deposited on ice-proximal or -distal slopes are typically rejected. This study is the first to quantitatively assess the utility of this approach.

Based on 10Be (n = 10) and Schmidt hammer sampling (n = 635) of ice-marginal moraines in the Pyrenees, and spatial analysis of the distribution of calibrated exposure ages (Tomkins et al., 2018b), it is clear that spatial criteria cannot explain the distribution of calibrated exposure ages for the studied moraines. For many moraines, the distribution of “good” and “bad” boulders is effectively random (*p* > 0.05), as assessed using global Moran’s *I* (Table 3). Moreover, the likelihood of selecting a “good” boulder is comparable for moraine crests, ice-proximal and -distal slopes and there are no consistent trends at the inter-landform scale (Fig. 7A). Although statistically significant spatial clustering is evident for the Arànser left and Soum d’Ech moraines (*p* < 0.05), as assessed using local Moran’s *I* (Fig. 6), the distribution of “good” boulder clusters follows no clear spatial pattern, with clusters distributed across moraine crests and moraine slopes.

While there are no clear spatial patterns at the inter-landform scale, the temporal distribution of calibrated exposure ages varies markedly between the studied landforms, with a number of important observations. First, moraine sedimentology appears to place a key control on post-depositional stability (Zreda et al., 1994; Putkonen and O’Neal, 2006), as age distributions for matrix-rich moraines (e.g. Arànser, Soum d’Ech) are strongly negatively skewed (Fig. 6), with many boulders younger than the assigned age of the landform. The frequency of “young” boulders for these moraines (Table 2) likely reflects the influence of diffusive slope processes (Applegate et al., 2010), as the transfer of sediment to the base of moraine slopes drives exhumation of entrained boulders and leads to increasingly subdued moraine topography (Putkonen and O’Neal, 2006). The clearest signal of moraine degradation is evident at the Arànser left (IQR = 7.9 ka; Skew = -1.02) and Arànser right moraines (IQR = 6.9 ka; Skew = -1.13) and this trend may be partially explained by forest growth and boulder toppling (Ivy-Ochs et al., 2007), as well as the effects of fluvial incision (Fig. 6).

In contrast, the boulder-rich, matrix-poor Outer Pleta Naua moraine stabilised rapidly after glacial retreat, as evidenced by the distribution and clustering of both its calibrated exposure ages (IQR = 0.6 ka; Shapiro Wilk *W* = 0.96, *p* = 0.07) and the corresponding 10Be dataset (Pallàs et al., 2006). In the absence of a supporting sediment matrix, boulder-rich moraines stabilise quickly and appear less susceptible to subsequent erosion (Ivy-Ochs et al., 2007; Pallàs et al., 2010). Finally, for moraines deposited by niche cirque glaciers, reworking of glacial deposits appears more significant than post-depositional modification, in line with previous studies (Heyman et al., 2011). In these environments, the age of the oldest boulder may overestimate the “true” age of the moraine (Putkonen and Swanson, 2003; Briner et al., 2005).

**Future directions**

The results described above have clear implications for future sampling approaches. The first is that while “good” boulders are not more likely on moraine crests, there is no clear penalty to moraine crest sampling. While this result is unlikely to hold true for recently deposited (< 1 ka) unconsolidated landforms (Putkonen and O’Neal, 2006), as over-steepened ice-proximal slopes stabilise (Briner et al., 2005; Dortch et al., 2010), it appears that over longer timescales, initial differences between moraine crests and ice-proximal and -distal slopes are masked by continued moraine degradation. Thus, in the absence of detailed geomorphological assessment of individual landforms, restricting sampling to moraine crests is a viable strategy to minimise the likelihood of boulder instability.

However, while boulder density is typically highest at moraine crests (Putkonen et al., 2008), there is no guarantee that these boulders are suitable for dating, as assessed using current criteria for sample selection (e.g. boulder height, Heyman et al., 2016). In this scenario, fewer samples could be obtained, but this often precludes rigorous statistical identification of outliers and could lead to unclear results given the ubiquity of post-depositional modification of moraines (Zech et al., 2005; Heyman et al., 2011). Alternatively, samples could be obtained from non-ideal boulders (e.g. < 1 m height). One strategy which is rarely utilised is to sample boulders on ice-proximal and -distal slopes, but evidence from the studied moraines indicates that this is a viable strategy, as the proportion of “good” boulders is comparable to moraine crests (Fig. 7A). Moreover, for many moraines, the spatial distribution of “good” boulders is random, while statistically significant clusters of “good” boulders are distributed across moraine crests and moraine slopes (Fig. 6). These observations indicate that refining selection criteria to include the entire population of moraine boulders would have no clear negative effect, and could prove beneficial for moraines where ideal boulders are rare or are distributed away from moraine crests.

While the above refinements may help to improve dataset clustering on individual landforms, these data indicate that landform characteristics have a clear impact on the temporal distribution of calibrated exposure ages (Fig. 5; Putkonen and O’Neal, 2006; Ivy-Ochs et al., 2007; Pallàs et al., 2010). Within this context, we suggest that landform stability should be prioritised, as differences between landforms appear far greater than differences between boulder groups on an individual landform (C *vs*. IS *vs*. OS). Clear differences are evident as a function of moraine sedimentology (Zreda et al., 1994), with rapid stabilisation of matrix-poor, boulder-rich moraines (e.g. Outer Pleta Naua; Pallàs et al., 2006; 2010; Ivy-Ochs et al., 2007) but prolonged degradation of unconsolidated landforms (e.g. Arànser; Putkonen and O’Neal, 2006; Dortch et al., 2010). Although moraine sedimentology has explanatory power for the studied moraines, the observed trends are unlikely to hold true in all settings due to climatic and topographic controls on moraine stability (Barr and Lovell, 2014). Moreover, restricting sampling to matrix-poor landforms could have unintended adverse effects, as moraines may incorporate supraglacial rock avalanche debris and may primarily preserve a non-climatic signal (Ballantyne et al., 2013). Alternatively, sampling unconsolidated landforms does not guarantee poor clustering (e.g. ), as evidenced by the distribution of 10Be ages (n = X; ) on the matrix-rich Taggart Lake lateral moraine in the Teton Range (Reference). Finally, restricting sampling to landforms with specific characteristics is often not viable, as key glacial chronological markers may be represented by only a small number of landforms.

Despite these limitations, landform stability appears to explain a major component of the distribution of TCN ages (Heyman et al., 2011). In turn, selection of the landform is critical, and care should be taken to select methods which are appropriate for its assumed age and stability and to collect a sufficient number of samples to enable robust outlier identification (Putkonen and Swanson, 2003). However, it is often extremely difficult to assess landform stability based on geomorphic evidence alone. Our approach, in light of strong regional evidence for a link between SH *R*-values and exposure ages for granitic surfaces (Engel et al., 2007; 2011; Tomkins et al., 2018a; 2018b; Wilson et al., 2019; Zasadni et al., 2020), indicates that preliminary SH sampling could be a useful method to assess landform stability, to identify boulders affected by post-depositional processes, and to prioritise individual boulders for analysis (Tylmann et al., 2018).

Based on the sensitivity approach described in Section 2.6, the number of SH samples required scales with the complexity of the underlying distribution (Fig. 7B), from those which are approximately normal to those which feature overlapping component Gaussian distributions (Fig. 5) or multi-directional skew (i.e. pre- and post-depositional skew). However, given that it is not possible to ascertain the underlying distribution a priori, a relatively large sample size is ultimately required. For most landforms, sampling a minimum of 20 boulders would be a reasonable approach to estimate a depositional age within 2σ (e.g. Tomkins et al., 2018a) but more would be required to improve precision to 1σ for complex datasets or if Schmidt hammer *R*-values were being used as a basis for cosmogenic nuclide sample selection (Tylmann et al., 2018). Based on this preliminary sampling, statistical approaches could be used to isolate component Gaussian distributions (Dortch et al., 2020) and to identify individual boulders which are consistent with the age of the landform and to reject those which are “young” or “old” (Heyman et al., 2011). Finally, it is important to note that the approach described here is not a panacea, and its effectiveness may vary as a function of lithology and climate (McCarroll, 1989; 1991; Tomkins et al., 2016), while the underlying measurements are sensitive to factors which have only a minor effect on cosmogenic nuclide concentrations (e.g. surface discontinuities, Williams and Robinson, 1983; lichen coverage, Matthews and Owen, 2008). However, when these limitations are accounted for, Schmidt hammer *R*-values can be used as a proxy for surface exposure age (Fig. 4). Given the ubiquity of geologic scatter (e.g. exhumation, erosion, shielding), incorporating time- and cost-efficient preliminary SH sampling as an additional tool for TCN sample selection could ultimately improve the chronological utility of the moraine record and enable a deeper understanding of the climatic drivers of glacial cycles.

**Conclusions**

Based on 10Be and Schmidt hammer sampling of ice-marginal moraines in the Pyrenees, this study provided the first quantitative analysis of the relative utility of moraine crest and moraine slope sampling for terrestrial cosmogenic nuclide dating. Using spatial analysis of calibrated exposure ages, we show that there is no clear penalty to moraine crest sampling. However, contrary to current sampling approaches, which typically sample exclusively on moraine crests due to perceived stability, we show that the proportion of “good” boulders is comparable between moraine crests and ice-proximal and -distal slopes, while the spatial distribution of “good” boulders is random for many moraines. Crucially, however, differences between landforms appear more significant than differences at the intra-landform scale; a result which indicates that the stability of the landform has a far greater impact on the distribution of boulder exposure ages than the characteristics and depositional context of individual boulders. In this study, moraine sedimentology likely accounts for the observed differences between landforms, with rapid stabilisation of matrix-poor, boulder-rich moraines and prolonged degradation for unconsolidated landforms. Although these trends are unlikely to be universally applicable given climatic and topographic controls on moraine stability, preliminary SH sampling could be used more widely to assess landform stability and to prioritise individual boulders for analysis.

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**Word Count**: 6395

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| **Table 1.** Summary data for terrestrial cosmogenic exposure ages from the sampled morainesa | | | | | | | | | |
| Moraine | Name | Isotope | Latitude (°) | Longitude (°) | Elevation (m) | Age (ka) | Internal ± (ka) | External ± (ka) | SH R± SEMb |
| Outer Pleta Nauac | OPN01 | 10Be | 42.6365 | 0.7399 | 2217 | 13.2 | 1.3 | 1.6 | - |
| OPN02 | 10Be | 42.6365 | 0.7406 | 2197 | 13.0 | 1.7 | 2.0 | 51.68 ± 0.5 |
| OPN03 | 10Be | 42.6365 | 0.7409 | 2195 | 12.6 | 1.2 | 1.5 | - |
| Arànser (Right)d | SAL-01 | 10Be | 42.4283 | 1.6300 | 2000 | 17.6 | 0.6 | 1.5 | 47.57 ± 0.83 |
| SAL-02 | 10Be | 42.4273 | 1.6321 | 1983 | 19.2 | 0.6 | 1.5 | 45.07 ± 0.84 |
| SAL-03 | 10Be | 42.4270 | 1.6326 | 1975 | 21.1 | 0.6 | 1.7 | 44.07 ± 0.82 |
| SAL-04 | 10Be | 42.4254 | 1.6358 | 1933 | 18.0 | 0.6 | 1.5 | 47.57 ± 0.84 |
| SAL-05 | 10Be | 42.4240 | 1.6389 | 1912 | 17.0 | 0.9 | 1.6 | 48.9 ± 0.77 |
| SAL-06 | 10Be | 42.4237 | 1.6395 | 1908 | 19.2 | 0.6 | 1.5 | 44.53 ± 0.74 |
| SAL-07 | 10Be | 42.4229 | 1.6415 | 1896 | 16.7 | 0.5 | 1.4 | 47.43 ± 0.96 |
| SAL-08 | 10Be | 42.4223 | 1.6447 | 1863 | 17.1 | 0.6 | 1.4 | 47.7 ± 0.9 |
| SAL-09 | 10Be | 42.4215 | 1.6481 | 1820 | 20.7 | 0.9 | 1.7 | 44.77 ± 0.8 |
| SAL-10 | 10Be | 42.4213 | 1.6489 | 1808 | 22.4 | 0.7 | 1.8 | 43.03 ± 0.95 |
| PIR-11-13 | 36Cl | 42.4213 | 1.6495 | 1809 | 18.2 | 1.6 | 2.1 | - |
| PIR-11-14 | 36Cl | 42.4209 | 1.6499 | 1805 | 17.3 | 1.7 | 2.2 | 47.6 ± 0.83 |
| Soum d'Eche | ECH01 | 10Be | 43.0863 | -0.0870 | 776 | 19.7 | 3.2 | 3.6 | 42.43 ± 0.98 |
| ECH02 | 10Be | 43.0858 | -0.0880 | 778 | 59.0 | 43.2f | 43.0 | - |
| ECH03 | 10Be | 43.0862 | -0.0873 | 779 | 17.2 | 3.3 | 3.5 | 38.86 ± 1.11 |
| ECH04 | 10Be | 43.0865 | -0.0867 | 781 | 16.8 | 3.0 | 3.3 | 38.77 ± 1.05 |
| a Full sample information used for exposure age calculation is provided in the Supplementary Information or is available on GitHub: <https://github.com/matt-tomkins/moraine-paper-2020>, b Mean of 30 SH R-values ± the Standard Error of the Mean, c OPN samples from Pallàs et al. (2006), d PIR samples from Palacios et al. (2015), e ECH samples from Rodés (2008), f Measurement error, *see* Rodés (2008). | | | | | | | | | |

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| **Table 2.** Age statistics for the sampled moraines | | | | | | | | |  |  |  |
| Moraine | Group | Methoda | Bandwidthb | Model fitc | Age (ka)d | IQRe | Skew | Normalityf | Young (%)g | Good (%)g | Old (%)g |
| Tallada | - | STD / IQR | 0.3731 | 0.9985 | 3.24 ± 0.68 | 1.2 ka | 0.34 | 0.44 | 6 | 80 | 14 |
| Outer Pleta Naua | - | Mean | 2.016 | 1 | 12.52 ± 0.42h | 0.6 ka | -0.24 | 0.07 | 0 | 100 | 0 |
| Arànser | Left | MAD | 0.7003 | 0.9978 | 23.29 ± 1.12i | 7.9 ka | -1.02 | < 0.01 | 44 | 56 | 0 |
| Right | MAD | 0.6796 | 0.9991 | 22.30 ± 0.91 | 6.9 ka | -1.13 | < 0.01 | 51 | 49 | 0 |
| Soum d’Ech | Outer | STD / IQR | 1.0734 | 0.998 | 26.20 ± 2.48 | 3.5 ka | -1.49 | < 0.01 | - | - | - |
| Inner | STD / IQR | 1.1661 | 0.9996 | 26.11 ± 1.74 | 3.5 ka | -1.05 | < 0.01 | - | - | - |
| Combined | STD / IQR | 0.9877 | 0.9989 | 27.28 ± 1.78 | 3.6 ka | -1.49 | < 0.01 | 24 | 76 | 0 |
| a,b Method used for kernel density estimation after Silverman (1986) and Dortch *et al*. (2020) and its associated numeric bandwidth, c All model *p* values < 0.01, d Reporteduncertainty (±) is the 1σ bounds (68%) of the highest probability component Gaussian, unless stated otherwise, e Interquartile range, f Shapiro-Wilk test for normality *p* values, g Based on the landform age ± 2σ, h Arithmetic mean of 60 samples ± total uncertainty, i Calculation based on a reduced dataset of 274 samples. Sample ARL-192 (1.97 ± 2.06 ka) is more than three standard deviations from the mean of the remaining samples and was removed for program stability. | | | | | | | | | | | |

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| **Table 3.** Spatial statistics for the sampled moraines | | | | | | | | | | |
|  |  | Number of samples | | | | Global Morans *I* | | “Good” boulder (%) | | |
| Moraine | Type | Total | ISa | Ca | OSa | Distance threshold (m)b | Simulated *p* valuec | ISa | Ca | OSa |
| Tallada | Terminal | 70 | 16 | 29 | 25 | 21.6 |  | 80 | 79 | 81 |
| Outer Pleta Naua | Terminal | 60 | 20 | 20 | 20 | 23.9 |  | 100 | 100 | 100 |
| Arànser (Left) | Latero-frontal | 275 | 199 | 51 | 25 | 59.5 |  | 53 | 57 | 76 |
| Arànser (Right) | Latero-frontal | 130 | 57 | 33 | 40 | 66.3 |  | 63 | 36 | 40 |
| Soum d’Ech | Laterals | 100 | 37 | 50 | 13 | 51.1 |  | 76 | 72 | 81 |
| a Inner ice-proximal slope (IS), moraine crest (C) and outer ice-distal slope (OS), b Defined as the minimum distance required to ensure that each boulder has at least two neighbours, c *p* values > 0.05 support no statistically significant spatial clustering. *p* values ≤ 0.05 are consistent with a non-random distribution and spatial clustering of the input data. | | | | | | | | | | |

Figure 1. Site photographs of the (A) Tallada, (B) Outer Pleta Naua, (C) Arànser and (D) Soum d’Ech moraines (denoted by red arrows). (E-F) Topographic maps of the Pyrenees (ASTER GDEM V3, UTM projection), showing the locations of the studied catchments and selected moraines and the distribution of Axial Zone granites within those catchments (Nomenclature following Porquet et al., 2017; Cauterets-Panticosa, Néouvielle, Maladeta, Mont-Louis-Andorra). The latter was derived from a 1:400,000 geological map produced by the IGME (*Spain*) and the BRGM (*France*). Also shown are the locations of major summits (Aneto, Carlit, Estats, Plana de Lles, Monte Perdido, Posets, Vignemale) and the maximum ice extent (MIE) during the global Last Glacial Maximum (gLGM; Calvet et al., 2011).

Figure 2. Geomorphological maps for the (A) Arànser and (B) Soum d’Ech moraines. These moraines likely correspond to the maximum ice extent (MIE) during the Würmian glacial stage (11.7 - 110 ka; Calvet et al., 2011). Locations and sample names for TCN dated boulders are shown (white circles; Rodés, 2008; Palacios et al., 2015). In (A), the locations of the proximal Fornell (F) and Setut (S) moraines are highlighted. These moraines are stratigraphically distinct from the sampled Arànser moraines but are currently undated. The margins of Arànser glacier can be traced further up valley but sampling was focused on the illustrated moraine area (light purple shading) in which the moraine margins are easily delineated (≤ 2 km from glacier terminus).

**Figure 3**. Geomorphological maps for the (A) Tallada and (B) Outer Pleta Naua moraines in the Val de Molières catchment of the Noguera Rigaborçana. Locations and sample names for TCN dated boulders are shown (white circles; Pallàs et al., 2006). The Inner Pleta Naua moraine was also investigated by Pallàs et al., (2006) and returned recalibrated 10Be ages of 6.3 ± 0.9 ka (IPN01) and 16.0 ± 2.5 ka (IPN02). Given the stratigraphic position of this deposit, and limiting ages from the Outer Pleta Naua and Molières moraines (MUL01 = 14.9 ± 2.6 ka, MUL03 = 14.9 ± 1.9 ka; Pallàs et al., 2006), it appears likely that IPN02 is affected by inheritance.

**Figure 4**. (A) Location of exposure age calibration sites (blue points) in the Bassies (B, *n* = 6), Carlit (C, *n* = 3), Noguera Rigaborçana (N, *n* = 4), Maladeta (Ma, *n* = 9), Malniu (Mn, *n* = 21), Molières (Mo, *n* = 2), Orri (O, *n* = 3) and Querol catchments (Q, *n* = 6). Underlying topography is ASTER GDEM V3 (UTM projection). Also shown are the locations of sampled moraines (orange points; *see* Fig. 1F) and the maximum ice extent (MIE) during the global Last Glacial Maximum (gLGM; Calvet et al., 2011). (B) Monte Carlo-derived orthogonal distance regression (ODR) between 54 10Be exposure ages (blue points ± external age uncertainty; Pallàs et al., 2006; 2010; Delmas et al., 2008; Crest et al., 2017) and their corresponding SH *R*-values (mean of 30 *R*-values ± Standard Error of the Mean; Tomkins et al., 2018b). 1σ (blue dashed lines) and 2σ prediction limits (grey dashed lines) were calculated using the ODR covariance matrix (Boggs and Rogers, 1990b). New TCN samples (10Be, 36Cl) from the studied moraines (*n* = 15) are shown as orange points. Inherited outliers from the original calibration dataset (*n* = 2; Tomkins et al., 2018b) are not shown for clarity. (C) Example of a 10Be dated boulder from the Arànser right moraine (SAL-10). Sample information for all exposure ages (*n* = 73) is provided in the Supplementary Information and on GitHub: <https://github.com/matt-tomkins/moraine-paper-2020>

**Figure 5.** Gaussian decomposition of calibrated boulder exposure ages for the Tallada (A), Outer Pleta Naua (B), Arànser (C-D) and Soum d’Ech moraines (E). Following P-CAAT guidelines (Dortch et al., 2013; 2020), we selected the highest probability component Gaussian (red shading) to represent the age of the landform as all are ≤ gLGM. The summed probability density estimate (PDE) and lower probability component Gaussians are denoted by black and grey distributions respectively. For each moraine, we include the bandwidth estimator used (e.g. STD / IQR; Silverman, 1986) and its associated numeric bandwidth, the P-CAAT model fit (R2), the total number of samples (n) and in brackets, the number of samples which are enclosed by the selected component Gaussian distribution at 2σ. Based on this approach, selected component Gaussians are interpreted to reflect the timing of moraine deposition or initial stabilisation. In contrast, younger component Gaussians may reflect post-depositional processes (e.g. moraine degradation, boulder exhumation or instability) while older component Gaussians likely incorporate pre-depositional processes (e.g. reworking of glacial deposits).

**Figure 6.** Results of local Moran’s *I* spatial autocorrelation for the Arànser left (A) and Soum d’Ech moraines (B). Points denote the location of sampled boulders, with neighbouring boulders linked by grey lines. Neighbours are calculated based on a fixed distance, defined as the minimum distance required to ensure that each boulder has at least two neighbours. Points are coloured based on the results of local Moran’s *I*, with regions of no statistically significant spatial clustering shown as white, while clusters of “good” (HH) and “bad” boulders (LL) and their contributing neighbours are shown in blue and red respectively. Outlier points (HL and LH; see van Eijk et al., 2019) are not shown for clarity. A histogram illustrating the distribution of calibrated boulder exposure ages is included for each moraine, coloured by the “good” (blue) and “bad” components (grey).

**Figure 7.** The likelihood of sampling a “good” boulder (%; within 2σ of the landform age) for each of the studied moraines (A), subset by boulder position (inner ice-proximal slope, moraine crest, outer ice-distal slope). Sensitivity results are shown for each moraine (B), illustrating the number of samples required to reproduce the associated landform age within 1σ and 2σ thresholds.

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