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

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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 assesses 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* = 645 moraine boulders, ~19,050 SH R-values) in the Pyrenees mountains, France/Spain. These data show that for the studied moraines, the spatial distribution of “good” boulders is effectively random, with no consistent clustering on moraine crests, ice-proximal or ice-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 should be prioritised in sample selection. In this study, boulder exhumation and instability was widespread for matrix-rich and steep-sided 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 (Buckland, 1840; Penck, 1905) 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 (Hays et al., 1976; Broecker and Denton, 1990). Recent developments in terrestrial cosmogenic nuclide (TCN) dating (Nishiizumi et al., 1989; Phillips et al., 1990) 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 (Hallet and Putkonen, 1994; Applegate et al., 2010). While prior exposure is possible (i.e. nuclide inheritance), post-depositional erosion, exhumation and shielding have been shown to profoundly influence TCN age distributions (Shanahan and Zreda, 2000; Briner et al., 2005; Zech et al., 2005; Hein et al., 2011; Heyman et al., 2011; Dortch et al., 2013; Murari et al., 2014; Allard et al., 2020).

To avoid geomorphic outliers, researchers typically select samples based on the depositional context and characteristics of individual surfaces (Akçar et al., 2011; Rinterknecht et al., 2014; 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 (Akçar et al., 2011) 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; Hughes et al., 2016), to minimise the likelihood of pre-depositional exposure,
* hard, “fresh” looking boulders or boulders which elicit a ping instead of a thud when struck with a hammer (*see* Dortch et al., 2010).

Of these, boulder location is critical, as boulders on moraine crests are prioritised, while those on moraine slopes are rejected, irrespective of their individual characteristics. It should be noted that this list is not exhaustive and additional criteria may be applied in other settings (e.g. wildfire spalling; Kendrick et al., 2016).

However, there is a paucity of quantitative research correlating boulder characteristics with tightly clustered TCN datasets (e.g. ), and with unclear results generated though ad hoc analysis (Dortch et al., 2010). Although a statistically significant correlation was found between increasing boulder height and dataset clustering (Heyman et al., 2016), the overall effect was minor, as a dominant fraction (>50%) of tall boulder groups were sufficiently scattered to fail a reduced chi square test (). More fundamentally, the influence of landform characteristics is often overlooked in ad hoc analysis (e.g. moraine sedimentology; Zreda et al., 1994; Putkonen and O’Neal, 2006; Ivy-Ochs et al., 2007). Within this context, further work is required to test existing criteria for TCN sample selection and to develop quantitative methods which minimise the effects of geomorphic processes (Dortch et al., 2020; Ward 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., 2012; Dortch et al., 2013).

In turn, 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). Despite this limitation, moraine crests are preferentially sampled for TCN dating (Hallet and Putkonen, 1994). 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* = 645 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 for a range of moraine types and moraine ages.

**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; Delmas et al., 2015; Oliva et al., 2019) but is now on the verge of total deglaciation (Marti et al., 2015). 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 sourced from the Hercynian Axial Zone which are suitable for 10Be dating (*see* Fig. 1E; 2A; Crest et al., 2017). 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 long post-depositional histories, alternative techniques are often more appropriate (e.g. Hughes et al., 2007; Lewis et al., 2009; Darvill et al., 2015b), although TCN dating has proved invaluable at sites where long-term moraine denudation is minimal (e.g. Owen et al., 2006; Pallàs et al., 2010; Morgan et al., 2011; Dortch et al., 2013; Dietsch et al., 2015; Balter et al., 2020).

Selected moraines include both left and right latero-frontal moraines in the Arànser catchment, Cerdanya (Fig. 3A, 2B). These moraines are large, matrix-rich, steep-sided (~30 - 40°), heavily forested (~100% cover), 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 2). On the north side of the Pyrenees, two lateral moraines were selected in the Gave de Pau catchment, Hautes-Pyrénées (Fig. 3B, 2A; Jalut et al., 1992; Calvet et al., 2011). At least two proximal (~60 m) but distinct lateral moraine ridges have been identified (Soum d’Ech moraines), 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. 4B, 2C), previously assigned to the Younger Dryas chronozone based on 10Be (*n* = 3; Pallàs et al., 2006), and the Tallada cirque moraine (Fig. 4A, 2C), 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). 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. The number of selected boulders varied as a function of moraine size (*n* = 60 - 275; Table 1) with typical patch sizes (mean area per sampled boulder) of ~14 m2 to ~46 m2. 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, 645 moraine boulders were sampled and ~19,050 SH R-values were generated. To compliment these data, boulder characteristics were measured and are provided in the Supplementary Information (S1-S2).

These data were analysed based on the assumption that the degree of weathering, as represented by SH R, 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; Winkler, 2005; Tomkins et al., 2016). Crucially, however, intra-landform variability in rock type is absent, as all sampled boulders share a common source area (*see* Fig. 2). 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 is 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 TCN 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). To further develop this dataset, two additional 10Be dated surfaces from the Val de Molières (Fig. 2C; MUL01 and MUL03; Pallàs et al., 2006) were sampled using the Schmidt hammer (*see* Supplementary Information; Table S1).

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 (*see* Small et al., 1997; Riebe et al., 2001; 2004; Kuhlemann et al., 2008; 2009; Portenga and Bierman, 2011; Marrero et al., 2018). Crucially, however, intra-landform variability in climate is absent as all boulders on an individual landform share a common precipitation and temperature regime. While climate 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 (R2 = 0.96, *p* < 0.01; Tomkins et al., 2018b), which comprises samples obtained from a range of elevations, catchments and topographic settings (*see* Fig. 5A), 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 and are available on GitHub: <https://github.com/matt-tomkins/moraine-paper-2020>). In turn, a TCN-SH calibration curve was constructed using logarithmic orthogonal distance regression (ODR, Boggs and Rogers, 1990a); an approach which improves on ordinary least squares regression by minimising orthogonal residuals to account for measurement uncertainties in both the independent and dependent variables. This unweightedapproach returns prediction estimates (1σ) of ± 1.6 - 1.8 ka (calculated using the ODR covariance matrix; Boggs and Rogers, 1990b), with a distribution that corresponds to the empirical rule (~70% of calibration data within 1σ interval, ~96% within 2σ, 100% within 3σ).

However, to produce wider (i.e. more tolerant) prediction intervals which explicitly incorporate measurement errors (*see* Viles et al., 2011; Jull et al., 2015), we utilise Monte Carlo simulated datasets (*n* iterations = 104) in which input variables are randomised based on their associated uncertainties (TCN ± external age uncertainty; SH ± Standard Error of the Mean). This approach 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 wider prediction estimates (1σ) of ± 2.0 - 2.3 ka, is described fully in the Supplementary Information (S4) 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 boulder 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). In addition, and to avoid circularity, it is important to note that all of the 54 10Be calibration surfaces utilised here are independent of the studied moraines.

**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. 6 and Table 3. 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 2; Supplementary Information S4).

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 here 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) based on Queens contiguity of Voronoi cells (polygons that share either an edge or a vertex; *see* Fig. X). At the global level, Moran’s *I* is used to assess whether the overall clustering of the data is significantly different from a random distribution. For datasets that are non-random (*p* < 0.05), local Moran’s *I* is used to identify the location of statistically significant boulder clusters. Current sampling approaches are based on the qualitatively-sound but often 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 a range of moraine types and ages. 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, the following approach was taken:

1. For each landform, random samples were drawn without replication across a range of sample sizes. The minimum sample size was set at *n* = 5 to reflect typical TCN sampling approaches, where collecting 5 - 6 samples is common (e.g. Pallàs et al., 2010). For each sample size, 1000 datasets were generated.
2. For each dataset, we utilised an automated version of P-CAAT to calculate a simulated landform age, allowing the numeric bandwidth estimator to switch between datasets to match the size and clustering of the input data (Dortch et al., 2020).
3. For each landform and at each sample size, we recorded the number of simulated landform ages which fell within the 1σ and 2σ uncertainty bounds of the landform age calculated using the full dataset, as defined in Section 2.4 and presented in Table 3. This process was refined until 95% of simulated landform ages fell within the 1σ and 2σ thresholds, the results of which are presented in Table X and Figure X.

These data provide important information on the sensitivity of the underlying statistical approach and the sample size required to reproduce the results obtained here.

**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 (*see* Fig. 5; *n* = 54; Tomkins et al., 2018b). Of the 19 36Cl and 10Be samples from the studied moraines, 15 were located and re-sampled with the SH (*see* Supplementary Tables 1-2). Of these, the vast majority closely match the existing calibration dataset (*n* = 13, *see* Fig. 5). 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 TCN ages would predict (~47 R). This difference could be explained by sub-surface weathering in the near-surface soil zone prior to boulder exhumation, potentially as a function of the morphological properties of the rock surfaces (Chartres and Walker, 1988) or variation in soil moisture content (Dixon et al., 2006). 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. 5). 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 boulder 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 3 (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. 3A), 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, Palacios et al., 2015; 10Be, *n* = 10). The distribution of these data is skewed (0.67) and non-normal (Shapiro-Wilk test, *W* = 0.90, *p* = 0.14). 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 (*n* = 12; 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 boulder exposure ages from the proximal Soum d’Ech lateral moraine ridges 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 boulder ages is near identical (Table 3; Fig. 6), 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 with subsequent analyses performed 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 (*see* Supplementary Figure S1). While the oldest radiometric 14C ages from this over-deepened glacial basin are now considered suspect due to contamination from mineral carbon *(see* Reille and Lowe, 1993; 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 supports 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 (ECH-03, -04). 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. Finally, it should be noted that 27.3 ± 1.8 ka is considered a maximum-limiting age, given the potential influence of sub-surface weathering, with a corresponding minimum-limiting age for moraine deposition of 24.1 ± 0.4 ka cal. BP (Reille and Andrieu, 1995).

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 corresponding calibrated boulder 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 (*see* Fig. 6B; 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 returns 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 (*see* Fig. 2C; MUL01 = 14.9 ± 2.6 ka, MUL03 = 14.9 ± 1.9 ka) and Inner Pleta Naua moraines (*see* Fig. 4B; IPN01 = 6.3 ± 0.9 ka, IPN02 (possible inheritance) = 16.0 ± 2.5 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 (SHR ≥ 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). Minor moraines occur inbound of the large arcuate terminal (*see* Fig. 4A), with evidence of incision of these deposits on their ice-proximal slopes, potentially by glacial erosion or rock/snow avalanche activity. However, the absence of unweathered glacially-modified boulders (e.g. SH R ≥ 70) suggests that any subsequent glaciers were minimally erosive.

**3.3. Temporal results**

While estimated landform ages are generally consistent with independent TCN ages and match wider Pyrenean glacier chronologies (Calvet et al., 2011; Delmas, 2015; Oliva et al., 2018), the age distribution of calibrated boulder ages varies significantly between the sampled moraines (*see* Fig. 6). The Arànser and Soum d’Ech moraines exhibit strong negative skew (Table 3), 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, 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 4. This approach reveals marked inter-landform variation, with statistically significant spatial clustering absent from the Tallada, Outer Pleta Naua, Arànser right and Soum d’Ech moraines (simulated *p* > 0.05). In turn, the spatial distribution of “good” and “bad” boulders for these moraines is effectively random.

The 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 (*see* Fig. X). A cluster of “bad” comparatively unweathered boulders occurs near the front of the moraine, which may reflect fluvial incision of the terminus, degradation of the lateral flanks and exhumation of moraine boulders. This pattern 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., 2015b). An additional “bad” cluster occurs where a minor stream has cross-cut and incised the moraine crest (Fig. 6). Given the proximity of this incised area to the terminus of the Setut glacier (*see* Fig. 3A), a meltwater origin seems likely. However, there is no clear overall spatial pattern, as both “good” and “bad” clusters occur on the moraine crest, and ice-proximal and -distal slopes.

Linked to this, while the proportion of “good” boulders varies markedly between the studied moraines (49 - 100%), this overall trend is relatively consistent across boulder groups (C, IS, OS) at the intra-landform scale (*see* Table 4, Fig. 9). For the Tallada and Soum d’Ech moraines, the maximum difference is limited to just 2% and 9% respectively. Considerably larger differences are evident on the Arànser left (23%) and right moraines (27%). Crucially, however, there are no consistent trends at the inter-landform scale and no boulder group performs consistently better 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. The Outer Pleta Naua landform age is the easiest to reproduce, requiring 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. 6). Both Tallada (Fig. 6A) and the Soum d’Ech moraines (Fig. 6E) feature lower probability component Gaussians, centred on 4.7 ± 0.9 ka and 24.4 ± 1.7 ka respectively, which exhibit considerable overlap with the highest probability component Gaussian. In contrast, there is minimal overlap between component Gaussians for the Arànser left moraine (Fig. 6C), despite the high degree of dataset skew and the large number of “bad” boulders (44%). The Arànser right moraine is intermediate in character (Fig. 6D), 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). The number of samples required scales with the complexity of the underlying distribution, from those which are approximately normal (Outer Pleta Naua) to those which feature overlapping component Gaussian distributions (e.g. Tallada) or multi-directional skew (i.e. pre- and post-depositional skew).

**4. Discussion**

Geotechnical controls on a steep lateral moraine undergoing paraglacial slope adjustment

While this pattern may not hold true in all settings, for example due to climatic and topographic controls on moraine stability, these data indicate that differences between landforms is often far more significant than differences at the intra-landform scale.

These data, in light of the temporal trends discussed above, highlight the importance of landform characteristics in the overall temporal distrution (Zreda et al., 1994; Putkonen and O’Neal, 2006; Ivy-Ochs et al., 2007; Pallàs et al., 2010).

Accurate dating of ice-marginal moraines is critical to our understanding of Quaternary glacial history and the climatic drivers of glacial cycles (Hallet and Putkonen, 1994). Within this context, efforts to minimise geomorphic bias of moraine TCN datasets may significantly improve the utility of the moraine record. While slope diffusion models predict prolonged boulder exhumation at moraine crests and relative stability on moraine slopes (Hallet and Putkonen, 1994; Putkonen and Swanson, 2003; Applegate et al., 2010), crests are preferentially sampled, while moraine slopes are generally avoided due to increased risks of boulder instability.

In this study, we have critically assessed these two competing ideas for moraines of varying age and geomorphology in the Pyrenees. It is important to note that while these moraines are unlikely to be representative of all moraine types or depositional settings, under the ‘falsifiability’ hypothesis of Hume (1739) and Popper (1959), this does not negate the wider validity of our results.

For example, take the following hypotheses:

1. *“Good boulders, which are consistent with the depositional age of the landform, are more likely on moraine crests”*
2. *“All swans are white”*

While these hypotheses are qualitatively sound, numerous datasets would be required to provide quantitative support for each.

In contrast, a comparatively small number of datasets, in which “good” boulders are more likely on moraine slopes or in which the distribution of “good” boulders is effectively random, would be required to falsify H1. These datasets are analogous to the “black swan” of Popper (1959). It is important to note, however, that this does not imply that the trends observed here are applicable for all moraines; there is almost certainly a population of moraines where crests *will* return the best results, much in the same way that the presence of a single black swan does not refute the dominance of white swans. However, what these data can do, as the black swan did for Popper (1959), is question the “universality” of the above hypothesis and whether it should form the basis for *all* moraine TCN sampling.

Within this theoretical framework, the data generated here indicate that spatial criteria (i.e. boulder position) cannot explain the distribution of calibrated boulder exposure ages for the studied moraines. There are no consistent trends between or within individual moraines while the likelihood of selecting a “good” boulder is comparable for moraine crests, ice-proximal and -distal slopes (Fig. 9). While statistically significant spatial clustering is evident for the Arànser and Soum d’Ech moraines, the locations of “good” boulder clusters conforms to neither a crest or slope stability model.

Despite this, however, there are a number of clear observations from these data. The first is that while “good” boulders are not more likely on moraine crests, there is no clear penalty to moraine crest sampling. If there is a sufficient population of moraine crest boulders, and in the absence of detailed geomorphological assessment (e.g. Palacios et al., 2019), then restricting sampling to the crest is a viable strategy. However, the opposite is also true, as the proportion of “good” boulders is comparable to both ice-proximal and -distal slopes. This trend implies a connection between the frequency of crest boulder exhumation and the frequency of slope boulder instability. Intuitively this seems likely because slope instabilities, for example due to fluvial incision or slope diffusion, likely propagate to moraine crests although this is as yet untested. Regardless, one potential weakness of restricting sampling to moraine crests is that this limits the population of potential boulders. Although boulder density is typically higher at moraine crests (Putkonen et al., 2008), this still remains a small proportion of the total population. Given the ubiquity of post-depositional modification of moraines (Heyman et al., 2011), limiting sampling to a small sub-population undoubtedly limits the likelihood of sampling a good boulder.

In turn, the most important observation is that differences between landforms appear far greater than differences between boulder groups on an individual landform.

Landform characteristics more important

**Future directions**

and, should not be used as a primary guide for moraine TCN sampling.

We found no consistent trends between or within individual moraines while the likelihood of selecting an exhumed boulder is comparable for moraine crests, ice-proximal and -distal slopes (Table 3). In general, however, exhumed boulders are far more likely for steep-sided, matrix-rich moraines, as these are particularly susceptible to slope diffusion, while fluvial incision can explain both lateral degradation near termini and cross-cutting by streams. Importantly, 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 are strongly negatively skewed, implying prolonged and continuous boulder exhumation after deposition. The most significant exhumation signal is evident at Aranser (*IQR* = 7.8 ka) and this may be partially explained by forest growth and boulder toppling (Ivy-Ochs et al., 2007); a process which may account for a similar pattern of exhumation for maxima moraines in the neighbouring Têt catchment (MIE Unit; Samples A1-A3 and B1-B3; Delmas et al., 2008). In contrast, the boulder-rich, matrix-poor Outer Pleta Naua moraine stabilised rapidly after glacial retreat, in line with similar well-dated moraines in the SE Pyrenees (Pallas et al., 2010) and the Alps (Ivy-Ochs et al., 2007). In the absence of a supporting sediment matrix, boulder-rich moraines stabilise quickly and appear less susceptible to subsequent erosion. Finally, for young cirque moraines, reworking of older glacial deposits appears more significant than exhumation (Table 3; Tallada), 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).

* No penalty to sampling on moraine crests. If there are sufficient good boulders, no problem (however a major challenge identifying these!)
* However, there appears no penalty to sampling moraine slopes - there may be ones that have rolled, shifted etc… but no evidence that this occurs at a faster rate than exhumation of the crest
* There is a potential advantage to widening sampling - currently we’re limiting sampling to a small population. Although density may be higher at the crest (), this is often a small % of the total overall number.
* Clearest message is that “landform stability” is more significant that boulder location - the pattern of “good” vs. “bad” is consistent at the landform scale. In turn, selection of the landform is more critical than the selection of the boulder.
* In this study, the OPN moraine is the best - matrix poor, boulder rich - likely stabilised rapidly. Clustering of 10Be ages and common weathering characteristics of the boulders.
* The worst is both Aranser moraines (skewed, exhumation, boulder toppling from trees, matrix rich).
* However, and given the scope of this project - these recommendations cannot be applied universaslly - focus on matrix poor might lead to rock avalanche sampling (climatic signal?) or even rock glaciers which have there own issues (Crump, Akcar). Alternatively, sampling matrix rich landform does not guarantee a mixed results bag, for example see results from Licciardi on matrix rich, partially forest, laterals in the Sierras. More work is clearly necessary to identify which landform characteristics can be used more equivocally (e.g. Drumlins vs. moraines), or whether a mixed bag is the reality.
* The second is that boulder characteristics alone appear to not have a great deal of predictive power for these moraines. A wide range of metrics, shown to have very poor correlation with the weathering of the boulders (R), and by association their age.
* Finally, SH testing may be the way forward (Tylmann), needs exploring further but importantly it’s not a panacea - it will not gaurentee success - doesn’t work on all rock types (Tomkins, 2016), is sensitive to surface characteristics which are unaffected by TCN, and may be sensitive to other processes which don’t affect the exposure age (e.g. sub-surface weathering). However, evidence suggests that when these limitations are accounted for (e.g. large sampling, consistent approach), there is correlation with TCN.
* Then, pre-sampling with the SH may be effective. For moraines with higher likelihoods of exhumation, pre-sampling may be effective. Sample a statistically robust number of boulders (30-50, ~1 day in the field), and analayse the skew to select a population for dating. We hope that this will imporove clustering.
* Not a panacea!

and

Based on our compilation of boulder dimensions, surface and depositional characteristics (*see* Data Repository), it is clear that these factors have little explanatory power for the studied moraines. While these data do not negate the importance of careful geomorphological assessment of moraine structure (Palacios et al., 2019), the decoupling of boulder characteristics and interpolated exposure ages raises questions about the prioritisation of boulder characteristics in CRE sample selection (Akçar et al., 2011). For moraines that stabilise rapidly (i.e. Outer Pleta Naua), even seemingly non-ideal boulders can return “good” ages (e.g. OPN17, ~0.5 m height, angular, ice-proximal slope, major fractures). Conversely, on moraines with long exhumation histories (i.e. Arànser), even ideal boulders can be exhumed (e.g. AR28, ~8.9 ka younger than landform age, ~1.1 m height, partially embedded on the crest, 7.6° slope). Within this context, we suggest that landform stability should be prioritised for CRE sample selection, with tightly clustered CRE datasets far more likely for rapidly stabilising matrix-poor, boulder-rich moraines (Ivy-Ochs et al., 2007; Pallàs et al., 2010). However, non-ideal landforms are often priority targets for CRE dating, as these often record the retreat stages of the largest glacier systems (e.g. Gave de Pau) or represent “missing” glacial stages in existing chronologies. In turn, quantitative methods to guide CRE sample selection for non-ideal landforms have clear utility for Quaternary glacial research.

**Future directions**

Our approach, in light of strong regional evidence for a link between SH *R* and exposure ages for granitic surfaces (Engel et al., 2007; 2011; Tomkins et al., 2018a; 2018b), indicates that preliminary SH sampling may be an effective technique for identifying exhumed boulders. Prior to CRE sampling, we recommend collection of statistically viable population of *R* values from a large sample of moraine boulders to refine CRE sampling strategies. Sample size should reflect the relative stability of the studied landform, with large populations required for moraines susceptible to prolonged post-depositional erosion. To assess how this requirement varies between the studied moraines, we randomly sampled each dataset 1000 times (without replacement), selecting *n* samples per model run and used an automated version of the Gaussian decomposition model of Dortch et al. (2013) to determine the associated landform age. We increased *n* for each model run until ≥ 95% of the 1000 simulations returned component Gaussians with a peak age which fell within the 2σ landform age boundaries (95% CI). Based on this approach, the number of required samples scales with the complexity of the underlying age distribution, with a small number required for tightly clustered and normally-distributed moraines (Outer Pleta Naua, *n* = 7) while more are required for moraines compromised by exhumation (Aranser, *n* = 9; Lourdes, *n* = 14). The greatest number of samples are required at Tallada (*n* = 19) which reflects the influence of both pre- and post-depositional exposure. Importantly, as the full age distribution of the studied moraine is unknown before sampling, we recommend sampling ≥ 20 boulders per moraine to account for exhumation or pre-exposure of boulders on non-ideal landforms. However, this value should be regarded as a minimum, as compilation of a larger dataset will widen the population of boulders for CRE selection. In the absence of confounding factors, we argue that SH *R* is an accurate proxy for surface exposure age and should be used routinely to identify exhumed boulders (boulder *R* > modal *R*), to assess the age distribution of the studied moraine (i.e. dataset skewness) and to pre-select boulders for CRE dating (modal *R*).

So what?

care should be taken to select methods which are appropriate for the assumed age and stability of the landform and to collect a sufficient number of samples to enable robust outlier detection. To compliment this approach,

The locations of these clusters was recorded with cluster occurrence presented as a proportion (%) of the total number of model runs (*n* = 104).

In turn, these analyses shed light, in a statistically robust manner, on the relative utility of moraine crest or moraine slope sampling for the studied moraines.

**Conclusions**

Intensive SH sampling of ice-marginal moraines in the Pyrenees, in combination with 10Be analysis, provides unique insight into the effects of boulder position on exposure age. We show that large, matrix-rich and steep-sided moraines are particularly susceptible to post-depositional erosion. However, restricting sampling to moraine crests is not effective at isolating exhumed boulders as their distribution is effectively random, and only isolated clusters have clear geomorphological explanations. As such, we recommend abandoning the crest-only strategy to widen the population of boulders to select from. However, we also show that boulder characteristics have limited explanatory power for the studied moraines. In light of this complexity, our data indicate that landform stability should be prioritised over boulder and spatial characteristics. Moraine sedimentology exerts a key control on post-depositional stability, with boulder-rich, matrix-poor moraines stabilising rapidly after deglaciation. In turn, CRE sample size should reflect the relative stability and age of the studied landform, with a large number of samples required in many settings to account for exhumation. Finally, our approach highlights the value of preliminary SH sampling to isolate exhumed boulders and to prioritise boulders for CRE dating, especially for non-ideal landforms. Wider application of this method may improve the chronological robustness of CRE datasets and the value of the moraine record in our understanding of Quaternary landscape evolution.

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| **Table 1.** Summary statistics for the sampled moraines | | | | | | | |
| Moraine | Type | # samples | # ISa | # Ca | # OSa | Area (km2)b | Patch sizec |
| Tallada | Terminal | 70 | 16 | 29 | 25 | 0.015 | ~15 m2 |
| Outer Pleta Naua | Terminal | 60 | 20 | 20 | 20 | 0.011 | ~14 m2 |
| Arànser (Left) | Latero-frontal | 275 | 199 | 51 | 25 | 0.421 | ~39 m2 |
| Arànser (Right) | Latero-frontal | 130 | 57 | 33 | 40 | 0.281 | ~46 m2 |
| Soum d’Ech | Laterals | 100 | 37 | 50 | 13 | 0.111 | ~33 m2 |
| a Inner ice-proximal slope (IS), moraine crest (C) and outer ice-distal slope (OS), b Sampling area, c mean area per sampled boulder | | | | | | | |

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| **Table 2.** 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 3.** Age statistics for the sampled moraines | | | | | | | | |
| Moraine | Group | Methoda | Bandwidthb | Model fitc | Age (ka)d | IQRe | Skew | Normalityf |
| Tallada | - | STD / IQR | 0.3731 | 0.9985 | 3.24 ± 0.68 | 1.2 ka | 0.34 | 0.44 |
| Outer Pleta Naua | - | Mean | 2.0160 | 1.0000 | 12.52 ± 0.42g | 0.6 ka | -0.24 | 0.07 |
| Arànser | Left | MAD | 0.7003 | 0.9978 | 23.29 ± 1.12h | 7.9 ka | -1.02 | < 0.01 |
| Right | MAD | 0.6796 | 0.9991 | 22.30 ± 0.91 | 6.9 ka | -1.13 | < 0.01 |
| Soum d’Ech | Outer | STD / IQR | 1.0734 | 0.9980 | 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 |
| 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 Arithmetic mean of 60 samples ± total uncertainty, h 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 4.** Spatial statistics for the sampled moraines | | | | | | | |
|  | Global Morans *I* | Class statistics (%) | | | “Good” boulder (%) | | |
| Moraine | Simulated *p* value | "Young" | "Good" | "Old" | IS | C | OS |
| Tallada | 0.3081 | 6 | 80 | 14 | 80 | 79 | 81 |
| Outer Pleta Naua | *NA* | 0 | 100 | 0 | 100 | 100 | 100 |
| Arànser (Left) | 0.003 | 44 | 56 | 0 | 53 | 57 | 76 |
| Arànser (Right) | 0.084 | 51 | 49 | 0 | 63 | 36 | 40 |
| Soum d’Ech | 0.054 | 24 | 76 | 0 | 76 | 72 | 81 |

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| **Table 5.** Sensitivity analysis | | | | |
|  | Landform age boundary (ka) | | # samples requireda | |
| Moraine | ± 1σ | ± 2σ | 1σ | 2σ |
| Tallada | 0.68 | 1.36 | 40 | 23 |
| Outer Pleta Naua | 0.42 | 0.84 | 3 | 3 |
| Arànser (Left) | 1.12 | 2.24 | 12 | 10 |
| Arànser (Right) | 0.91 | 1.82 | 26 | 16 |
| Soum d’Ech | 1.78 | 3.56 | 41 | 11 |
| a Number of samples required to return ≥ 95% of simulated landform ages within ± 1σ and ± 2σ | | | | |

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**. Moraine locations and likely boulder flow pathways (yellow arrows) for the (A) Soum d’Ech, (B) Arànser and (C) Val de Molières moraines (Outer Pleta Naua, Tallada). Relevant glacier limits and ice flow pathways are shown following Pallàs et al. (2006) and Calvet et al. (2011). The distribution of Axial Zone granites is shown in (A), but is excluded from plots (B) and (C) for clarity. Boulders on the Soum d’Ech moraines were likely sourced from the Cauterets-Panticosa granites surrounding Vignemale (3298 m), a major accumulation area for the Gave de Pau glacier, but a contribution from the Néouvielle granites to the east cannot be excluded (*see* Fig. 1E; Porquet et al., 2017). In (C), the location and recalibrated ages of samples MUL01 and MUL04 are shown (Pallàs et al., 2006). These samples correspond to a stabilisation or readvance of the Molières glacier following the gLGM, and comprise two of the 54 TCN-SH calibration surfaces (Tomkins et al., 2018b).

Figure 3. 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 Arànser left moraine can be tracked further up valley (*see* Fig. 2B) 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 4**. 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).

**Figure 5**. (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). 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 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 6.** 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 to represent the age of the landform as all are ≤ gLGM (red shaded Gaussian). The summed probability density estimate (PDE) and lower probability component Gaussians are denoted by black and grey distributions respectively.

**~~Figure 7.~~** ~~Results of Monte Carlo simulated (~~*~~n~~* ~~= 10~~~~4~~~~) local Moran’s~~ *~~I~~* ~~spatial autocorrelation for the Tallada (A-B) and Outer Pleta Naua moraines (C-D). Results are based on Queen’s contiguity of Voronoi cells with the binary “Good/Bad” grouping as the predictor variable. Results are plotted as a proportion (%) of the total number of model runs. The age distribution of “good” (green shading) and “bad” boulders (grey shading) is shown for each moraine in plots B and D.~~

**Figure 8.** Results of Monte Carlo simulated (*n* = 104) local Moran’s *I* spatial autocorrelation for the Arànser (A-B) and Soum d’Ech moraines (C-D). Results are based on Queen’s contiguity of Voronoi cells with the binary “Good/Bad” grouping as the predictor variable. Results are plotted as a proportion (%) of the total number of model runs. The age distribution of “good” (green shading) and “bad” boulders (grey shading) is shown for each moraine in plots B and D.

**Figure 9.** The likelihood of sampling a “good” boulder (%; within 2σ of the landform age) for each of the studied landforms, subset by boulder position (inner ice-proximal slope, moraine crest, outer ice-distal slope). These data are based on Monte Carlo simulated datasets (*n* = 104), where bar heights represent the mean proportion (%) of “good” boulders and uncertainty bars represent the standard deviation.

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