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 (TCN) of ice-marginal moraines can provide unique insights into Quaternary glacial history. However, geomorphic processes can profoundly influence the distribution of TCN ages. Models of moraine evolution predict the greatest ground lowering at moraine crests, but these areas are preferentially sampled due to perceived stability. In this study, we assess the relative utility of moraine crest and moraine slope sampling for a range of moraine types (terminal, lateral, latero-frontal) and moraine ages (Holocene to Last Glacial Maximum) using 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. These data show that X

These data show that exhumation is widespread for large, matrix-rich and steep-sided moraines deposited at the Last Glacial Maximum, but sampling on the crest is not effective at isolating exhumed boulders. For these moraines, the distribution of exhumed boulders is effectively random while the probability of selecting an exhumed boulder is comparable for moraine crests, ice-proximal and -distal slopes. Within this context, we recommend abandoning the crest-only strategy to widen the population of boulders to select from. However, there is a lack of quantitative evidence linking boulder characteristics to well-clustered TCN datasets; a situation which sets the context for boulder selection “superstition”. Based on our compilation of boulder characteristics, we find that these factors have little explanatory power for the studied moraines, a result which raises questions about the efficacy of geomorphic insight. Instead, it is increasingly clear that landform stability should be prioritised over spatial and boulder criteria, with boulder-rich, matrix-poor moraines more likely to stabilise rapidly after deglaciation. For non-ideal landforms, which are often priority targets for TCN dating, we recommend preliminary SH sampling to identify exhumed boulders and to prioritise individual boulders for analysis.

**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 have transformed our understanding of Quaternary glaciations by permitting direct analysis of the fragmentary glacial stratigraphic record (Gibbons et al., 1984; Nishiizumi et al., 1989; Phillips et al., 1990; 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).

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 moraine crest boulders are prioritised, while moraine slope boulders 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. χ2 ≤ 1), 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 (χ2 ≤ 2). 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) but the degree to which the wider depositional environment overrides the influence of boulder characteristics is not known. Within this context, further work is required to test existing criteria for TCN sample selection and to develop quantitative methods which minimise and account for 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 TCN 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 (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 due to perceived stability (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: are moraine crests more informative than moraine slopes?

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 for a range of moraine types (terminal, lateral, latero-frontal) and moraine ages.

**Methods**

**Moraine selection**

Five 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). Selected moraines encompass the primary deglaciation phases of the Pyrenees since the global Last Glacial Maximum (gLGM) and are lithologically uniform as they are dominated by granitic moraine boulders sourced from the Hercynian Axial Zone (*see* Fig. 1E; 2A; Crest et al., 2017; Barnard et al., 2019). 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; ~76% of published 10Be and 26Al ages (*n* = 15,690) are younger than 30 ka, based on a compilation by Jakob Heyman; available at <http://expage.github.io/>, accessed: 14/04/2020). In contrast, for moraines with long post-depositional histories, alternative techniques are often more appropriate (e.g. U-series, Hughes et al., 2007; OSL, Lewis et al., 2009; 10Be-26Al depth profiles, 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; Pallas 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°), extensively 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, 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).

**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 (Fig. 1). 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 ~59 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 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. To compliment these data, a wide range of boulder characteristics were recorded including dimensions, morphology (angularity, sphericity), surface characteristics (vegetation, fracturing) and depositional context (slope angle, matrix).

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 surfaces have provided 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; an interpretation supported by the strong correlation between 52 10Be TCN ages (Pallàs et al., 2006; 2010; Delmas et al., 2008; Crest et al., 2017) and SH R values for granite and granodiorite surfaces across the Pyrenees (R2 = 0.96, *p* < 0.01; Tomkins et al., 2018b). To further develop this dataset, two additional 10Be ages from the Noguera Ribagorçana (MUL01 and MUL03; Pallàs et al., 2006) were sampled using the Schmidt hammer (*see* Supplementary Information; Table S1). These samples are proximal to the Outer Pleta Naua (~0.8 km) and Tallada moraines (~1.7 km; *see* Fig. 2C).

**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. 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). This approach improves on ordinary least squares regression (Tomkins et al., 2018b) by minimising orthogonal residuals and is appropriate in this instance because both methods have associated measurement uncertainties (*see* Viles et al., 2011; Jull et al., 2015). Moreover,

Error variances

by incorporating error in both the independent (TCN; ± external age uncertainty) and dependent variables (SH, ± Standard Error of the Mean). This analysis 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, with reported uncertainties derived from a 1σ prediction limit (calculated using the ODR covariance matrix; Boggs and Rogers, 1990b). 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.

**Calculating landform ages**

To determine the timing of moraine deposition at each site, we analysed 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. X and Table X. 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 X).

Based on landform age analysis (Table 2), 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. In addition, the use of logistic analysis is also appropriate because the *magnitude* of the difference from the landform age is typically not of interest. For example, an inherited boulder which returns an age 50% greater than the landform age is numerically distinct from one which returns an age 300% greater than the landform age. However, both would be classed as “bad” if the objective was to determine the timing of landform deposition. In turn, “good” boulders are interpreted to reflect the timing of moraine deposition or initial stabilisation, while those classed as “bad” are likely compromised by pre- or post-depositional exposure.

**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. Implicit in current sampling approaches is that (i) the distribution of “good” boulders is non-random and that (ii) “good” clusters are more likely on moraine crests; assumptions that can be explicitly tested for the studied moraines using global and local Moran’s *I* respectively.

**Uncertainty propagation**

The above analyses provide information on the relative occurrence and spatial clustering of “good” and “bad” boulders for a range of moraine types and ages. However, each individual calibrated boulder exposure age has an associated uncertainty which must be propagated fully. To achieve this, the above analyses have been automated using a Monte Carlo style approach as follows:

1. For each landform, calibrated exposure ages were simulated using a truncated normal distribution (*n* = 104, *minimum* = 0, *maximum* = ∞; Mersmann et al. 2018) using calibrated exposure ages and their 1σ prediction bounds as input parameters. These simulations follow the empirical rule, where ~68% of simulated ages fall within the 1σ prediction bounds, ~95% within the 2σ prediction bounds and ~99.7% within the 3σ prediction bounds.
2. Using these simulated data, we utilised an automated version of P-CAAT (Dortch et al., 2020) to calculate a landform age for each simulated dataset. For consistency, this calculation utilised the “STD/IQR” bandwidth estimator (Silverman, 1986) and used the highest probability component Gaussian distribution to represent the age of the landform (Dortch et al., 2020).
3. Using these new landform ages, simulated ages were sorted into “good” and “bad” groups based on the 2σ (95%) age boundaries of the landform age. The relative proportion (%) of these groups was recorded.
4. Finally, the spatial distribution of “good” and “bad” ages for each simulated dataset was assessed using global and local Moran’s *I*, as described previously. For each model run, and when global Moran’s *I* revealed a statistically significant non-random distribution (*p* < 0.05), local Moran’s *I* was used to identify “good” and “bad” clusters. 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.

**Results**

**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. X; *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* Table X). Of these, the vast majority closely match the existing calibration dataset (*n* = 13, *see* Fig. X). 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 is attributed to sub-surface weathering in the near-surface soil zone prior to boulder exhumation at ~17 ka, 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. X). 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, while analysis of the Soum d’Ech moraines is based on an assumed correspondence between weathering (SH R) and surface exposure, the influence of sub-surface weathering cannot be excluded as an additional contributory factor.

**Landform ages**

Landform ages calculated using P-CAAT, in addition to associated model fits (Dortch et al. 2020), are reported in Table X. Based on this approach, latero-frontal moraines in the Arànser catchment were deposited at 23.3 ± 1.2 ka (left lateral) and 22.3 ± 1.2 ka (right lateral). As these estimates are consistent within measurement uncertainties, and given the comparable stratigraphic positions of these deposits, 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) but the oldest sample (SAL-10; 21.6 ± 0.7 (1.8) ka) is consistent with both landform ages within measurement uncertainty. The selection of the oldest moraine age accords with standard procedures for interpreting moraine ages as minimum limiting ages (Putkonen and Swanson, 2003; Briner et al., 2005). In support of the calculated landform ages, and the underlying calibrated boulder exposure ages, there is a close correspondence between the 10Be and 36Cl ages of the sampled boulders and their equivalent calibrated exposure ages (*n* = 11; Table X, Fig. X).

In the Gave de Pau catchment, calibrated boulder exposure ages from proximal lateral moraine ridges return landform ages of 27.97 ± 1.10 ka (outer, *n* = 60) and 28.0 ± 1.10 ka (inner, *n* = 40). 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 or degradation. Within this context, we assign these deposits a combined landform age of 27.97 ± 1.10 ka based on the full dataset (*n* = 100).

While it must be noted that this estimate is significantly older than the corresponding 10Be ages (~17 - 20 ka; Rodés, 2008), we favour the oldest component Gaussian based on limiting 14C ages obtained from proximal palaeolake sediment sequences (*see* Fig. X) at Lac de Lourdes (~2 km) and Biscaye (~3.7 km). These palaeolakes occupy over-deepened glacial basins formed during the Würmian glacial maximum (Reille and Andrieu, 1995).

30.9 ± 1.6 14C ka BP (Jalut et al., 1992) nope, till

27.1 ± ? 14C ka BP (Reille and Andrieu, 1995) - Biscaye

22.1 ± 0.4 14C ka BP (Reille and Andrieu, 1995) - Lourdes

Of the four 10Be ages available for the outer moraine (Rodés, 2008), only one could be readily identified. This sample (ECH-01) returned comparable 10Be (18.9 ± 3.7 ka) and calibrated exposure ages (), although the high 10Be measurement uncertainty precludes confident comparison of these estimates. Of the remaining samples, sample ECH-02 returned an age of 58.2 ± 44.6 ka but this can be explained by measurement error (Rodés, 2008). Samples ECH-04 and ECH-03 returned ages of ~16.0 ka (ECH-04) and ~16.4 ka (ECH-03).

In the Val de Molières catchment of the Noguera Rigaborçana, landform ages for the Outer Pleta Naua moraine derived from 10Be (*n* = 3; 12.2 - 12.8 ka; Pallàs et al., 2006) and SH R (*n* = 60; 12.5 ± 0.3 ka) are consistent with deposition during the Younger Dryas and agree within measurement uncertainties (Table X). 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, rock avalanche activity, or avalanche. However, the absence of unweathered glacially-modified boulders (e.g. SH *R* ≥ 70) on the outer moraine suggests that any subsequent glaciers were minimally erosive and were incapable of significantly modifying the existing moraine.

**Temporal analysis**

Temproal skew is different! Interesting! Relative good vs. bad% overall, and for crest groups.

**Spatial analysis**

Any trends

~~While it is possible that maxima moraines in these catchments were deposited significantly later (16 - 18 ka), this chronology is inconsistent with wider evidence from across the Pyrenees (Jalut et al., 1992; Pallàs et al., 2006; 2010; Delmas et al., 2008; 2011; Calvet et al., 2011; Palacios et al., 2015; Tomkins et al., 2018b), as moraines deposited at or near glacial maxima have been dated to 25.3 ± 3.7 ka (~~*~~n~~* ~~= 3; Noguera Rigaborçana), 25.0 ± 2.2 ka (~~*~~n~~* ~~= 1; Ariège), 24.7 ± 0.9 ka (~~*~~n~~* ~~= 25; Têt), ≥ 24.21 ka (~~~~14~~~~C, Gállego), 23.3 ± 0.8 ka (~~*~~n~~* ~~= 6; Querol), 21.2 ± 2.5 ka (~~*~~n~~* ~~= 12; Malniu), 20.7 ± 2.5 ka (~~*~~n~~* ~~= 2; La Llosa) and 20.5 ± 1.9 ka (~~*~~n~~* ~~= 4; Duran). These data appear consistent with a MIS 2 maximum prior to 20 ka (Oliva et al., 2019).~~

While landform ages are consistent with wider Pyrenean glacier chronologies, the age distribution of boulder samples varies significantly between the sampled moraines. Both Arànser and Gave de Pau 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 and reworking of glacial material (Applegate et al., 2010). In contrast, boulder ages on the Outer Pleta Naua moraine are normally distributed (*W* = 0.96, *p* = 0.07), tightly clustered (*IQR* = 0.55 ka) and exhibit no significant spatial clustering (Global Moran’s *I* = -0.023, *p* = 0.152). These data appear consistent with rapid post-depositional stabilisation. Statistically significant spatial clustering is absent at the Tallada moraine (*I* = 0.111, *p* = 0.055) but is clearly identified at both Arànser (*I* = 0.101, *p* = 0.004) and the Gave de Pau moraines (*I* = 0.112, *p* = 0.027) which may reflect a combination of post-depositional processes which drive moraine evolution.

However, the spatial distribution of boulder ages does not conform to either a crest or slope stability model (Fig. 4; Hallet and Putkonen, 1994), with no consistent trends between or within individual moraines. The distribution of ages is comparable between moraine groups (Table 3; Fig. 5) while the distribution of statistically significant clusters at the Arànser and Gave de Pau moraines is effectively random, as “good” and “bad” clusters occur on moraine crests, ice-proximal and -distal slopes. There are minor exceptions to this rule, where statistically significant boulder clusters have plausible geomorphological explanations. At Arànser, a cluster of high *R* exhumed boulders occurs near the front of the moraine, which likely reflects fluvial incision of the terminus and degradation of the lateral flanks (e.g. Duran valley; Palacios et al., 2015b). An additional exhumed cluster occurs where a minor stream has cross-cut and incised the moraine crest (Fig. 2C, 4A); this is likely a major meltwater source from the other moraines coming out of the other cirque!

~~Based on MANOVA, there is a significant difference in boulder characteristics between “good” and “bad” groups at the population level (~~*~~p~~* ~~< 0.01). Logistic regression reveals four significant predictors at~~ *~~p~~* ~~= 0.05. These include the characteristics of the underlying matrix (~~*~~p~~* ~~= 0.046; 0 = matrix-supported, 0.5 = some combination of matrix/clast-support, 1 = clast-supported), as sampling a clast-supported boulder increases the probability of selecting a “good” boulder by a factor of 1.70 (95% CI: 1.01 - 2.90). Boulder angularity is also significant (~~*~~p~~* ~~< 0.01; Powers, 1953), as sampling a rounded over an angular boulder influences the probability by a factor of 0.30 (95% CI: 0.16 - 0.54). The remaining predictors relate to the depositional environment, as sampling a boulder on the ice-proximal slope rather than the moraine crest influences the probability by a factor of 0.50 (~~*~~p~~* ~~= 0.021; 95% CI: 0.28 - 0.90). Finally, the height of the boulder relative to the moraine crest is also significant (~~*~~p~~* ~~< 0.01) and influences the probability by a factor of 0.31(95% CI: 0.13 - 0.71). In summary, matrix-supported, rounded boulders, deposited near crests but on ice-proximal slopes have a higher probability of returning a “bad” age at the population level.~~

~~It is important to note, however, that these factors are likely inherited from landform characteristics, as well-clustered boulders on the Outer Pleta Naua moraine are predominantly clast-supported (56/60) and angular (33/60). In turn, this landform, and the characteristics of its boulders, has a disproportionate effect on population level analysis. When these analyses are repeated at the landform level, MANOVA reveals no significant differences between groups at~~ *~~p~~* ~~= 0.05 for the Gave de Pau (~~*~~p~~* ~~= 0.17), Outer Pleta Naua (~~*~~p~~* ~~= 0.98) and Tallada moraines (~~*~~p~~* ~~= 0.23). Significant differences are recorded at Aranser (~~*~~p~~* ~~= 0.018) but the identified predictors are inconsistent with population level results. Significant predictors (~~*~~p~~* ~~= 0.05) include the presence of surface vegetation (~~*~~p~~* ~~= 0.008; Factor = 7.99, 95% CI: 1.78 - 39.20), the degree of fracturing (~~*~~p~~* ~~= 0.004; Factor = 4.35, 95% CI: 1.64 - 11.99), the underlying slope angle (~~*~~p~~* ~~= 0.002; Factor = 0.94, 95% CI: 0.91 - 0.98) and the height of the boulder relative to the moraine crest (~~*~~p~~* ~~= 0.019; Factor = 0.02, 95% CI: 0.001 - 0.49). For this moraine, fractured boulders with high surface vegetation cover are more likely to return “good” ages, while increases in slope angle and relative height have a negative effect. This dichotomy between population and landform level results highlights the challenge of untangling the respective influences of boulder and landform characteristics. In turn, the most striking result is that no predictor has consistent explanatory power across moraine groups and at the population level. This analysis points to a decoupling of boulder characteristics and exposure ages and raises questions about the efficacy of geomorphic insight (Akçar et al., 2011).~~

**Discussion**

Boulder location is critical, as moraine crest boulders are prioritised, while moraine slope boulders are rejected, irrespective of their individual characteristics.

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 significant 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 for CRE dating, while moraine slopes are generally avoided due to increased risks of boulder instability.

In this study, we have critically assessed these two competing ideas and found that spatial criteria (i.e. boulder position) cannot explain the distribution of boulder ages and, in the absence of detailed geomorphological assessment (e.g. Palacios et al., 2019), should not be used to guide CRE sampling strategy. 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).

If spatial criteria cannot be used to isolate exhumed boulders, then the depositional context and characteristics of individual boulders may have stronger explanatory power. Much attention has been devoted to choosing the “best” boulders based on geomorphic expertise (Akçar et al., 2011; Rinterknecht et al., 2014). Previous studies have advocated sampling (i) the tallest boulders, to minimise the likelihood of post-depostional shielding (Heyman et al., 2016), (ii) the largest boulders, to minimise post-depositional instability (Akçar et al., 2011), (iii) those on flat, stable surfaces (Gosse et al., 1995) or on moraine crests (Akçar et al., 2011), (iv) boulders embedded in the moraine matrix (Ivy-Ochs et al., 2007), (v) hard, “fresh” looking boulders, (vi) boulders which elicit a ping instead of a thud when struck with a hammer (*see* Dortch et al., 2010) and (vii) rounded boulders with evidence of glacial transport, as subglacial erosion may have removed the accumulated in-situ cosmogenic signal (Hughes et al., 2016). In contrast, angular boulders may have originated from rockfalls, and through supraglacial transport to glacier margins or direct deposition onto moraines (Porter and Swanson, 2008), may retain a cosmogenic signal from prior exposure. However, there is a paucity of quantitative research correlating boulder characteristics (e.g. i-vii) to tightly clustered CRE datasets (e.g. χ2 ≤ 1), 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 is minor, as a dominant fraction (>50%) of tall boulder groups were sufficiently scattered to fail a reduced chi square test (χ2 ≤ 2). More fundamentally, any ad hoc approach is inherently flawed as compiled boulder sets were initially collected according to a set of specific criteria (Tylmann et al., 2018), thus precluding a truly representative compilation. Finally, the influence of landform characteristics is often overlooked in ad hoc analysis, but the degree to which the wider depositional context overrides boulder characteristics is not known. These circumstances set the context for boulder selection “superstition”, which equates some boulder characteristics to reliably clustered datasets in the absence of quantitative evidence (Skinner, 1948).

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.

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*).

**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 | ~31 m2 |
| Arànser (Right) | Latero-frontal | 120 | 57 | 23 | 40 | 0.281 | ~59 m2 |
| Soum d’Ech | Lateral | 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.** Age statistics for the sampled moraines | | | | | | |
| Moraine | Bandwidtha | Model fit | *p* value | Age (ka)b,c | IQRd | Skew |
| Tallada | 0.45 |  |  | 3.42 ± 0.73 | 1.2 ka | 0.34 |
| Outer Pleta Naua | 0.15 |  |  | 12.47 ± 0.32 | 0.5 ka | -0.23 |
| Arànser (Left) | 0.83 |  |  | 23.28 ± 1.20 | 7.8 ka | -1.02 |
| Arànser (Right) |  |  |  |  |  |  |
| Soum d’Ech | 0.60 |  |  | 27.97 ± 1.10 | 3.6 ka | -1.47 |
| a Numeric bandwidth used for kernel density estimation (“STD/IQR” bandwidth estimator; Silverman, 1986; Dortch et al., 2020), b Landform age derived from non-simulated data, c Reporteduncertainty (±) is the 1σ bounds (68%) of the selected component Gaussian, d Interquartile range | | | | | | |

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| **Table 3.** Spatial statistics for the sampled morainesa | | | | | | | |
|  | Global Morans *I* | Class statistics (%) | | | “Good” boulder (%)b | | |
| Moraine | # significant datasets | Young | Good | Old | IS | C | OS |
| Tallada | 3% | 4b | 84 | 11c | 85 ± 1 | 79 ± | 90 ± |
| Outer Pleta Naua | < 1% | 0 | 98 | 2 | 100 ± | 95 ± | 100 ± |
| Arànser (Left) | 89% | 43d | 57 | 0 | 54 ± | 59 ± | 76 ± |
| Arànser (Right) | 92% |  |  |  |  |  |  |
| Soum d’Ech | 97% | 46d | 53 | 1 | 57 ± | 50 ± | 54 ± |
| a Derived from simulated datasets. b rockfall or avalanching, c reworking, d exhumation | | | | | | | |

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| **Table 4.** 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 (Left)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). | | | | | | | | | |

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), showing the locations of the studied catchments and selected moraines and the distribution of Axial Zone granites *within* those catchments (Cauterets-Panticosa, Néouvielle, Maladeta, Mont-Louis-Andorra; Porquet et al., 2017). 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).

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 location of the Fornell moraine is denoted by (F). Stratigraphically, this moraine corresponds to a readvance or stabilisation of the Arànser glacier following the deposition of the main sampled lateral moraines.

**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**. Orthogonal distance regression (ODR) between 54 10Be exposure ages (white 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 blue points. Inherited outliers from the original calibration dataset (*n* = 2; Tomkins et al., 2018b) are not shown for clarity. Sample information for all exposure ages (*n* = 73) is provided in the Supplementary Information.

**Figure 6.** Gaussian decomposition of calibrated boulder exposure ages for the Tallada (A-B), Outer Pleta Naua (C-D), Arànser left (E-F), Arànser right (G-H) and Soum d’Ech moraines (I-J). Following P-CAAT guidelines (Dortch et al., 2013; 2020), we selected the highest probability component Gaussian for landforms younger than the global Last Glacial Maximum (gLGM) and the oldest Gaussian for landforms deposited at or prior to the gLGM. In each plot, samples shaded in red contribute to the selected Gaussian, while samples shaded in grey are younger or older than the selected Gaussian.

**Figure 7.** Results of Monte Carlo simulated (*n* = 104) 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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