

Please cite the Published Version

Tomkins, Matt D, Dortch, Jason M, Hughes, Philip D, Huck, Jonny J, Pallàs, Raimon, Rodés, Ángel, Allard, James L, Stimson, Andrew G, Bourlès, Didier, Rinterknecht, Vincent, Jomelli, Vincent, Rodríguez-Rodríguez, Laura, Copons, Ramon, Barr, lestyn D, Darvill, Christopher M and Bishop, Thomas (2021) Moraine crest or slope: An analysis of the effects of boulder position on cosmogenic exposure age. Earth and Planetary Science Letters, 570. ISSN 0012-821X

DOI: https://doi.org/10.1016/j.epsl.2021.117092

Publisher: Elsevier BV

Version: Accepted Version

Downloaded from: https://e-space.mmu.ac.uk/628109/

Usage rights: O In Copyright

Additional Information: This is an Author Accepted Manuscript of a paper accepted for publication in Earth and Planetary Science Letters, published by and copyright Elsevier.

Enquiries:

If you have questions about this document, contact openresearch@mmu.ac.uk. Please include the URL of the record in e-space. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.mmu.ac.uk/library/using-the-library/policies-and-guidelines)

- ¹ Moraine crest or slope: an analysis of the effects of
- ² boulder position on cosmogenic exposure age
- 3 Matt D. Tomkins^{1,2}, Jason M. Dortch³, Philip D. Hughes^{1,2}, Jonny J. Huck¹, Raimon
- 4 Pallàs⁴, Ángel Rodés⁵, James L. Allard^{1,2}, Andrew G. Stimson¹, Didier Bourlès⁶,
- 5 Vincent Rinterknecht⁶, Vincent Jomelli⁶, Laura Rodríguez-Rodríguez⁷, Ramon
- 6 Copons⁸, lestyn D. Barr^{9,2}, Christopher M. Darvill^{1,2}, Thomas Bishop¹
- 7 ¹Department of Geography, University of Manchester, Manchester, M13 9PL, UK
- 8 ²Cryosphere Research at Manchester, Manchester, UK
- 9 ³Kentucky Geological Survey, University of Kentucky, Lexington, USA
- 10 ⁴Departament de Dinàmica de la Terra i de l'Oceà, Universitat de Barcelona, 08028 Barcelona, Spain
- ⁵Scottish Universities Environmental Research Centre, Rankine Avenue, East Kilbride G75 0QF, UK
- ⁶Aix-Marseille Univ., CNRS, IRD, INRA, Coll France, UM 34 CEREGE, Technopôle de l'Environnement
 Arbois-Méditerranée, BP80, 13545 Aix-en-Provence, France
- ⁷Dpto. Ciencias de la Tierra y Física de la Materia Condensada, Universidad de Cantabria, Avenida de los
 Castros s/n, 39005 Santander, Spain
- ⁸Snow and Mountain Research Centre of Andorra (CENMA), Andorran Research Institute (IEA), Sant
 Julià de Lòria, Andorra
- ⁹Department of Natural Sciences, Manchester Metropolitan University, Manchester, UK

19 Keywords

- 20 Cosmogenic nuclides
- 21 Moraine
- 22 Geologic uncertainty
- 23 Degradation
- 24 Weathering
- 25 Schmidt hammer

26 Abstract

- 27 Terrestrial cosmogenic nuclide dating of ice-marginal moraines can provide unique insights
- 28 into Quaternary glacial history. However, pre- and post-depositional exposure histories of
- 29 moraine boulders can introduce geologic uncertainty to numerical landform ages. To avoid
- 30 geologic outliers, boulders are typically selected based on their depositional context and
- 31 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 typically rejected. This 33 study provides the first quantitative assessment of the relative utility of moraine crest and 34 moraine slope sampling using new and published ¹⁰Be and ³⁶Cl ages (n = 19) and Schmidt 35 hammer sampling (SH; n = 635 moraine boulders, ~19,050 SH R-values) in the northern and 36 southern Pyrenees. These data show that for many of the studied moraines, the spatial 37 38 distribution of "good" boulders is effectively random, with no consistent clustering on moraine crests, ice-proximal or -distal slopes. In turn, and in contrast to prior work, there 39 is no clear penalty to either moraine crest or moraine slope sampling. Instead, we argue that 40 landform stability exerts a greater influence on exposure age distributions than the 41 characteristics of individual boulders. For the studied landforms, post-depositional stability is 42 strongly influenced by sedimentology, with prolonged degradation of matrix-rich 43 unconsolidated moraines while boulder-rich, matrix-poor moraines stabilised rapidly after 44 deposition. While this pattern is unlikely to hold true in all settings, these data indicate that 45 differences between landforms can be more significant than differences at the intra-landform 46 scale. As ad hoc assessment of landform stability is extremely challenging based on 47 geomorphological evidence alone, preliminary SH sampling, as utilised here, is a useful 48 49 method to assess the temporal distribution of boulder exposure ages and to prioritise individual boulders for subsequent analysis. 50

51 **I. Introduction**

52 Ice-marginal moraines are classic features of glaciated mountain ranges and are prominent

53 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. Recent
- 56 developments in terrestrial cosmogenic nuclide (TCN) dating have transformed our
- 57 understanding of Quaternary glaciations by permitting direct analysis of the fragmentary
- 58 glacial stratigraphic record (Zreda and Phillips, 1995). Despite this progress, TCN dating can
- 59 be complicated by geologic processes which result in pre- or post-depositional exposure of 60 rock surfaces and which account for apparent TCN ages that pre- or post-date the assumed
- 61 age of the landform (Applegate et al., 2010). Of these, post-depositional erosion,
- 62 exhumation and shielding have been shown to profoundly influence TCN age distributions
- 63 (Briner et al., 2005; Zech et al., 2005; Heyman et al., 2011; Stübner et al., 2017; Chevalier
- 64 and Replumaz, 2019).

To avoid geologic outliers, researchers select samples based on the depositional context and characteristics of individual surfaces. Previous studies have advocated sampling:

- boulders on moraine crests or on flat, stable surfaces (Gosse et al., 1995),
- the tallest boulders, to minimise the likelihood of post-depositional shielding
 (Heyman et al., 2016),
- the largest boulders or boulders embedded in the moraine matrix (lvy-Ochs et al.,
 2007), to minimise the likelihood of post-depositional instability,

well-rounded boulders which preserve evidence of glacial transport (Darvill et al., 2015), to minimise the likelihood of pre-depositional exposure.

However, while these criteria have good qualitative reasoning, many have not been tested 74 quantitatively. In turn, further work is required to test existing criteria for sample selection 75 and to develop quantitative methods which minimise the effects of geologic processes 76 77 (Dortch et al., 2013; 2021). These developments have the potential to significantly improve the robustness of TCN datasets and the chronological utility of the moraine record 78 (Applegate et al., 2012). Within this context, this paper focuses on a fundamental 79 component of TCN sample selection; the effect of moraine crest sampling on boulder 80 exposure age. Of the above criteria, boulder location is critical, as boulders on moraine 81 crests are prioritised, while those on moraine slopes are typically rejected, irrespective of 82 their individual characteristics. 83

While this approach is gualitatively sound, early numerical models of moraine evolution 84 predicted the greatest ground-lowering at moraine crests (Hallet and Putkonen, 1994; 85 86 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). 87 However, moraines continue to degrade through time as a function of moraine height and 88 sedimentology (Putkonen and Swanson, 2003; Putkonen et al., 2008; Schaller et al., 2009), as 89 diffusive processes remove fine-grained material from moraine crests and deposit material at 90 the base of moraine slopes (Applegate et al., 2010). Over time, these processes drive 91 exhumation of boulders which have been shielded from cosmogenic exposure. In turn, the 92 age distribution of moraine crest boulders may primarily reflect an initial stabilisation phase 93 (~1 ka; Briner et al., 2005; Dortch et al., 2010), modified by the ongoing process of moraine 94 degradation, rather than the timing of initial moraine deposition. In contrast, slope diffusion 95 models and lichenometric methods predict relative stability on moraine slopes (Hallet and 96 97 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 98 the moraine. This dichotomy between model predictions and sampling procedures raises a 99 fundamental and currently unanswered question: should moraine crests or moraine slopes 100 be prioritised in TCN sample selection? 101

To address this uncertainty, we utilise 19 new and published ¹⁰Be and ³⁶Cl TCN ages and 635 Schmidt hammer calibrated-exposure ages (SH; 19,050 SH *R*-values) from ice-marginal moraines in the northern and southern Pyrenees. Weathering-based analyses are utilised here to enable intensive sampling of boulders across the moraine surface, with results verified against independent TCN ages. In total, these data provide the first quantitative assessment of the relative utility of moraine crest and moraine slope sampling.

108 **2. Methods**

109 2.1. Moraine selection

- 110 Six moraines of varying age, geomorphology and sedimentology were selected in the
- 111 Pyrenees (Fig. I); a mountain range which was extensively glaciated during Pleistocene cold
- stages (see Fig. 1F; Calvet et al., 2011). Moraines were selected to encompass the primary
- deglaciation phases of the Pyrenees since the global Last Glacial Maximum (LGM) and all
- 114 feature large populations of quartz-rich granitic moraine boulders, sourced from Axial zone
- granite outcrops in the Arànser, Gave de Pau and Noguera Rigaborçana glaciated valleys
- 116 (Fig. IE), and which are suitable for ¹⁰Be dating. While this focused approach does not
- 117 comprise all moraine types or depositional settings, these sites do encompass a range of
- moraine types commonly found in cirque and valley landsystems and which are often
- 119 priority targets for TCN dating (i.e. \leq LGM).
- 120 Selected moraines include both left (north) and right (south) latero-frontal moraines in the
- 121 Arànser catchment, Cerdanya (Fig. 2A). These moraines are matrix-rich (matrix-supported),
- steep-sided (30 40°), heavily forested (Mountain pine: *Pinus uncinata*), and record the
- maximum ice extent of the Aranser glacier during the Würmian cold stage (110 11.7 ka;
- 124 Calvet et al., 2011). The right latero-frontal moraine has previously been dated using ${}^{36}CI$ (*n*
- 125 = 2; Palacios et al., 2015). To supplement these data, a further 10 boulders were selected
- for ¹⁰Be analysis (Table I). Methods used for sample preparation, ¹⁰Be measurement and
- 127 exposure age calculation are detailed in the Supplementary Information.
- 128 On the north side of the Pyrenees, matrix-rich lateral moraines were selected in the Gave
- de Pau catchment (Fig. 2B). At least two neighbouring (~60 m) but distinct lateral moraine
- ridges have been identified (Soum d'Ech moraines; Fig. ID), with the outer moraine
- 131 previously dated using ¹⁰Be (n = 4; Rodés, 2008). As at Arànser, these moraines likely
- 132 correspond to the Würmian MIE but their distinctive morphologies (multiple nested ridges
- 133 vs. a single large moraine) likely reflects a topographic control on moraine deposition (open
- topography vs. confined valley; Barr and Lovell, 2014; Palacios et al., 2015).
- 135 On the south side of the Pyrenees, and in the Val de Molières catchment of the Noguera
- 136 Rigaborçana, sampled sites include the boulder-rich (clast-supported), matrix-poor Outer
- 137 Pleta Naua terminal moraine (Fig. 3B, IB), previously assigned to Greenland Stadial I based
- on ¹⁰Be (n = 3; Pallàs et al., 2006), and the Tallada cirque moraine (Fig. 3A, IA), which
- 139 consists of a single sharp-crested, arcuate terminal moraine with two minor ice-proximal
- ridges. Both the Outer Pleta Naua and Tallada moraines are primarily composed of wedged angular boulders, with little or no sediment matrix. Although undated, the Tallada moraine
- angular boulders, with little or no sediment matrix. Although undated, the Tallada moraine
 is assumed to be late-Holocene in age, as evidenced by minimal boulder weathering (Pallàs
- et al., 2006), while its elevation (~2400 m), topographic setting (enclosed cirque; ~0.16 km²)
- and aspect (NNE) likely contribute to the inter-annual preservation of a small snowfield
- 145 (~0.03 km²). These factors may have enabled glacier growth or re-advance during more
- 146 recent climatic periods (e.g. the Little Ice Age).

147 **2.2. Sampling approach**

148 To investigate the depositional and post-depositional histories of these moraines, glacial 149 boulders were selected to cover the entire moraine surface, including the moraine crest

- (C), the inner ice-proximal slope (IS) and the outer ice-distal slope (OS), while the number 150 of selected boulders varied as a function of moraine size (n = 60 - 275). In turn, boulder 151 selection was primarily motivated by spatial location and the construction of a dense matrix 152 of sampling points, rather than individual boulder characteristics. Each boulder was sampled 153 using an N-type Schmidt hammer (SH) to assess the relative degree of weathering following 154 155 the sampling approach of Tomkins et al. (2018a). All boulders were of sufficient size (> 25 kg; Sumner and Nel, 2002) and sampled areas were free of surface discontinuities (Williams 156 and Robinson, 1983) and lichen (Matthews and Owen, 2008). Thirty R-values were recorded 157 for each boulder by a single operator and no outliers were removed following Niedzielski et 158 al. (2009). Schmidt hammer functioning was assessed regularly using the manufacturer's test 159 anvil, with instrument and age calibration performed following Tomkins et al. (2018a). In 160 total, 635 moraine boulders were sampled across the selected sites and 19,050 SH R-values 161 162 were generated. To compliment these data, the dimensions, surface features and depositional context of each sampled boulder were recorded (see Supplementary 163
- 164 Information).

165 Schmidt hammer *R*-values correspond to the degree of surface weathering, assuming

166 minimal lithological variation between tested rock surfaces (McCarroll, 1989), and are

167 inversely proportional to surface exposure age. The rate and style of weathering may also

be modified by climate (Riebe et al., 2004; Portenga and Bierman, 2011; Marrero et al.,

169 2018). At the intra-landform scale, lithologic-climatic variability is absent as all sampled

boulders share a common source area and climatic regime. At the inter-landform scale,
variability in rock type is minimal, as all sampled boulders were coarse- to medium-grained

granites and granodiorites. Finally, while regional climatic variability could account for

variability in weathering rates across the studied sites, previous work has shown that rates

of sub-aerial weathering of granite are consistent over large spatial scales for regions of

similar climate (Tomkins et al., 2018b).

176 2.3. Calculating SH-calibrated exposure ages

177 As granitic lithologies have proved effective for calibrated-relative age dating, SH R-values

are used here as a proxy for exposure age based on a ¹⁰Be-SH calibration dataset developed

by Tomkins et al. (2018b). This dataset comprises 52 10 Be ages, distributed between 4.2 ±

180 0.3 ka and 51.8 ± 4.5 ka (Fig. 4), obtained from granite and granodiorite glacial boulders and

181 glacially-sculpted bedrock from across the central and eastern Pyrenees and their

182 corresponding SH *R*-values (Tomkins et al., 2018b). This dataset has been updated to include

183 two additional ¹⁰Be dated surfaces from the Val de Molières (MUL01 and MUL03; Pallàs et

al., 2006; see Supplementary Table I).

185 To utilise these data, ¹⁰Be ages were recalculated using the CRONUS Earth Web Calculator

186 (Version 2.0; Marrero et al., 2016, available at: <u>http://cronus.cosmogenicnuclides.rocks/2.0/</u>,

accessed: 01/09/2020), relative to the production rate dataset in Borchers et al. (2016) and

the time-dependent Lm scaling scheme (Lal, 1991; Stone, 2000), and assuming 0 mm ka⁻¹

189 erosion. Recalculated ¹⁰Be ages are minimum estimates, as no corrections were made for

190 shielding by snow, sediment or vegetation, surface erosion, or isostatic adjustment. To

- ensure consistency, all ¹⁰Be and ³⁶CI TCN ages discussed in this paper have been
 recalculated using these input parameters. This includes published ages from Pallàs et al.
 (2006), Rodés (2008), and Palacios et al. (2015), in addition to the 10 new ¹⁰Be dated
- 193 (2006), Rodes (2006), and Palacios et al. (2015), in addition to the 10 new Be dated 194 samples from the Arànser catchment. Full sample details used for exposure age calculation
- 195 are provided in the Supplementary Information.

In turn, a ¹⁰Be-SH calibration curve was constructed using logarithmic orthogonal distance
 regression (ODR, Boggs and Rogers, 1990) which minimises orthogonal residuals to account

- 198 for measurement uncertainties in both the independent and dependent variables. We utilise
- 199 Monte Carlo simulations to explicitly incorporate measurement errors; an approach which
- is preferable to a weighted ODR which requires unnecessary assumptions regarding
 weighting constants and is biased by TCN age-uncertainty collinearity (lvy-Ochs et al., 2007;
- 202 Dortch et al., 2021). Our analytical procedure, which returns prediction estimates (1σ) of ±

 $203 \quad 2.0 - 2.3$ ka, is described fully in the Supplementary Information and has been implemented

in SHED-Earth (<u>http://shed.earth</u>), an online calculator developed to enable wider and more

- 205 consistent application of our approach (Tomkins et al., 2018a). To assess the accuracy of the
- ¹⁰Be-SH calibration curve, 15 ¹⁰Be and ³⁶Cl ages from the studied moraines were located and
- 207 re-sampled with the SH.
- Based on this calibration curve, mean R-values from the 635 sampled boulders were
- 209 converted into "SH-calibrated exposure ages" through interpolation. While uncertainty
- 210 estimates for individual SH-calibrated exposure ages are larger than typical uncertainties
- associated with individual TCN exposure ages, landform age estimates can be of comparable
- precision to established techniques when derived from large SH datasets (e.g. n boulders \geq
- 30; Tomkins et al., 2018b) and when appropriate statistical approaches for outlier
- identification and error propagation are employed (Applegate et al., 2012; Dortch et al.,
- 215 **2013; 2021)**.

216 **2.4. Calculating landform ages**

To determine the timing of moraine deposition at each site, we analysed the distribution of SH-calibrated exposure ages using the Probabilistic Cosmogenic Age Analysis Tool (P-CAAT Version 1.0; Dortch et al. 2021). This method builds on the earlier work of Dortch et al. (2013) and 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. The results of this analysis are presented in Fig. 5 and Table 2. To assess the validity of these landform ages, we compared these data to the

- distribution of ¹⁰Be and ³⁶Cl ages from the studied landforms (Table I; Pallàs et al., 2006;
- 225 Rodés, 2008; Palacios et al., 2015).
- Based on landform age analysis, individual boulders were sorted into "good" and "bad"
- groups, which are defined by the 2σ (95%) age boundaries of the calculated landform age.
- 228 Boulders which returned SH-calibrated exposure ages within 2σ of the landform age were
- classed as "good", while those younger or older than the landform age (> 2σ) were classed
- 230 $\,$ as "bad". Selection of a broad 2σ threshold is appropriate given the measurement

- 231 uncertainties associated with SH sampling, in addition to the systematic and geologic
- 232 uncertainties inherited from TCN dating. Logistic analysis is used to distinguish boulders
- which correspond to the timing of moraine deposition or initial stabilisation ("good") from
- those which are likely compromised by pre- or post-depositional exposure ("bad").

235 2.5. Spatial analysis

The spatial distribution of "good" and "bad" boulders was analysed using global and local

- 237 Moran's *I* spatial autocorrelation and based on a row-standardised distance-band weights
- matrix, where the distance band threshold is the minimum distance required to ensure that
- each boulder has at least two neighbours (Table 3). The Python implementation is available
 on GitHub: <u>https://github.com/matt-tomkins/moraine-crest-or-slope</u>. At the global level,
- 241 Moran's *I* was used to assess whether the overall clustering of the data was significantly
- different from a random distribution. For datasets that are non-random (p < 0.05), local
- 243 Moran's I was used to identify the location of statistically significant boulder clusters (Fig. 6).
- 244 Current sampling approaches are based on the qualitatively-sound but quantitatively-
- 245 untested assumptions that (i) the distribution of "good" boulders is non-random, and that
- 246 (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.

248 **2.6. Sensitivity Analysis**

- 249 The above analyses provide important information on the relative occurrence and spatial
- clustering of "good" and "bad" boulders for moraines of varying age and morphology.
- 251 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., 2021).
- To evaluate the reproducibility of our results, sensitivity testing was performed to evaluate the number of samples required to reproduce the estimated landform age based on 1σ and 2σ thresholds. The full analytical approach is described in the Supplementary Information and the results are presented in Fig. 7B.
- 258 **3. Results**

259 **3.1. SH-calibrated exposure ages**

- There is a strong correlation between recalculated ¹⁰Be ages and their corresponding SH *R*values (Fig. 4; n = 54). Moreover, of the 15 ¹⁰Be and ³⁶Cl dated boulders re-sampled with the SH, the majority closely match the existing calibration dataset (n = 13). These observations indicate that when lithological variation is minimised, the relative degree of rock surface
- weathering can be used as a proxy for surface exposure age.
- Exceptions to this correlation are samples ECH03 (17.2 \pm 3.5 ka) and ECH04 (16.8 \pm 3.3
- ka) from the Soum d'Ech moraines (Rodés, 2008) which are significantly more weathered
- 267 (~38 R) than their corresponding ¹⁰Be ages would predict (~47 R). This difference likely

- reflects sub-surface weathering prior to boulder exhumation. However, the scale of this influence is unlikely to be universal given the close correspondence between sample ECH01
- $(19.7 \pm 3.6 \text{ ka})$ and the existing calibration dataset (see Fig. 4). While sub-surface weathering
- of boulders under thin soil cover (~25 cm) can occur (Darmody et al., 2005), boulders are
- often protected from weathering by sediment burial, as evidenced by the emergence of
- unweathered boulders from glacial tills and alluvium (Ehlmann et al. 2008). In turn, as SH-
- calibrated exposure ages from the Soum d'Ech moraines may well incorporate the effects of
- both sub-aerial and sub-surface weathering, and could also be influenced by weathering rate
- variability (e.g. differences between the Atlantic- (wet) and Mediterranean-influenced (dry)
- 277 Pyrenees), it is possible that the estimated depositional age is an overestimate.

278 3.2. Landform ages

- Landform ages derived from SH-calibrated exposure ages and associated P-CAAT model parameters are reported in Table 2 (Dortch et al. 2021). Based on this approach, latero-
- frontal moraines in the Aranser catchment were deposited at 23.3 \pm 1.1 ka (left) and 22.3 \pm
- 282 0.9 ka (right). As these estimates are consistent within measurement uncertainties, and given
- the comparable morpho-stratigraphy of these deposits (Fig. 2A), we consider moraine
- deposition to be contemporaneous. No independent dating evidence is available for the left lateral moraine, but 12 TCN ages are now available for the right lateral moraine (36 Cl, n = 2;
- ¹⁰Be, n = 10). Using P-CAAT and selecting the oldest component Gaussian distribution that
- contains \geq 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 \pm 2.2 ka (Mean bandwidth estimator; Numeric
- bandwidth = 0.8108, R^2 = 0.9997, p < 0.01), while the oldest sample is 22.4 ± 1.8 ka (SAL-
- IO). Both estimates are consistent within measurement uncertainties with the SH-derivedlandform ages.
- 292 In the Gave de Pau catchment, SH-calibrated exposure ages from the proximal Soum d'Ech
- lateral moraines return landform ages of 26.2 \pm 2.5 ka (outer, n = 61) and 26.1 \pm 1.7 ka

(inner, n = 39). While these moraines are morpho-stratigraphically distinct, they cannot be

- statistically distinguished. 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 SH-calibrated exposure ages is near identical (Table 2), we assign these deposits a landform age of 27.3 \pm 1.8 ka based on P-CAAT (n = 100; STD / IQR bandwidth estimator; Numeric bandwidth = 0.9877, R² = 0.9989, p < 0.01), and perform subsequent
- 301 analyses on the combined dataset for computational ease.
- While this estimate is significantly older than the corresponding 10 Be ages (16.8 ± 3.3 ka,
- 17.2 \pm 3.5 ka, 19.7 \pm 3.6 ka; Rodés, 2008), it is consistent with limiting ¹⁴C ages obtained
- from a proximal palaeolake sediment sequence at Lac de Lourdes (Reille and Andrieu,
- 1995). While the oldest radiometric ¹⁴C ages from this over-deepened glacial basin are now
- 306 considered suspect due to contamination from mineral carbon (Pallàs et al., 2006), a
- 307 younger AMS ¹⁴C age from glaciolacustrine clays suggests initial ice-free conditions by 24.1 \pm 308 0.4 ka cal. BP (20.025 \pm 0.175 ka BP; Sample depth = 920 – 960 cm), as calculated using

- IntCal 13 (Reimer et al., 2013), while an AMS ¹⁴C age from an overlying organic rich layer
- 310 (gyttja) indicates the culmination of glaciolacustrine sedimentation and deglaciation of the
- lower Gave de Pau by 18.8 \pm 0.3 ka cal. BP (15.460 \pm 0.150 ka BP; Sample depth = 740 –
- ³¹² 750 cm; Reille and Andrieu, 1995). Based on these data, the younger ¹⁰Be ages from Soum
- d'Ech can be considered suspect. Continued glacial occupation of the Soum d'Ech site until
- \sim 19.7 ka, as inferred from the oldest ¹⁰Be age (ECH01; 19.7 ± 3.6 ka), appears unlikely given
- initial deglaciation of low ground by ~24.1 ka. Instead, it appears likely that the ECH samples
- are representative of final moraine stabilisation, rather than initial deposition. This
- interpretation is supported by sensitivity analysis (see Section 3.5), as the number of TCN
- ages (n = 3) is below the threshold required to consistently reproduce the landform age
- derived from the full dataset at 2σ (n = 11) and 1σ (n = 41).
- 320 In the Val de Molières catchment of the Noguera Rigaborçana, recalculated ¹⁰Be ages on the
- Outer Pleta Naua moraine range from 12.6 \pm 1.5 ka to 13.2 \pm 1.6 ka (n = 3; Pallàs et al.,
- 322 2006). These estimates are consistent with the SH-calibrated exposure ages, which range
- from 11.8 ± 2.0 ka to 13.1 ± 2.0 ka (n = 60). As the SH-calibrated exposure ages conform to
- a normal distribution (Fig. 5B; Shapiro-Wilk test, W = 0.96, p = 0.07), are well-clustered (IQR = 0.6 ka), and return an excellent P-CAAT model fit with a single component Gaussian ($R^2 = 1$, p < 0.01), we use the arithmetic mean (\bar{x}) to represent the age of the landform and
- 326 $(R^2 = 1, p < 0.01)$, we use the arithmetic mean (\bar{x}) to represent the age of the lat 327 estimate the total uncertainty (t) following Dortch et al. (2021) as follows:

$$t = \sqrt{SU^2 + GU^2}$$

- 329 where systematic uncertainty (SU) incorporates measurement errors:
- $SU = \frac{\sqrt{Sum of the squared errors}}{Number of observations}$

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
- 333 cosmogenic nuclide concentrations:
- $GU = Standard \ deviation$
- In turn, the Outer Pleta Naua moraine was likely deposited at 12.5 ± 0.4 ka. Applying the same analytical approach ($\bar{x} \pm t$) to the corresponding ¹⁰Be ages produces 12.9 ± 1.0 ka,

337 which is statistically indistinguishable. Moreover, these estimates are stratigraphically

- 338 consistent with independent landform ages in the Val de Molières catchment (Pallàs et al.,
- 2006), with maximum and minimum limiting ages for moraine deposition provided by
- samples from the Molières (MUL01 = 14.9 ± 2.6 ka, MUL03 = 14.9 ± 1.9 ka) and Inner Pleta
- Naua moraines respectively (Fig. 3B; IPN01 = 6.3 ± 0.9 ka; Pallàs et al., 2006).

342 Finally, the Tallada cirque moraine returned a landform age of 3.2 ± 0.7 ka. While this SH-

343 derived estimate cannot be independently verified, the limited weathering of the moraine

- boulders (SH $R \ge 60$), in combination with the topographic setting of the Tallada cirque,
- 345 appears consistent with a late-Holocene origin.

346 **3.3. Temporal distribution**

- Estimated landform ages are generally consistent with independent TCN ages (n = 19) but
- 348 the age distribution of SH-calibrated exposure ages varies significantly between the sampled
- moraines (Fig. 5). For the Aranser and Soum d'Ech moraines, the distribution of SH-
- calibrated exposure ages is strongly negatively skewed (Table 2), in line with exhumation
- 351 models (Applegate et al., 2012), while Tallada is normally distributed with a slight positive
- 352 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 Aranser left (56%) and Aranser right moraines (49%). For moraines
- corresponding to the ~gLGM, most "bad" boulders are younger than the assumed age of
- deglaciation (Table 2), while the Holocene Tallada moraine contains a small but significant
- 360 component of boulders which are older than the assumed age of deglaciation (14%). Logistic
- 361 analysis indicates that boulder characteristics (e.g. boulder height) did not have a consistent
- 362 statistically significant effect on the distribution of "good" and "bad" boulders across the
- 363 sampled moraines (see Supplementary Information).

364 **3.4. Spatial distribution**

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

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

- 372 (i) at the moraine terminus,
- 373 (ii) where the moraine crest has been cross-cut and incised by a minor stream and,
- 374 (iii) where boulders have accumulated at the base of the moraine slope.

Additional clusters are also evident on the ice-proximal slope (Fig. 6A). Clusters (i) and (ii) 375 376 are likely fluvial in origin, with the former explained by incision of the terminal deposits, which may have led to degradation of the lateral flanks and exhumation of moraine 377 boulders. This pattern of post-depositional degradation matches the spatial clustering of ³⁶Cl 378 ages on a comparable gLGM moraine deposited in the nearby Duran valley (see Fig. 11 in 379 Palacios et al., 2015). The second cluster may be partially explained by meltwater erosion, 380 given the proximity of the incised area to the former terminus of the Setut glacier (Fig. 2A). 381 The origins of the remaining "young" clusters are less clear, but these ultimately reflect 382 instability of the ice-proximal slope, although it is not yet clear whether this was driven by 383 autogenic moraine stabilisation or external factors (e.g. subsequent glacial advance, fluvial 384

erosion). Clusters of "good" boulders were also identified on the Arànser left moraine but
these are distributed across moraine crests and ice-proximal and -distal slopes and follow
no clear spatial pattern. Finally, local Moran's *I* identified both "young" and "good" clusters
on the outer Soum d'Ech moraine (Fig. 6B) but there is no clear geomorphological evidence
which explains their distribution.

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

395 3.5. Sensitivity results

Based on the sensitivity analysis described in Section 2.6, there are clear differences in the number of SH samples required to reproduce the landform ages obtained from the full datasets (n = 60 - 275; Fig 7B). The Outer Pleta Naua landform age requires only three samples at both 1σ and 2σ . Landform ages for both the Arànser left and right moraines can be reproduced with relatively few samples at both 1σ ($n \le 26$) and 2σ ($n = \le 16$), while both the Soum d'Ech and Tallada moraines require ≥ 40 samples to reproduce the landform age at 1σ .

403 These trends are largely explained by the degree of overlap between component Gaussian distributions (see Fig. 5). Both the Tallada (Fig. 5A) and Soum d'Ech moraines (Fig. 5E) 404 feature lower probability component Gaussians, centred on 4.7 \pm 0.9 ka and 24.4 \pm 1.7 ka 405 respectively, which overlap with the highest probability component Gaussian. In contrast, 406 407 there is minimal overlap between component Gaussians for the Aranser left moraine (Fig. 5C), despite the high degree of dataset skew and the large number of "bad" boulders (44%). 408 The Aranser right moraine is intermediate in character (Fig. 5D), with clear unidirectional 409 skew but a greater degree of overlap between the highest probability Gaussian (22.3 \pm 0.9 410 ka) and younger lower probability component Gaussians (17.6 \pm 2.9 ka; 20.9 \pm 0.9 ka). This 411 distribution explains the larger number of samples required at both 1σ and 2σ relative to the 412 Arànser left moraine. Ultimately, as the degree of overlap between component Gaussians 413 increases, more samples are required to isolate the highest probability component Gaussian 414 and eliminate PDE skew. Despite this, all landform ages could be reproduced with relatively 415 few samples at both 1σ (n \leq 40) and 2σ (n \leq 26). While these values exceed typical sample 416 417 size recommendations for TCN dating (Putkonen and Swanson, 2003), they are based upon strict thresholds (\geq 95% of simulated landform ages within 1 σ or 2 σ of the full dataset 418 landform age) and should be utilised by researchers when pre-screening a larger population 419 of boulders prior to targeted TCN sampling. 420

421 **4. Discussion**

422 Efforts to minimise sampling bias of moraine TCN datasets may significantly improve the 423 utility of moraine chronologies in determining glacial history and the climatic drivers of

- 424 glacial cycles. However, while careful geomorphological assessment of individual boulders is
- 425 necessary to isolate those influenced by pre- or post-depositional processes, many criteria
- for TCN sample selection have not been tested quantitatively. Of these, boulder location is
 traditionally thought to be critical, as moraine crest boulders are prioritised due to
- 428 perceived stability (e.g. Gosse et al., 1995; Hallet and Putkonen, 1994), while those
- 429 deposited on ice-proximal or -distal slopes are typically rejected. This study is the first to
- 430 quantitatively assess this approach.
- Based on ¹⁰Be (n = 10) and Schmidt hammer sampling (n = 635) of ice-marginal moraines in 431 the Pyrenees, it is clear that the spatial distribution of SH-calibrated exposure ages is both 432 complex and site-specific. For many moraines, the distribution of "good" and "bad" boulders 433 434 is effectively random (p > 0.05), as assessed using global Moran's *I* (Table 3), while in others, clusters of "good" and "bad" boulders have clear geomorphological explanations. More 435 fundamentally, the likelihood of selecting a "good" boulder is comparable for moraine 436 crests, ice-proximal and -distal slopes (Fig. 7A). Although statistically significant spatial 437 clustering is evident for the Aranser left and Soum d'Ech moraines (p < 0.05; Fig. 6), the 438 distribution of "good" boulder clusters is complex, with clusters distributed across moraine 439 440 crests and moraine slopes.
- While there are no consistent spatial patterns at the inter-landform scale, the temporal 441 442 distribution of SH-calibrated exposure ages varies markedly between the studied landforms, with a number of important observations. First, moraine sedimentology appears to place a 443 key control on post-depositional stability (Zreda et al., 1994; Putkonen and O'Neal, 2006), 444 as age distributions for matrix-rich moraines (e.g. Aranser, Soum d'Ech) are strongly 445 negatively skewed (Fig. 6), with many boulders younger than the assigned age of the 446 landform. The frequency of "young" boulders for these moraines (Table 2) likely reflects the 447 influence of diffusive slope processes (Applegate et al., 2010), as the transfer of sediment to 448 the base of moraine slopes drives exhumation of entrained boulders (Porter and Swanson, 449 2008) and erosion of moraine crests (Schaller et al., 2009) and leads to increasingly subdued 450 moraine topography (Putkonen and O'Neal, 2006). The clearest signal of moraine 451 degradation is evident at the Aranser left (IQR = 7.9 ka; Skew = -1.02) and Aranser right 452 453 moraines (IQR = 6.9 ka; Skew = -1.13) and this trend may be partially explained by forest growth and boulder toppling (lvy-Ochs et al., 2007), as well as the effects of fluvial incision 454
- 455 (Fig. 6), while historic land use may also play a role (Pallàs et al., 2010).
- In contrast, the boulder-rich, matrix-poor Outer Pleta Naua moraine stabilised rapidly after 456 glacial retreat, as evidenced by the distribution and clustering of both its SH-calibrated 457 exposure ages (IQR = 0.6 ka; Shapiro Wilk W = 0.96, p = 0.07) and the corresponding ¹⁰Be 458 dataset (Pallàs et al., 2006). The sedimentology of the Outer Pleta Naua moraine is likely a 459 function of catchment size and glacier area, and the short transport distance from the 460 bedrock source area (Fig. 3; \leq 300 m). In the absence of a supporting sediment matrix, 461 462 boulder-rich moraines stabilise quickly and appear less susceptible to subsequent erosion (Ivy-Ochs et al., 2007; Pallàs et al., 2010). Finally, for moraines deposited by niche cirque 463 464 glaciers, reworking of glacial, periglacial or rockfall material appears more significant than

- post-depositional modification, in line with previous studies (Heyman et al., 2011). In these
 environments, the age of the oldest boulder may overestimate the "true" age of the
- 467 moraine (Putkonen and Swanson, 2003; Briner et al., 2005).

468 Implications for TCN sampling of moraines

The results described above have implications for future sampling approaches. First, while 469 "good" boulders are not more likely on moraine crests, we find there is no clear penalty to 470 moraine crest sampling, as initial differences between moraine crests and ice-proximal and -471 distal slopes appear to be masked by continued moraine degradation. Thus, in the absence 472 of detailed geomorphological assessments of individual landforms, restricting sampling to 473 474 moraine crests is a viable strategy to minimise the likelihood of boulder instability, assuming there are sufficient numbers of boulders to select from. This finding is unlikely to hold true 475 476 for recently deposited (< I ka) unconsolidated landforms (Putkonen and O'Neal, 2006), whose over-steepened ice-proximal slopes have yet to stabilise (Briner et al., 2005; Dortch 477 478 et al., 2010).

Second, our results show that sampling boulders on ice-proximal and -distal slopes can be as 479 effective as sampling moraine crests (Fig. 7A). While boulder density is typically highest at 480 moraine crests (Putkonen et al., 2008), there is no guarantee that these boulders are the 481 best options for TCN dating. Moreover, if sample selection criteria are rigorously applied, 482 the number of suitable boulders available for dating could fall below a critical level. Without 483 robust statistical identification of outliers, this could lead to unclear results given the 484 ubiquity of post-depositional modification of moraines (Zech et al., 2005; Heyman et al., 485 2011). One strategy which is rarely utilised is to select boulders for TCN dating from ice-486 proximal and -distal slopes, but evidence from the studied moraines indicates that this is a 487 viable strategy, as the proportion of "good" boulders is comparable to moraine crests (Fig. 488 7A). For many moraines, the spatial distribution of "good" boulders is random, while 489 statistically significant clusters of "good" boulders are distributed across moraine crests and 490 moraine slopes (Fig. 6). These observations indicate that redefining selection criteria to 491 492 include the entire population of moraine boulders would have no clear negative effect and could prove beneficial for moraines where ideal boulders are rare or are distributed away 493 from moraine crests. 494

Third, our data indicate that landform characteristics have a clear impact on the temporal 495 distribution of SH-calibrated exposure ages (Fig. 5; Putkonen and O'Neal, 2006; Ivy-Ochs et 496 497 al., 2007; Pallas et al., 2010). Within this context, we suggest that landform stability should be prioritised, as differences between landforms appear far greater than differences between 498 boulder groups on an individual landform (C vs. IS vs. OS). Differences are evident as a 499 function of moraine sedimentology (Zreda et al., 1994), with rapid stabilisation of matrix-500 501 poor, boulder-rich moraines (e.g. Outer Pleta Naua; Pallàs et al., 2006; 2010; lvy-Ochs et al., 2007) but prolonged degradation of unconsolidated landforms (e.g. Aranser; Putkonen and 502 O'Neal, 2006; Dortch et al., 2010). Although moraine sedimentology has explanatory power 503 504 for the studied moraines, the observed trends are unlikely to hold true in all settings due to 505 climatic and topographic controls on moraine stability (Barr and Lovell, 2014). Moreover,

- 506 restricting sampling to matrix-poor landforms could have unintended adverse effects, as
- 507 moraines may incorporate supraglacial rock avalanche debris and may primarily preserve a
- 508 non-climatic signal. Alternatively, sampling unconsolidated landforms does not guarantee
- poor clustering (e.g. $\chi^2 > 1$), particularly in regions where moraine denudation is limited by
- climate (Zech et al., 2005; Morgan et al., 2011; Balter et al., 2020) or where topographic
- 511 factors promote moraine stability (Barr and Lovell, 2014). Finally, restricting sampling to
- 512 landforms with specific characteristics is often not viable, as key glacial chronological
- 513 markers may be represented by only a small number of landforms.
- 514 Within this context, we suggest that landform selection is critical, and care should be taken
- 515 to select methods which are appropriate for its assumed age and stability and to collect a 516 sufficient number of samples to enable robust outlier identification (Putkonen and Swanson,
- 517 2003). However, it is often challenging to assess landform stability based on
- 518 geomorphological evidence alone. Our approach, in light of strong regional evidence for an
- 519 inverse correlation between SH *R*-values and exposure ages for granitic surfaces (Tomkins
- et al., 2018a; 2018b), indicates that preliminary SH sampling could be a useful method to
- 521 assess landform stability, to identify boulders affected by post-depositional processes, and to
- prioritise individual boulders for analysis based on *R*-value clustering (Tylmann et al., 2018).
- 523 Based on the sensitivity approach described in Section 2.6, the number of SH samples
- required scales with the complexity of the underlying distribution (Fig. 7B), from those
- which are approximately normal to those which feature overlapping component Gaussian
- distributions (Fig. 5) or multi-directional skew (i.e. pre- and post-depositional skew).
- 527 However, given that it is not possible to ascertain the underlying distribution a priori, a
- relatively large sample size is ultimately required. For most landforms, sampling a minimum of \sim 30 boulders would be a reasonable approach to estimate a depositional age within 2 σ (*n*
- 530 \geq 23), but more would be required ($n \geq$ 40) to improve precision to 1 σ for complex
- 531 datasets or if Schmidt hammer *R*-values were being used as a basis for cosmogenic nuclide
- 532 sample selection (Tylmann et al., 2018). Collecting a minimum of 30 40 samples is
- 533 necessary to ensure a full understanding of the underlying age distribution, even for complex
- 534 datasets. Based on this preliminary sampling, statistical approaches could be used to isolate
- component Gaussian distributions (Dortch et al., 2013; 2021) and to identify individual
- 536 boulders which are consistent with the age of the landform and to reject those which are
- 537 "young" or "old" (Heyman et al., 2011).
- Finally, it is important to note that the effectiveness of this approach may vary as a function of lithology and climate (McCarroll, 1989), while the underlying measurements are sensitive to factors which have only a minor effect on cosmogenic nuclide concentrations (e.g. surface discontinuities, Williams and Robinson, 1983; lichen coverage, Matthews and Owen, 2008). However, when these limitations are accounted for, Schmidt hammer *R*-values can be used as a proxy for surface exposure age (Fig. 4). Given the ubiquity of geologic scatter (e.g. exhumation, erosion, shielding), incorporating time- and cost-efficient preliminary SH
- sampling as an additional tool for TCN sample selection could ultimately improve the

- 546 chronological utility of the moraine record and enable a deeper understanding of the
- 547 climatic drivers of glacial cycles.

548 **Conclusions**

Based on ¹⁰Be and Schmidt hammer sampling of ice-marginal moraines in the Pyrenees, this 549 study provided the first quantitative analysis of the relative utility of moraine crest and 550 moraine slope sampling for terrestrial cosmogenic nuclide dating. Using spatial analysis of 551 SH-calibrated exposure ages, we show that there is no clear penalty to moraine slope 552 sampling. However, contrary to current sampling approaches, which typically prioritise 553 moraine crest boulders due to perceived stability, we show that the proportion of "good" 554 555 boulders is comparable between moraine crests and ice-proximal and -distal slopes, while for many moraines, the spatial distribution of "good" boulders is effectively random. 556 Crucially, however, differences between landforms appear more significant than differences 557 558 at the intra-landform scale; a result which indicates that the stability of the landform can have a far greater impact on the distribution of boulder exposure ages than the 559 characteristics and depositional context of individual boulders. In this study, moraine 560 sedimentology likely accounts for the observed differences between landforms, with rapid 561 stabilisation of matrix-poor, boulder-rich moraines and prolonged degradation for 562 unconsolidated landforms. Although these trends are unlikely to be universally applicable 563 given climatic and topographic controls on moraine stability, our data indicate that 564 preliminary SH sampling is a valuable tool to assess landform stability and to prioritise 565 individual boulders for further analysis. 566

567 Acknowledgements

MT was funded by a University of Manchester President's Doctoral Scholar Award. The 568 fieldwork for this paper was supported by a British Society for Geomorphology 569 Postgraduate Research grant awarded to MT. ¹⁰Be analysis was performed at the ASTER 570 AMS national facility (CEREGE), which is supported by the CNRS/INSU, by the ANR, 571 through the "projets thématiques d'excellence" programme for the "Equipements 572 d'excellence" ASTER-CEREGE action, and by the Institut de Recherche pour le 573 Développement (IRD). MT, JD, PH and RP designed the project, with refinements from IB 574 and CD. MT, JA and AS conducted Schmidt hammer sampling. ¹⁰Be sampling and analysis 575 was undertaken by RP, AR, DB, VR, VJ, LRR and RC. MT and JH conducted spatial analysis. 576 MT, IH and TB improved error propagation. All authors contributed to the manuscript. We 577 would like to thank Professor W. Amidon for his constructive review. We thank Dr. G. 578 Evatt and Dr. A. Smedley at the University of Manchester for their comments, D. Tomkins 579 580 and Dr. B. van Bodegraven for fieldwork support, and the contributors to the open-source libraries PySAL and GeoPandas. 581

582 Word Count: 6500

- 583
- 584

Moraine	Name	lsotope	Latitude (°)	Longitude (°)	Elevation (m)	Age (ka)	Internal ± (ka)	External ± (ka)	SH R ± SEM ^ь
	OPN01	¹⁰ Be	42.6365	0.7399	2217	13.2	1.3	1.6	-
Outer Pleta Naua ^c	OPN02	¹⁰ Be	42.6365	0.7406	2197	13.0	1.7	2.0	51.68 ± 0.5
	OPN03	¹⁰ Be	42.6365	0.7409	2195	12.6	1.2	1.5	-
	SAL-01	¹⁰ Be	42.4283	1.6300	2000	17.6	0.6	1.5	47.57 ± 0.83
	SAL-02	¹⁰ Be	42.4273	1.6321	1983	19.2	0.6	1.5	45.07 ± 0.84
	SAL-03	¹⁰ Be	42.4270	1.6326	1975	21.1	0.6	1.7	44.07 ± 0.82
	SAL-04	¹⁰ Be	42.4254	1.6358	1933	18.0	0.6	1.5	47.57 ± 0.84
A mànagar (p: 1 a)d	SAL-05	¹⁰ Be	42.4240	1.6389	1912	17.0	0.9	1.6	48.9 ± 0.77
	SAL-06	¹⁰ Be	42.4237	1.6395	1908	19.2	0.6	1.5	44.53 ± 0.74
Aranser (Right)	SAL-07	¹⁰ Be	42.4229	1.6415	1896	16.7	0.5	1.4	47.43 ± 0.96
	SAL-08	¹⁰ Be	42.4223	1.6447	1863	17.1	0.6	1.4	47.7 ± 0.9
	SAL-09	¹⁰ Be	42.4215	1.6481	1820	20.7	0.9	1.7	44.77 ± 0.8
	SAL-10	¹⁰ Be	42.4213	1.6489	1808	22.4	0.7	1.8	43.03 ± 0.95
	PIR-11-13	36 C	42.4213	1.6495	1809	18.2	1.6	2.1	-
	PIR-11-14	³⁶ Cl	42.4209	1.6499	1805	17.3	1.7	2.2	47.6 ± 0.83
	ECH01	¹⁰ Be	43.0863	-0.0870	776	19.7	3.2	3.6	42.43 ± 0.98
Soum d'Eche	ECH02	¹⁰ Be	43.0858	-0.0880	778	59.0	43.2 ^f	43.0	-
	ECH03	¹⁰ Be	43.0862	-0.0873	779	17.2	3.3	3.5	38.86 ± 1.11
	ECH04	¹⁰ Be	43.0865	-0.0867	781	16.8	3.0	3.3	38.77 ± 1.05

Table 1. Summary data for terrestrial cosmogenic exposure ages from the sampled moraines^a

^a Full sample information used for exposure age calculation is provided in the Supplementary Information or is available on GitHub: <u>https://github.com/matt-tomkins/moraine-crest-or-slope</u>, ^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).

585

Moraine	Group	Method ^a	Bandwidth⁵	Model fit ^c	Age (ka) ^d	IQR ^e	Skew	Normality ^f	Young (%) ^g	Good (%) ^g	Old (%) ^g
Tallada	-	STD / IQR	0.3731	0.9985	3.2 ± 0.7	I.2 ka	0.34	0.44	6	80	14
Outer Pleta Naua	-	Mean	2.016	I	12.5 ± 0.4^{h}	0.6 ka	-0.24	0.07	0	100	0
Arànser	Left	MAD	0.7003	0.9978	23.3 ± 1.1 ⁱ	7.9 ka	-1.02	< 0.01	44	56	0
	Right	MAD	0.6796	0.9991	22.3 ± 0.9	6.9 ka	-1.13	< 0.01	51	49	0
	Outer	STD / IQR	1.0734	0.998	26.2 ± 2.5	3.5 ka	-1.49	< 0.01	-	-	-
Soum d'Ech	Inner	STD / IQR	1.1661	0.9996	26.1 ± 1.7	3.5 ka	-1.05	< 0.01	-	-	-
	Combined	STD / IQR	0.9877	0.9989	27.3 ± 1.8	3.6 ka	-1.49	< 0.01	24	76	0

 Table 2. Age statistics for the sampled moraines

^{a,b} Method used for kernel density estimation (see Dortch *et al.*, 2021) and its associated numeric bandwidth, ^c All model *p* values < 0.01, ^d Reported uncertainty (±) is the 1 σ bounds (68%) of the highest probability component Gaussian, unless stated otherwise, ^e Interquartile range, ^f Shapiro-Wilk test for normality *p* values, ^g Based on the landform age ± 2 σ , ^h Arithmetic mean of 60 samples ± total uncertainty, ⁱ Calculation based on a reduced dataset of 274 samples. Sample ARL-192 (1.97 ± 2.06 ka) is more than three standard deviations from the mean of the remaining samples and was removed for program stability.

Table 3. Spatial statistics for the sampled moraines

		Number of samples				Global Morans I			"Good" boulder (%)		
Moraine	Туре	Total	ISª	Ca	OSª	Distance threshold (m) ^b	I	Simulated <i>p</i> value ^c	ISª	Ca	OSª
Tallada	Terminal	70	16	29	25	21.6	0.0980	0.0719	80	79	81
Outer Pleta Naua	Terminal	60	20	20	20	23.9	NAd	NAd	100	100	100
Arànser (Left)	Latero-frontal	275	199	51	25	59.5	0.0915	0.0064	53	57	76
Arànser (Right)	Latero-frontal	130	57	33	40	66.3	0.065 I	0.1194	63	36	40
Soum d'Ech	Laterals	100	37	50	13	51.1	0.1519	0.0106	76	72	81

^a Inner ice-proximal slope (IS), moraine crest (C) and outer ice-distal slope (OS), ^b Defined as the minimum distance required to ensure that each boulder has at least two neighbours, ^c p values > 0.05 support no statistically significant spatial clustering. p values \leq 0.05 are consistent with a non-random distribution and spatial clustering of the input data, ^d Spatial autocorrelation was not possible for the Outer Pleta Naua moraine as all boulders were classed as "good" based on the 2σ threshold.

587

- 588 **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
- 590 V3, WGS 84 UTM 31N), showing the locations of the studied catchments and selected moraines and
- 591 the distribution of Axial Zone granites within those catchments. The latter was derived from a
- 1:400,000 geological map produced by the IGME (Spain) and the BRGM (France). Also shown are the
- 593 locations of major summits (Aneto, Carlit, Estats, Plana de Lles, Monte Perdido, Posets,
- 594 Vignemale) and the extent of glaciers during the global Last Glacial Maximum (LGM; Calvet et al.,
- 595 **2011**).
- 596 **Figure 2.** Geomorphological maps for the (A) Aranser and (B) Soum d'Ech moraines (WGS 84
- 597 UTM 31N). These moraines likely correspond to the maximum ice extent (MIE) during the
- 598 Würmian glacial stage (11.7 110 ka; Calvet et al., 2011). Locations and sample names for TCN
- 599 dated boulders are shown (white circles; Rodés, 2008; Palacios et al., 2015). In (A), the locations of 600 the proximal Fornell (F) and Setut (S) moraines are highlighted. These moraines are stratigraphically
- 601 distinct from the sampled Aranser moraines but are currently undated. The margins of Aranser
- 602 glacier can be traced further up valley but sampling was focused on the illustrated moraine area (light
- purple shading) in which the moraine margins are easily delineated (≤ 2 km from glacier terminus).
- **Figure 3**. Geomorphological maps for the (A) Tallada and (B) Outer Pleta Naua moraines in the Val de Molières catchment of the Noguera Rigaborçana (WGS 84 UTM 31N). Locations and sample names for TCN dated boulders are shown (white circles; Pallàs et al., 2006). The Inner Pleta Naua moraine was also investigated by Pallàs et al., (2006) and returned recalculated ¹⁰Be ages of 6.3 ± 0.9 ka (IPN01) and 16.0 ± 2.5 ka (IPN02). Given the stratigraphic position of this deposit and limiting ages from the Outer Pleta Naua and Molières moraines (MUL01 = 14.9 ± 2.6 ka, MUL03 = 14.9 ± 1.9 ka; Pallàs et al., 2006), it appears likely that IPN02 is affected by inheritance.
- 611 **Figure 4**. (A) Location of exposure age calibration sites (blue points) in the Bassies (B, n = 6), Carlit (C, n = 3), Noguera Rigaborçana (N, n = 4), Maladeta (M_a, n = 9), Malniu (M_n, n = 21), Molières (M_o, 612 613 n = 2), Orri (O, n = 3) and Querol catchments (Q, n = 6). Underlying topography is ASTER GDEM V3 (WGS 84 UTM 31N). Also shown are the locations of sampled moraines (orange points; see Fig. 614 IF) and the maximum ice extent (MIE) during the global Last Glacial Maximum (LGM; Calvet et al., 615 2011). (B) Monte Carlo-derived orthogonal distance regression (ODR) between 54 ¹⁰Be exposure 616 ages (blue points ± external age uncertainty) and their corresponding SH R-values (mean of 30 R-617 values \pm Standard Error of the Mean; Tomkins et al., 2018b), plus 1 σ (blue dashed lines) and 2σ 618 prediction limits (grey dashed lines). Independent TCN samples (¹⁰Be, ³⁶Cl) from the studied 619 620 moraines (n = 15) are shown as orange points. Inherited outliers from the original calibration dataset 621 (n = 2; Tomkins et al., 2018b) are not shown for clarity. (C) Example of a ¹⁰Be dated boulder from
- 622 the Aranser right moraine (SAL-10).
- 623 Figure 5. Gaussian decomposition of SH-calibrated boulder exposure ages for the Tallada (A),
- 624 Outer Pleta Naua (B), Arànser (C-D) and Soum d'Ech moraines (E). Following P-CAAT guidelines
- 625 (Dortch et al., 2013; 2021), we selected the highest probability component Gaussian (red shading) to
- 626 represent the age of the landform as all are \leq LGM. The summed probability density estimate (PDE) 627 and lower probability component Gaussians are denoted by black and grey distributions,
- respectively. For each moraine, we include the bandwidth estimator used and its associated numeric
- bandwidth, the P-CAAT model fit (R^2), the total number of SH-calibrated exposure ages(n) and in
- 630 brackets, the number of ages which are enclosed by the selected component Gaussian distribution at
- 2σ . Based on this approach, selected component Gaussians are interpreted to reflect the timing of

- 632 moraine deposition or initial stabilisation. In contrast, younger component Gaussians may reflect
- 633 post-depositional processes (e.g. moraine degradation, boulder exhumation or instability) while
- 634 older component Gaussians likely incorporate pre-depositional processes (e.g. reworking of glacial
- 635 deposits).

636 Figure 6. Results of local Moran's I spatial autocorrelation for the Aranser left (A) and Soum d'Ech moraines (B). Points denote the location of sampled boulders, with neighbouring boulders linked by 637 grey lines. Neighbours are calculated based on a fixed distance, defined as the minimum distance 638 639 required to ensure that each boulder has at least two neighbours, and were analysed using inverse distance weighted (IDW). Points are coloured based on the results of local Moran's I, with regions of 640 641 no statistically significant spatial clustering shown as white, while clusters of "good" (HH) and "bad" 642 boulders (LL) and their contributing neighbours are shown in blue and red, respectively. Outlier points (HL and LH) are not shown for clarity. A histogram illustrating the distribution of calibrated 643 boulder exposure ages is included for each moraine, coloured by the "good" (blue) and "bad" 644 645 components (grey).

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

650 **References**

- Applegate, P.J., Urban, N.M., Keller, K., Lowell, T.V., Laabs, B.J.C., Kelly, M.A., Alley, R.B., 2012. Improved
 moraine age interpretations through explicit matching of geomorphic process models to cosmogenic
 nuclide measurements from single landforms. Quaternary Research 77, 293–304.
 <u>https://doi.org/10.1016/j.yqres.2011.12.002</u>
- Applegate, P.J., Urban, N.M., Laabs, B.J.C., Keller, K., Alley, R.B., 2010. Modeling the statistical distributions of
 cosmogenic exposure dates from moraines. Geoscientific Model Development 3, 293–307.
 <u>https://doi.org/10.5194/gmd-3-293-2010</u>
- Balter, A., Bromley, G., Balco, G., Thomas, H., Jackson, M.S., 2020. A 14.5-million-year record of East Antarctic
 Ice Sheet fluctuations from the central Transantarctic Mountains, constrained with cosmogenic ³He, ¹⁰Be,
 ²¹Ne, and ²⁶Al. The Cryosphere Discussions 1–41. <u>https://doi.org/10.5194/tc-2020-57</u>
- Barr, I.D., Lovell, H., 2014. A review of topographic controls on moraine distribution. Geomorphology 226,
 44–64. <u>https://doi.org/10.1016/j.geomorph.2014.07.030</u>
- Boggs, Paul T., Rogers, J.E., 1990. Orthogonal distance regression, in: "Statistical Analysis of Measurement
 Error Models and Applications: Proceedings of the AMS-IMS-SIAM Joint Summer Research Conference
 Held June 10-16, 1989,." Presented at the Contemporary Mathematics, p. 186.
 https://doi.org/10.6028/nist.ir.89-4197
- Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., Nishiizumi, K., Phillips, F., Schaefer, J.,
 Stone, J., 2016. Geological calibration of spallation production rates in the CRONUS-Earth project.
 Quaternary Geochronology 31, 188–198. https://doi.org/10.1016/j.quageo.2015.01.009
- Briner, J.P., Kaufman, D.S., Manley, W.F., Finkel, R.C., Caffee, M.W., 2005. Cosmogenic exposure dating of late
 Pleistocene moraine stabilization in Alaska. GSA Bulletin 117, 1108–1120.
 https://doi.org/10.1130/B25649.1
- 673 Calvet, M., Delmas, M., Gunnell, Y., Braucher, R., Bourlès, D., 2011. Chapter 11 Recent Advances in Research
 674 on Quaternary Glaciations in the Pyrenees, in: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Developments
 675 in Quaternary Sciences, Quaternary Glaciations Extent and Chronology. Elsevier, 127–139.
 676 https://doi.org/10.1016/B978-0-444-53447-7.00011-8
- 677 Chevalier, M.-L., Replumaz, A., 2019. Deciphering old moraine age distributions in SE Tibet showing bimodal
 678 climatic signal for glaciations: Marine Isotope Stages 2 and 6. Earth and Planetary Science Letters 507, 105–
 679 118. <u>https://doi.org/10.1016/j.epsl.2018.11.033</u>
- Darmody, R.G., Thorn, C.E., Allen, C.E., 2005. Chemical weathering and boulder mantles, Kärkevagge, Swedish
 Lapland. Geomorphology, Weathering and landscape evolution 67, 159–170.
 <u>https://doi.org/10.1016/j.geomorph.2004.07.011</u>

- Darvill, C.M., Bentley, M.J., Stokes, C.R., 2015. Geomorphology and weathering characteristics of erratic
 boulder trains on Tierra del Fuego, southernmost South America: Implications for dating of glacial
 deposits. Geomorphology 228, 382–397. <u>https://doi.org/10.1016/j.geomorph.2014.09.017</u>
- Dortch, J.M., Owen, L.A., Caffee, M.W., Li, D., Lowell, T.V., 2010. Beryllium-10 surface exposure dating of
 glacial successions in the Central Alaska Range. Journal of Quaternary Science 25, 1259–1269.
 https://doi.org/10.1002/jqs.1406
- Dortch, J.M., Owen, L.A., Caffee, M.W., 2013. Timing and climatic drivers for glaciation across semi-arid
 western Himalayan–Tibetan orogen. Quaternary Science Reviews 78, 188–208.
 https://doi.org/10.1016/j.quascirev.2013.07.025
- Dortch, J.M., Tomkins, M.D., Saha, S., Murari, M.K., Schoenbohm, L.M., Curl, D., 2021. Probabilistic
 Cosmogenic Age Analysis Tool (P-CAAT), a tool for the ages. Manuscript in preparation.
- Ehlmann, B.L., Viles, H.A., Bourke, M.C., 2008. Quantitative morphologic analysis of boulder shape and surface
 texture to infer environmental history: A case study of rock breakdown at the Ephrata Fan, Channeled
 Scabland, Washington. Journal of Geophysical Research: Earth Surface 113.
 https://doi.org/10.1029/2007/F000872
- Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., Middleton, R., 1995. Precise cosmogenic ¹⁰Be measurements in western North America: Support for a global Younger Dryas cooling event. Geology 23, 877–880.
 <u>https://doi.org/10.1130/0091-7613(1995)023<0877:PCBMIW>2.3.CO;2</u>
- Hallet, B., Putkonen, J., 1994. Surface Dating of Dynamic Landforms: Young Boulders on Aging Moraines.
 Science 265, 937–940. <u>https://doi.org/10.1126/science.265.5174.937</u>
- Heyman, J., Applegate, P.J., Blomdin, R., Gribenski, N., Harbor, J.M., Stroeven, A.P., 2016. Boulder height –
 exposure age relationships from a global glacial ¹⁰Be compilation. Quaternary Geochronology 34, 1–11.
 https://doi.org/10.1016/j.quageo.2016.03.002
- Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W., 2011. Too young or too old: Evaluating cosmogenic
 exposure dating based on an analysis of compiled boulder exposure ages. Earth and Planetary Science
 Letters 302, 71–80. <u>https://doi.org/10.1016/j.epsl.2010.11.040</u>
- Ivy-Ochs, S., Kerschner, H., Schlüchter, C., 2007. Cosmogenic nuclides and the dating of Lateglacial and Early
 Holocene glacier variations: The Alpine perspective. Quaternary International, From the Swiss Alps to the
 Crimean Mountains Alpine Quaternary stratigraphy in a European context 164–165, 53–63.
 https://doi.org/10.1016/j.quaint.2006.12.008
- Lal, D., 1991. Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models.
 Earth and Planetary Science Letters 104, 424–439. <u>https://doi.org/10.1016/0012-821X(91)90220-C</u>
- Marrero, S.M., Hein, A.S., Naylor, M., Attal, M., Shanks, R., Winter, K., Woodward, J., Dunning, S., Westoby,
 M., Sugden, D., 2018. Controls on subaerial erosion rates in Antarctica. Earth and Planetary Science
 Letters 501, 56–66. <u>https://doi.org/10.1016/j.epsl.2018.08.018</u>
- Marrero, S.M., Phillips, F.M., Borchers, B., Lifton, N., Aumer, R., Balco, G., 2016. Cosmogenic nuclide
 systematics and the CRONUScalc program. Quaternary Geochronology 31, 160–187.
 <u>https://doi.org/10.1016/j.quageo.2015.09.005</u>
- Matthews, J.A., Owen, G., 2008. Endolithic lichens, rapid biological weathering and schmidt hammer r-values
 on recently exposed rock surfaces: storbreen glacier foreland, jotunheimen, norway. Geografiska Annaler:
 Series A, Physical Geography 90, 287–297. https://doi.org/10.1111/j.1468-0459.2008.00346.x
- McCarroll, D., 1989. Potential and Limitations of the Schmidt Hammer for Relative-Age Dating: Field Tests on
 Neoglacial Moraines, Jotunheimen, Southern Norway. Arctic and Alpine Research 21, 268–275.
 <u>https://doi.org/10.2307/1551565</u>
- Morgan, D.J., Putkonen, J., Balco, G., Stone, J., 2011. Degradation of glacial deposits quantified with cosmogenic nuclides, Quartermain Mountains, Antarctica. Earth Surface Processes and Landforms 36, 217–228.
 <u>https://doi.org/10.1002/esp.2039</u>
- Niedzielski, T., Migoń, P., Placek, A., 2009. A minimum sample size required from Schmidt hammer
 measurements. Earth Surface Processes and Landforms 34, 1713–1725. <u>https://doi.org/10.1002/esp.1851</u>
- Palacios, D., Gómez-Ortiz, A., Andrés, N., Vázquez-Selem, L., Salvador-Franch, F., Oliva, M., 2015. Maximum
 extent of Late Pleistocene glaciers and last deglaciation of La Cerdanya mountains, Southeastern Pyrenees.
 Geomorphology 231, 116–129. <u>https://doi.org/10.1016/j.geomorph.2014.10.037</u>
- Pallàs, R., Rodés, Á., Braucher, R., Bourlès, D., Delmas, M., Calvet, M., Gunnell, Y., 2010. Small, isolated glacial
 catchments as priority targets for cosmogenic surface exposure dating of Pleistocene climate fluctuations,
 southeastern Pyrenees. Geology 38, 891–894. <u>https://doi.org/10.1130/G31164.1</u>
- 738 Pallàs, R., Rodés, Á., Braucher, R., Carcaillet, J., Ortuño, M., Bordonau, J., Bourlès, D., Vilaplana, J.M., Masana,
- E., Santanach, P., 2006. Late Pleistocene and Holocene glaciation in the Pyrenees: a critical review and new evidence from ¹⁰Be exposure ages, south-central Pyrenees. Quaternary Science Reviews 25, 2937–2963.
 <u>https://doi.org/10.1016/j.quascirev.2006.04.004</u>

- Portenga, E.W., Bierman, P.R., 2011. Understanding Earth's eroding surface with ¹⁰Be. GSAT 21, 4–10.
 <u>https://doi.org/10.1130/G111A.1</u>
- Porter, S.C., Swanson, T.W., 2008. ³⁶Cl dating of the classic Pleistocene glacial record in the northeastern Cascade Range, Washington. Am J Sci 308, 130–166. <u>https://doi.org/10.2475/02.2008.02</u>
- Putkonen, J., Connolly, J., Orloff, T., 2008. Landscape evolution degrades the geologic signature of past
 glaciations. Geomorphology, Glacial Landscape Evolution Implications for Glacial Processes, Patterns and
 Reconstructions 97, 208–217. <u>https://doi.org/10.1016/j.geomorph.2007.02.043</u>
- Putkonen, J., O'Neal, M., 2006. Degradation of unconsolidated Quaternary landforms in the western North
 America. Geomorphology, Quaternary landscape change and modern process in western North America
 751 75, 408–419. <u>https://doi.org/10.1016/j.geomorph.2005.07.024</u>
- Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research 59, 255–
 261. <u>https://doi.org/10.1016/S0033-5894(03)00006-1</u>
- Reille, M., Andrieu, V., 1995. The late Pleistocene and Holocene in the Lourdes Basin, Western Pyrénées,
 France: new pollen analytical and chronological data. Veget Hist Archaebot 4, 1–21.
 https://doi.org/10.1007/BF00198611
- Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L.,
 Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T.J., Hoffmann,
 D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards,
 D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C.S.M., Plicht, J. van der, 2013. IntCal13 and Marine13
 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. Radiocarbon 55, 1869–1887.
 https://doi.org/10.2458/azu_js_rc.55.16947
- Riebe, C.S., Kirchner, J.W., Finkel, R.C., 2004. Erosional and climatic effects on long-term chemical weathering
 rates in granitic landscapes spanning diverse climate regimes. Earth and Planetary Science Letters 224,
 547–562. <u>https://doi.org/10.1016/j.epsl.2004.05.019</u>
- Rodés, Á., 2008. La última deglaciación en los pirineos: de superficies de exposición mediante ¹⁰be, y modelado
 numérico de paleoglaciares (http://purl.org/dc/dcmitype/Text). Universitat de Barcelona.
- Schaller, M., Ehlers, T.A., Blum, J.D., Kallenberg, M.A., 2009. Quantifying glacial moraine age, denudation, and
 soil mixing with cosmogenic nuclide depth profiles. Journal of Geophysical Research: Earth Surface 114.
 https://doi.org/10.1029/2007JF000921
- Stone, J.O., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research: Solid
 Earth 105, 23753–23759. <u>https://doi.org/10.1029/2000JB900181</u>
- Stübner, K., Grin, E., Hidy, A.J., Schaller, M., Gold, R.D., Ratschbacher, L., Ehlers, T., 2017. Middle and Late
 Pleistocene glaciations in the southwestern Pamir and their effects on topography. Earth and Planetary
 Science Letters 466, 181–194. <u>https://doi.org/10.1016/j.epsl.2017.03.012</u>
- Sumner, P., Nel, W., 2002. The effect of rock moisture on Schmidt hammer rebound: tests on rock samples
 from Marion Island and South Africa. Earth Surface Processes and Landforms 27, 1137–1142.
 https://doi.org/10.1002/esp.402
- Tomkins, M.D., Huck, J.J., Dortch, J.M., Hughes, P.D., Kirkbride, M.P., Barr, I.D., 2018a. Schmidt Hammer
 exposure dating (SHED): Calibration procedures, new exposure age data and an online calculator.
 Quaternary Geochronology 44, 55–62. <u>https://doi.org/10.1016/j.quageo.2017.12.003</u>
- Tomkins, M.D., Dortch, J.M., Hughes, P.D., Huck, J.J., Stimson, A.G., Delmas, M., Calvet, M., Pallàs, R., 2018b.
 Rapid age assessment of glacial landforms in the Pyrenees using Schmidt hammer exposure dating (SHED).
 Quaternary Research 90, 26–37. <u>https://doi.org/10.1017/qua.2018.12</u>
- Tylmann, K., Woźniak, P.P., Rinterknecht, V.R., 2018. Erratics selection for cosmogenic nuclide exposure dating an optimization approach. Baltica 31, 100–114. <u>https://doi.org/10.5200/baltica.2018.31.10</u>
- Williams, R.B.G., Robinson, D.A., 1983. The effect of surface texture on the determination of the surface hardness of rock using the schmidt hammer. Earth Surface Processes and Landforms 8, 289–292.
 <u>https://doi.org/10.1002/esp.3290080311</u>
- Zech, R., Glaser, B., Sosin, P., Kubik, P.W., Zech, W., 2005. Evidence for long-lasting landform surface
 instability on hummocky moraines in the Pamir Mountains (Tajikistan) from ¹⁰Be surface exposure dating.
 Earth and Planetary Science Letters 237, 453–461. <u>https://doi.org/10.1016/j.epsl.2005.06.031</u>
- Zreda, M.G., Phillips, F.M., 1995. Insights into alpine moraine development from cosmogenic ³⁶Cl buildup
 dating. Geomorphology, Glacial Geomorphology: Process and Form Development 14, 149–156.
 <u>https://doi.org/10.1016/0169-555X(95)00055-9</u>
- Zreda, M.G., Phillips, F.M., Elmore, D., 1994. Cosmogenic ³⁶Cl accumulation in unstable landforms: 2.
 Simulations and measurements on eroding moraines. Water Resources Research 30, 3127–3136. https://doi.org/10.1029/94WR00760















Moraine	Name	lsotope	Latitude (°)	Longitude (°)
	OPN01	¹⁰ Be	42.6365	0.7399
Outer Pleta Naua ^c	OPN02	¹⁰ Be	42.6365	0.7406
	OPN03	¹⁰ Be	42.6365	0.7409
	SAL-01	¹⁰ Be	42.4283	1.63
	SAL-02	¹⁰ Be	42.4273	1.6321
	SAL-03	¹⁰ Be	42.427	1.6326
	SAL-04	¹⁰ Be	42.4254	1.6358
	SAL-05	¹⁰ Be	42.424	1.6389
b d	SAL-06	¹⁰ Be	42.4237	1.6395
Aranser (Right)	SAL-07	¹⁰ Be	42.4229	1.6415
	SAL-08	¹⁰ Be	42.4223	1.6447
	SAL-09	¹⁰ Be	42.4215	1.6481
	SAL-10	¹⁰ Be	42.4213	1.6489
	PIR-11-13	³⁶ Cl	42.4213	1.6495
	PIR-11-14	³⁶ Cl	42.4209	1.6499
	ECH01	¹⁰ Be	43.0863	-0.087
	ECH02	¹⁰ Be	43.0858	-0.088
Soum d Ech	ECH03	¹⁰ Be	43.0862	-0.0873
	ECH04	¹⁰ Be	43.0865	-0.0867

Table	I. Summary	/ data foi	r terrestrial	cosmogenic	exposure	ages from	the sar	nple

^a Full sample information used for exposure age calculation is provided in the Supp tomkins/moraine-paper-2020, ^b Mean of 30 SH R-values ± the Standard Error of th al. (2015), ^e ECH samples from Rodés (2008), ^f Measurement error, see Rodés (20

d moraines				
Elevation (m)	Age (ka)	Internal ± (ka)	External ± (ka)	SH R \pm SEM ^b
2217	13.2	1.3	1.6	-
2197	13	1.7	2	51.68 ± 0.5
2195	12.6	1.2	1.5	-
2000	17.6	0.6	1.5	47.57 ± 0.83
1983	19.2	0.6	1.5	45.07 ± 0.84
1975	21.1	0.6	1.7	44.07 ± 0.82
1933	18	0.6	1.5	47.57 ± 0.84
1912	17	0.9	1.6	48.9 ± 0.77
1908	19.2	0.6	1.5	44.53 ± 0.74
1896	16.7	0.5	1.4	47.43 ± 0.96
1863	17.1	0.6	1.4	47.7 ± 0.9
1820	20.7	0.9	1.7	44.77 ± 0.8
1808	22.4	0.7	1.8	43.03 ± 0.95
1809	18.2	1.6	2.1	-
1805	17.3	1.7	2.2	47.6 ± 0.83
776	19.7	3.2	3.6	42.43 ± 0.98
778	59	43.2 ^f	43	-
779	17.2	3.3	3.5	38.86 ± 1.11
781	16.8	3	3.3	38.77 ± 1.05

ed moraines^a

lementary Information or is available on GitHub: https://github.com/matt-

ie Mean, ^c OPN samples from Pallàs et al. (2006), ^d PIR samples from Palacios et 08).

Moraine	Group	Method ^a	Bandwidth ^b	Model fit ^c	Age (ka) ^d
Tallada	-	STD / IQR	0.3731	0.9985	3.2 ± 0.7
Outer Pleta Naua	-	Mean	2.016	Ι	12.5 ± 0.4 ^h
Aràncor	Left	MAD	0.7003	0.9978	23.3 ± 1.1 ⁱ
Aranser	Right	MAD	0.6796	0.9991	22.3 ± 0.9
	Outer	STD / IQR	1.0734	0.998	26.2 ± 2.5
Soum d'Ech	Inner	STD / IQR	1.1661	0.9996	26.1 ± 1.7
	Combined	STD / IQR	0.9877	0.9989	27.3 ± 1.8

 Table 2. Age statistics for the sampled moraines

^{a,b} Method used for kernel density estimation after Silverman (1986) and Dortch *et al*. (2020) and its uncertainty (±) is the 1 σ bounds (68%) of the highest probability component Gaussian, unless stated Based on the landform age ± 2 σ , ^h Arithmetic mean of 60 samples ± total uncertainty, ⁱ Calculation b more than three standard deviations from the mean of the remaining samples and was removed for

IQR ^e	Skew	Normality ^f	Young (%) ^g	Good (%) ^g	Old (%) ^g
I.2 ka	0.34	0.44	6	80	14
0.6 ka	-0.24	0.07	0	100	0
7.9 ka	-1.02	< 0.01	44	56	0
6.9 ka	-1.13	< 0.01	51	49	0
3.5 ka	-1.49	< 0.01	-	-	-
3.5 ka	-1.05	< 0.01	-	-	-
3.6 ka	-1.49	< 0.01	24	76	0

s associated numeric bandwidth, ^cAll model p values < 0.01, ^d Reported | otherwise, ^e Interquartile range, ^fShapiro-Wilk test for normality p values, ^g

based on a reduced dataset of 274 samples. Sample ARL-192 (1.97 \pm 2.06 ka) is program stability.

		N	umber of	samples	
Moraine	Туре	Total	IS ^a	C^a	OSª
Tallada	Terminal	70	16	29	25
Outer Pleta Naua	Terminal	60	20	20	20
Arànser (Left)	Latero-frontal	275	199	51	25
Arànser (Right)	Latero-frontal	130	57	33	40
Soum d'Ech	Laterals	100	37	50	13

Table 3	. Spatial	statistics	for the	sampled	moraines
---------	-----------	------------	---------	---------	----------

^a Inner ice-proximal slope (IS), moraine crest (C) and outer ice-distal slope (OS) neighbours, ^c p values > 0.05 support no statistically significant spatial clustering input data, ^d Spatial autocorrelation was not possible for the Outer Pleta Naua I

Global Morans I				
Ι	Simulated p value ^c	IS ^a	C ^a	OSª
0.0980	0.0719	80	79	81
NA^{d}	NA ^d	100	100	100
0.0915	0.0064	53	57	76
0.0651	0.1194	63	36	40
0.1519	0.0106	76	72	81
	Il Morans <i>I</i> <i>I</i> 0.0980 NA ^d 0.0915 0.0651 0.1519	Il Morans / / Simulated p value ^c 0.0980 0.0719 NA ^d NA ^d 0.0915 0.0064 0.0651 0.1194 0.1519 0.0106	I Morans I "God I Simulated p value ^c IS ^a 0.0980 0.0719 80 NA ^d NA ^d 100 0.0915 0.0064 53 0.0651 0.1194 63 0.1519 0.0106 76	I Morans I "Good" boulder I Simulated p value ^c IS ^a C ^a 0.0980 0.0719 80 79 NA ^d NA ^d 100 100 0.0915 0.0064 53 57 0.0651 0.1194 63 36 0.1519 0.0106 76 72

), ^b Defined as the minimum distance required to ensure that each boulder has at least two ; *p* values ≤ 0.05 are consistent with a non-random distribution and spatial clustering of the moraine as all boulders were classed as "good" based on the 2σ threshold.