**Supplementary Material: Extended Methods**

1. **Geomorphological mapping imagery**

**Table S1**. Imagery information details

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| --- | --- | --- | --- | --- | --- |
| **Imagery source** | **Type** | **Resolution** | **Band combination** | | **Source** |
| Aerial Photographs | Photograph | 1:70,000 | - | *Servicio Aéreo Fotogramétrico*, Chile. www.saf.cl | |
| Sentinel 2 | Satellite Image | 10 m | 8 4 3 | European Space Agency  https://scihub.copernicus.eu/dhus/#/home | |
| Google Earth | Satellite Image | - | - | https://earth.google.com/ | |
| Shuttle Radar Topography Mission | DEM | 30 m | - | USGS EROS Center  https://opentopography.org/ | |

1. **Laboratory methods for 10Be analysis**

**10Be Laboratory process**

The boulders and surface cobbles samples were prepared in a combination of the cosmogenic labs from Pontificia Universidad Católica in Santiago, Chile, and Edinburgh University, UK. AMS measurements were done at Köln University, Germany. Whereas the samples from the outwash terrace located on the Otway lobe, were prepared entirely at Scottish Universities Environmental Research Centre (SUERC) as part of the UK NERC Cosmogenic Isotope Analysis Facility (CIAF).

***Moraine boulders and cobbles from outwash moraine and shoreline berms***

The quartz separation was done at Universidad Católica (UC) in Santiago, Chile and Edinburgh University, UK (EU). At UC, the samples were crushed and sieved to yield the 750-125 μm size fraction. Then, the samples were treated with aqua regia (HNO3:HCl=3:1) in order to eliminate any organic material and carbonates. The next step was a flotation process, where the samples were treated with 0.4%HF, and then some drops of eucalyptus oil were added, along with a mix of water and dodecylamine with CO2 gas. This allowed the feldspar and micas to acquire hydrophobic characteristics and thus float and be removed. Following this, the ferromagnesian minerals were separated from the rest of the sample by density separation with heavy liquid. Finally, the samples were leached in acid solutions of 1% HF and 0.8% HNO3, in an ultrasound bath for three days.

Samples prepared at the University of Edinburgh's Cosmogenic Nuclide Laboratory were crushed and sieved to isolate the 250-710 μm grain fractions, which were etched in an HCl and H2SiF6  solution on a shaker table for at least two days to remove/weaken non-quartz minerals. The samples were then etched a minimum of three times (24 h each) in a dilute HF and HNO3 solution in a heated ultrasonic bath to purify remaining quartz grains and remove meteoric 10Be (Hein, 2009). 10Be was selectively extracted from 7-23 g (average 19 g) of the pure quartz following standard methods from Hein et al. (2009). The samples and process blanks (n =4) were spiked with 0.25 mg of 9Be carrier (Scharlau Be carrier, 1000 mg/l, density 1.02 g/ml).

All 10Be concentrations are based on 2.79 x 10-11 nominal 10Be/9Be ratio (Nishiizumi *et al*., 2007) for NIST SRM4325 standard and a 10Be half-life of 1.36 Ma. The 10Be/9Be measurements were carried out at Cologne AMS (Dewald et al., 2013), normalized to the revised standard values reported by Nishiizumi et al. (2007). The 10Be concentration is reported after substraction of the 10Be atoms from the respective blanks. Process blank corrections ranged between 2.9% and 7.4% of the sample 10Be/9Be ratios. The analytical uncertainties of the 10Be concentrations were calculated by summing in quadrature the uncertainties in the mass of 9Be added during the sample processing and the AMS measurement uncertainties of both the sample and blank. The final 10Be concentrations and uncertainties are reported in **Table 1** (Main text).

***Depth profiles***

For the depth profile samples all physical and chemical preparation and 10Be/9Be AMS measurements were carried out at the Scottish Universities Environmental Research Centre (SUERC) as part of the NERC Cosmogenic Isotope Analysis Facility(CIAF). Surface cobbles were treated individually, whereas depth samples were treated as amalgams. All samples were crushed whole, milled and sieved, and the >250 μm to <500 μm fraction was then passed through a roll magnetic separator to separate the non-magnetic minerals prior to chemical analysis. Feldspars were separated by froth flotation. The quartz was then isolated and purified by repeat etching in 2% HF and 2% HNO3 in high-energy ultrasonic tanks to dissolve non quartz minerals and remove >30% of the starting mass to avoid contamination by meteoric 10Be. Quartz purity was assayed by ICP-OES. All samples were dissolved in 40% HF dry-downs on a hotplate. Dried samples were converted to chloride form and 0.2 mg of 9Be carrier was added to each sample. The solutions were passed through anion exchange columns to remove Fe and other contaminants, and then through cation exchange columns to separate Ti, Be and Al. The separate Be fractions were precipitated as Be(OH)2 and converted to BeO at 900°C. BeO was mixed with Nb powder (1:6) and pressed into Cu cathodes for AMS analysis.

10Be/9Be ratios were measured on a 5MV tandem accelerator together with quality control standards. Measured nuclide ratios were normalised to NIST-SRM4325, with nominal 10Be/9Be ratio of 2.79 × 10-11. The reported uncertainties of the nuclide concentrations include 2.5% for the AMS and chemical preparation. Blank corrections ranged between 4 and 11% of the sample 10Be/9Be ratios. The uncertainty of the blank measurements is included in the stated uncertainties. All nuclide concentration data are given in **Table 1** (Main text).

1. **Field and Laboratory methods for OSL analysis**

Samples for luminescence dating were collected in opaque tubes and prepared for analysis under subdued lighting conditions. To calculate the environmental dose-rate throughout burial for each sample, U, Th and K concentrations were measured for ca. 80 g of the bulk sediment sample using high-resolution gamma spectrometry. Water contents of 5 ± 2 % were estimated considering the field and saturated water contents, and the environmental history for each sample. Cosmic dose-rates were calculated after Prescott and Hutton (1994). Environmental dose-rates determined for all samples are shown in Table 1. Grains of K-feldspar were used to determine equivalent doses (De). Samples were first treated with a 10 % v/v dilution of 37

% HCl and with 20 % v/v of H2O2 to remove carbonates and organics, respectively. Dry sieving then isolated the grainsize used for analysis, which was then subject to density separation using sodium polytungstate (<2.58 g cm-3 K-feldspar dominated) and not etched using hydrofluoric acid. Finally, grains of K-feldspar were mounted on a 9.8 mm diameter aluminium single-grain disc for analysis, which contained a 10 by 10 grid of 300 µm (212 – 250 µm grainsize) diameter holes to ensure each hole contained only one grain.

All luminescence measurements were performed using a Risø TL/OSL DA-15 automated single-grain system equipped with a 90Sr/90Y beta source (Bøtter-Jensen et al. 2003) fitted with a blue filter pack (BG39, Coring 7-59) in front of the photomultiplier tube. Single aliquot regenerative dose (SAR) protocols (Murray and Wintle, 2000) were used for the post-IR IRSL analyses performed at 225 °C (Thomsen et al. 2008), termed the pIRIR225 signal. A preheat temperature of 250 °C for 60 s was used prior to stimulations of 2 s using the infra-red laser at 225 °C. The IRSL signal measured performed at 50 °C prior to the pIRIR225 measurement and the elevated temperature bleach of 330 °C for 200 s at the end of each Lx/Tx cycle were performed using the IR LEDs. The location of the single-grain discs was performed at room temperature, rather than elevated temperatures to prevent thermal annealing of the IRSL signal (after Smedley and Duller, 2013). The first 0.3 s and final 0.6 s of stimulation were summed to calculate the initial and background IRSL signals, respectively. The grains were accepted after applying the following screening criteria and accounting for the associated uncertainties: (1) whether the test dose response was greater than three sigma above the background, (2) whether the test dose uncertainty was less than 10 %, (3) whether the recycling and OSL-IR depletion ratios were within the range of ratios 0.9 to 1.1, and (4) whether recuperation was less than 5 % of the response from the largest regenerative dose.

Grains from sample SSK1901\_OSL were used for dose-recovery experiments and successfully recovered a given dose within 10 % using the pIRIR225 signal. Fading rates (*g*-values, Aitken 1985) were determined for three aliquots of each sample and normalised to a tc of two days (Huntley and Lamothe 2001; Fig. 6). The large uncertainties on the individual *g*-values measured were derived from the uncertainty in the fit of the data, which is typical of fading measurements for the pIRIR signal (e.g. Smedley et al. 2016). To derive a more reliable estimate of the fading rate, the weighted mean and standard error for all the samples was calculated for pIRIR225 signals (0.4 ± 2.0 %/decade). Given that the pIRIR225 fading rate is low with large uncertainties for each sample (Table 1) and in line with previous pIRIR225 studies (e.g. Roberts 2012; Trauerstein et al. 2014; Kolb and Fuchs 2018), we did not correct the pIRIR225 ages for fading.

De values were calculated from all grains passing all the screening criteria. The minimum age model (MAM; Galbraith and Laslett, 1993; Galbraith et al. 1999) was applied to determine an age for the samples as the asymmetrical De distributions suggested the samples were partially bleached prior to burial (Fig. 1). The scatter in the De distribution arising from intrinsic and extrinsic sources were combined in quadrature to determine σb for the MAM (Smedley et al. 2019). The overdispersion values arising from intrinsic sources for sample SSK1901\_OSL (32 ± 1%) were derived from the dose-recovery experiments, while the over-dispersion arising from variability in the internal dose-rates of K-feldspar grains for both samples was assumed to be 10 % (after Smedley and Pearce, 2016). Additional over-dispersion (20 %) was incorporated to account for the variability in single-grain De distributions caused by external microdosimetry (after Smedley et al. 2017). The De values were then divided by the environmental dose-rates to determine an age for each sample (Table 2).

Table S2. Luminescence dating results for sample SSK1901\_OSL (212-250 μm) from the Skyring lobe. Environmental dose-rates were determined using high- resolution gamma spectrometry. The dose-rates were calculated using the conversion factors of Guerin et al. (2011) and alpha (Bell, 1980) and beta (Guerin et al. 2012) dose-rate attenuation factors. Water contents (5 ± 2 %) were estimated considering the field water contents, and the environmental history for each sample; these values are expressed as a percentage of the mass of dry sediment. An internal K-content of 10 ± 2 % (Smedley et al. 2012) were used to determine the internal dose-rates. An a-value of 0.10 ± 0.02 (Balescu and Lamothe, 1993) was used to calculate the alpha dose-rates. Cosmic dose-rates were determined after Prescott and Hutton (1994). Dose-rates were calculated using the Dose Rate and Age Calculator (DRAC; Durcan et al. 2015). The *g*-values (%/decade) were measured using the pIRIR225 signal for three aliquots of K-feldspar for each sample, normalised to 2 days and are presented as weighted means and standard errors. The number of grains that were used to determine a De value (n) are shown as a proportion of the total grains measured (N). The MAM was used to determine the De for age calculations, applying a σb value of 0.4.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | U (ppm) | Th (ppm) | K (%) | Internal dose-rate (Gy/ka) | External alpha dose-rate  (Gy/ka) | External beta dose-rate  (Gy/ka) | External gamma dose-rate  (Gy/ka) | Cosmic dose-rate (Gy/ka) | Total dose-rate (Gy/ka) | *g*-value (%/dec.) | n/N | OD (%) | De (Gy) | Age (ka) |
| SSK1901\_OSL | 1.70±0.19 | 7.46±0.19 | 1.02±0.19 | 0.77±0.15 | 0.10±0.02 | 1.06±0.14 | 0.76±0.05 | 0.24±0.02 | 2.92±0.21 | 0.4±2.0 | 183/4600 | 62±1 | 43.2±1.8 | 14.8±1.2 |

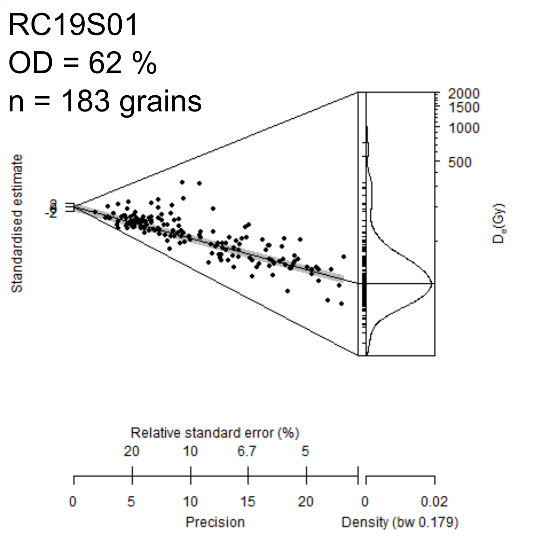


Fig. 1. Abanico plots of the De values determined for OSL dating, where the grey shading shows the MAM De for each distribution.

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