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Constraining the age and formation of stone runs in the Falkland Islands using Optically Stimulated Luminescence

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Abstract

The stone runs of the Falkland Islands are thought to be periglacial blockfields but their age and detailed origin remain enigmatic. We examine the fine sediments that underlie two stone runs in order to establish whether Optically Stimulated Luminescence (OSL) dating is an appropriate technique to constrain the date of emplacement of the fine sediments and, hence, the stone runs. Six samples were collected from two accessible sections during the Scotia Centenary Antarctic expedition in 2003. All samples were used to explore the main luminescence characteristics of the sediment, followed by quartz SAR dating procedures on four of the samples. Age estimates range from in excess of 54 ka to 16 ka, suggesting that the overlying stone runs remained active until 16 ka or later. Saturation of luminescence from quartz limits age estimates for the oldest samples in the sequences, however these are not critical to define the upper limit to the emplacement age for the overlying stone runs. The sediments also contain feldspars and initial results suggest that these may be useful in extending the timescale further, but require further samples to be obtained from other parts of the sequence. Extending the method to other stone runs in the Port Stanley Formation may allow estimates of the age of stabilisation of the stone runs to be extended into the 1–250 ka timescale. Luminescence dating of the underlying sediments, used in conjunction with cosmogenic isotope dating of the surface boulders from a range of locations along the stone runs, appears to offer a useful route towards decoding the depositional history of these impressive deposits.

Keywords: OSL dating; Stone runs; Falkland Islands; Palaeoclimate

1. Introduction

One of the most distinctive geomorphological feature of the Falkland Islands, 52° S and 60° W in the South Atlantic Ocean, is the occurrence of considerable areas of boulders that fill many of the valleys and blanket many open hillsides. These boulder spreads occur on both the main islands of West and East Falkland but are especially well-developed in East Falkland near to the main town of Stanley (Fig. 1). Charles Darwin provided an early account of these features in 1845, observing "in many parts of the islands the bottoms of the valleys are covered in an extraordinary manner by myriads of great loose angular fragments of the quartz rock, forming 'streams of stones'". However, in spite of numerous scientific

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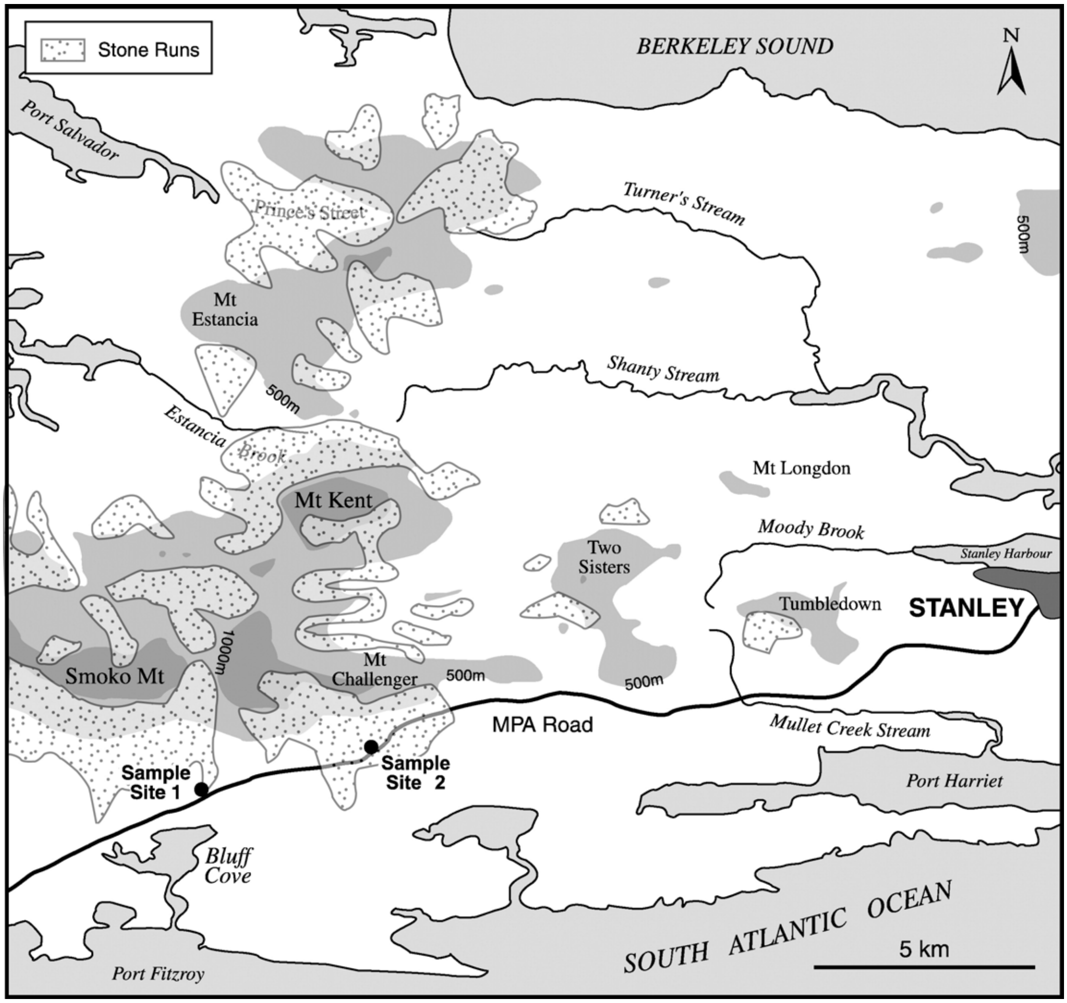

Fig. 1. Location of the two sample sites along the Mount Pleasant Airfield (MPA) road and places mentioned in the text.

investigations and agreement that they are periglacial blockfields (see Rosenbaum, 1996; Aldiss and Edwards, 1999; Stone, 2000), the detailed origin of the Falkland Islands 'stone runs' has remained enigmatic and their age unknown. The work reported here explores the use of Optically Stimulated Luminescence (OSL) dating of sediments underlying two stone runs in East Falkland. To our knowledge it provides the first OSL-constrained estimates of the ages of formation of the stone runs, which in turn allows discussion of the environmental conditions that prevailed during the deposition of these unique features.

2. The Falkland Islands stone runs

The stone runs of both West and East Falkland are principally associated with, and lie downslope of, outcrops of the Devonian quartzites of the Port Stanley and the older Silurian Port Stephens Formations (Aldiss and Edwards, 1999). Consisting of pale grey, hard quartzites and sitting atop the softer sandstones, siltstones and mudstones of the Fox Bay Formation, the Port Stanley Formation forms much of the high ground on East Falkland (Fig. 1). Stratigraphically beneath the Port Stanley and Fox Bay Formations lie the feldspathic quartzites of the Port Stephen Formation (Aldiss and Edwards, 1999). In West Falkland, these beds are slightly tilted and subsequent erosion of the softer beds has produced a dip and scarp landscape with the harder quartzites forming the scarps. In East Falkland, tectonic movement and intense folding has vertically tilted the Port Stanley beds and subsequent erosion of the fractured intervening softer beds has resulted in a striking line of hills to the west of the town of Stanley (Fig. 1) composed of steeply inclined quartzites. The predominant joint sets of these quartzites are both perpendicular

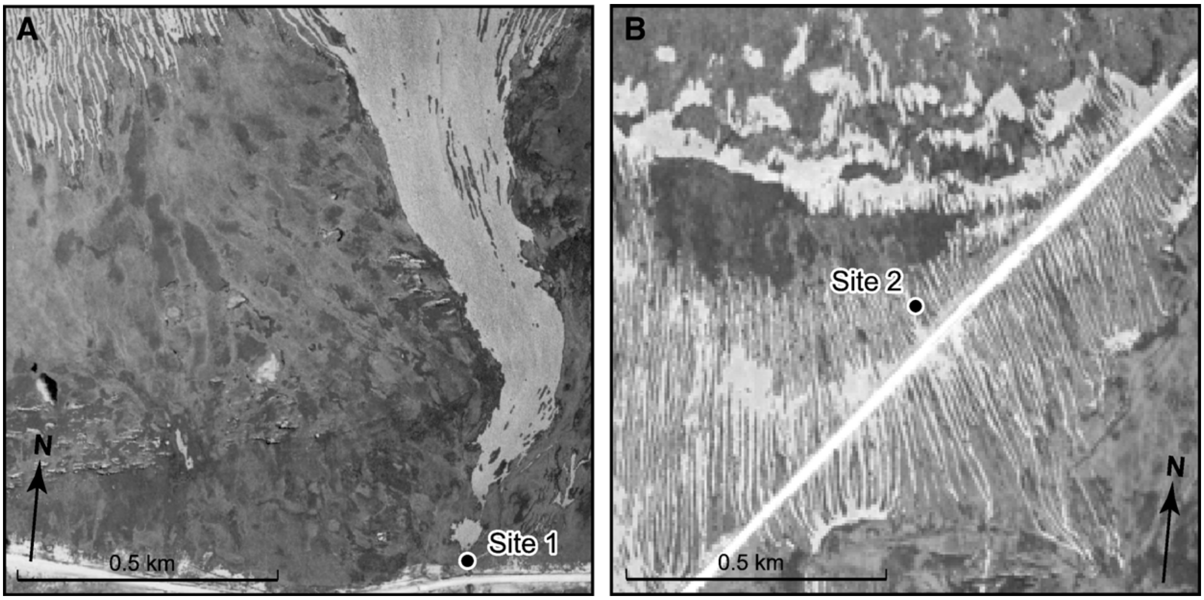

Fig. 2. A and B. Vertical aerial photographs taken at 2286 m above the stone runs below Smoko Mountain and Mount Challenger, to the west of the town of Stanley, showing the locations of the sample sites. Images used with the permission of the Director, Department of Agriculture and Mineral Resources (copyright Falkland Islands Government).

and parallel to bedding, with joint spacings of 0.1–2.0 m (Rosenbaum, 1996).

Some of the most extensive stone runs are associated with quartzite outcrops on East Falkland. Prince's Street (4 km long and 400 m wide) is the largest of these (Fig. 1), but a more typical stone run might be 100 m wide and up to 2 km long (Fig. 2A,B). The stone runs cover gently sloping ground (0.5–10°) and are mainly composed of locally-derived quartzite blocks (although a few dolerite blocks have been recorded), which range from 30 cm to 2 m long axis, with individuals of up to 5 m long occurring locally. Larger runs extend

Fig. 3. In excess of 3 km long and 500 m wide at its widest point, the large stone run shown on Fig. 2A leading down to Site 1, is composed of locally-derived quartzite boulders up to 2 m long axis.

considerable distances downslope, overtopping bedrock outcrops and ‘flowing’ between bedrock narrows before extending over lower gradients in the valleys (Fig. 3). Smaller runs on marginally steeper slopes may be only a few metres across, tens or hundreds of metres long and separated by unsorted stony sediments that have been colonised by white grass, with the better drained and coarser sediments adjacent to the stone runs colonised by dark ferns and heath (Stone and Aldiss, 2000) (Fig. 4). Although much longer and composed of larger boulders, these slope-parallel boulder runs are similar in appearance to the smaller periglacial stone stripes commonly found on sloping ground in cold climates.

In the Falkland Islands, the individual boulders on the surface of the runs are mainly tabular in shape with angular edges that exhibit little sign of surface abrasion. Many stone runs exhibit only a poorly developed fabric, but in some the fabric is stronger especially close to the run margins where they abut bedrock outcrops. In these locations the tabular blocks are vertically imbricate and packed together on edge, with long axes parallel to the slope. The largest boulders are located on the surface of the runs and there exists a marked decrease in mean long axis with depth (Fig. 4). Although boulders in the upper parts of undisturbed stone runs are uniformly pale grey in colour, at depth in any section the surfaces of the underlying smaller clasts are stained orange-brown by limonite. In the upslope parts of the stone runs, the lowermost clasts may rest directly on bedrock (Rosenbaum, 1996) with an absence of matrix. However, over much of the length of the runs, the boulders and clasts usually sit conformably on top of a stiff grey or yellow-brown diamict (mainly matrix-supported (Dmm), but with some clast-supported (Dcm)) that often extends to several metres in depth and sometimes shows a strong slope-parallel fabric. In some places, particularly where stream sections or road cuttings occur, this diamicton can be seen to rest directly on top of bedrock. At the lower end of the slopes, the stone runs merge into the alluvium of the valley floors, but it is unclear whether the boulders sit on top of, or are submerged by, the alluvium since everywhere the junction is masked by thick accumulations of peat. Rosenbaum (1996) reports that in some areas the lowermost edge of the stone run material is thinly overlain by marine sediments and may pass below present sea level.

Although in terms of form, size and extent the Falkland Islands stone runs are considered to be unique in the contemporary world, similar but much smaller and more restricted examples do occur elsewhere in periglacial environments (Rosenbaum, 1996; Stone, 2000). The origins and formation of the Falkland Island stone runs have been much debated; Darwin (1845) invoking the action of earthquakes to explain the original dislodgement of boulders from the craggy outcrops above and their subsequent downslope transport onto the

Fig. 4. Small stone runs are a few metres across and separated by unsorted stony sediments colonised by grasses. Better-drained stony sediments along the borders of the stone runs support low heathland shrubs that encroach over the runs themselves. The size of boulders within the runs declines with depth.

slopes below. Thomson (1877) suggested that the stone runs resulted from mechanical weathering of the cliffs above to produce boulders and postulated their subsequent downslope movement by soil creep induced by freeze–thaw cycles. Andersson (1906) interpreted the stone runs as analogues for the mud flows seen in the Arctic, and attributed their formation to solifluction processes. Subsequent theories have emphasised a structural control, highlighting a close spatial correlation of the stone runs with quartzite outcrops upslope (Baker, 1924; Joyce, 1950; Greenway, 1972). Although there is an agreement that the stone runs are relict blockfields produced by periglacial mass movement, their age remains enigmatic. Clark (1972), Clapperton (1975, 1993), Rosenbaum (1996) and Aldiss and Edwards (1999) argue on morphostratigraphic grounds that they date from the Last Glacial Maximum (the global LGM is ca. 21±3 ka). In the Falklands, the last cold stage (incorporating the LGM) spans ca. 30–17 ka (Wilson et al., 2002). However, a cosmogenic exposure age of 133±6.6 ka based on paired analyses of ^{10}Be and ^{36}Cl from a single stone run boulder (Wilson, 2002, pers. comm.), suggests that the boulder surface might have been continuously exposed in either the stone run or in scree (or indeed as in situ bedrock before dislodgement), and potentially subject to cosmic radiation since well before the LGM. Nevertheless, in spite of the above morphostratigraphic agreement, and the single cosmogenic age determination that sits at odds with it, the age of the final emplacement of the stone runs in their present locations has yet to be determined using independent dating methods.

This paper reports on the use of Optically Stimulated Luminescence (OSL) methods to date material extracted at various depths from beneath two separate stone runs in East Falkland in an attempt to (a) test the properties of the Falkland Island sediments to establish whether OSL can be used to date them; (b) establish whether the dates of deposition of the sediments at various depths beneath the stone runs are consistent with an LGM or later date of emplacement or, alternatively, a composite age that spans a wider time frame possibly commencing well before the LGM; and (c) clarify the general environmental conditions operating at the time of formation of the stone runs.

3. Methods

3.1. Luminescence dating

Luminescence dating depends on energy storage in sedimentary minerals in response to exposure to ionising radiation from the sample and its environment. Part of the stored energy can be released by laboratory stimulation using a suitable photon source, resulting in measurable luminescence. Luminescence signals in minerals can be erased by heat or exposure to light. Therefore, exposure to light during erosion or transport acts as a zeroing mechanism for sediments. Termination of such optical bleaching by enclosure of the sediment at time of final deposition thus initiates the last cycle of accumulation of the signals used for age estimation. The dating procedure combines calibrated luminescence measurements of the sample (to determine the *equivalent dose*) with measurements of the radiation dosimetry of the sample and its environment (the *dose rate*). The luminescence age is thus the quotient of *equivalent dose* over *dose rate*. If the sample has been fully zeroed prior to deposition the luminescence age should correspond to the physical depositional age. Conversely where incomplete zeroing occurs, it can represent accumulated signals over many cycles of erosion, transport, partial bleaching and deposition. Such outcomes may nonetheless constrain an upper limit to the depositional age, which may be useful in some circumstances.

The magnitude of residual (i.e. unzeroed) signals in sediment dating can be minimised by using photostimulation (or optical stimulation), to target readily reset luminescence systems, and there are several potential methods for detecting signs of residuality. The use of regenerative procedures for determining the stored dose within single aliquots or mineral grains (Murray and Wintle, 2000; Sommerville et al., 2001, 2003) allows use of dose-distributional analysis within sediments as a means of diagnosing heterogeneous systems incorporating materials of varying age (e.g. Olley et al., 1998, 1999; Lepper et al., 2000; Duller et al., 2000; Spencer et al., 2003). There is also information in the decay shapes of OSL stimulation curves which can be used to assess the extent to which natural signals match those generated by single-cycle irradiation in the laboratory (e.g. Huntley et al., 1985; Aitken, 1998; Bailey et al., 2003). Also the differential sensitivities to bleaching of readily accessed luminescence signals from quartz and feldspars (Sanderson et al., 2001, 2004) can reveal patterns of apparent dose that may help to characterise the depositional conditions.

The challenges presented in OSL dating of stone run sediments from the Falkland Islands were considerable. At the outset of this study we had no prior knowledge of the luminescence sensitivities and dose response of materials available from the sediments to assess the viability of quartz- or feldspar-derived methods for luminescence studies. Nor was it clear, given the uncertainties surrounding formation models for these features, whether such sediments would be effectively zeroed at the time of in situ deposition of the stone runs. Furthermore, for practical reasons it was not possible to undertake on-site gamma dosimetry at the time of sampling. Both internal and external dosimetry were thus reconstructed from laboratory measurements and the sampling regime was constrained to avoid the gamma-dose interface between the top sediments and the bottom of the boulder layer. The work was therefore undertaken in two stages. An initial exploration of the luminescence properties of all samples collected used polymineral extracts and multiple stimulation (OSL, IRSL and TL) assessments to investigate sensitivities and apparent doses from available mineral phases. This was followed by quantitative analysis and age determination of four samples using the quartz SAR OSL method (Murray and Wintle, 2000). Residuality was assessed using a combination of the exploratory measurements and the dose distribution of the SAR data set.

3.2. Field sampling

Field sampling was undertaken in January 2003 at two sediment exposure sites representing two separate unnamed stone runs in East Falkland (Figs. 1 and 2). Both exposures consisted of vertical sections incised by stream action into the lower part of the stone runs. The large surface boulders and smaller underlying clasts of each stone run rest conformably on top of diamictons that extend to depth. Site 1 (lat. 51°44.121′ S, long. 58°09.271′ W) is located at the lobate downslope end of a substantial 2-km-long stone run which extends downslope from the east side of Smoko Mountain (Figs. 1, 2A and 5). The section at Site 1 consists of a turf/peat surface punctuated by several boulders to a depth of 0.6 m (Unit 1) representing the downslope edge of a substantial stone run. Immediately below this is about 1 m of stiff yellow-brown diamict with few clasts and no discernable fabric (Unit 2). At 1.6 m below the surface the base of the section is obscured by boulders fallen from above into the stream bed (Unit 3).

Site 2 (lat. 51°43.865′ W, long. 58°07.033′ S) consists of a stream section located in a gully on the north side of the main Mount Pleasant Airfield (MPA) road, some 16 km west of Port Stanley, and at the downslope end of a 0.75-km-long stone run that descends from the crags of Mount Challenger (Figs. 1, 2B, 5 and 6). The section at Site 2 is 3.6 m deep with Unit 1 composed of large boulders up to 1 m long axis resting on top of 1.6 m of clast-supported diamict that shows a strong slope-parallel fabric (Unit 2). Below this is 1.4 m of

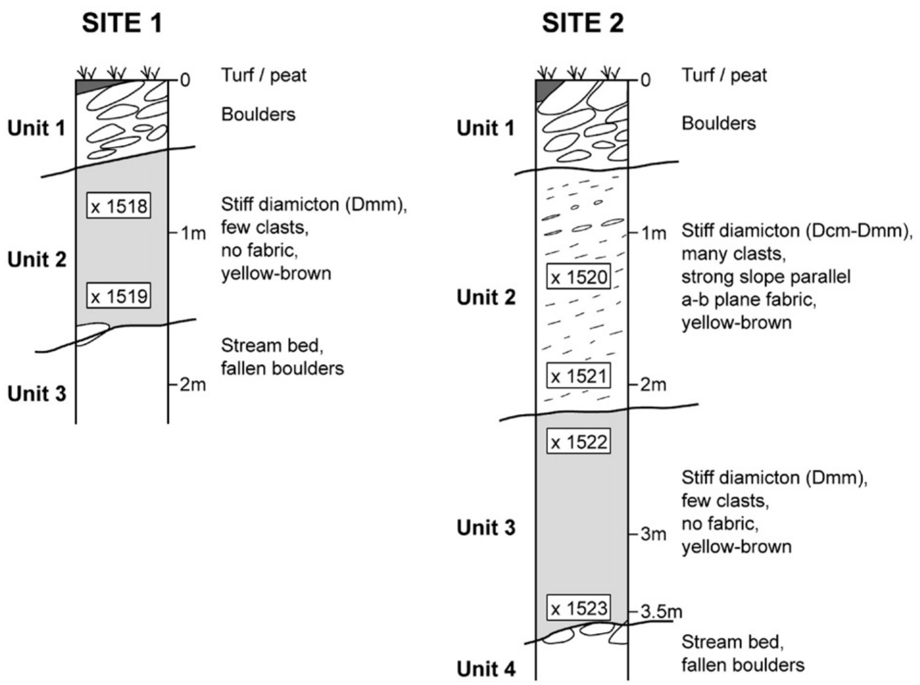

Fig. 5. Section logs of sample Sites 1 and 2 showing the location and SUTL number of the OSL sampling. Both sections show the upper part capped by boulders and the lower part partly obscured by boulders fallen from above and in both, Unit 1 sits conformably on top of Unit 2.

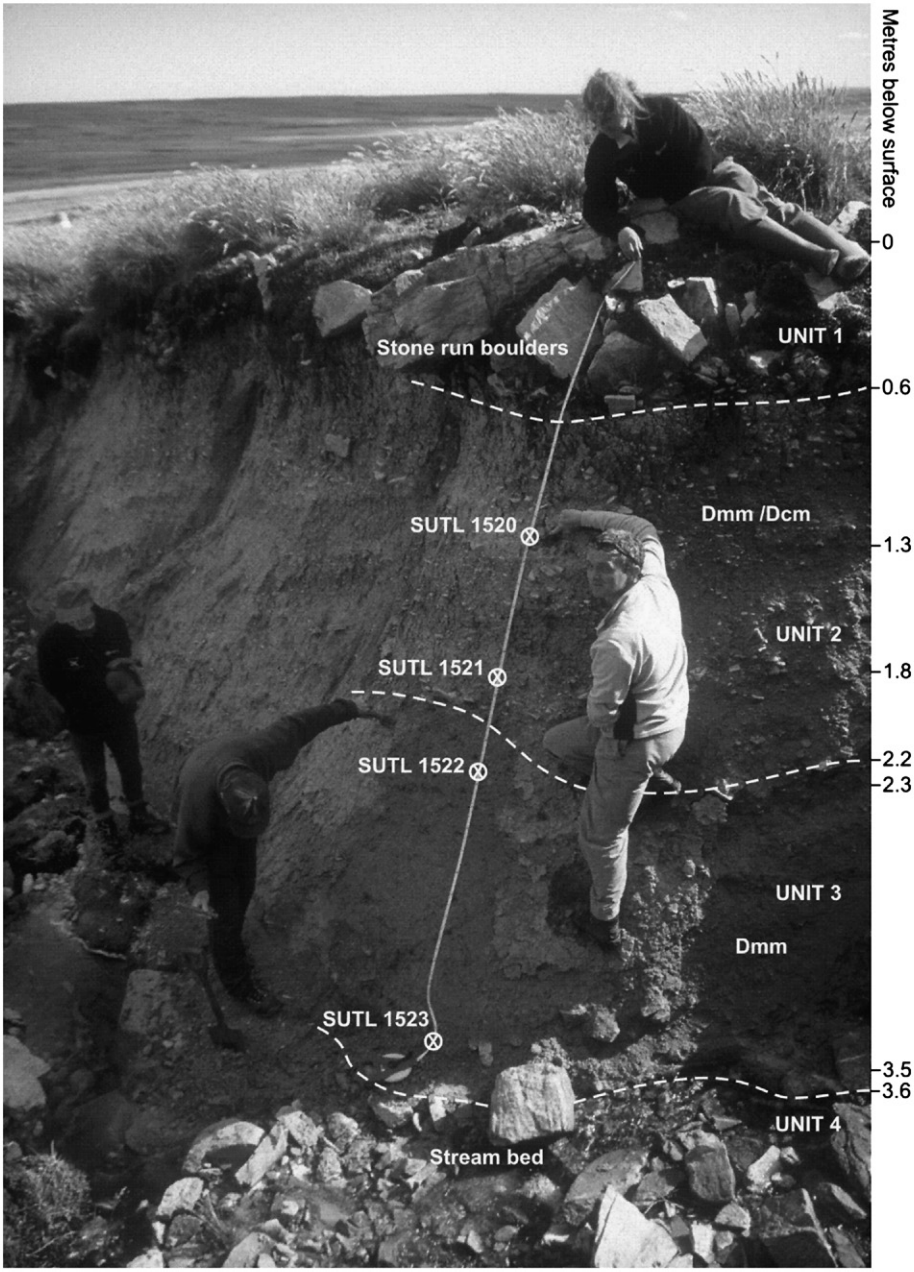

Fig. 6. The stream-incised section at Site 2 reached in excess of 3.6 m deep. Unit 2 had a strong slope-parallel fabric in clast-supported and matrix-supported diamict (Dcm/Dmm). Unit 3 (Dmm) showed few clasts and no fabric.

matrix-supported diamict with few clasts and no discernable fabric, before the boulder-strewn stream bed is encountered (Unit 4).

OSL tube samples were collected from the upper and lower parts of each section together with intermediate depths where the section depth allowed (Figs. 5 and 6). At each sampling point the section was cleaned back immediately prior to insertion of the sampling tubes in order to avoid incorporation of sediments that had been exposed to daylight. All tube samples were collected by driving 15–20 cm lengths of 19 mm diameter copper pipe, sealed at the outer end with black duct tape, horizontally into the section. Following insertion, each tube was extracted from the section, immediately sealed at the other end with black duct tape, labelled, and stored in a light-proof black bag and transported within a light-proof box. In all cases at least two replicate tube samples were obtained from each stratigraphic unit in the sediment.

At each tube sampling location, 'bulk' samples of sediment were also recovered for subsequent laboratory water content and dosimetry measurements. These samples were recovered firstly by cleaning the section surface of exposed 'dry' sediment, and then excavating sediments from >10 cm depth into the section. These samples were double-bagged and kept in cool conditions prior to delivery to the laboratory. Gamma ray spectra were not recorded on site owing to a lack of suitable equipment, hence dosimetry estimation was based upon laboratory measurements of beta and gamma-dose rates. Section details, including the laboratory (SUTL) numbers assigned to each upon arrival at the SUERC luminescence dating laboratories, are summarised in Fig. 5.

4. Luminescence analysis

4.1. Sample preparation

All sample handling and preparation was conducted under safelight conditions in the SUERC luminescence dating laboratories, following well-established procedures. A full technical description is available in an internal laboratory report (Sanderson and Bingham, 2004). Bulk samples were used to recover polymineral samples for initial exploratory measurements, and for water content and dose-rate determinations. The tube samples were used to extract minerals for quantitative dose determination, using the quartz SAR method in the first instance.

Material from the *bulk samples* was wet sieved to extract a 90–150 μm size fraction which, after 1 M HCl treatment and subsequent washing, formed the 'polymineral' samples. Two discs from each sample (except SUTL1522 for which insufficient material remained after acid treatment) were dispensed for polymineral analysis. The remaining material from the bulk samples was used to estimate water content, based on initial, saturated and dry weights. The dried material was then used for Thick Source Beta Counting (TSBC), and High Resolution Gamma Spectrometry (HRGS).

Mineral extraction from the *tube samples* aimed to recover both quartz and feldspar together, although as noted above, the main aim at this stage was to conduct quartz SAR measurements. Following 50 °C drying and sieving, a 90–125 μm fraction was treated with 1 M HCl (30 min), 15% HF (15 min) followed by repeat HCl treatment prior to four-stage density separation with sodium polytungstate solutions at densities of 2520, 2580, 2620 and 2740 kg m^{-3}. Alkali feldspar samples (2520–2580 and 2580–2620 kg m^{-3} fractions) were retained for possible future use and the 2620–2740 kg m^{-3} fraction etched in 40% HF for 40 min followed by further HCl treatment and washing. Sixteen discs per sample were dispensed, each comprising approximately 1 mg of quartz for SAR analysis.

4.2. Dose-rate measurements

Dose-rate measurements from the bulk samples were undertaken both by Thick Source Beta Counting (TSBC) (Sanderson, 1988) and High Resolution Gamma Spectrometry (HRGS) using a 50% relative efficiency "n" type hyperpure Ge detector (EG and G Ortec Gamma-X). Gamma spectra were analysed to determine count rates from the major line emissions from ^{40}K, and from selected nuclides in the U decay series (^{234}Th, ^{226}Ra+^{235}U, ^{214}Pb, ^{214}Bi and ^{210}Pb) and the Th decay series (^{228}Ac, ^{212}Pb and ^{208}Tl). Net rates and activity concentrations for each of these nuclides were used to determine dry infinite matrix dose rates for alpha, beta and gamma radiation, and used in combination with measured water contents, TSBC results, estimated internal alpha activity and modelled cosmic ray dose rates to determine the overall effective dose rates for age estimation.

4.3. Luminescence measurements

Polymineral discs were subjected to a multiple stimulation procedure using a Risø DA15 automatic luminescence reader (Botter-Jensen et al., 2000). Samples were initially pre-heated at 220 °C for 1 min, and then subjected to sequential infra-red stimulated (IRSL), post-IR blue OSL stimulation, and TL measurements. Following readout of the natural luminescence signals, samples were irradiated with 1 Gy and 5 Gy ^{90}Sr beta doses and re-measured to assess luminescence sensitivity, linearity of dose response and sensitivity changes for the material under IRSL, OSL and TL stimulation. The natural signals, in conjunction with these readings, were used to provide first estimates of the stored dose in each sample.

The quartz discs from the tube samples were subjected to a SAR sequence (Murray and Wintle, 2000). OSL measurements of the natural signal and regenerated dose points were interleaved with 5 Gy test dose measurements to account for laboratory-induced sensitivity changes. Regeneration at 20, 40, 60, 80, 100 and 200 Gy was performed followed by a recycling check at the

Table 1
Equivalent doses (in Gy) determined from the polymineral experiments using IRSL, OSL and TL

SUTL	IRSL stored dose		OSL stored dose		TL stored dose	
	2 discs	Mean	2 discs	Mean	2 discs	Mean
1518	13±4 70±20	42±30	16±5 34±10	25±9	83±4 70±4	76±7
1519	82±30 115±40	99±20	15±2 80±20	47±30	350±20 420±20	380±30
1520	430±80 220±40	330±150	95±20 270±50	180±120	230±7 170±4	200±30
1521	250±50 210±40	230±30	390±80 66±9	230±230	240±7 170±4	210±40
1522	n/a	n/a	n/a	n/a	n/a	n/a
1523	1300±300 550±120	920±520	430±110 170±30	300±190	320±10 440±20	380±60

Individual dose values and estimated uncertainties from two aliquots are tabulated together with the mean value.

20 Gy point. Samples were presented in four different pre-heating groups, and both zero Gy and IR response measurements taken at the end of each run. Four samples were selected for full SAR analysis representing the top samples (SUTL1518, 1520) and bottom samples (SUTL1519, 1523) from each site. SUTL1521 and 1522 were not subjected to SAR OSL runs, since the exploratory analyses had shown little depth progression of the dose estimates from Site 2 samples (SUTL1520–23). An exploratory feldspar SAR run was performed on two discs from sample SUTL1519, to assess the potential of utilising the feldspars in future work to overcome quartz saturation. This confirmed the high degree of sensitivity and reproducibility of alkali feldspars from this material, their good recycling behaviour, and their ability to respond to doses beyond the saturation limit of quartz. In the absence of a direct association between the lower samples in the sections and the depositional age of the stone runs, this was not extended at this stage. However, the presence of feldspars with bright and reproducible luminescence has been noted for future studies.

5. Results

5.1. Preliminary experiments

The preliminary experiments aimed to assess luminescence sensitivities and to estimate equivalent dose from the polymineral samples to assess dating suitability. Luminescence sensitivities of the polymineral samples were variable, leading to highly scattered equivalent dose estimates from the multiple stimulation runs. Clear IRSL responses indicated the presence of feldspars, whilst OSL decay shapes were indicative of a quartz-rich mineralogy (Table 1).

Assuming a 3 mGy a^{-1} total effective dose rate, the results from the upper samples of Site 1 (1518) (Table 1) apparently correspond to material of approximately Late Glacial age, for both IRSL and OSL. The lower sample of Site 1 (1519) appears to be much older. TL stored doses were larger, almost certainly due to the relative difficulty of achieving a low residual TL dose by optical re-setting. At Site 2 (SUTL1520–1523) preliminary data were broadly consistent with potentially higher depositional ages (50–100 ka) for upper and lower samples. These preliminary results were used in formulating the decision to concentrate tube sample preparation in the first instance on quartz extraction for OSL SAR analysis, a procedure shown elsewhere to give highly precise and accurate results. However, it was noted that because of the magnitude of many of the stored doses, especially at Site 2, the quartz system might be close to saturation.

5.2. Dose-rate measurements and calculations

Table 2 shows the activity concentrations and infinite matrix dose rates obtained by HRGS, together with measured dry beta dose rate by TSBC. Table 3 combines these data with estimated water content, absorbed dose fractions and cosmic ray dose rates to provide total dose-rate estimates for each sample. Mean parent

Table 2
Activity concentrations of K, U and Th (via HRGS) and dose rates (via HRGS and TSBC) based on dose-rate conversion from Aitken (1983)

Sample SUTL	Activity concentrations/Bq kg^{-1}			Dry infinite matrix dose rates HRGS/mGy a^{-1}			TSBC/mGy a^{-1}
	K	U	Th	D_a (dry)	D_b (dry)	D_g (dry)	D_b (dry)
1518	402.4± 9.4	26.6±0.7	40.1±0.4	13.29±0.16	1.68±0.03	1.07±0.01	1.79±0.09
1519	278.4±14.0	30.3±1.4	42.4±1.0	14.55±0.36	1.40±0.04	1.04±0.02	1.98±0.23
1520	359.8±14.9	40.6±2.0	78.0±1.6	23.36±0.53	2.00±0.05	1.65±0.03	2.09±0.08
1521	394.7±9.4	33.1±0.8	55.4±0.5	17.53±0.20	1.84±0.03	1.32±0.01	2.08±0.05
1522	383.3±15.3	28.8±1.4	48.4±1.1	15.30±0.37	1.71±0.04	1.18±0.02	2.18±0.07
1523	430.8±11.0	29.7±0.8	51.4±0.6	16.03±0.21	1.87±0.03	1.26±0.01	2.12±0.06

Table 3
Annual dose rates

Sample SUTL	Water contents			Effective b dose rate[a]/ mGy a^{-1}	D_g (wet) by HRGS/ mGy a^{-1}	Total dose rate[b]/mGy a^{-1}
	FW	SW	Assumed			
1518	36	58	20±10	1.50±0.15	1.17±0.10	2.86±0.16
1519	20	37	20±10	1.56±0.18	1.18±0.10	2.93±0.19
1520	10	46	20±10	1.61±0.17	1.18±0.10	2.97±0.17
1521	16	63	20±10	1.69±0.18	1.23±0.11	3.11±0.18
1522	21	61	20±10	1.73±0.18	1.23±0.11	2.95±0.20
1523	27	49	20±10	1.61±0.16	1.18±0.12	2.98±0.20

[a] Effective beta dose rate combining water content corrections with inverse grain size attenuation factors obtained by weighting the 200 μm attenuation factors of Mejdahl (1979) for K, U, and Th by the relative beta dose contributions for each source determined by Gamma Spectrometry.

[b] Including a cosmic ray dose-rate contribution based on Prescott and Hutton (1994).

concentrations from all six samples were 1.21±0.07% K, 2.55±0.16 ppm U and 12.97±0.05 ppm Th, consistent with typical values for quartz-rich sediments. The mean Th/U concentration ratio for all six samples was 5.1±0.11.

5.3. SAR OSL age determinations

Data from samples SUTL1518, 1519, 1520 and 1523 from the SAR determinations were analysed to produce individual dose response curves and estimated doses for each disc. Measurements were scrutinised for OSL decay shape consistency, zero level and residual IR which were satisfactory in all cases, although a clear dependency of test dose response on the regenerative dose prior to each test dose was noted, indicating that slowly depleting signal components were accumulating during the SAR runs.

There was no evidence of significant differences in normalised OSL ratios between the subsets of pre-heated discs. Accordingly composite dose response curves for each sample were constructed and used to estimate equivalent dose values for each of the individual discs, and their combined sets. Both linear and exponential fits

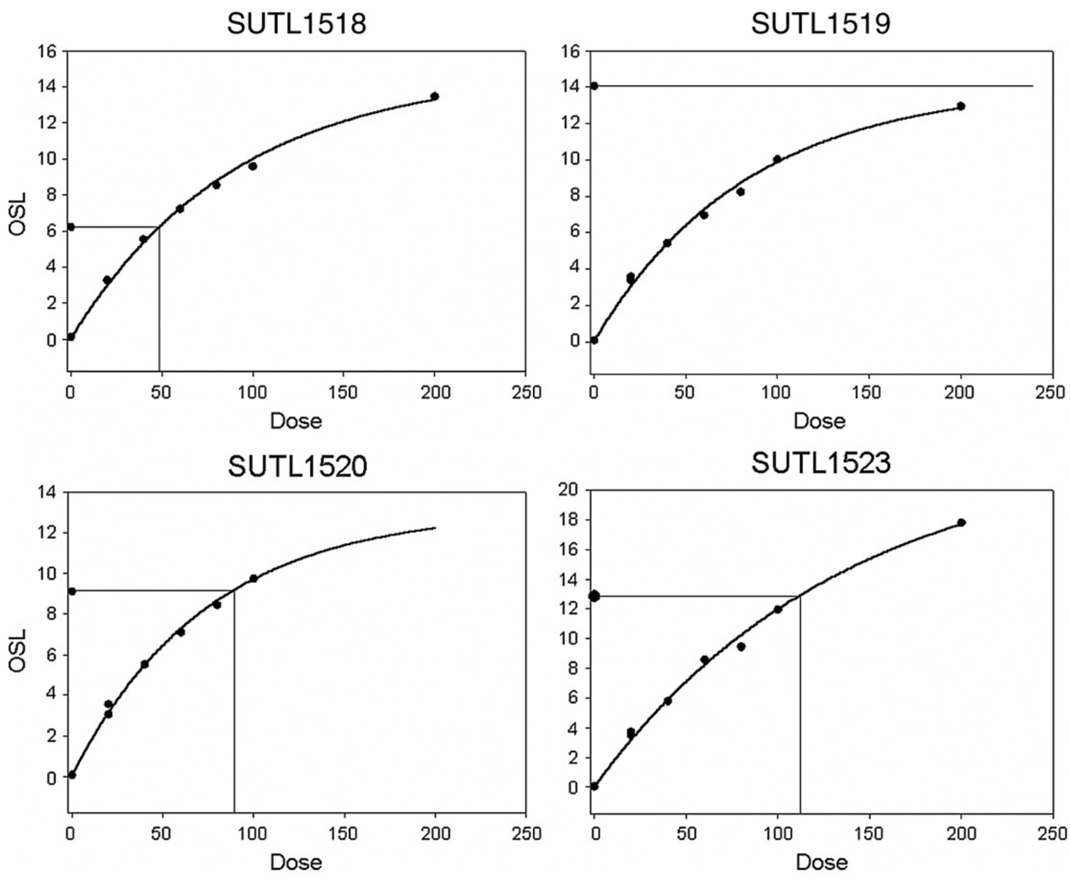

Fig. 7. SAR regression curves used to calculate the equivalent doses for samples SUTL 1518.

Table 4
SAR results and age determinations based both on unweighted and weighted combinations of data from the individual discs

Sample	1518	1519	1520	1523
Mean sensitivity/ count per Gy	6860	6240	2870	1800
Sensitivity change/ % per cycle	6.5	−4.6	−1.4	−0.6
Recycling ratio	1.01±0.02	1.01±0.06	1.18±0.05	1.06±0.07
No. of discs	15	7 [a]	16	8
Equivalent dose estimates/Gy				
Median	47.3	159.1	79.9	95.6
Min	35.4	91.2	55.6	17.9
Lower quart	41.8	146.9	72.6	66.3
Upper quart	51.0	176.2	103.5	240.3
Max	101.0	213.4	291.1	376.2
Weighted mean	44.9±1.3	120.8±89.3	72.9	24.9
Mean	46.7±2.0	158.6±14.3	102.9	152.5
F	2.8	0.9	1.1	0.5
Weighted age/ka	15.7±1.1	41.2±30.6	24.5	8.4
Median age/ka	16.6	54.3	26.9	32.1
Mean age/ka	16.3±1.3	54.1±6.2 [a]	34.6	51.2

The regression curves upon which the equivalent doses are calculated are shown in Fig. 7.

[a] Note that for sample 1519, 9 out of 16 discs gave stored dose estimates at or above saturation limits. The data from the remaining 7 discs summarised here, thus represent a lower limit to the mean age of the sample.

were explored for dose estimation. The exponential fits are more appropriate since many of the discs examined gave results in the non-linear and saturating parts of the dose response curve, as illustrated in Fig. 7. Table 4 summarises the SAR results, including summary statistics for the dose and age estimates. The *F* statistic suggested by Spencer et al. (2003) as a means of detecting excess variation associated with partial bleaching is also tabulated across the whole distribution of data. Whereas for young samples in the linear dose response region this ratio (of the variance between discs compared with the pooled errors assessed from measurement sources) has been shown to be highly sensitive to detection of heterogeneous samples, in this study extremely good *F* ratios were obtained from all samples. However, this was the result of high internal errors associated with doses in the saturating dose response region, and these cannot be taken alone as an indication of full initial bleaching. Nor were decay shapes of the quartz informative in these data sets.

Sample SUTL1518, in the upper portion of Site 1, has similar unweighted and weighted equivalent dose estimates that, combined with dosimetry information, yield an estimated age range of ~15.7–16.3 ka. The data set is quite coherent suggesting good homogeneity and effective zeroing. For the lower part of Site 1, in sample SUTL1519, natural signal ratios exceeded the upper limits of dose response curves preventing dose estimates from more than half the discs examined. The age estimate of 54.3 ka is based on those discs (7 out of 16 examined) where stored doses could be estimated. The equivalent dose for the remaining samples of SUTL1519 is >200 Gy; therefore the age estimate must be regarded as a lower limit to the mean age of the sample. The dose recovered from the exploratory feldspar SAR run was 190±10 Gy, corresponding to approximately 60–70 ka, which again may be a lower limit. For the upper portion of Site 2, the unweighted, weighted, and median dose estimates are broadly similar in sample SUTL1520 resulting in age estimates of ~24.5 to 34.6 ka. The stone run in this location therefore appears to have enclosed the sediment some time after approximately 26.9 ka. For sample SUTL1523, in the lower part of Site 2, variable equivalent dose results were obtained. The weighted estimate is strongly influenced by a single low dose value, and it appears that this sample is rather heterogeneous. The lack of a marked age progression down this section may suggest disturbance and mixing without complete zeroing during the depositional process, in which case the date for final deposition in this location may be younger than the median age estimate of 32.1 ka.

6. Discussion

The three aims of this study were to (a) establish whether OSL can be used to date sediments from the Falklands stone runs; (b) establish whether the dates of deposition of the sediments at various depths beneath the stone runs suggests an LGM date of emplacement or, alternatively, a composite age that spans a wider time frame commencing well before the LGM; and (c) clarify the mode of formation of the stone runs by comparing the OSL ages with general environmental conditions at that time.

Firstly, this study demonstrates that the sediments contain both quartz and feldspar with sufficient luminescence sensitivities to facilitate dating analysis. The quartz SAR OSL technique can be used to estimate relative ages for the sealing of the quartzite-derived sediments that underlie the stone runs of the Falkland Islands. For the top layers of the two sections explored here the quartz SAR results can be used to estimate termini post quem for the deposition of the boulders. For the oldest samples the results are limited by the combination of saturation of the quartz dose response (pronounced at 150–200 Gy), producing an age of older than about 54 ka. The oldest sample examined here

(SUTL1519) shows saturation and failure of the laboratory dose response curve to reach natural levels in several aliquots, raising doubts as to the extent of initial zeroing in the lower sedimentary units of this deposit. Potentially the saturation problems might be overcome and the age range extended by using feldspars, rather than quartz, for luminescence dating. The experiments conducted show that the feldspars present in each of these samples have sufficient IRSL and post-IRSL blue OSL sensitivity to be potentially suitable for age ranges over the 1–250 ka timescale, and would therefore merit further investigation if older sequences are examined elsewhere. The feldspathic quartzites of the Port Stephens Formation, which crop out along the north coast of east Falkland and more widely in West Falkland may offer the best opportunities in this respect, since these rocks also produce stone runs, albeit smaller and sparser than the Port Stanley runs. The next stage in this process would be to evaluate the relationships between the IRSL and OSL dose estimates of the feldspathic quartzite, to resolve whether or not SAR methods could be applied there (Wallinga et al., 2000) and whether fading presents any obstacles. The other major issue with both quartz and feldspar systems is the extent to which the sediments can be considered to have been reset at the time of deposition.

Second, notwithstanding the caveats above, the results have demonstrated an increasing age with depth within the sediments beneath the stone runs (Table 4). The boulders overlying Sites 1 and 2 are likely to have been emplaced into their current positions after 16.6 ka and 26.9 ka respectively. Given the similar morphologies and settings of both sites, this apparent contrast in the ages of the upper sediments was unexpected and it is possible that the sediments in the upper layers of one or both of the sites were incompletely zeroed. It is also possible that sampling depth might be a control — the top sample of Site 1 (SUTL1518) being derived from 0.83 m below the boulder-strewn surface, whereas the top sample from Site 2 (SUTL1520) was derived from 1.3 m below the surface (a similar depth to SUTL1519, classed as the lower sampling site at Site 1). The extent to which the upper layers at each site may have been subsequently disturbed by boulder movement within the stone runs resulting in uncovering and recovering of the sediment, and the extent to which such disturbance may have partially or fully reset the luminescence system, is also unclear and additional sites and further samples would be required to test these ideas. It would be advantageous to utilise field gamma spectrometry at the time of sampling, so that samples closer to the boulder interfaces could be included, and to undertake more detailed sedimentary characterisation with a view to examining possible formation models.

Supplementing the luminescence technique with additional dating methods would also help to test the above hypotheses. In particular, cosmogenic dating of *both upper and lower* surfaces of the stone run boulders could clarify the length of time boulders have typically remained in situ and hence whether any boulder turning may have disturbed the upper sediment surface. With respect to the samples at the base of the sections, the study has suggested that at Site 1, the lower sediment is significantly older than the upper sediment, but that quartz saturation effects prevent any age estimation other than the comment that the sediment is likely to be older than 54 ka. Similarly at Site 2, the median basal age (32.1 ka) is slightly older than the median upper age (26.9 ka), but the age-with-depth trend is less marked, possibly on account of highly variable disc-to-disc luminescence signals. If the 54 ka basal age of Site 1 is inaccurate as a result of saturation effects, then according to Site 2 the sediments that underlie the stone runs may have begun to accumulate at least 32.1 ka ago, with the stone runs themselves beginning to form upslope at that time. The runs may then have extended downslope to reach the location of the 2 sites sampled here sometime after 26.9 ka. In Site 1 the boulders do not appear to have enclosed the underlying sediment until after 16.6 ka. Alternatively, if the 54 ka age is correct or, more likely, is actually a minimum, then the deposition of the underlying deposits beneath the stone runs pre-dates the LGM and may well have spanned most of the last glacial cycle and perhaps beyond. The latter suggestion may be supported by the cosmogenic age of 133 ± 6.6 ka, derived for a surface boulder by Wilson (2005 pers. comm.), raising the possibility that the stone runs are much older than had been previously thought. A potential problem with this hypothesis remains that cosmogenic inheritance may limit the utility of this technique in dating boulders whose exposure history, prior to coming to rest, is ambiguous. A third possibility is that some parts of the stone runs (in the valley bottom core and low angled sections) may be older, and have moved further, than other parts (at the margins and higher angled sections) of the stone runs. Since the units may subsequently merge together, it would then be possible for surface activity to reset the OSL signal of the topmost material as recently as 16.6 ka, in spite of its stratigraphic position atop material that may date from before 54 ka.

The third aim of this study was to clarify the mode of formation of the stone runs by setting the estimated age within a wider environmental context. Although the sediments that underlie the stone runs have attracted little interest until now, they do appear to hold at least some clues to the genesis of the runs themselves. Since the stone runs lie conformably on top of the sediments it appears likely that whereas the lower sediments may pre-date the arrival of the overlying boulders at that point on the slope (possibly by some considerable time), it is probable that the upper sediments may be more or less coeval with the basal boulders of the stone runs. Indeed, although no matrix occurs within the lowermost smaller clasts in the runs, a few small isolated quartzite boulders occur within the sediments underlying the stone runs, but it is unclear whether this is a post-depositional artefact associated with loading. Since there is a strong relationship between the occurrence of the stone runs and the outcrops of both the Port Stanley and the Port Stephen quartzites in both West and East Falkland and the dimensions of the boulders within the runs matches the predominant joint sets of the in situ quartzites, then the quartzite crags and free faces above the stone runs almost certainly represent the boulder source. It follows that the initiation of the stone runs themselves requires in situ breakdown of the quartzite from upslope bedrock outcrops. In addition, substantial thicknesses of the sediments dated here are known to underlie many of the stone runs and blanket many lower valley slopes. However, the sediment layers become thinner upslope and are more or less absent along the ridges. It seems reasonable to suggest that downslope movement of the sediments progressively exposed more of the quartzite outcrops above and so led to increasing opportunity both for boulder generation and for subsequent downslope transport. This pattern supports the earlier proposal that deposition of the upper sediments underlying the runs was more or less coeval with arrival of the basal boulders. The subsequent sorting of the boulders within the stone runs, with the coarser grades moving upwards and outwards at a faster rate than the finer grades, is probably related to the well-known frost-sorting mechanisms that occur within the active layer of periglacial environments where the greater surface area of matrix-supported larger clasts results in more rapid migration away from the plane of freezing than for smaller clasts, although how this might operate in the clast-supported situation of the boulder runs is unclear. It seems likely that once the stone runs became clast-supported, any remaining fine-grained matrix would have been washed out during melt phases.

Although the older sediments that underlie the stone runs may be substantially older than 54 ka (and possibly older than 133 ka), the results presented here suggest that the main period of deposition of the sediments beneath the stone runs ends sometime after 26.9 ka at Site 2 and 16.6 ka at Site 1. In the Falklands, Wilson et al. (2002) place the last cold stage, including the LGM, at ca. 30–17 ka, this mapping approximately with the OSL dates above. In the nearby sub-Antarctic island of South Georgia in the Scotia Sea, the LGM seems to have occurred before 18.5 ka, since deglaciation was under way by then (Rosqvist et al., 1999). Interestingly, ^{14}C and ^{10}Be dating by McCulloch et al. (2005) show the LGM in southernmost South America to have occurred after ca. 31 ka, culminating at 25–23 ka. Over this time period the climate of the Falkland Islands was extremely cold but probably drier than at present, with extensive areas of permafrost at low levels and with glacier cover only in the highest peaks (Roberts, 1984). Thus, it seems likely that whilst the main period of emplacement of the stone runs themselves spans a period from before the LGM and continued through the LGM, downslope boulder movement in the stone runs may well have continued until after at least 16.6 ka.

7. Conclusion

OSL dating of the sediments that underlie the Falkland Islands stone runs suggests that the main period of activity occurred during the cold climates that pertained in the Falkland Islands about 32 ka–27 ka ago. However, evidence also exists to suggest that parts of the stone runs may have been in existence since before at least 54 ka and so may substantially pre-date the LGM. There is also evidence of activity and re-setting of the underlying sediments until about 16.6 ka. These ages both support and extend the time frame of previous work that suggested the likely period of maximum stone run activity coincided with the LGM, a period when glaciers occupied the higher peaks of West Falkland and permafrost conditions prevailed elsewhere (Clark, 1972; Clapperton, 1975; 1993; Aldiss and Edwards, 1999).

In conclusion, OSL dating techniques seem to be a potentially useful tool in establishing the likely age and shedding light on the genesis of the Falkland Islands stone runs. In addition to showing the value of the SAR quartz procedure for dating the younger (upper) sediments, based on the initial profiling results there appears to be significant potential for SAR feldspar luminescence dating of the older (lower) sediments. What is clear from the work reported here is that more detailed sedimentological and sample information is needed, together with detailed observations from other stone runs in the Falkland Islands, to demonstrate any OSL age reductions up-section within the underlying sediments and paired with cosmogenic dating of the upper and lower surfaces of the surface boulders above. Together with paired OSL and cosmogenic sampling along the length of the stone runs to include valley-fill, valley-side and source outcrops, such dating would allow the hypothesis of progressive formation during multiple glacial cycles to be tested.

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