Relict Blockstreams at Instheia, Valldalen-Tafjorden, Southern Norway: Their Nature and Schmidt Hammer Exposure Age

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ABSTRACT

Two small relict blockstreams occur at Instheia, a col at 910 m asl on the watershed between Valldalen and Tafjorden (Møre og Romsdal), southern Norway. Both blockstreams display morphological and sedimentological characteristics indicative of boulder accumulations that have moved downslope by solifluction, probably under a permafrost climatic regime. These comprise preferred orientation and dip patterns of boulders; inverse grading, with surface boulders overlying successively finer, well-sorted cobble, pebble and fine-grained (sand/silt dominated) sediment layers; imbrication, with the packing of small boulders behind larger boulders; and proximity to boulder-strewn hillslopes whose constituent boulders (organised into lobes and terraces) feed downslope into the blockstreams. Schmidt hammer exposure ages indicate that the blockstreams were last active during the Younger Dryas Stadial-Holocene transition. Blockstream development probably began at ~ 15 ka, following the Last Glacial Maximum, and lasted for ~ 5 ka. Since then any fine-grained material within the near-surface parts may have been progressively removed. The relatively rapid development of the blockstreams suggests that larger-scale forms of considerably greater age in the southern hemisphere may also have formed rapidly and have been inactive for long periods.

KEY WORDS: blockstreams; schmidt hammer exposure-age dating; Younger Dryas Stadial-Holocene transition; Norway

INTRODUCTION

Accumulations of coarse rock debris are common in many upland areas of past and present periglacial conditions (Ballantyne and Harris, 1994; French, 2007). Such debris accumulations may assume different morphological expression, depending on the local topographic context, primarily slope gradient and elevation, and the severity of climate. Thus, blockfields, blocklopes, blockstreams, boulder lobes, debris flows, talus, rock avalanches and rock glaciers are frequently distinguished. However, because these forms can occur in close proximity and often grade into one another, they can be difficult to isolate and delimit. Furthermore, the age and origin of some of these features have proved to be contentious (Rea, 2013). Establishing the mechanics and timing of their formation is important for developing integrated models of Quaternary landscape evolution and change.

Blockstreams (also termed rock streams, stone runs and kurums) are one manifestation of coarse debris accretion by mass-wasting processes (Wilson, 2013). Generally, they are linear deposits that extend further downslope than across slope, but may appear to be broader than they are long where their distal reaches have been covered by soil and vegetation development. They vary in topographic setting from open hillslopes to valley axes. Most reports of blockstreams concern relict features (e.g. Boelhouwers et al., 2002; Nelson et al., 2007; Gutiérrez and Gutiérrez, 2014), and indicate that variations in plan form, dimensions, morphology, structure and composition exist. Plan configurations range from straight or sinuous single-thread forms to dendritic, braided or anastomosing styles. Their width ranges from a few metres to several hundred metres, and their length from a few metres to 5 km (Jennings, 1969; Clark, 1972; Grab, 1999). Generally, openwork rock debris is common to all blockstreams but their surfaces may be diversified by randomly distributed pits and elongated...
depressions, and/or extensive longitudinal furrows. Prominent surface steps, ridges and lobes may be present. Blockstream development is favoured by well-jointed igneous and metamorphic rocks because the joints predispose them to macrogelivation, thermal stress fracturing (Hall, 1999; Boelhouwers, 2004; Collins and Stock, 2016) and/or deep chemical weathering, resulting in the production of blocky debris. Many examples have been recorded on basalt, dolerite and quartzite. Stratigraphically, blockstreams display inverse grading and lack interstitial fine-grained material in at least their uppermost part (Clark, 1972; Caine, 1983; Boelhouwers, 1999). Some blockstreams extend downslope from summit and plateau blockfields as a result of debris transport; others originate from hillslope scarpas or tor-like outcrops. Active blockstreams are apparently less frequent than relict occurrences and have fewer detailed accounts: Harris et al. (1998) is a rare instance.

Several attempts have been made to establish the age of relict blockstreams. Caine and Jennings (1968) obtained a 14C age of 35.2 ± 1.6/0–2.15 ka from wood beneath blockstream debris in southeastern Australia, attributing blockstream formation to a subsequent cold stage, corresponding with the (global) Last Glacial Maximum (LGM; ~ 27–19 ka). Samples of basal soil and peat covering Tasmanian blockfields have yielded 14C ages of 4.7–3.08 ka, indicating blockfield (and by inference blockstream) stability throughout the late Holocene; additionally, weathering rind thickness measurements of blockfield clasts suggest stability has persisted for the past ~ 13 ka (Caine, 1983). Cosmic isotopes 36Cl surface exposure dating applied to blockstreams and blockfields in southeastern Australia has given a cluster of ages within the limits of the LGM, with a weighted mean exposure age of 21.9 ± 0.5 ka (Barrows et al., 2004). However, two boulders returned ages of 498 and 157 ka, demonstrating that some blockstream elements are considerably older than the LGM. Cosmic isotopes 10Be and 26Al surface exposure dating of blockstreams in the Falkland Islands produced ages ranging from 731 ka to 42 ka, indicating that development of these features spanned at least 690 ka, that their activity likely extends over several cold stages and that they are long-lived, composite landforms (Wilson et al., 2008). Optically stimulated luminescence ages ranging from > 54 ka to 16 ka on samples of fine-grained material beneath Falkland Islands blockstreams suggest that some Falkland blockstreams were active during the LGM (Hansom et al., 2008).

Although relict blockstreams have been identified in many areas that experienced severe periglacial conditions, only a few brief descriptions of them exist in Scandinavia (e.g. Nicholson, 2009). This apparent absence may be because of the extent of glacier ice cover during the LGM; examples from elsewhere are in locations that were beyond the limits of LGM ice. However, this is unlikely to account for their absence because numerous reports exist of blockfields on Scandinavian mountains, especially from Norway (Whalley et al., 1997, 2004; Fjellanger et al., 2006; Juliussen and Humlum, 2007). Given the close morphological and topographical association between some blockfields and blockstreams, the latter are probably more extensive in Scandinavia than so far reported.

This paper focuses on a small area of coarse rock debris at Insteheia, southern Norway, the disposition and nature of which are considered diagnostic of relict blockstreams. Specific aims are: (1) to describe the morphological and sedimentological characteristics of the blockstream; (2) to apply Schmidt hammer exposure-age dating (SHD) to blockstreams for the first time; and (3) to discuss the implications of our findings for theories of blockstream development and processes of formation.

RESEARCH AREA

Insteheia (910 m asl; grid reference MQ 159094) is a broad col aligned southwest-northeast on the watershed between Valldalen and Tafjorden (Møre og Romsdal), southern Norway (Figures 1 and 2). Slopes to the north of the col rise to Mejfellet (1100 m asl), and those to the south rise to Hegguraksla (1219 m asl). The latter are longer and steeper than those to the north but both slopes are strewn with boulders organised into lobes and terraces. North-facing slopes are also diversified by low degraded bedrock scarpas and are cliffed, in parts, above ~ 1150 m asl. Much of the col is vegetated and the blockstreams are not immediately obvious on aerial photographs. Large-scale patterned ground is evident across some vegetated area of the col and blockfields dominate the Hegguraksla ridge.

The bedrock geology of the site is migmatitic gneiss (Tveten et al., 1998). During the LGM, the col lay well below the upper altitudinal limit of the Scandinavian ice sheet. Although there has been considerable debate about ice thicknesses and the extent of ice-free terrain in this northwestern part of southern Norway at the LGM (e.g. Nesje et al., 1987; Follstad, 1990; Brook et al., 1996; Winguth et al., 2005), the upper altitudinal limit of the ice sheet appears to have lain at 1400–1800 m asl with a steep gradient towards the North Atlantic, which leads to uncertain estimates of the deglaciation date at Insteheia. Ground over 900–1000 m asl may have been ice-free by 16–15 ka as a consequence of rapid down wastage (Goehring et al., 2008). However, the col was not inundated by glacier ice during the Younger Dryas Stadial (YDS; 12.9–11.7 ka) which, in this area, is evidenced by valley glacier moraines in Valldalen to the north and end moraines of two small cirque glaciers to the east beneath Blåfjellet (Figure 1; AB Carlson et al., 1983). More recent attempts to constrain glacier limits in Norway (Hughes et al., 2016; Stroeven et al., 2015) have been at the ice-sheet scale but do not resolve the timing of deglaciation and cannot be considered as more reliable for the local pattern of YDS ice in the Valldalen-Tafjorden area.

At present, Insteheia is within the alpine zone but well below the lower limit of present-day discontinuous permafrost, estimated to lie above 1600 m asl in this area of western
Norway (Etzelmüller et al., 2003; Lilleøren et al., 2012). Climatic data for AD 1961–90 for Tafjord meteorological station (15 m asl), 9 km south-southeast of Instheia, reveal a mean annual air temperature (MAAT) of 6.9 °C and mean annual precipitation (MAP) of 965 mm (Aune, 1993; Førland, 1993). Using a lapse rate of 0.65 °C per 100 m (Lilleøren et al., 2012), the MAAT at Instheia reduces to 1.1 °C with mean monthly temperatures below 0 °C for 6 months of the year (Table 1). MAP at Instheia for AD 1971–2000 is within the range 2000–3000 mm; the mean number of days with a snow depth >25 cm is 50–100, rising to between 200 and 350 days for 5–25 cm depth (<URL>http://www.senorge.no</URL>). More than half of the MAP at Instheia is likely to fall as snow given the estimated negative temperature values for 6 months of the year.

The floor of the col and the slopes falling southwest towards Tafjord and northeast towards Valldalen are covered by coarse rock debris in the form of blockstreams. The boulder-strewn lower hillslopes north and south of the col merge downslope with the blockstreams, suggesting that these slopes were the source (‘feeders’) of the debris. For clarity, we term the blockstream descending southwest from the col blockstream A and that to the northeast blockstream B.

FIELD METHODS AND RATIONALE

Long-axis gradients of the blockstreams and some of the feeder accumulations on the lower hillslopes were determined with an Abney level. At each of four locations (Figure 2), 30 boulders were measured for their long (a) axis orientation and dip of their a-b plane. These locations were ‘paired’, with each pair (i.e. sites 1 and 3; sites 7 and 8) comprising a blockstream sample and an associated sample from the adjacent feeder area. At a single location on each blockstream (E1 and E2), shallow (~0.6 m deep) pits were hand excavated to examine the vertical structure of the boulder accumulations. Fine-grained material (<2 mm) sampled from a depth of ~0.5–0.6 m in each pit was subjected to particle size analysis using a Malvern Mastersizer (Malvern, UK), following organic matter digestion and dispersion in a weak solution of sodium hexametaphosphate (Calgon). Schmidt hammer R-values were measured on surface boulders using two mechanical ‘N-type’ Schmidt hammers (Proceq, 2006), the reliabilities of which were checked before and after use with the manufacturer’s test anvil (McCarroll, 1987, 1994; Winkler and Matthews, 2014). Mean R-values were derived from single blows on each of 100 boulders at eight locations; four of the locations were those used for boulder orientation and dip measurements. The other four were from another location on blockstream A; from the highest part of the col (the blockstream divide); and from another location on blockstream B and its associated feeder area. All locations along with representative surface gradients and directions are indicated in Figure 2. Boulder surfaces selected for SHD measurements were horizontal or near-horizontal, and corners, cracks, lichen thalli and wet areas were avoided (Matthews and Wilson, 2015).
Schmidt hammer R-values derived from boulder-rich landforms are an indicator of the time elapsed since exposure of rock surfaces of uniform lithology to subaerial weathering and, in the case of blockstreams, the timing of boulder stabilisation. The technique has developed as one of high-precision calibrated dating for which statistical confidence intervals can be generated (Matthews and Owen, 2010; Matthews and Winkler, 2011; Matthews and McEwen, 2013; Matthews and Wilson, 2015). At least two surfaces of known age (young and old control points), lithologically equivalent to the rock surface being dated, are required for calibration.

For the present paper, we used two young and three old control surfaces (Matthews and Wilson, 2015). The first young control is from the boulders of a rockfall that occurred about 10 years ago at 900 m asl on the north side of Langfjelldalen, 19 km northeast of Insteheia; the second is from bedrock outcrops in a series of road cuts, with an average age of ~ 20 years, between the village of Fjøra, on Tafjorden, and the mountain farm of Nysætra at 750 m asl (Figure 1). The three old control surfaces are boulders on YDS moraines (AB Carlson et al., 1983). The first is at 850–900 m asl in Alnesdalen, 23 km northeast of Insteheia; the other two are at 950–1050 m asl in Trollkyrkjebotn to the north of Blåfjellet (Figure 1). These sites have been assigned an age of 11.5 ka in accordance with the very late persistence of the YDS ice-sheet maximum in western Norway (Bondevik and Mangerud, 2002; Stroeven et al.,

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Table 1  Mean monthly and annual air temperatures and precipitation for Tafjord meteorological station (15 m asl) AD 1961-90, and estimated mean monthly and annual temperatures for Insteheia (910 m asl).

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|--------|
| Air temperature (°C) |
| Tafjord | 0.5 | 0.7 | 2.7 | 5.2 | 10.1 | 12.7 | 13.9 | 13.7 | 10.5 | 8 | 3.6 | 1.3 | 6.9 |
| Instheia | -5.3 | -5.1 | -3.1 | -0.6 | 4.3 | 6.9 | 8.1 | 7.9 | 4.7 | 2.2 | -2.2 | -4.5 | 1.1 |
| Precipitation (mm) |
| Tafjord | 100 | 76 | 82 | 53 | 35 | 41 | 60 | 64 | 101 | 107 | 115 | 131 | 965 |

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Figure 2  Plan of the Instheia blockstreams A and B (grey shading) showing directions of selected surface gradients (e.g. ← 3°), locations of excavated pits (E1 and E2), Schmidt hammer exposure-age dating (SHD) sites (1–8), and plots of a axis orientations (full rose) and a-β plane dips (half rose) for four of the SHD sites. Class intervals are 20° for orientation data and 10° for dip data.
2015) and also allowing for a short phase of moraine stabilisation and glacier retreat following the YDS termination at 11.7ka in the Greenland ice core chronology (Rasmussen et al., 2006; Walker et al., 2009; AE Carlson, 2013). The lithology of the Trollkyrkjebotn sites is augengneiss rather than the migmatitic gneiss of the other sites (Tveten et al., 1998), which may have an influence on the R-values from these control points. However, any effect is considered to be minor because R-values from the other control site of the same age (Alnesdalen) are not significantly different.

### SCHMIDT HAMMER EXPOSURE-AGE CALIBRATION AND AGE ESTIMATION

Age calibration is described for this area by Matthews and Wilson (2015). The high-precision calibration equation was based on combined data for both of the young control surfaces and combined data for the three old control surfaces (Table 2). Thus, the calibration equation was based on two control points of known age and each control point utilised all the data available from the control surfaces. This is justified by the generally consistent mean R-values found from control surfaces of known age in the area (Matthews and Wilson, 2015). The equations used for age calibration include calculation of 95 per cent confidence intervals around predicted SHD ages; the calibration equation is a standard linear regression equation.

We followed the approach used in previous high-precision calibrated SHD studies and inferred a linear R-value-age relationship between the young and old control sites. Justification for adopting a linear relationship over the Lateglacial and Holocene timescale is provided by the work of Shakesby et al. (2011), who demonstrated that for a hard crystalline rock (granite) a linear trend was present when several intermediate and firmly dated age control points were available. Furthermore, field data demonstrating low rates of post-glacial weathering for hard crystalline igneous and metamorphic rocks are available for arctic-alpine areas of Scandinavia (André, 1996, 2002; Nicholson, 2009). Over much longer timescales weathering likely departs from a linear trend (Colman, 1981; Colman and Dethier, 1986). Therefore, given the short duration of weathering at Insteheia (< ~ 15ka), we consider use of a linear R-value-age relationship for the control sites to be warranted.

### RESULTS

#### Blockstream Dimensions and Morphology

Exposed boulders occupy ~ 0.2km² of the Insteheia col in several areas of irregular plan form (Figure 2). An additional ~ 0.35km² of adjacent ground is covered by thin (<0.3 m) vegetated peat from which boulders project and in which gaps reveal underlying boulders, demonstrating that the boulders extend substantially further than indicated by the surface exposures alone. Blockstream description and measurement were restricted to the areas of exposed boulders.

Blockstream A extends southwest from the col for ~ 0.8km along the valley axis as a generally narrow (~15–250m wide) zone of openwork boulders with a single thread to braided plan form (Figure 3a, b). The downvalley terminus is a prominent topographic step extending over a distance of 10m at a gradient of 12°. Water issues from the base of the step and continues downslope in an open fluvial channel constrained by vegetated banks. Above the step, blockstream gradients are reduced to within the range 0–5° with no marked breaks of slope and boulder b axes are generally between 0.15 and 1.5m. In several places water flow was seen at shallow depth (<0.5m) between boulders, in other areas flow was heard, and vegetation debris draped across and around some boulders indicates recent surface water flow. At a distance of ~ 0.6km up-valley from its terminus, the blockstream gradient is 0° over a distance of 60m and numerous small (<1m wide) pools of shallow (<0.2m deep) standing water were present when these sites were visited in early August. Many of the boulders in this area are covered by moss.

The continuity of blockstream A is disrupted as the col is approached by a more extensive cover of vegetated peat; exposed boulders form several distinct ‘islands’ (Figure 3c) and adjacent boulder-strewn ‘feeder’ slopes rise at gradients of up to 12°.

### Table 2 Schmidt-hammer R-values from the control sites: data used for the calibration equation are shown in bold.

| Control point                  | Age (years) | Mean R-value | Standard deviation | Confidence interval (95%) | N  |
|-------------------------------|-------------|--------------|--------------------|---------------------------|----|
| **Young sites**               |             |              |                    |                           |    |
| Langfjelldalen rockfall       | 10          | 55.59        | 7.61               | 0.77                      | 375|
| Fjøra road cuttings           | 20          | 57.18        | 7.02               | 0.71                      | 375|
| Young sites combined          | 15          | **56.39**    | **7.32**           | **0.53**                  | **750**|
| **Old sites**                 |             |              |                    |                           |    |
| Alnesdalen moraine            | 11,500      | 39.64        | 9.69               | 0.99                      | 375|
| Trollkyrkjebotn moraine (west)| 11,500      | 39.58        | 7.6                | 0.77                      | 375|
| Trollkyrkjebotn moraine (east)| 11,500      | 37.44        | 8.46               | 0.86                      | 375|
| Old site combined             | **11,500**  | **38.89**    | **8.62**           | **0.5**                   | **1125** |
Blockstream B extends northeast from the col for ~0.2 km as a broad swathe of openwork boulders that is substantially shorter (downslope) but wider (across slope) than A. The apparent terminus of blockstream B is less pronounced than that of A, with a gradual transition from boulders to vegetated ground extending over ~20–30 m. Boulders are evident downslope of the transition zone, being visible in gaps in the vegetation. These boulders indicate that the blockstream has a greater downslope extent than is currently exposed. The range of boulder $b$ axes is again predominantly between 0.15 and 1.5 m, although there are several boulders in the range 1.5–2.5 m (Figure 3d). No water was seen or heard beneath blockstream B although persistent fluvial flow begins ~100 m downslope of the terminus.

Throughout all areas of the blockstreams, the $a$-$b$ planes of the majority of boulders appear to dip upslope (Figure 3e). In addition, there are a few large boulders upslope of which smaller boulders are jammed because their onward movement has been effectively prevented.

Boulders exposed in the predominantly vegetated areas define shallow (<50 cm deep) irregular troughs or pits (Figure 3f) suggestive of the depressed rims of large-scale sorted patterned ground. This inference is supported by the slightly elevated adjacent ground that we interpret as the raised cells of elongate polygons and stripes.

**Boulder Orientation and Dip**

Boulder orientation and dip data for pairs of samples (1 and 3, 7 and 8) from blockstream and feeder area boulders are presented in Figure 2. For all samples, the majority of $a$ axis orientations fall within ±45° of the slope aspect; most boulders are therefore aligned parallel or sub-parallel to the local slope aspect. Some transverse or sub-transverse boulder alignments are evident in each sample, most prominently in feeder area samples 3 and 8 with 40 and 13 per cent of their boulders, respectively. Upslope-dipping boulders...
dominate (73–86%) each site. Most boulders dip at < 30°; maximum boulder dip is 48°.

**Blockstream Structure and Particle Size**

The hand-excavated pits show similar arrangements of inversely graded coarse debris (Figure 4). Below the cover of surface boulders, there are successively finer, well-sorted cobble, pebble and sand/silt-rich sediment layers. The fine-grained materials encountered at the base of the pits yielded 43 per cent sand, 45 per cent silt and 12 per cent clay at E1, and 80 per cent sand, 17 per cent silt and 3 per cent clay at E2. Cumulative frequency curves for each sample plotted against the frost-susceptibility limit of Beskow (1935) are shown in Figure 5. For the most part, both samples plot within the frost-susceptible zone.

**Schmidt Hammer R-Value Measurements and SHD Ages**

Schmidt hammer R-values for the control sites are summarised in Table 2 and combined frequency distributions for the two young sites and the three old sites are shown in Figure 6. These data indicate an R-value difference of 17.5 units between recently exposed rock surfaces (~15 years; mean R-value 56.39) and surfaces dating from 11.5 ka (mean R-value 38.89). Two of the three old control surfaces, Alnsedalen moraine and Trollkyrkjebotn moraine (west), have indistinguishable mean R-values, whereas the mean R-value from Trollkyrkjebotn moraine (east) differs from these according to their 95 per cent confidence intervals; however, given that they do not differ if 99 per cent confidence levels are used, it is considered appropriate to combine all three sites into a single control point. These data were used to derive the high-precision calibration equation of y = 37022.951 - 656.28571x.

Frequency distributions of R-values from blockstream samples (Figure 7) are generally similar (despite the high variability of values; range 18–67) in being near-symmetrical. In this respect, they mirror the combined frequency distribution for the old control sites and may be interpreted as indicating a single population of boulders. The SHD exposure age of each blockstream sample, based on mean R-values (Table 3), was determined from the calibration equation. These ages and their 95 per cent confidence intervals ($C_t$), together with the error components...
used to estimate the confidence intervals – i.e. the sampling error associated with each blockstream sample ($C_s$) and the error in the calibration curve ($C_c$) – are listed in Table 4. Ages range from 7.24 to 11.17 ka – a span of ~ 4 ka. As most of the 95 per cent confidence intervals overlap, the ages cannot be regarded as statistically different from one another at the 5 per cent significance level.

Whilst the age of site 2 (7.24 ka) does not differ statistically from the second youngest site (8: 9.5 ka), it does differ from all the other sites, as explored below. The average age of the samples is 9.96 ka, but if site 2 is excluded from the calculation, the average age is 10.35 ka. Irrespective of the difference and the reliability of the age of site 2, stabilisation of the blockstreams dates from the YDS-Holocene transition.

**DISCUSSION**

**Blockstream Origin**

In contrast to some relict blockstreams elsewhere (e.g. Caine, 1983; Boelhouwers et al., 2002; Wilson et al., 2008), those at Instheia occupy rather small land surface areas. This may reflect the short time interval (~5 ka) in which they developed. Nevertheless, they display characteristics that are commensurate with more extensive cases, namely: (1) patterns of preferred boulder orientation and dip that are usually regarded as indicative of downslope movement; (2) inverse grading of debris, indicative of the frost sorting of clasts, with surface boulders overlying well-sorted cobble, pebble and fine-grained sediment layers that are frost susceptible; (3) imbricate smaller boulders packed behind larger boulders indicating that their downslope movement has been impeded; and (4) a close spatial association with large-scale sorted patterned ground and boulder-strewn hillslopes on which boulders are organised into lobes and terraces, and which merge downslope as they feed into the blockstreams. The inference is that blockstream development is the result of former permafrost-related hillslope processes (Potter and Moss, 1968; Aldiss and Edwards, 1999; Boelhouwers, 1999; Boelhouwers et al., 2002; Wilson, 2013).

Alternative origins for the blockstreams are difficult to substantiate. Boulder emplacement by fluvial action can be rejected because adjacent hillslopes provide insufficient catchment area to generate high-magnitude runoff capable of moving boulders of the noted dimensions. Furthermore, the hillslopes lack networks of incised fluvial channels suggesting that they are characterised by patterns of diffuse surface and/or subsurface flow. Glacial processes can also be rejected as an explanation for boulder accumulation, because blockstream morphology and structure do not conform to known styles of glacial deposition. Similarly, the movement of boulders downslope from the col to both southwest and northeast cannot be reconciled with ice movement across this area.

Several processes working in combination or succession have been proposed to explain blockstream structure and downslope movement, but the apparent absence of currently active forms of similar scale to relict examples has restricted understanding (see Wilson, 2013, for a recent review). It has frequently been proposed that blockstreams moved downslope in association with a matrix of fine-grained sediment by solifluction (with or without the presence of permafrost), although in most cases it is difficult to demonstrate a former matrix. Such movement has been inferred to generate patterns of preferred boulder orientation and dip similar to the ones recorded at Instheia (Potter
and Moss, 1968; Boelhouwers, 1999; Boelhouwers et al., 2002). The absence of fine-grained material in the surface and near-surface parts of blockstreams has led to the assumption that after blockstream movement ceased the flow of surface or subsurface water removed the matrix. Although this may have happened, it raises the issue of how distinct patterns of boulder orientation and dip originate. If such patterns develop during blockstream movement, then the later removal of matrix would likely cause some rearrangement of boulders as they settle, as noted by Potter and Moss (1968). Therefore, boulder orientations and dips may represent, at least in part, settlement fabrics rather than transport fabrics. At present, at Instheia and other relict blockstreams, the former content and nature of interstitial fine-grained material are not known with certainty and thus the mechanics of downslope movement and the

Table 3 Schmidt-hammer R-values from the blockstream samples.

| Sample | Mean R-value | Standard deviation | Confidence interval (95%) | N |
|--------|--------------|-------------------|---------------------------|---|
| 1      | 41.36        | 9.3739            | 1.87                      | 100|
| 2      | 45.38        | 8.836             | 1.76                      | 100|
| 3      | 39.98        | 7.5749            | 1.51                      | 100|
| 4      | 39.87        | 8.6633            | 1.73                      | 100|
| 5      | 41.44        | 8.398             | 1.67                      | 100|
| 6      | 39.4         | 7.4301            | 1.48                      | 100|
| 7      | 40.48        | 7.6818            | 1.53                      | 100|
| 8      | 41.94        | 9.7825            | 1.95                      | 100|

Table 4 Schmidt hammer exposure-age dating (SHD) ages for the blockstream samples.

| Sample | SHD age (years) | C_t - 95% confidence interval (years) | C_s (years) | C_c (years) |
|--------|-----------------|---------------------------------------|-------------|-------------|
| 1      | 9880 ±1270      | ±1205                                 | 1227        | 331         |
| 2      | 7240 ±1205      | ±1045                                 | 1156        | 335         |
| 3      | 10 785 ±1045    | ±1180                                 | 991         | 329         |
| 4      | 10 855 ±1180    | ±1150                                 | 1134        | 329         |
| 5      | 9825 ±1150      | ±1099                                 | 1099        | 331         |
| 6      | 11 165 ±1099    | ±1030                                 | 974         | 329         |
| 7      | 10 455 ±1060    | ±1060                                 | 1005        | 330         |
| 8      | 9500 ±1320      | ±1320                                 | 1280        | 332         |

Note: Each SHD age has a 95 per cent confidence interval (C_t) derived from the sampling error of the blockstream sample (C_s) and the error associated with the calibration curve (C_c).
significance of boulder orientation and dip cannot be satisfactorily resolved.

Allied to the issue of boulder orientation and dip patterns is the cause of the inverse grading recorded in the two excavations. The up-freezing of blocks and the associated 'sieve-effect', by which smaller particles migrate downwards, has been invoked to explain this characteristic (Potter and Moss, 1968; Aldiss and Edwards, 1999; Boelhouwers, 1999). This is likely to have been most effective where blockstreams possessed a matrix of frost-susceptible material due to its propensity to retain moisture and promote frost heave. Inverse grading of blocks may therefore indicate a former matrix of fine-grained material.

Although both of the above characteristics have been noted in previous blockstream research, the chronological order of the respective processes does not seem to have been considered. Blockstream inverse grading probably preceded the establishment of orientation and dip patterns in the surface boulders, because the continued up-freezing of blocks would have likely generated more random patterns of orientation and dip. Given that preferred orientation and dip patterns were also recorded at the two feeder sites at Instheia, and that both transport distances and the time span of downslope movement were relatively short, we suggest that inverse grading is an early-stage process in blockstream evolution.

Blockstream Age

The SHD ages indicate that the surficial boulders of the blockstreams became inactive in the transition from the YDS to the Holocene. Because there are no significant differences in SHD ages between the 'axial' blockstream sites and the 'feeder' areas, we infer that the whole system was probably active and then became relict at approximately the time defined by the mean SHD age ± uncertainty. We infer that blockstream development is likely to have begun in a permafrost environment following the retreat of LGM ice at ~15 ka BP, with frost-wedged boulders from hillside outcrops and local glacially plucked boulders, in association with fine-grained material, being soliflucted downslope. Blockstream activity is likely to have continued through the YDS: if there had been limited or no activity in the YDS, older SHD ages would be expected.

The relatively young age from site 2 is from the area of blockstream A where the gradient is 0° and standing water occupies numerous small pools. This younger age (7.24 ± 1.2 ka) is not incompatible with some blockstream activity during brief early-Holocene cooling events, such as those at 9.7–10.2 ka (the Erdalen Event in Norway) and at 8.2 ka (the Finse Event in Norway) when mountain glaciers expanded (Dahl et al., 2002; Nesje et al., 2008) and periglacial activity was likely enhanced. At these times, the annual freeze-thaw regime may have induced more effective frost heaving and reactivated the frost sorting of boulders at a location where soil moisture became concentrated. Alternatively, late-lying snow may have persisted at this location throughout the Holocene, shortening the total exposure time for the boulders.

Although the SHD ages indicate that most blockstream activity ceased at the transition from the YDS to the Holocene, the present status of the blockstreams was likely attained after they had experienced a lengthy period of non-permafrost conditions during the Holocene. During this period, any fine-grained material is likely to have been removed from their near-surface parts under a periglacial environment characterised by a cool temperate climatic regime with seasonally frozen ground, particularly as a consequence of snowmelt runoff from adjacent slopes.

Wider Implications

Blockstreams have challenged scientists for over 170 years since Darwin (1845) wrote about 'streams of stones' in the Falkland Islands, and they remain enigmatic features of the (former) periglacial realm. Most blockstream studies have focused on examples that are considerably larger than those at Instheia and also considerably older (associated with periglacial environments adjacent to the limits of the LGM or earlier ice sheets). The wider significance of the Instheia blockstreams is threefold: (1) they post-date the LGM and developed within a period of ~5 ka, and so confirm the development of blockstreams under a permafrost regime; (2) they demonstrate that many of the characteristics reported from larger and older blockstreams can develop within a relatively short time frame and over limited transport distances; and (3) they indicate that the frost sorting responsible for inverse grading is an early-stage process in blockstream evolution and that once established, it persists.

Additionally, the presence of blockstreams at Instheia suggests that similar features should occur elsewhere in Scandinavia. Their apparent absence may be because previous workers have not discriminated them from blockfields, resulting in a major omission from the inventory of periglacial hillslope landforms and from the broader understanding of landscape evolution in this part of northwest Europe.

CONCLUSIONS

Relict blockstreams at Instheia possess characteristics commensurate with examples from other regions of the world. They lack fine-grained material in their surface and near-surface parts; show a well-sorted vertical structure with overall inverse grading; contain more fine-grained material with increasing depth; display patterns of boulder orientation and dip that indicate downslope movement; exhibit boulder imbrication with clusters of smaller boulders packed behind larger boulders; and pass upslope into boulder-strewn hillslopes with lobate and terrace morphology.
Several unanswered questions about blockstream formation remain, in particular the former presence of fine-grained material, its role in downslope movement and the timing of its removal. SHD ages suggest that blockstream-forming processes were active as LGM ice withdrew from Insteheia, and that slope changes in periglacial, particularly permafrost, environments can occur relatively quickly.

Downslope movement of the blockstreams spanned a period of up to ~5 ka. This short interval contrasts markedly with the longer time spans (~5–7 ka x 103) recorded for blockstream development in the southern hemisphere. Our results suggest that blockstreams can develop relatively rapidly under suitable environmental conditions and that the older ages of relict blockstreams elsewhere may indicate very long periods of inactivity combined with the propensity of boulder landforms to persist in the landscape.

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