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Daily fine sediment dynamics on an active Alpine glacier outwash plain

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Abstract Previous studies of channel morphological change have frequently relied upon sparse spatial and temporal data sets, often failing to quantify small-scale changes in channels composed of sand and fine gravel. This study reports the use of a high resolution 3D laser scanner (LMS Z210) in the assessment of fluvial sediment budgets in the proglacial zone of the Ferpècle and Mont Miné glaciers, Switzerland. High resolution (>500 points m^{-2}) data obtained across 4000 m^2 of braid plain during the early part of the meltwater season permitted Digital Elevation Models (DEMs) of the bed surface to be produced. Subtraction of successive daily DEMs revealed an overall pattern of erosion in the upstream section of the study reach with deposition occurring in the downstream section. The scanner was able to quantify a major episode of avulsion and medial bar erosion that occurred within the central part of the study reach. Transient lobes and sediment sheets could also be identified at the downstream end of the reach, as could lobe front progradation. Relatively minor changes in channel morphology could also be detected such as bar edge accretion, bank erosion, and chute development.

Key words 3D laser scanning; braided river; channel change; channel morphology; DEM; fine sediment; proglacial

INTRODUCTION

Proglacial environments provide excellent field laboratories to study process form relationships for braided rivers, due to the diurnal fluctuations in the discharge hydrograph, and associated fluctuations in sediment supply, resulting in rapid channel changes (Fenn & Gurnell, 1987). Such changes require better quality topographical data to produce Digital Elevation Models (DEMs) of river reaches at a variety of scales from the bar unit (Heritage *et al.*,1998), to the reach (Fuller *et al.*, 2003a,b; Brasington *et al.*, 2000, 2003), to large rivers (e.g. Lane *et al.*, 2003). However, although the spatial resolution of data acquisition has improved, there is still a need to demonstrate how current techniques can provide information on morphological change at a higher spatial and temporal resolution. This is particularly an issue in geomorphologically active environments, such as proglacial areas. This paper uses a field laser scanner to survey daily changes in the channel morphology of a proglacial braided stream, and link sediment budget information to changes in channel morphology. This instrument has only recently been used in geomorphological studies (e.g. Nagihara *et al.*, 2004; Heritage & Hetherington, 2005, this volume). The technique has the potential to offer a breakthrough in the measurement of landforms, achieving high data point density overcoming interpolation issues and operator bias inherent in earlier DEM based studies (Lane, 1998; Walker & Wilgoose, 1999; Lane *et al.,* 2003).

STUDY SITE CHARACTERISTICS

The study was carried out in the proglacial zone of the Ferpècle and Mont Miné glaciers, Valais, Switzerland. A large outwash fan is dissected by a braided river channel that drains into a proglacial lake dammed by a terminal moraine. This study concentrates on a 4000 m^2 reach of braided channel towards the tail of the outwash fan, situated at an altitude of 1916 m a.s.l. Sediment deposits consist of fine gravels in a sand matrix. Median grain sizes of surface material typically ranged from 10 mm at the upstream end of the reach to 5 mm towards the downstream end. Meltwater discharge displays a strong diurnal signal during the summer months, and the combined discharge from both glaciers typically reaches 15 $m^3 s^{-1}$ during this period (Milan, 1990).

METHODOLOGY

The study section and the surrounding confined flood plain were surveyed over a period of 10 days in early June 2004. The LMS Z210 scanning laser manufactured by Riegl Instruments was used to collect a series of independent data sets recording range distance, relative height, surface colour and reflectivity (Heritage & Hetherington, 2005).

Two high-resolution scans were carried out on either side of the study area using the field laser attached to a toughbook computer. Both survey stations were slightly elevated from the river, one being on a central roche moutonee and the other on a moraine. Survey control was facilitated by RiSCAN Pro survey software, capable of visualizing point cloud data in the field. Scans were collected with substantial overlap to reduce data shadow and increase data point density. Before scans were taken, a total of 20 reflectors were placed on and around the outwash fan and left *in situ* for the duration of the study. These reflectors can be automatically located by the RiScan software and then linked to common points in other scans. All the reflector points were also surveyed using an EDM theodolite defining the project co-ordinate system. Further independent data points were also collected to validate the scanner DEMs, 60% of these points were within ±0.02 m in the vertical with no errors greater than ±0.04 m. Volume change computations between successive surveys were calculated to establish the temporal losses and gains of sediment within the study section. Discharge was measured at the outlet of the study reach on 13 occasions and a detailed photographic record was also kept to further support conclusions drawn from DEM subtractions.

RESULTS AND DISCUSSION

Figure 1 shows a DEM subtraction that compares scans of the study site taken on the first day (1 June) with those taken on the last day (10 June). Significant change has taken place to the study reach, with a general trend of erosion in the upstream part of the reach and deposition in the downstream part. Erosion of a large medial bar is evident

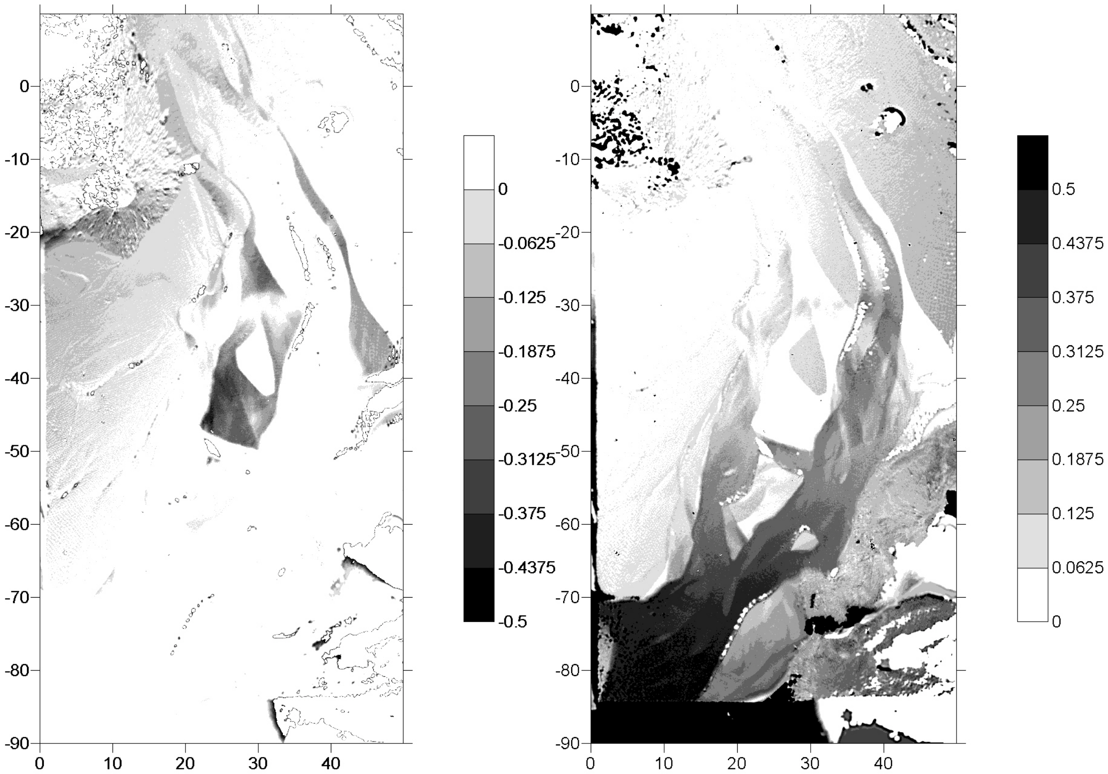

Fig. 1 10-day sub-barform scale change (metres of erosion and deposition) on the Ferpècle and Mont Miné glacier outwash plain.

in the centre of the reach, with only a small fragment of the original bar remaining. Channel avulsion is also clear with the left-hand anabranch cutting through the medial bar and joining the right anabranch. The subsequent increase in discharge into the right anabranch as a result of this avulsion may have triggered bank erosion here. The broad temporal resolution of 10 days gives a general impression of activity within the study reach. However, it fails to capture the complexities of channel change in response to the diurnal flow regime within the reach.

Daily change DEMs capture this much more effectively and these changes are summarized in Table 1 and Figs 2 to 5. Channel evolution and bar development within this system appear to have many parallels with previous studies including choking avulsion (Leddy *et al.*, 1993), deposition of forced bar surfaces (Wathen & Hoey, 1998), chute development and bar dissection (Ashmore, 1991) and general progradation at bar tails.

At the bar unit scale the main medial bar feature that was positioned between the two primary anabranches showed major changes to planform shape and size over the 10-day period. This feature was eroded at its upstream and downstream ends to differing extents with the downstream end experiencing the most scour (Figs 2–5). This change was associated with the shifting of the main channel on the left to a position that meant that it removed the entire front portion of the bar (Fig. 4) and then contributed to further bank erosion on the right side of the system. Erosion from this barform roughly corresponded to downstream deposition of transient sheets and lobes. Choking avulsion appeared to be the main bar-scale process observed (Leddy *et al.*,

Table 1 Summary of changes occurring at the Ferpècle and Mont Miné glacier outwash plain, June 2004.

Date	Evidence of erosion	Evidence of deposition	Discharge ($m^3 s^{-1}$)
1–2 June 2004	Tail of the main medial bar (grid ref. 25, –40) Minor bank/bar edge erosion (20, –75)	Bedload sheets (20, –80) Right-hand edge of the medial bar (35, –30)	0.95
2–3 June 2004	Most anabranches New anabranch (25, –45)	Choking avulsion in the anabranch (15, –45) bar edge aggradation (40, –25)	0.18–0.58
3–4 June 2004		Minor aggradation where the meltwaters of Mont Miné meet those of the Ferpècle glacier, (2, –70 and 2, –85).	0.13
4–5 June 2004	Substantial loss of left hand tail of the medial bar (30, –45)	Two migrating lobes of sediment at the lower end of the reach (15, –80 and 10, –75)	0.44–0.72
5–6 June 2004		Progradation at the lobe tail (5, –80) bank at 20, –80 appears to be aggrading.	0.05
6-7 June 2004	Scour of tail of medial bar (32, –45) Scour along the right hand bank (42, –32) Bank scour (5, –80)	Mobile lobes/slugs (5, –82)	0.86
7–9 June 2004	Chute development (20, –60)		0.17–0.64
9–10 June 2004	Major upstream avulsion Substantial scour at the head of the medial bar (30, –25) and right hand bar tail (35, –35).	Aggradation (2, 75)	1.05

1993; Ashmore, 1991). Evidence from successive scans indicates substantial development of the left-hand anabranch that appeared to show a dramatic shift to the right. This occurred in two stages. Early on in the study (1–3 June) deposition of sediment in the former left anabranch, and incision into a high flow channel to the right were recorded (Fig. 2). This channel gradually scoured the downstream face of a medial bar. Towards the end of the study (8–10 June), this channel appeared to choke with sediment probably originating from the downstream left bar edge as it rapidly migrated headwards (Fig. 5). Choking would have had the effect of ponding water back and forcing it over the bar surface further upstream. A new channel appears to have been produced as a result of these processes, dissecting the medial bar. Bar progradation was also observed towards the downstream part of the study reach (Fig. 3); however, there did not appear to be any evidence of sediments accumulating at the head of bars in this study. Sediment lobes and sheets were identified in the lower part of the study reach (Fig. 3). These were highly mobile, transitional forms and were likely to have been derived largely from the reworking on the main medial bar sediments a short distance upstream. The movement of this sediment does appear to have a significant influence upon channel form, as was shown by the avulsion episode.

The results when viewed at the scale of the sub-barform indicate that changes to the shape and volume of bars altered throughout the study period, even when the study reach was subjected to low flows. Sediment accumulation on bar edges, and associated bank erosion, as the right-hand anabranch migrated into the outwash fan was clearly evident from successive scans. Small-scale changes to the shape of bar bank faces was detected by the scanning equipment and could thus be elucidated after DEM analysis. Migrating small dunes and ripples that were noted in the field were not apparent

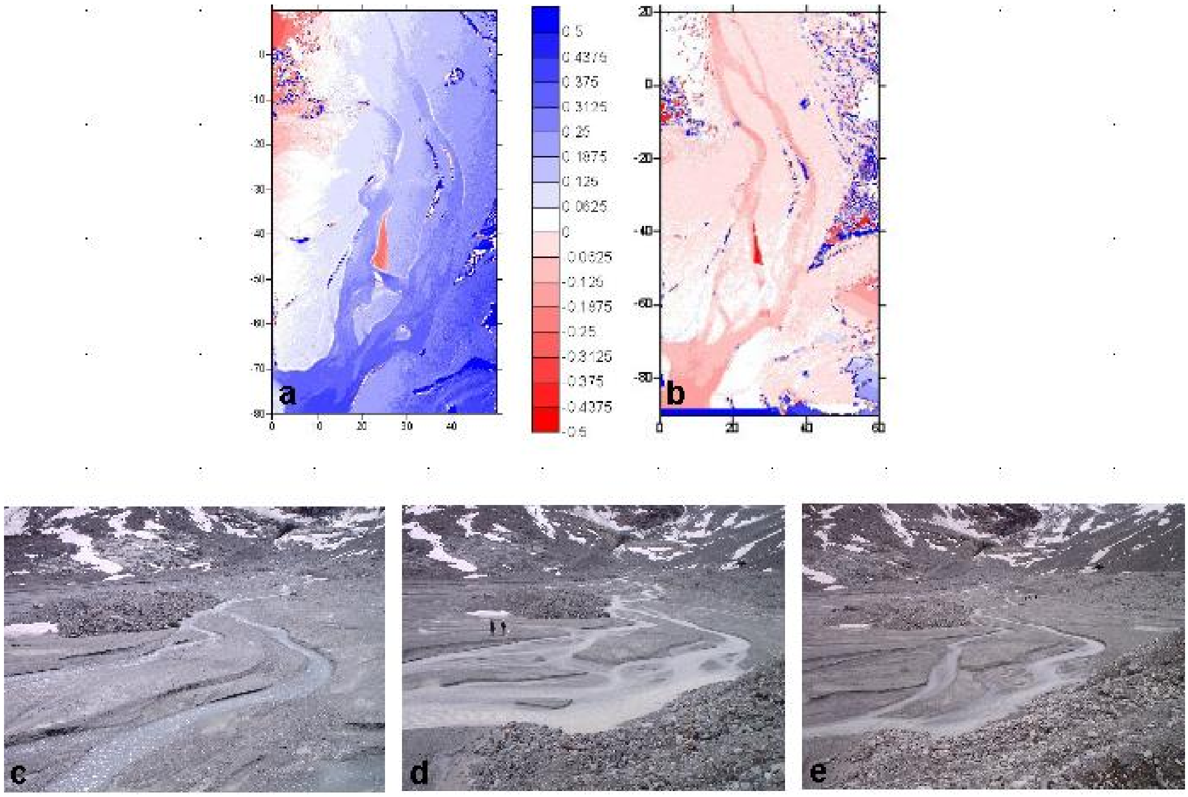

Fig. 2 Sub-barform scale change on the Ferpècle and Mont Miné glacier outwash plain: (a) 1– 2 June 2004; (b) 2–3 June 2004; photos: (c) 1 June, (d) 2 June, (e) 3 June.

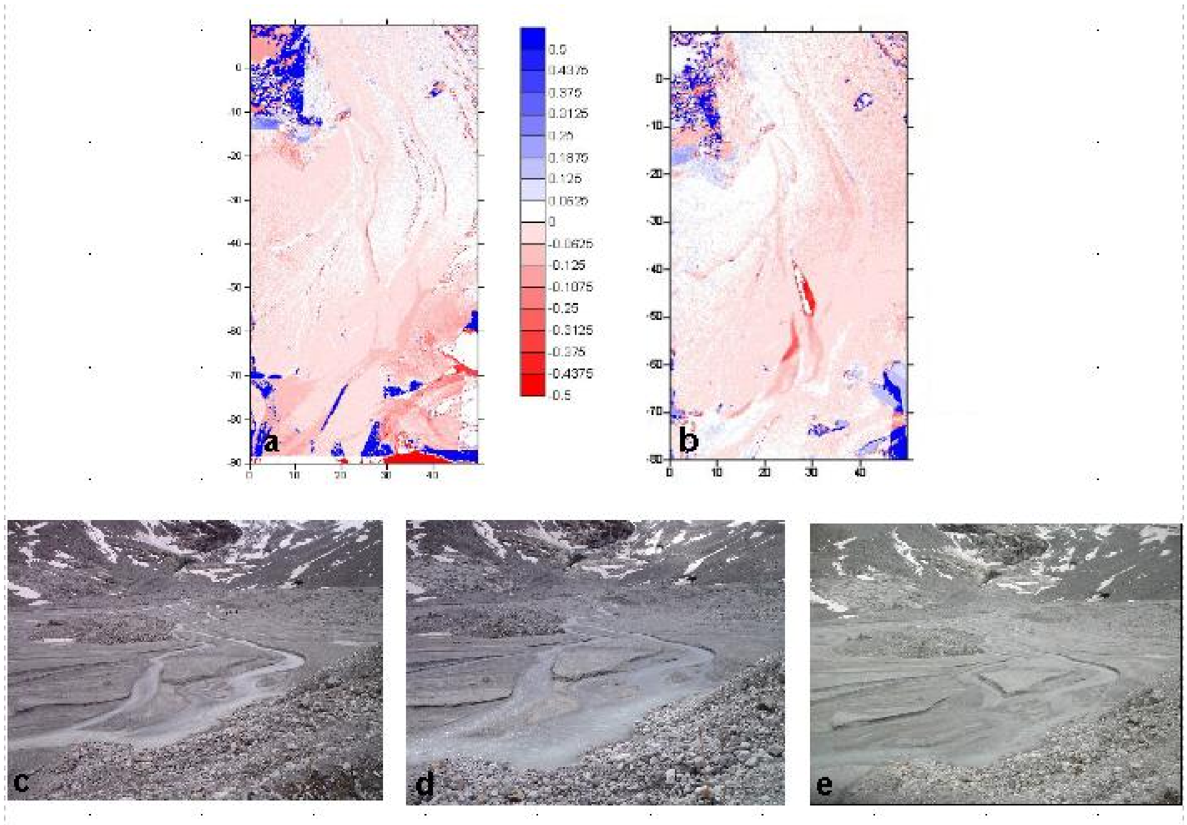

Fig. 3 As above: (a) 3–4 June; (b) 4–5 June; photos (c) 3 June (d) 4 June, (e) 5 June.

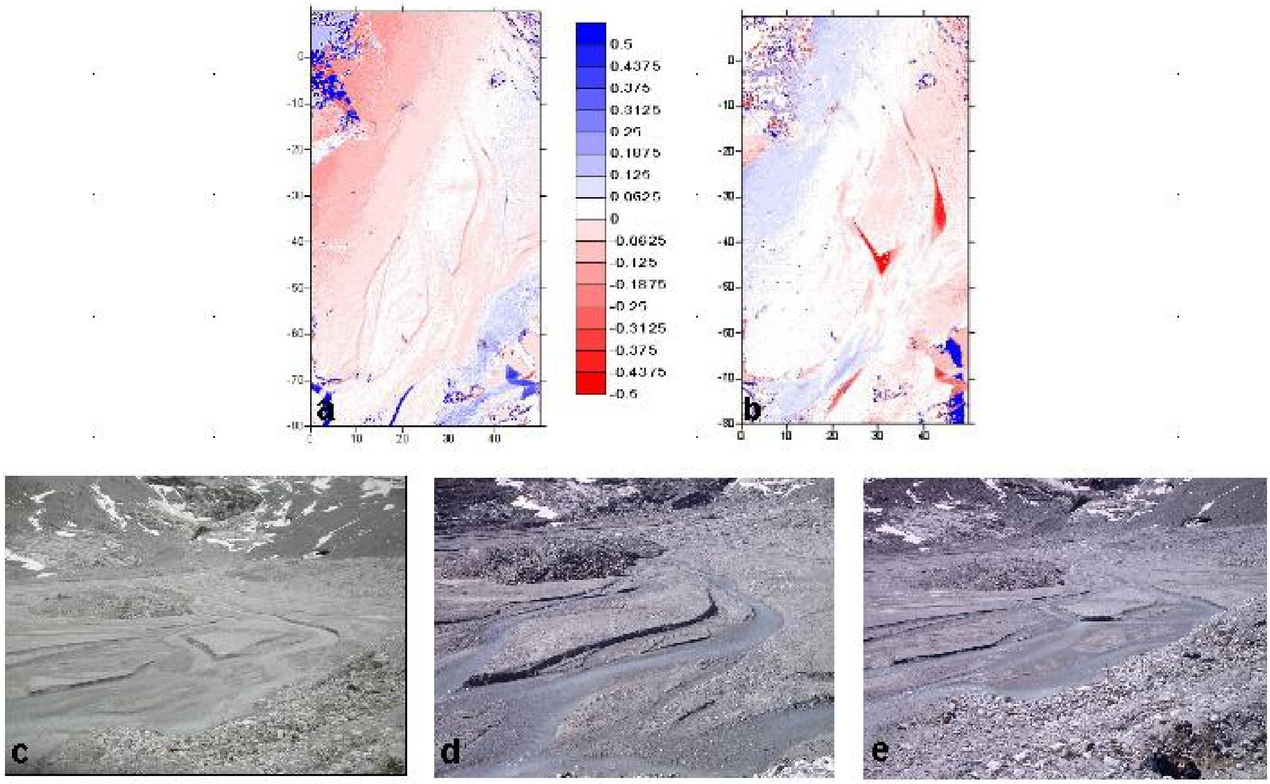

Fig. 4 Sub-barform scale change on the Ferpècle and Mont Miné glacier outwash plain: (a) 5–6 June 2004; (b) 6–7 June 2004; photos (c) 5 June, (d) 6 June, (e) 7 June.

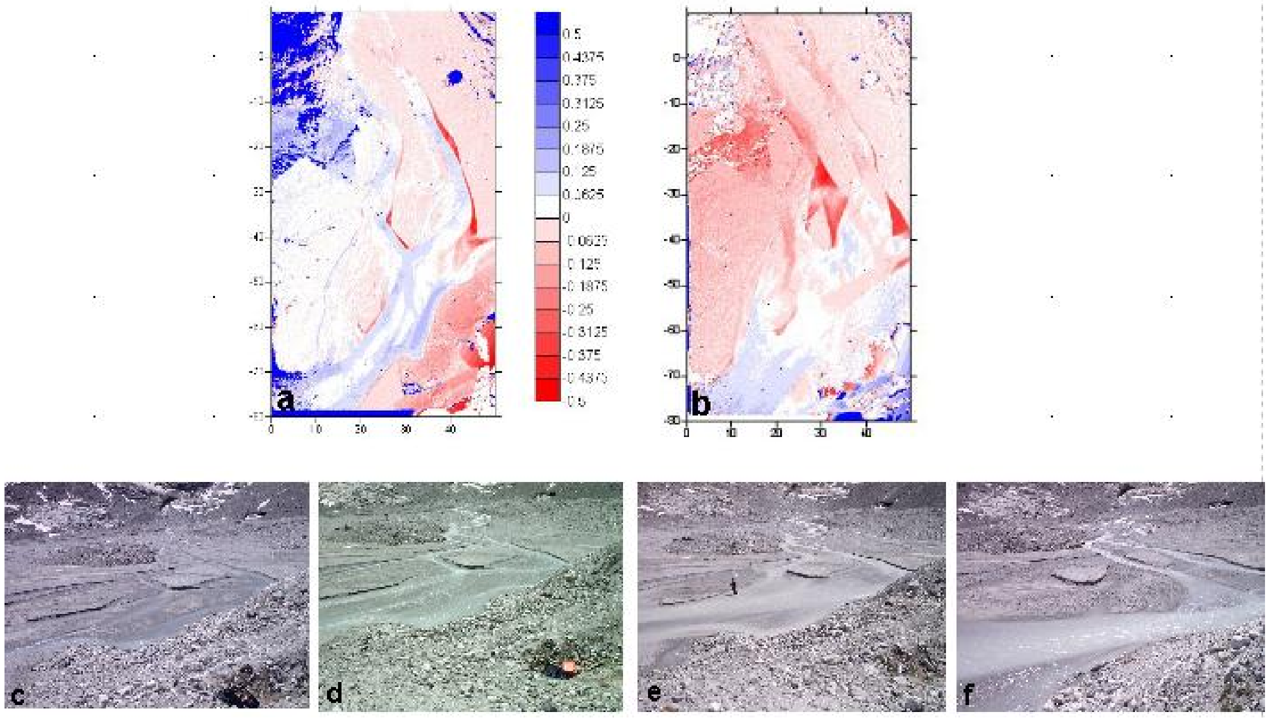

Fig. 5 Sub-barform scale change on the Ferpècle and Mont Miné glacier outwash plain: (a) 7–9 June 2004; (b) 9–10 June 2004; photograph: (c) 7 June, (d) 8 June, (e) 9 June, (f) 10 June.

after DEM subtraction for any of the study periods; however larger dune slip faces were. Chute channel development and consequent bar dissection similar to that described by Ashmore (1991) is also prevalent on some bar surfaces. A particularly good example of this is shown after DEM subtraction for the period 1–2 June 2004 where chutes developed towards the left of the study site (Fig. 2).

CONCLUSIONS

(a) Laser scanning technology can be used to elucidate information on various scales of morphological change from reach to sub-bar.
(b) Sub-bar-scale changes including chute channel and run development and bank erosion are evident after DEM subtraction between measurement days. This is possible with a minimum of two scans from opposite aspects.
(c) Bar-scale change occurred throughout the 10-day study including a major avulsion episode. The main medial bar was reduced in its planform area by approximately 70%.
(d) Redistribution of sediment from this bar was probably responsible for the transient sheets and lobes apparent ion the downstream part of the reach.

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