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Inter- and Intra-catchment Variations in Proglacial Geomorphology: An Example from Franz Josef Glacier and Fox Glacier, New Zealand

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Abstract

Proglacial outwash plains, or "sandar," can be recognized to be a part of a geomorphic, sedimentary, and hydrological system. At a global scale, glacial meltwater regimes and hence proglacial fluvial systems are strongly determined by glacier basal water conditions and glacier behavior. At a catchment scale it is necessary to consider that proglacial fluvial sedimentation can have a range of frequency and magnitude regimes. This paper presents geomorphological and sedimentological data from Franz Josef Glacier and Fox Glacier sandar, which have adjacent catchments. We determine that glaciofluvial facies are the most abundant sediment-landform association at both sites. However, we also observe considerable intra-catchment variability with respect to the magnitude-frequency regime of fluvial deposition and the relative importance of fluvial processes for sandur character. Franz Josef Glacier sandur is relatively high relief and superficially composed of boulder bedforms that are laterally and longitudinally extensive. It has a sedimentology dominated by massive, poorly sorted sediments containing outsized clasts. Franz Josef Glacier sandur thus has a character consistent with formation by episodic high-magnitude fluvial flows, i.e. jökulhlaups. In contrast, Fox Glacier sandur is of low cross-section relief and comprises two distinct components: an aggrading braided river and paraglacial debris fan deposits. With the exception of the contemporary ice margin, Fox Glacier sandur is of significantly finer-grained material than that at Franz Josef Glacier. We suggest that the contemporary Fox Glacier sandur contains widespread evidence that refutes a hypothesis of high-magnitude episodic events. Additionally, contemporary paraglacial inputs from recently deglaciated valley walls at Fox Glacier are far more important to sandur sedimentation than water or sediment from Fox Glacier. These results present a conceptual model of the predominant contemporary land-forming processes within a glaciated tectonically active region with exceptionally high denudation rates. Intra-catchment variability has important implications for predicting sediment fluxes in response to hydro-climatic forcing.

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Introduction and Background

Proglacial systems are among the most dynamic geomorphic environments on Earth. They are predominantly a product of glacial and glaciofluvial processes. As such they are ideal sites for recognizing climate change effects on glaciers and proglacial landscapes, both directly through meltwater and sediment fluxes, and indirectly through river channel morphodynamics. Over the past 40 years proglacial systems have thus been characterized in terms of landforms and sediments (e.g. Fahnestock and Bradley, 1973; Maizels, 1979; Sambrook-Smith, 2000).

However, proglacial landforms and sediments are extremely variable and can be very complex. Glacial meltwater regimes and hence proglacial fluvial systems are strongly determined by glacier basal water conditions and glacier behavior (Table 1). Cold-based glaciers and polythermal glaciers such as those in Antarctica and the High Arctic, respectively, tend to lack supraglacial material and commonly generate thrust moraines (e.g. Fitzsimons, 1997; Evans, 1989) (Table 1). In contrast, temperate valley glaciers in alpine regions have been documented to have proglacial areas comprising glaciofluvial landforms and hence abundant fine-grained facies (Evans and Twigg, 2002; Glasser and Hambrey, 2002) (Table 1).

At a catchment scale it is necessary to consider that proglacial fluvial sedimentation can have a range of frequency and magnitude regimes (Marren, 2005). Proglacial sedimentation can be dominated by seasonal and diurnal ice and snow ablation cycles (climatically driven) or by episodic (climatically decoupled) events, such as glacier surges and jökulhlaups, for example (e.g. De Jong, 1990; Marren, 2005).

Within glaciated catchments, a series of water and sediment sources and fluxes, and deposition styles can be identified. Water sources and fluxes are predominantly ice, snow, and groundwater inputs, and sedimentation styles are due to direct glacial activity, glaciofluvial reworking and/or paraglacial activity, which comprises deformation, reworking, and resedimentation by mass movements, and eolian processes (e.g. Warburton, 1990; Fitzsimons, 1996; Matthews et al., 1998; Ballantyne, 2002).

Understanding this range of proglacial sediments and associated landforms is important for three main reasons: (1)

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TABLE 1

Selected case studies of sediment-landform associations at glacier margins, highlighting the control of glacier thermal regime.

Glacier type (thermal regime)	Site (example)	Principal landforms	Principle facies (and interpretation)	Other comments	References
Cold-based	Sorsdale, East Antarctica	Thrust-block moraines	Stratified diamicts and massive diamicts (glaciomarine)	Sediment was frozen basally during entrainment, transportation, and deposition.	Fitzsimons (1997)
Polythermal	Ellesmere Island	Proglacial/ subglacially formed thrust moraine ridges.	Stratified and glaciotectonised sediment with numerous dropstones and a prolific bed of shells (glaciomarine). Usually overlain by 5 m of angular cobbles and boulders (glaciofluvial outwash)	Sediment is frozen so high preservation potential. Moraine ridges act to trap glaciofluvial sediment.	Evans (1989)
	Storglaciaren, arctic Sweden	Ice-cored lateral and frontal moraines, braided proglacial area.	Sandy gravel, silty gravel, massive sand, and silty sand (glaciofluvial). Deformed–massive clast-rich sandy diamicton (actively deforming subglacial till). Massive block gravels (supraglacial sedimentation/ice-marginal and subglacial reworking).	Sandy gravel is most abundant. Deforming basal till has been the most important factor controlling glacier flow.	Etienne et al. (2003)
Temperate (outlet) sub-types: debris-rich, surge-dominated, and "active"	Breiðamerkurjökull and Fjallsjökull, southern Iceland	Dump, push, and squeeze moraines, many glaciofluvial forms and subglacial landform assemblages.	Angular, relatively flat clasts (rockfall debris). Subrounded–subangular clasts in a poorly sorted matrix, rich in fine sediments (basal ice debris).	Lack of supraglacial sediment.	Evans and Twigg (2002)
	Kviarjökull, southern Iceland		Rounded and subrounded clasts. Clasts spherical and set in a structureless–sorted sand and gravel matrix (glaciofluvial).	Pitted or kettled outwash (sandar).	Spedding and Evans (2002)
Temperate (valley)	European Alps	Emphasized supraglacial sedimentation, derived principally from valley-side debris, ranging from bedrock masses, valley-side fans, and soils, to fluvial sediments transported by supraglacial streams.			Eyles (1983)
	Soler Glacier, Patagonia	Asymmetrical moraine ridges.	Sandy boulder gravel (ice-marginal), sandy gravel (glaciofluvial), angular gravel (supraglacial) and diamicton (basal glacial).	Postdepositional modification: melting ice-cored material and redistribution of finer material across the proglacial area by eolian processes and fluvial reworking.	Glasser and Hambrey (2002)
	Tasman valley, New Zealand	Collapse moraine ridges and hummocky topography.	Abundant fine-grained facies (ice-contact lake and subaqueous sediment flows) together with coarse material (ice-rafted debris).	This is an analogue for the modern Tasman glacier.	Mager and Fitzsimons (2007)
	Five glaciers from the Southern Alps, New Zealand	Bar forms on braided outwash plain, end moraines, debris flow fans, and rockfall piles.	Boulder gravel (rockfall/stream-dominated debris fan/supraglacial), sandy boulder gravel (end moraine/ glaciofluvial), sandy cobble gravel (glaciofluvial braided outwash), Muddy sandy boulder gravel (lateral moraine facies), sandy silt, silty sand (both glaciofluvial braided outwash).	Boulder gravel is most abundant. Facies beyond the glacier snout are almost entirely glaciofluvial.	Hambrey and Ehrmann (2004)

understanding contemporary controls on water and sediment fluxes from glaciated regions, for use in management and conservation of these regions; (2) predicting future responses of water and sediment fluxes from glaciated regions due to climate change; and (3) accurately understanding geologic, geomorphic, and sedimentological records in presently deglaciated regions.

There have been a series of studies over the last 15 years that enable a pseudo-database to be compiled of detailed descriptions of modern proglacial sediment-landform associations in glaciated catchments (Table 1). Studies have been made globally and frequently concentrate on the most ice-proximal zones of proglacial systems. Examples come from the Canadian Arctic (e.g. Evans, 1989), maritime Antarctica (e.g. Fitzsimons, 1990), Svalbard (e.g. Glasser and Hambrey, 2001), southern Iceland (e.g. Evans and Twigg, 2002), Patagonia (e.g. Glasser and Hambrey, 2002), and arctic Sweden (e.g. Etienne et al., 2003). Similar studies from tectonically active zones, where many of Earth's alpine glaciers are located and where exceptionally high denudation rates can be recorded are rare. Notable exceptions are Hambrey and Ehrmann (2004), who examine modification of clasts during glacial transport at five glaciers in the Mt. Cook area of the Southern Alps, New Zealand, and Mager and Fitzsimons (2007) who analyzed glaciolacustrine sedimentation and Pleistocene end-moraine facies in the Tasman Valley as an analogue for processes acting at the contemporary Tasman Glacier.

Studies aiming to develop models of proglacial systems on a catchment scale have generally focused on meltwater discharge, sediment sources, and hydrologic characteristics. Distinction and characterization of the landforms and sedimentology of braided proglacial outwash plains or "sandar" by Fahnestock and Bradley (1973) and Maizels (1979, 1997) has been conceptually extended to include meltwater and sediment discharge regimes (e.g. Warburton, 1990; Marren, 2005). It is a fundamental consideration that while proglacial systems can be controlled by climatically driven glacier ice dynamics (e.g. Marren, 2002), it is also possible that non-climatically driven episodic events such as glacial surges (e.g. Russell et al., 2001), and jökulhlaups (e.g. De Jong, 1990; Russell et al., 2006; Carrivick, 2005, 2006) dominate. The geomorphic effectiveness of episodic events is a function of the flood hydrograph (Rushmer et al., 2002; Rushmer, 2007), and also catchment characteristics such as topography, geology, and sediment supply (e.g. Carrivick et al., 2004a, 2004b). It is these extrinsic factors that can account for intra-catchment variations in glacier behavior, glacier hydrology, and proglacial water and sediment flux regimes (De Jong, 1990).

The aims of this paper are threefold. Firstly, we will test a literature-derived suggestion of what proglacial sediment-landform associations could be expected (Table 1) with reference to a glaciated region within a tectonically active region and with exceptionally high denudation rates. This test will be through a documentation of the geomorphology and sedimentology at each site and through a determination of the relative abundance of sediment-landform associations. Secondly, we will examine intra-catchment variability of proglacial fluvial systems in this region by examining the magnitude-frequency regime of fluvial deposition and the relative importance of fluvial processes for valley-floor character. Thirdly, we will present a conceptual model of predominant contemporary land-forming processes at these two sites.

Franz Josef Glacier and Fox Glacier

Franz Josef Glacier and Fox Glacier are both temperate alpine valley glaciers (Figs. 1A, 1B) situated on the western slopes of the Southern Alps, in South Westland, New Zealand (Fig. 1C). The proglacial zones of these two glaciers are selected for this study for two reasons. First, they share a catchment divide (Fig. 1D), and therefore can be assumed to experience similar weather conditions. Second, mapping and hypsometric analysis reveals that both glaciers have a very similar geometry and orientation (Fig. 1D), and area–altitude distribution (Fig. 2). A subtlety is that the Fox Glacier ablation area is oriented in a westerly direction, while that of the Franz Josef Glacier is oriented north-northwest. At 68 km^2 Fox Glacier catchment is ~45% larger than that of Franz Josef Glacier catchment, which is 47 km^2 (Fig. 1D; Table 2). The difference in catchment area is accounted for by steep hillslopes of 1100–1900 m a.s.l. in the Fox Glacier catchment (Fig. 2). Climatically driven ablation over each catchment is assumed to follow the same diurnal and seasonal patterns. Tectonic uplift and denudation have both been estimated to be about 12 mm a^{-1} in the area (Hovius et al., 1997). Precipitation approaches 14,000 mm a^{-1} west of the Southern Alps main divide (Henderson and Thompson, 1999).

Franz Josef Glacier and Fox Glacier are ~10 km and ~12 km long, respectively (Fig. 1D; Table 2). The mean glacier slope is thus 0.11 and 0.9 for Franz Josef Glacier and Fox Glacier, respectively (Table 2), although these figures hide the fact that both glaciers have narrow steep ablation tongues (Figs. 1A, 1B). These lowermost sections of each glacier descend ~1200 m in a series of icefalls over just 4–6 km to ~300 m a.s.l. (Figs. 1A, 1B, 1D). The ablation area of Franz Josef Glacier is 1.4% debris-covered, and that of Fox Glacier is 0.9% debris-covered (Table 2). Both catchments have underlying bedrock comprising highly metamorphosed schist and gneiss, and vegetation is dominated by a podocarp-broadleaf rainforest (Fig. 1B). The upper part of each glacier comprises a wide accumulation basin that reaches over 3000 m a.s.l. (Fig. 1D). This area is critical in maintaining mass balance gradients on the glaciers. For comparison, Balfour Glacier and La Perouse Glacier immediately to the south are both valley-confined but do not have a wide accumulation basin. They consequently feature low angled and stagnating snouts and are therefore likely to be in negative mass balance. Franz Josef Glacier terminates at a ~400 m wide (Table 2) by 3 km long valley-confined outwash plain (sandur) of the upper Waiho River. This proglacial system continues to be confined between terminal moraines for a further 3 km to its confluence with the Callery River. Fox Glacier also terminates in a valley-confined sandur, and this is also ~400 m wide (Table 2) and 5 km long. Fox Glacier is the source of the Fox River, which joins the Cook River ~13 km downstream from the Fox Glacier snout.

Franz Josef Glacier and Fox Glacier have both recently advanced but have a history of alternating advance and recession over the last 150 years (Suggate, 1950; Sara, 1968). Franz Josef Glacier is well-documented to experience "extreme" episodic meltwater discharges; glacial outburst floods or "jökulhlaups" (e.g. Goodsell et al., 2005; Davies et al., 2003), but there are to date no such reports from Fox Glacier. However, it has recently been supposed that subglacial drainage efficiency and water storage within Fox Glacier are responsible for surface velocity responses to rainfall inputs and time lags between rainfall events (Purdie et al., 2008). With this exception, it is the notable absence of reports from Fox Glacier that make it unclear whether or not jökulhlaups occur from Fox Glacier.

Methods

Fieldwork was undertaken in October 2005 and comprised geomorphological and sedimentological observations within 2 km

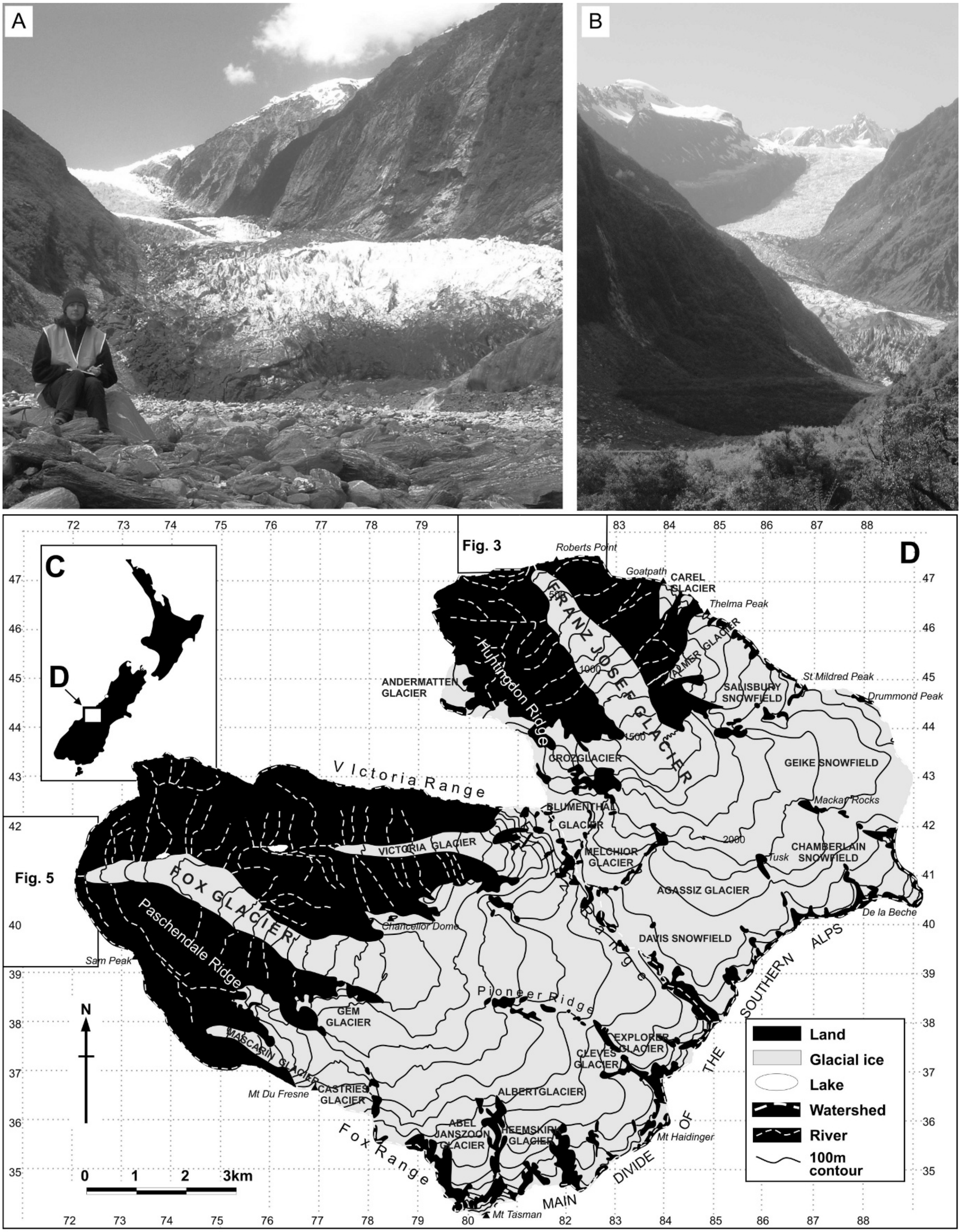

FIGURE 1. Franz Josef Glacier (A) and Fox Glacier (B) are both steep valley glaciers that descend from a broad accumulation area. They are located on the western side of the Southern Alps, New Zealand (C). While each catchment shape and orientation is similar, the ablation area of each glacier has a different orientation, and the glaciers share a catchment divide (D). The locations of Figures 3 and 5 are indicated. The grid is the New Zealand Map Grid Projection.

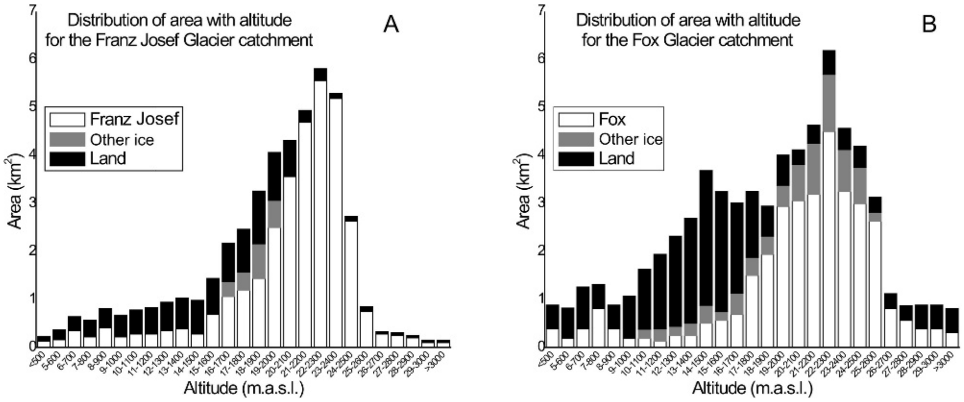

FIGURE 2. Franz Josef Glacier and catchment hypsometry (A) and Fox Glacier and catchment hypsometry (B). Hypsometry was calculated from the digitized contour lines in Figure 1.

of present glacier snouts at Franz Josef Glacier and Fox Glacier. This zone was considered because other examinations of sediment-landform associations have generally been restricted to the same zone (e.g. authors listed in Table 1), and because terrain responses to deglaciation occur most rapidly and intensively immediately following glacier retreat (e.g. Ballantyne, 2002). Direct observations were restricted to valley floors.

Landforms at each site were mapped in plan form using a handheld Garmin Etrex Global Positioning System (GPS) with horizontal accuracy of ~5–10 m. Vertical elevation changes along eight discrete valley cross sections, each of 100–300 m length, were recorded with a Sokkia Total Station with a user accuracy of ~0.05 m. Cross sections at Franz Josef Glacier were surveyed from obvious marginal wash limits, which are both depositional terraces and scour lines situated several meters above the valley floor, to the active Waiho River bank. On the basis of this mapping and cross-sectional topography, the fluvial geomorphology at each site was thus quantitatively mapped and characterized by areal extent and relative relief. Subjective observations were also made, including degree of braiding, number of channel segments, total channel length, number of bars, bifurcations, and links (cf. Maizels, 1979).

Sedimentological sampling at both sites was informed by our geomorphological mapping. Observations comprised surface characterization and objective recording of natural exposures. For surface characterization, measurements of the 10 largest clasts were made at ~10 m intervals on sedimentary surfaces, along valley floor cross-sectional surveys, and also on longitudinal transects on bar-forms. Clast *a*, *b*, *c* axis lengths and clast *a–b* plane long axis orientation and dip were measured in order to determine grain size, shape, and fabric. Clast *a–b* plane long axis orientation was measured in the field with a magnetic compass relative to north, and dip was measured with a clinometer relative to horizontal.

Up to four natural exposures of each facies type were logged. A description of the situation of the exposure relative to geomorphological features was noted. Exposures were recorded for lateral continuity of beds and units, and discrete vertical profiles were logged at selected points of interest. Diagnostic features, or those that refute a distinct magnitude-frequency fluvial sedimentation regime, were targeted (Marren, 2005). Photomosaics aided interpretations of lateral continuity/disruption of beds. Vertical profiles were logged for discrete patterns and trends in grain size, sediment sorting, texture, grading, bedding, clast support, small-scale bedforms, bed thickness, unit thickness, the degree and nature of imbrication and sedimentary structures, all following the guidelines presented by Jones et al. (1999). These observations permitted distinction of facies and facies assemblages (Miall, 1977, 1985), as well as interpretations of transport mode, for example. All observations and measurements were made in the field. Grain size was measured for clasts >10 mm *a*-axis, and visually estimated for finer fractions. Thus silts, sands, and fine gravels were distinguished by eye and touch and categorized as "silty sand" or "sandy gravel," for example. Textural identification was also subjective but considered the presence/absence and nature of matrix material and pore space character in addition to clasts within a bed. Beds, and hence facies, were distinguished between marked changes in texture, sorting, and/or grain size. Facies geometry and position were recorded on the basis of a marked change in sedimentary character and also upper and lower bounding surfaces and contacts.

Description of Landforms

Some properties of the Franz Josef Glacier sandur have previously been described by Davies et al. (2003) who focused on explaining different types of jökulhlaups and in particular those associated with glacier advance. Hambrey and Ehrmann (2004) noted that the proglacial areas of Franz Josef Glacier and Fox Glacier are dominated by glaciofluvial material. However, they do not report on the magnitude-frequency regimes of the sedimentation in these areas, nor do they document any variability

TABLE 2

Selected characteristics of the Franz Josef Glacier catchment and the Fox Glacier catchment. Debris cover and rate of recession are those values reported by Hambrey and Ehrmann (2004).

	Catchment	Glacier					Proglacial area (sandur)	
	Area (km^2)	Area (km^2)	Length (km)	Mean slope (−)	Debris (%)	Recession rate + (m/a)	Mean slope (−)	Mean width (km)
Franz Josef Glacier	47.3	34	10.1	0.11	1.4	29.5	0.02	0.4
Fox Glacier	67.7	35.7	12.5	0.09	0.9	25.0	0.014	0.4

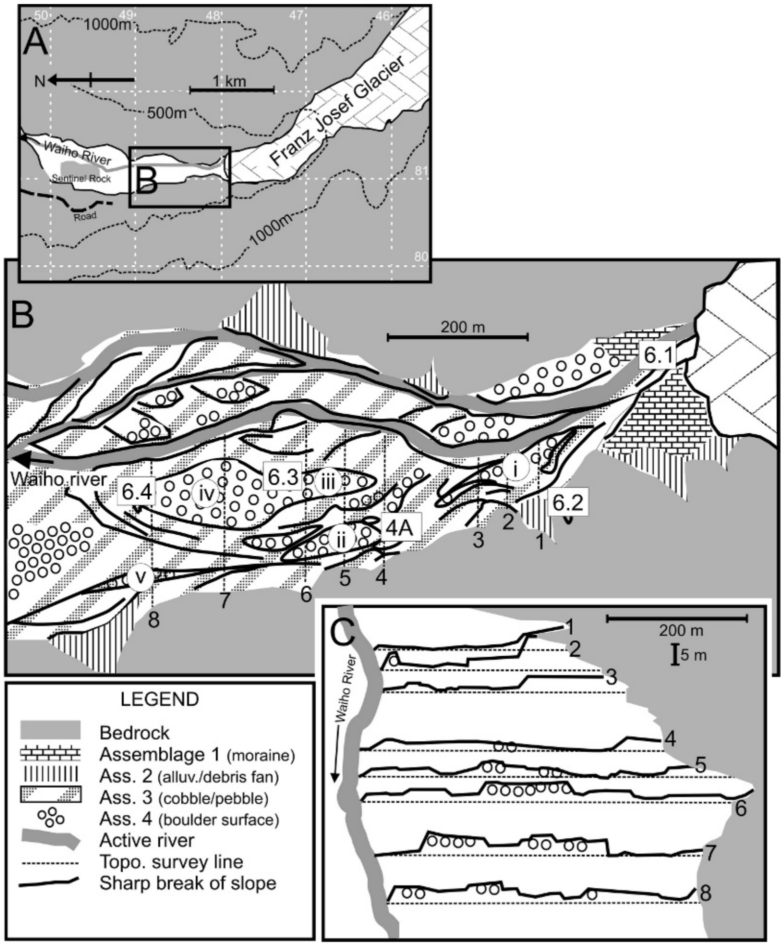

FIGURE 3. Overview of the upper Franz Josef Glacier valley-confined sandur (A), and geomorphological map pertaining to October 2005 (B). Topographical survey lines are depicted for valley cross sections in (C). The location of Figures 4A and 6.1–6.4 are indicated, as are boulder bars i–v (see Fig. 8).

between the two systems. We draw attention to the fact that these systems are highly dynamic and that our descriptions and interpretations pertain only to conditions in October 2005.

Our observations and measurements complement and extend those of these previous studies. The ice-proximal Franz Josef Glacier sandur comprises a confined valley-wide outwash zone of ~150–750 m width (Fig. 3A). This outwash zone contains the active Waiho River, bedrock promontories (Fig. 4A), and extensive boulder and gravel deposits (Davies et al., 2003). In the Franz Josef sandur area, boulder deposits occupy ~70% of the area and are commonly arranged into bar-forms (Fig. 3B). Coarse gravel deposits cover ~20% of the area. The remaining 10% is characterized by medium gravel and sand (5%) and the active Waiho River. The contemporary Waiho River occupies a bifurcating channel of low sinuosity (Fig. 3B). On a given cross section, the active Waiho River occupies the lowermost elevation zone, although abandoned channels in the extreme west of the sandur are at a very similar altitude (Fig. 3C). A Franz Josef Glacier sandur cross section is characterized by a series of sharp breaks of slope (Fig. 3C). Laterally and longitudinally extensive boulder deposits occupy the highest part of a given cross section, and tend to have a tabular profile (Davies et al., 2003) (Fig. 3C). Coarse gravel deposits occupy depressions between boulder deposits and infill the abandoned channel. Exceptions to these landform patterns are a small area of hummocky boulder-dominated gravel terrain adjacent to the ice margin, and a series of minor (tens of meters) valley-marginal alluvial fans (Fig. 3B). Both of these landforms are distinct by position and constituent material, the latter of which will be presented in the ''Description of Sediments'' section. It is notable that several alluvial fans occur in proximity to valley-marginal bedrock protrusions (Fig. 4A). In many valley-marginal situations bedrock protrusions exhibit a high-water ''wash limit,'' where mosses and lichen have been scoured off the rock. The altitude of these scour lines is matched by the elevation of depositional gravel surfaces at valley margins (Fig. 4A), which is a second type of ''wash limit.''

Fox Glacier proglacial area also comprises a valley-wide sandur, in this case of ~150–500 m wide (Fig. 5A). The Fox Glacier sandur contains the active braided Fox River (10%), bedrock promontories (5%), occasional boulders and extensive gravel deposits (45%) (Fig. 5B). There is a similar zone of hummocky boulder-dominated gravel terrain adjacent to the present ice margin (5%). Close inspection reveals three differences between the Fox Glacier proglacial area and the Franz Josef Glacier proglacial area: (1) boulders do not occur on large bar-forms and are only observed in two situations ([a] within 400 m of the present Fox Glacier snout, and [b] within shallow gullies incised into valley-marginal fan terraces [Fig. 5B]); (2) very large and coalescing gravel fans dominate the northern side of the valley and occupy 35% of the entire proglacial area (Fig. 5B); and (3) depositional and scour wash limits (Fig. 4B) are only observed in the valley center, rather than at valley margins.

Description of Sediments

Sediment observed at both Franz Josef Glacier and Fox Glacier is exclusively non-cohesive. Sediment sizes ranged from coarse-grained sand to boulders. Facies codes used to classify these sediments are given in Table 3. An examination of the distribution, geometry, and vertical stratigraphy of these facies

FIGURE 4. Depositional and scour wash limits at Franz Josef Glacier (A), and Fox Glacier (B). Note that in both cases the greatest height of the wash limit from the present sandur surface is by the most prominent bedrock outcrop. This indicates a point of greatest flow acceleration and subsequent scour.

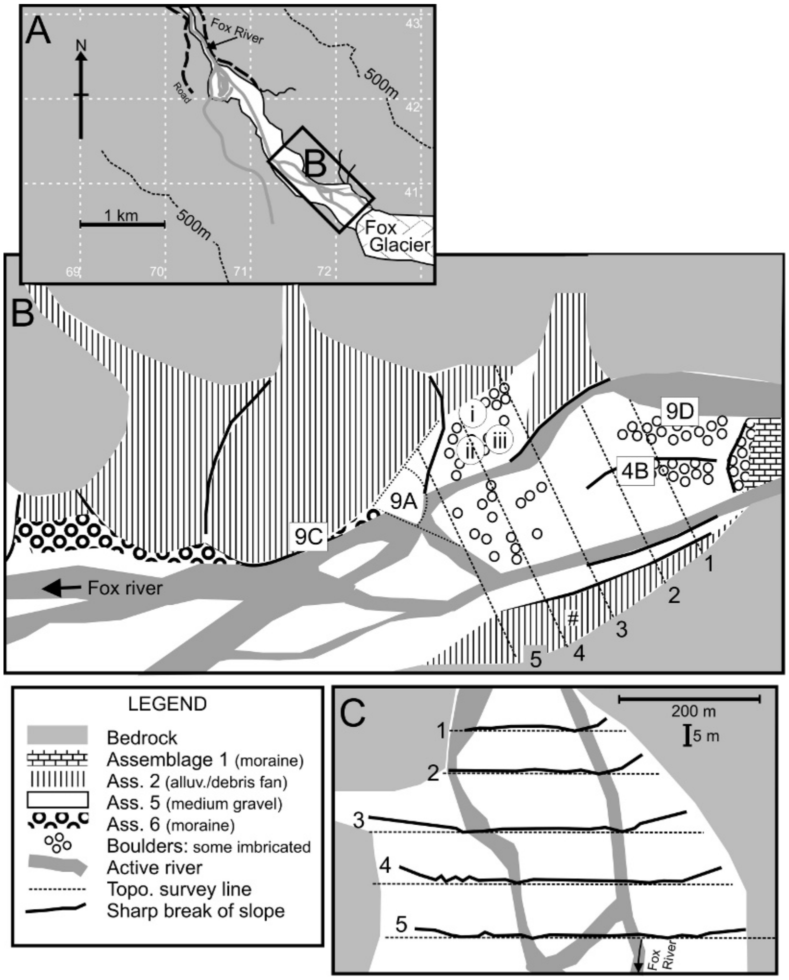

FIGURE 5. Overview of the upper Fox Glacier valley-confined sandur (A), and geomorphological map (B). Topographical survey lines are depicted for valley cross sections in (C). The location of Figures 4B and 9A–9D are indicated, as are boulder bars i–iii (see Fig. 8). # denotes an exceptionally large (15+ m) boulder that has fallen from cliffs and left a scar trail through trees.

permits facies assemblages in the proximal reach of both the Franz Josef Glacier and Fox Glacier sandar to be distinguished. These facies are summarized in Table 4 and our facies assemblage descriptions are based on the classification for poorly sorted sediments (Moncrieff, 1989; modified by Hambrey, 1994) in order to permit comparisons with other areas.

FRANZ JOSEF GLACIER

Natural sediment exposures are frequently found in the proximal reach of the Franz Josef Glacier sandur due to the incised nature of the surface (Fig. 3C). The thickness (up to 5 m) and longitudinal extent (up to 230 m) of these reveals a very large volume of "coherent" material. Facies identified on the Franz Josef Glacier sandur are reported in Figure 3B. They were observed to be horizontally bedded and with a general absence of distinct contacts between constituent facies. The vast majority of clasts are of metamorphosed schist and gneiss, as easily distinguished by a distinctive green-gray-white and banded appearance.

Facies Assemblage 1 is the least prevalent facies assemblage and is only observed proximal to the present ice margin (Table 4; Fig. 3B), typically in sections of 4–5 m unit thickness and with laterally continuous features (Fig. 6A). The unconsolidated nature

TABLE 3

Facies scheme used to interpret sediments of Franz Josef Glacier and Fox Glacier sandar.

Facies	Sedimentary characteristics	Interpretation and pertinent references
Gm	Massive, matrix-supported gravels, cobbles, or boulders, poorly sorted, ungraded.	Rapid rates of deposition from fluidal flows. Rapid deposition from poorly sorted or "higher-concentrated" flows (Carling, 1987; Miall, 1992).
Gs	Clast-supported, well-sorted or moderately well-sorted, stratified, ungraded or normally graded gravels and cobbles, likely *a–b* plane imbrication.	Deposition from turbulent concentrated flows (Costa, 1988; Todd, 1989). Deposition from high-energy basal tractive load preventing deposition of finer sediment (Maizels, 1997). Possible non-Newtonian grain dispersion deposits (Russell and Marren, 1999).
Gh	Horizontally bedded gravels, graded or ungraded, likely *a–b* plane imbrication.	Deposition of bedload sheets under planar bed conditions (Hein and Walker, 1977). Suspension transport prior to late stage traction transport.
Gp	Planar, cross-stratified gravels.	Downstream-dipping forests indicate the progradation and migration of bars (Bluck, 1979; Todd, 1996).
Sm	Massive sand.	Rapid deposition of sand (Carling, 1987; Costa, 1988).
Sh	Fine to coarse horizontally bedded sand.	Very low-energy Newtonian deposition, and/or fluidal infilling of minor channels.

TABLE 4

Summary of the character of six distinct facies identified on Franz Josef Glacier and Fox Glacier sandar. The remaining 10% of each site is bedrock and active river channel.

Facies assemblage (% abundance) (e.g. Fig.)	Facies (see Table 1)	Character	Interpretation
1 Franz Josef (5) Fox (5) (Fig. 6A)	Gm	Massive profile dominated by subangular boulders supported within a medium gravel matrix.	Moraine, lack of geomorphological pattern or shape suggests passive melt-out and dumping of sedimentary material, which is predominantly supraglacial.
2 Franz Josef (5) Fox (35) (Fig. 6B)	Gs Gh	Crudely bedded profile dominated by coarse gravel and cobbles supported within a sand-gravel matrix.	Paraglacial debris fan deposits, formed by episodic events, probably rainfall-triggered.
3 Franz Josef (20) (Fig. 6C)	Gs Gp (Gm)	Poorly bedded profile dominated by subrounded pebbles and cobbles, some of which are imbricated. Gravel veneer.	Coarse gravel fluvial bar, formed by high-magnitude sediment-laden outburst (rapid rise to peak discharge and short-lived) flows.
4 Franz Josef (60) (Fig. 6D)	Gs Sm Gm	Massive coarse gravel and pebble beds within a sand-gravel matrix. Clast-supported boulder surface.	Hyperconcentrated deposits formed by outburst (rapid rise to peak discharge and short-lived) flows with high sediment concentrations.
5 Fox (45) (Fig. 9C)	Gh/Gp Sm Sh	Bedded and sorted profile dominated by medium gravel supported within a sand-gravel matrix. Bedded sands.	Glaciofluvial deposits formed by seasonal and diurnal ice- and snowmelt–dominated regime.
6 Fox (5) (Fig. 9D)	Gm Gs Sh	Massive profile dominated by subrounded clast-supported boulders and coarse cobbles, with a high interstitial silty-sand matrix content.	Moraine formed by passive melt-out and dumping of sedimentary material, which is predominantly glaciofluvial.

of these sediments is emphasized by large cones of material at section bases (Fig. 6A). Facies Assemblage 1 is dominated by facies Gm, i.e. boulders supported within a medium gravel matrix. Individual boulder clasts tend to be subangular and can exceed 3 m although are more typically 1.5–1.8 m in diameter (Fig. 6A). Some facies (Gs) have crude bedding and sorting is present in discontinuous blocks, but throughout Facies Assemblage 1 there is no preferential clast *a–b* plane long axis orientation (Fig. 6A). Documentation of Facies Assemblage 1 was limited because it was too dangerous to make very close inspection of those sediments due to their unconsolidated nature and the presence of unstable boulders (Fig. 6A). However, it should be noted for later interpretations that a minority of boulders situated upon, and fallen from, these exposures were observed to display striations, facets, and very occasionally crescentic cracks and chattermarks. These features of glacial abrasion are limited to fine-grained lithologies, which are a minority among the diverse range of metamorphic rocks at Fox Glacier (Hambrey and Ehrmann, 2004).

Facies Assemblage 2 occurs on ~5% of the sandur in discrete valley-marginal locations and specifically in association with tributary gullies and streams and bedrock promontories (Figs. 3B, 4A). A typical Facies Assemblage 2 section comprises facies Gs and Gh (Table 4), i.e. crude beds of coarse gravel and cobbles supported within a silty-sand and gravel matrix (Fig. 6B). Pebble and cobble clasts in Facies Assemblage 2 have a preferential *a–b* plane dip that is horizontal. Lowermost beds contain isolated "floating" boulders (Fig. 6B). In all matrix-rich beds, the matrix comprises dense sandy gravel and gives Facies Assemblage 2 a relative cohesion due to a compacted gravel and silty-sand matrix. Crudely distinguished facies Gh beds can be identified between predominant gravel, pebble, and cobble grain sizes, sorting, and relative matrix abundance (Fig. 7A). Uppermost units contain clasts that have a tendency for *a*-axis alignment to the horizontal (Fig. 7A). Overall, a Facies Assemblage 2 profile coarsens upwards slightly.

Facies Assemblage 3 occupies 20% of the Franz Josef Glacier proglacial area and is situated within topographic lows of the sandur (Fig. 3B). Facies Assemblage 3 is observed in exposures up to 3 m thick and is dominated by facies Gs and Gp, i.e. it is poorly bedded. Facies Assemblage 3 Gs beds comprise subrounded pebbles and cobbles, some of which are imbricated (Fig. 6C). Some Facies Assemblage 3 beds are clast-supported although the vast majority have a matrix of sandy gravel. Some isolated "floating" boulders occur within and between these beds. These boulders are subangular and subrounded boulders and do not have any preferential axis alignment. Mid and lower parts of Facies Assemblage 3 comprise facies Gp, matrix-supported coarse gravel and poorly sorted pebble beds, which grade into each other (Fig. 7B). Occasional facies Gh are coarse gravel and pebble beds that are clast-supported and imbricated (Fig. 7B). The whole Facies Assemblage 3 vertical profile therefore tends to fine upwards, although this is not so marked where an overlying gravel veneer is present (Fig. 6C).

Facies Assemblage 4 occupies ~60% of the Franz Josef Glacier sandur (Table 4) and is dominated by facies Gm and Sm, although some crudely bedded coarse gravel and pebbles within a sand-gravel matrix can be observed. The matrix gives Facies Assemblage 4 relative cohesion and hardness. In general, a typical Facies Assemblage 4 vertical profile coarsens upwards, and this trend is much more obvious than in the other facies assemblages identified at Franz Josef Glacier. Facies Assemblage 4 also has matrix-rich lower beds, either facies Gh gravels or occasionally massive facies Sh sand beds, as depicted in Figure 7C. Beds in Facies Assemblage 4 profiles do not have clear boundaries such as erosive contacts and this is also in contrast to beds in other facies. In all Facies Assemblage 4 beds clasts are matrix-supported, tending to a horizontal *a*-axis alignment, and of a subrounded to rounded shape (Fig. 7C). The most notable feature of Facies Assemblage 4 is a superficial tabular deposit of large boulders (Fig. 3B). Some of these boulder clasts are imbricated (Fig. 7C), all are subrounded and most, in contrast with other sediments of the Franz Josef sandur, are lichen and/or moss covered (Fig. 6D). Analysis of boulders on five of these bars shows considerable variability in sorting; those on bar (i) are well-sorted, clasts on bar (ii) are very poorly sorted, and clasts on bars (iii), (iv), and (v) are

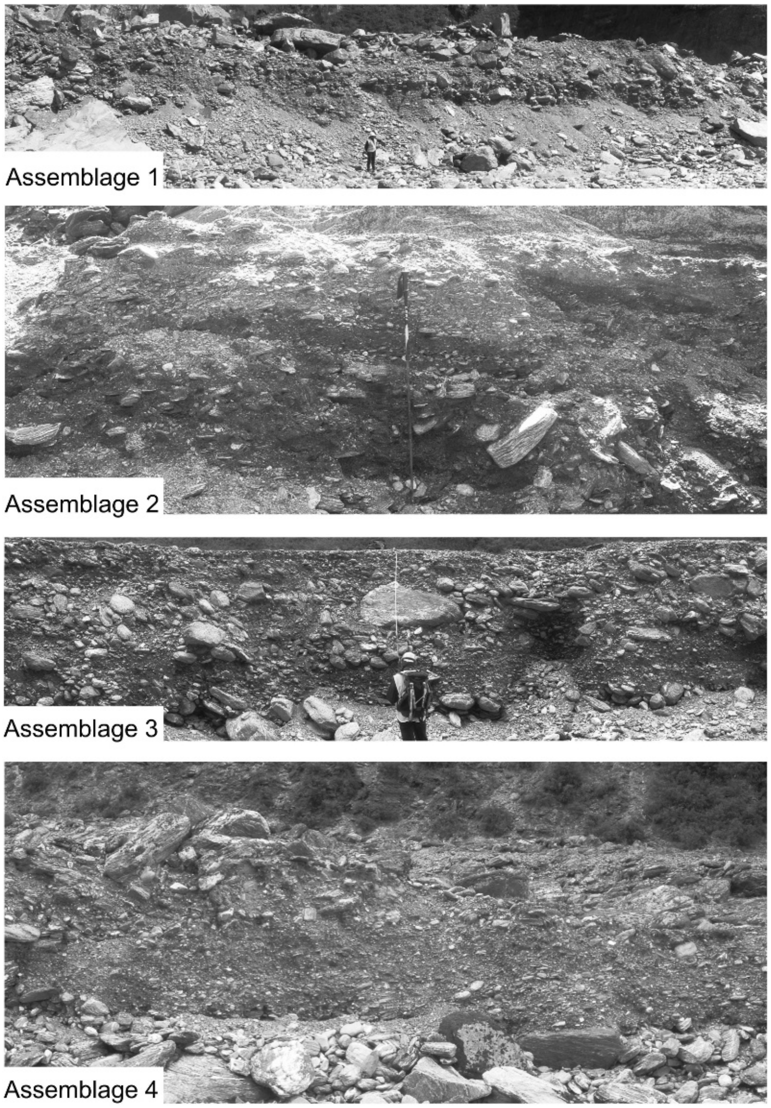

FIGURE 6. Four distinct sedimentary facies observed on the Franz Josef Glacier sandur. Facies Assemblage 1 is interpreted as moraine, Facies Assemblage 2 as gully-sourced paraglacial deposits, Facies Assemblage 3 as high-magnitude glaciofluvial deposits, and Facies Assemblage 4 as hyperconcentrated flow deposits.

moderately well-sorted (Fig. 8A). However, clast roundness does not vary significantly between bars, or downstream (Fig. 8B). Boulder bar clasts across the entire Franz Josef Glacier sandur are subrounded and tend towards a bladed shape (Fig. 8C).

FOX GLACIER

The ice-proximal proglacial area at Fox comprises the active river and associated sandur, coalescing alluvial fans, ice-marginal moraine, and bedrock promontories. The Fox Glacier sandur contains clasts on the sandur surface that visibly fine downstream, from a boulder-dominated zone to cobble-dominated clasts within 1 km and then to pebble-dominated clasts to 2 km. Boulders also occur on a series of bars on the north side of the valley (Figs. 5B, 9A). Boulders on these bars are moderately to poorly sorted (Fig. 8D), display no significant variations in roundness within a single bar, or between different bars (Fig. 8E), and tend to be subangular to subrounded, and are neither equant nor bladed in shape (Fig. 8F). Boulders on these bars and in the ice-proximal zone are predominantly subangular and subrounded, moderately well-sorted, and frequently imbricated. All are of a metamorphosed schist and gneiss lithology and the only superficial difference between these and the boulder deposits at Franz Josef is the general absence of lichen and moss. However, the angle of imbrication (*a–b* axis plane) of boulder clasts is orientated diagonally down valley, i.e. west (Fig. 9B).

Natural sediment exposures at Fox Glacier are scarce, due to the general absence of breaks of slope across valley sections (Figs. 5B, 9A). Therefore, sedimentary observations of Facies Assemblage 5 are restricted to just two exposures of 1.5 m thickness and ~10 m length (each) on the banks of the active Fox River, and also to observations and measurements of superficial sediments, as depicted in Figure 9A. Facies Assemblage 5 comprises bedded and sorted medium gravel clasts supported within a sand-gravel matrix. There are also bedded sands which are generally not laterally continuous. Facies Assemblage 5 has a surface of subrounded cobble and pebble clasts that are imbricated, form clast clusters, and are well sorted.

Valley-marginal coalescing fans at Fox Glacier are situated beneath large tributary gullies (Fig. 9B). The truncation of one of these fans by the Fox River reveals Facies Assemblage 2 (Table 4). These fans overlie, and appear to be buttressed by, sediments with a character very similar to Facies Assemblage 6, though in places the angularity of the boulders suggests Facies Assemblage 1, too. Facies Assemblage 2 at Fox Glacier sandur comprises pebble and cobble clasts, some of which are held within a dense coarse gravel matrix (facies Gs). Facies Assemblage 2 at Fox Glacier is therefore finer-grained and slightly more poorly sorted than Facies

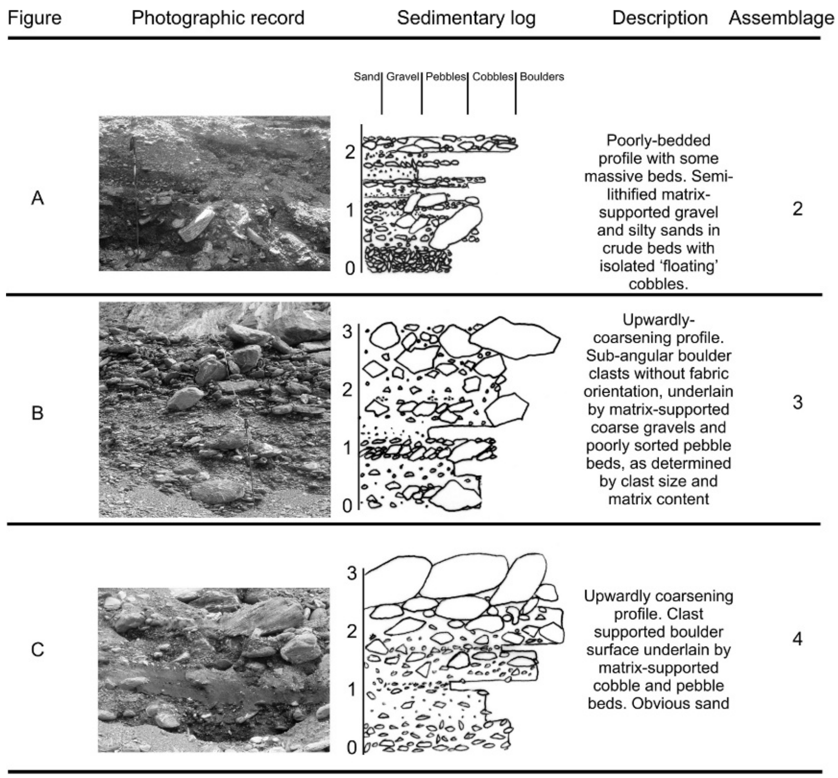

FIGURE 7. Representative vertical profiles of facies observed at Franz Josef Glacier. Note that Facies Assemblage 1 was not logged due to safety considerations (see Fig. 6.1). Facies Assemblage 2 is interpreted as gully-sourced paraglacial deposits, Facies Assemblage 3 as high-magnitude glaciofluvial deposits, and Facies Assemblage 4 as multi-phase hyperconcentrated flow deposits. Vertical height scale is in meters.

Assemblage 2 at Franz Josef Glacier, but is otherwise identical. Clasts within Facies Assemblage 2 are subangular and subrounded and heterolithic. Very crude beds (facies Gh) can be distinguished on the basis of varying clast sizes, and a subjective lithic-matrix ratio. Most individual beds cannot be traced laterally for more than a few meters. A typical 3 m thick Facies Assemblage 2 profile at Fox Glacier coarsens upwards (Fig. 9C).

Facies Assemblage 6 (Table 4) at Fox Glacier is depicted in Fig. 9D. This assemblage (facies Gm) is typically limited to just two vertical meters of exposure and has a pseudo-massive texture. Some very crude vertical sorting occurs, i.e. facies Gs. Facies Assemblage 6 is thus dominated by subangular clast-supported boulders and coarse cobbles with very low interstitial matrix content (Fig. 9D). Some clasts show striations, crescentic cracks, and chattermarks, and clasts have no preferential *a–b* plane long axis orientation. Facies Assemblage 6 is very similar to Facies Assemblage 1 observed at Franz Josef. However, Facies Assemblage 6 comprises less angular clasts and is more sorted than Facies Assemblage 1.

Interpretation

Morainic deposits (Facies Assemblages 1 and 6; Table 4) are interpreted as such because they have a clast size distribution dominated by boulders with little interstitial matrix. Morainic clasts were observed to be the largest of any on either sandur. Unsorted, angular to subangular clasts without a preferential *a–b* plane long axis orientation, such as those of Facies Assemblage 1, are most likely to be supraglacially derived (Hambrey and Ehrmann, 2004). Clasts bearing facets, striations, crescentic cracks, and chattermarks, which were present on some of the Facies Assemblage 6 clasts, are indicative of subglacial transportation (e.g. Miller, 1996). Unsorted clast size distributions suggest that this material has undergone active rather than passive transport (Boulton, 1978), and were deposited en masse, i.e. without time for sorting due to diminishing competence. Moraines within the study area occur immediately in front of the present-day ice margins of both Franz Josef Glacier (Fig. 3) and Fox Glacier (Fig. 5). There is also an indication of some moraine beneath the alluvial fan sediments on the north side of the Fox Glacier valley, and thus we make a tentative suggestion that these aggrading fans could be partly buttressed by, and infilling accommodation space behind, lateral moraines.

Coarse-grained alluvial/debris fan deposits (Facies Assemblage 2; Table 4) are distinctive by situation and areal geometry (Fig. 5B), as well as sedimentology (e.g. Blair, 2002). They comprise a poorly bedded profile that is dominated by fine–coarse granules and cobbles set within a silty-sand–gravel matrix (facies Gh and Gs). This profile implies sequential deposition from multiple phases of flow, some of which had exceptionally high sediment:water ratios (e.g. Blair, 2002). It is thus indicative of predominantly hyperconcentrated debris flow phases of flow (Pierson, 1981; Costa, 1988). Some granular fall deposits are interpreted where massive granular sand and angular gravel tabular deposits exist. Overall, a lack of a preferential fabric alignment indicates mass flow that was deposited en masse, which we attribute to downslope collapse and mixing of heterogeneous glacigenic sediments from surrounding valley walls. We therefore suggest that these are paraglacial debris fans, though they are not exclusively produced by debris flow processes. Phases of debris fan deposition are likely to be predominantly precipitation controlled, although some periglacial, snow avalanche, and freeze-thaw activity could also be a supply, as suggested by granular phases of angular clast deposition (McEwan and Matthews, 1998).

Sediments from high-magnitude fluvial deposition (Facies Assemblage 3; Table 4) contain some normally graded deposits, but are dominantly massive to poorly bedded sediments dominated by subrounded pebbles and cobbles, some of which are imbricated. Normally graded beds have resulted from declining flood power and tractive force during falling stage (Nemec and Steel, 1984; Smith 1986; Todd 1989; Maizels, 1993). The falling stage provided sufficient time for clasts to become deposited grain-

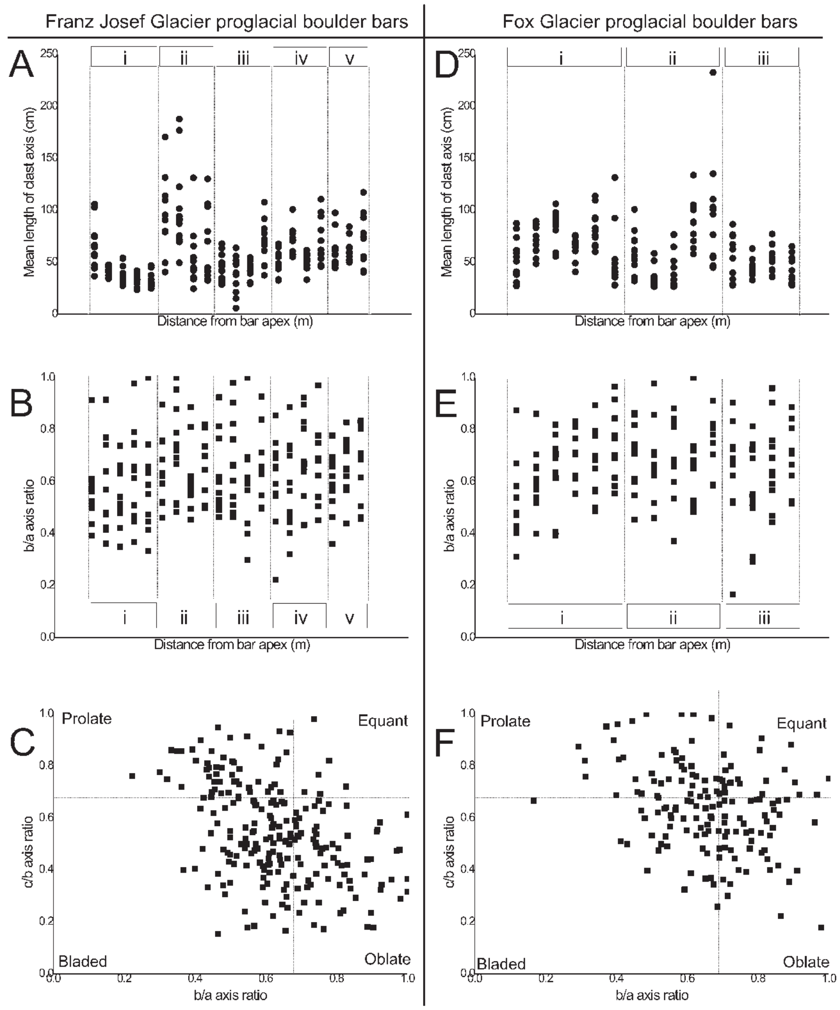

FIGURE 8. Boulder clusters analysis at Franz Josef Glacier and Fox Glacier. The 10 largest boulder clasts were measured at 10 m intervals on discrete boulder bars, as numbered i, ii, iii, iv, and v. Analysis comprises within-bar clast size variation (A, D), within-bar clast roundness variation (B, E), and overall roundness (C, F). Boulder bars at Franz Josef Glacier and Fox Glacier are located in Figures 3 and 5, respectively.

by-grain, and for progressively finer clasts to be deposited. In contrast, massive – poorly bedded sediments could be produced by rapid rising stage deposition from sediment-rich flows (Carling, 1987, 1989; Russell and Knudsen, 1999; Carrivick et al., 2004b; Carrivick 2007b). Imbricated clasts distinguish tractive fluvial transport and deposition, although it should be noted that many clasts had a poorly defined shape (Fig. 8). Imbrication tends to develop more frequently amongst disc-, rod-, and blade-shaped particles and imbrication should not be measured in clasts with an axial ratio of less than 2:2:1 (Rust, 1975). Poor bedding and matrix content illustrates high-magnitude flows and rapid drop-out deposition. Recognition of both tractive and suspended deposits together illustrates that flow(s) had extremely variable hydraulics and sediment supply, both spatially and temporally (e.g. Rushmer, 2006, 2007). These deposits are similar to those suggested by Kneller and Branney (1995) and documented by Manville and White (2003), who inferred a sediment-laden flow with a granular base flow. However, since Facies Assemblage 3 sediments contain superficial gravel sheets, flows are interpreted to have progressed to a rather more fluidal flow, i.e. with tractive bedload at the base of a water column. An alternative explanation is that the gravel veneer overlying these sediments is an armored surface produced by frost heave activity and eolian winnowing, as is common in some proglacial areas with coarse sediment (e.g. Boulton and Dent, 1974).

Hyperconcentrated deposits (Facies Assemblage 4; Table 4) are characterized by a massive or coarsening-upwards profile that is dominated by subrounded clast-supported boulders and coarse cobbles, with high interstitial matrix content. These deposits imply a dispersive pressure within a high-density bedload layer, which concentrates coarser clasts near the surface of the depositional layer or emplaces the coarser clasts on top of the high-density bedload layer (Nemec and Steel, 1984; Costa, 1988; Todd, 1989, 1996; Sohn, 1997). From the caliber, volume, and sedimentology of the material it is clear that these were also very high-energy flows (e.g. Carrivick et al., 2004a, 2004b). Outsized clasts within some sections were emplaced by dispersive pressure present within the high-density bedload layer (Nemec and Steel, 1984; Costa, 1988; Todd, 1996). The presence of some sections with no preferred clast alignment additionally reflects high concentration flows and rapid deposition rates, as little time was allowed for an organized fabric to develop (Miall, 1977). Thus, overall, Facies Assemblage 4 constitutes sediment-laden flows that were deposited rapidly en masse. Rapid deposition is likely to have been due to a sudden reduction in flow competence, and this is most likely to be due to emergence from a subglacial conduit. These deposits are the same as the boulder deposits reported by Davies et al. (2003).

Facies Assemblage 5 is composed of facies (Table 4) that clearly are the product of fluvial deposition that is competence-driven. Thus there is considerable vertical and spatial heterogeneity due to sequential deposition related to discharge fluctuations, and to shifting channel patterns in response to these water fluxes, respectively.

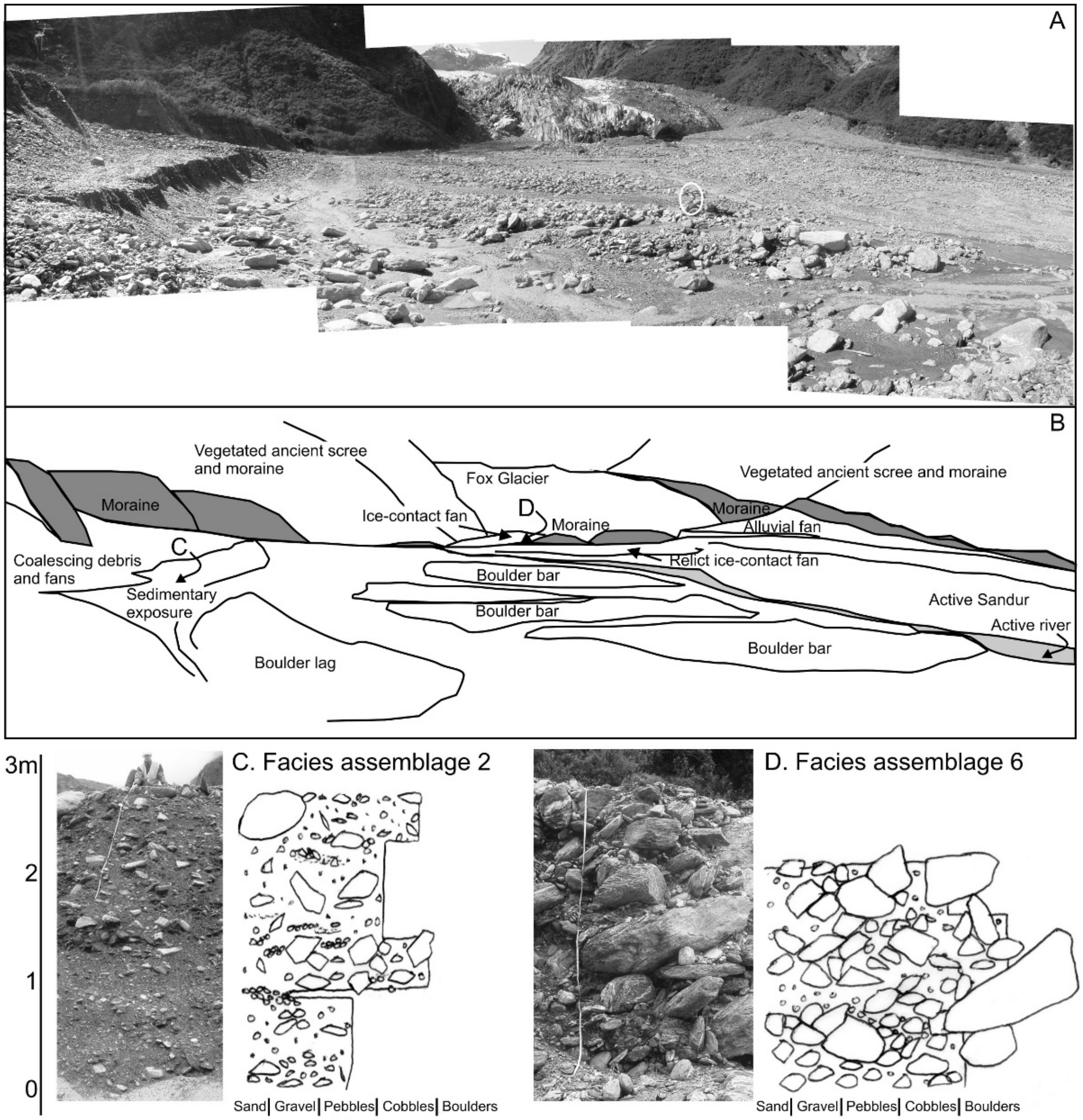

FIGURE 9. Panorama of the upper Fox Glacier sandur (A) and interpretation (B), pertaining to October 2005. Person encircled in A for scale. Representative vertical profiles of two distinct facies observed at Fox Glacier are illustrated in (C) and (D). Facies Assemblage 5 (C) is interpreted to be gully-derived debris fan deposits, and Facies Assemblage 6 (D) is interpreted to be glaciofluvially reworked moraine material. Vertical height scale is in meters.

Discussion

In this discussion we will consider the dominant processes that result in the proglacial sediment-landform associations that we observe at Franz Josef Glacier and Fox Glacier. We will suggest reasons for the different characteristics between the two systems and highlight important questions that still need to be addressed. Finally, this section will produce a summary conceptual model of the proglacial systems.

The proglacial area of Franz Josef Glacier is dominated by glaciofluvial material (Table 4; Fig. 3B), which is itself comprised of reworked morainic deposits from supraglacial and subglacial transport. Hambrey and Ehrmann (2004) have already documented and discussed the glacial transport and modification of clasts. We therefore focus on glaciofluvial material. In the absence of available discharge data, our geomorphological and sedimentological observations on Franz Josef Glacier sandur indicate flow discharges far greater than would be expected by the size and geometry of the glacier catchment if proglacial fluvial discharges were solely a direct result of ice/snow ablation, i.e. without storage (Fig. 1; Table 5). These geomorphological features are both scour and depositional wash limits (Maizels, 1995) situated several meters in altitude above the present valley floor (Figs. 3, 4A), and laterally and longitudinally extensive boulder bars containing imbricated and thus fluvially transported subrounded clasts of up to several meters in diameter (Costa, 1983; Carling, 1989). Such boulders have been transported by flows with high sediment concentration. High sediment concentrations can dampen turbulence and increase the bulk density and yield strength of the flow, thus enabling boulder transport through buoyancy and dispersive pressure (Costa, 1983, 1988; Maizels, 1997) (Fig. 3). Using the paleocompetence technique of Costa (1983) it can be determined that the diameter of these imbricated boulders (Fig. 8A), as well as the volume of sediment in these deposits, indicates flow velocities and hence discharges at least an order of magnitude greater than that theoretically possible due to direct glacier ice or nival melt,

TABLE 5

Crude calculation of maximum potential glacial and nival melt from Franz Josef and Fox Glaciers and catchments. Note that even theoretical maximum melt rates are at least an order of magnitude smaller than discharges implied by geomorphological and sedimentological evidence.

Stage	Calculation	Notes	Comment	Assumptions
1	$Q_M \approx Q^*$	Energy available for melt (Q_M) ≈ net radiant energy balance (Q^*).	The maximum ice or snow melt is determined by the amount of energy available for this process, rather than by the amount of ice or snow present (Oke, 1996).	Unshaded snow and a clear sky.
2	$Q^* = 0.8\,(1 - \alpha)\,K\downarrow$	Net radiant energy balance = a function of the incoming shortwave radiation ($K\downarrow$) and albedo (α). 0.8 accounts for longwave energy losses.	The maximum potential incoming shortwave radiation at a given latitude is a function of the solar constant and the projected area on the Earth receiving that radiation.	At 45°S, in June, this is ~500 Wm^{-2}. Average ice albedo = 0.9. Average snow albedo = 0.5.
3	$S = (Q^* / \rho\,\ell_f)$	The surface melt (S) (in mm of water) is a function of the net radiant energy balance, the density of water (ρ), and the latent energy of fusion of ice (ℓ_f) (from Church, 1988).	$\rho = 1000\ kgm^{-3}$ $\ell_f = 0.334\ MJkg^{-1}$	Flat, isotropic ice or snow surface, no wind, no infiltration. All available radiant energy is utilized.
4	Area Franz Josef Glacier ice beneath ELA = 20.25 km^2. Area Fox Glacier beneath ELA = 27.00 km^2. Area Franz Josef catchment beneath end of summer snowline = 48.40 km^2. Area Fox catchment beneath end of summer snowline = 105.56 km^2.	Calculated from glacier and catchment hypsometry, as presented in Figures 1 and 2. The end of summer snowline for Franz Josef Glacier is assumed to be 1560 m a.s.l. (as reported in Goodsell et al., 2005)	*S* (mm) can be converted to a volume per day for glacier ice by considering the area of the glacier beneath the ELA, and for nival melt by considering the area of catchment beneath the end of summer snow line.	Ice is not debris-covered. Snow covers all land and ice areas. Conveyance of melt to proglacial river is instantaneous and without transmission losses.
5	Volume Franz Josef Glacier ice melting = $2.43 \times 10^6\ m^3\ day^{-1}$. Volume Fox Glacier ice melting = $3.24 \times 10^6\ m^3\ day^{-1}$. Volume Franz Josef catchment snow melting = $29.04 \times 10^6\ m^3\ day^{-1}$. Volume Fox catchment snow melting = $63.4 \times 10^6\ m^3\ day^{-1}$.	= 56.25 $m^3\ s^{-1}$ = 75 $m^3\ s^{-1}$ = 672.22 $m^3\ s^{-1}$ = 1468 $m^3\ s^{-1}$	Total volume melting = Stage 3 * Stage 4	Volume is released at a constant rate over 12 hours
	Values used in these calculations compare well to Owens et al. (1984), who observed 7.2 cm ice per day melting on Franz Josef Glacier, and Takeuchi et al. (1999), who calculated heat flux for melting on Franz Josef Glacier to be 275 Wm^{-2}.			
6	Flow velocities inferred from the size of fluvially transported (imbricated) boulders (up to 1.8 m)on the Franz Josef sandur area are up to 6.9 m s^{-1}, and thus with discharges of ~5000 $m^3\ s^{-1}$. See Costa (1983) for theory and Carrivick (2007a, 2007b) for application of method.			

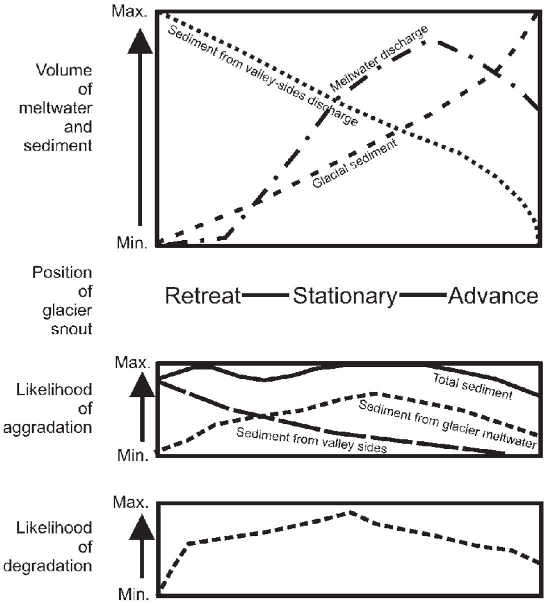

FIGURE 10. Association of proglacial aggradation and degradation with glacier mass balance and water and sediment supply. Adapted from Maizels (1979).

assuming no storage (Table 5). The fact that boulders have a near-identical sorting for a considerable lateral and longitudinal extent (Fig. 8B) and the presence of scour lines and depositional surfaces several meters above the present depositional valley floor (Fig. 4A) are further indication of an "episodic" or "event-dominated" proglacial fluvial regime. Flow conditions clearly reached a magnitude capable of valley-wide inundation. These observations indicate a short-lived, high-magnitude discharge, since such a necessary volume of water would only sustain a short-lived event, and a rapid flow cutoff. A rapid flow cutoff is evidenced by massive deposits. A prolonged falling stage would produce progressively decreasing flood power and tractive force and hence well-sorted boulder deposits (Nemec and Steel, 1984; Smith, 1986; Todd, 1989; Maizels, 1993; Rushmer, 2007).

Sediment architecture can typically be traced on a valley-wide scale (Fig. 6), and in places is dominated by poorly sorted and massive profiles with "floating" clasts (Fig. 7). These features are indicative of hyperconcentrated flow (Costa, 1988), and thus of high-magnitude flow conditions (e.g. Rushmer, 2006). Additionally, the presence of thick (>2 m), coarsening-upwards profiles (Maizels, 1993), and large-scale gravel and pebble beds (Fig. 6) refutes a hypothesis of low-magnitude, high-frequency sedimentation (Rust, 1972). An absence of reactivation surfaces, silt and sand beds, thin beds, and channel-fill sediments further supports an interpretation of a high-magnitude event-dominated regime (Rust, 1972; Bluck, 1979) at Franz Josef Glacier. This regime is not exclusively proglacial, since coarse-grained poorly sorted conglomerate facies, which can be indicative of high-magnitude flows and outburst floods, have been reported from many environments and situations (Moncrieff, 1989), for example coastal (e.g. Nemec and Steel, 1984), lacustrine basins (e.g. Kim et al., 1995), active extensional basin fault-scarps (Gawthorpe and Hardy, 2002), and volcanic crater lake breakout floods (Manville and White, 2003).

In contrast, glaciofluvial material in the proglacial area of Fox Glacier is less significant in its areal extent than that at Franz Josef Glacier. It is alluvial/debris fan material that is the most important constituent of the proglacial area of Fox Glacier. This fact could appear to be curious, since the tributary valleys for each gully are of similar dimensions at each site, and both catchments have a near-identical geology and are likely to receive similar weather conditions. However, a combination of sediment supply and accommodation space on the proglacial area could account for the discrepancy in proglacial sedimentation between the two sites. Subcatchments directly above the Fox Glacier proglacial area are at a higher altitude than at Franz Josef Glacier (Figs. 2A, 2B). The corollary is there is increased sediment supply at Fox Glacier. This alluvial/debris fan sediment finds accommodation space at Fox Glacier due to a slightly wider valley floor (than at Franz Josef Glacier) and lateral moraines that stand aside from the valley walls (Fig. 5).

We therefore speculate that at Franz Josef Glacier the system is supply limited, whereby glaciofluvial activity across the sandur is sufficient to remobilize sediment inputs from both the glacier and from valley sides. This does not appear to be the case at Fox Glacier, where contemporary glaciofluvial activity on the sandur is insufficient to remove alluvial and debris from tributary gullies and valleys. The system at Fox Glacier can therefore be termed transport-limited. However, we note that contemporary proglacial aggradation could be burying outburst deposits at Fox Glacier, and that imbricated boulder bars marginal to the main sandur (Fig. 9B) suggest past outburst floods. The boulder lag in Figure 9 is most likely to be a product of glaciofluvial removal of finer-grained sediment from the lateral moraine and debris-fan deposits.

Therefore the vast majority of the glaciofluvial material, i.e. the active sandur, at Fox Glacier reveals widespread geomorphological and sedimentological evidence of low-magnitude high-frequency fluvial sedimentation. This evidence includes a braided shallow-relief drainage pattern of a scale less that that of the confining valley (Marren, 2005) (Fig. 5), and an absence of marginal terraces or scour lines. Sedimentologically, clasts are relatively sorted (spatially) and within the 2 km length of this study fine progressively downstream (Nemec and Steel, 1984; Smith, 1986; Todd, 1989; Maizels, 1993). Thus Fox Glacier sandur has a predominantly aggradational regime (Maizels, 1979) (Fig. 10). We suggest that overall aggradation is occurring relatively uniformly over the entire valley, since there is an absence of slope breaks and the material is homogenous. On these suppositions, Maizels' (1979) model (Fig. 10) would suggest glacier retreat, which is clearly the overall trend at Fox Glacier, although intermittent readvances have occurred recently (see earlier in this paper). These observations indicate that high-magnitude flows, such as jökulhlaups, have either not occurred from Fox Glacier, or that geomorphological and sedimentological evidence of them has not been preserved (or has become buried). A similar study that compares two adjacent sandar, one of which is subjected to a jökulhlaup, whilst the other is not, was made by De Jong (1990) in West Greenland.

The proglacial systems of Franz Josef Glacier and Fox Glacier clearly exhibit differences, which some could say are subtle, despite having very similar climates and catchments (see section 1). Observed contrasts in geomorphology and sedimentology therefore raise some interesting questions. It could be suggested that a proglacial regime is directly linked either to glacier mass balance fluctuations, and/or to wider catchment characteristics, for example. However, whether the net balance of a glacier is increasing, stable, or decreasing, proglacial meltwater and sediment conditions can produce net aggradation, degradation, or even both on different parts of a given sandur (Maizels, 1979; Gustavson and Boothroyd, 1987; Lawson, 1995; Rushmer, 2007) (Fig. 10). Despite the fact that both Franz Josef Glacier and Fox Glacier are advancing, the apparent relative contributions of

FIGURE 11. Example of gully deposits that have backfilled, breached and even overtopped moraine at the margin of the Fox Glacier sandur.

meltwater and sediment vary between each site. This conflicts with Maizels' (1979) model (Fig. 10), which could be too simplistic by not recognizing relative sandur confinement, for example. Nonetheless, a key controlling factor is the supply (volume and caliber) of sediment, either from a glacier, from existing sandur channel banks (e.g. Warburton, 1990), or from valley sides (Fig. 11), as well as meltwater capacity and capability (Fahnestock and Bradley, 1973; Sambrook-Smith, 2000).

These observations and interpretations compare and contrast with those from other regions (Table 1). For example, sediment-landform associations in Svalbard and Iceland comprise substantial sheets and moraines composed of glacial diamicton (e.g. Hambrey and Glasser, 2003; Evans and Twigg, 2002, respectively). These proglacial zones have a very strong glacial imprint. Proglacial zones in maritime Antarctica are dominated by glaciolacustrine facies (e.g. Fitzsimons, 1990). The European Alps and Patagonia have sediment-landform associations dominated by rockfall and glaciofluvial activity (Glasser and Hambrey, 2002), and the glacial signature is consequently relatively weak (c.f. Hambrey and Ehrmann, 2004). Our observations suggest that ice-proximal proglacial systems within a temperate maritime climate and active tectonic uplift are strongly controlled by the magnitude frequency regime of glaciofluvial activity. If glaciofluvial activity is of insufficient magnitude (competence), alluvial/debris flow inputs can become areally as important since the system is transport-limited.

A further issue that arises from these interpretations is the apparent absence of geomorphological and sedimentological evidence for jökulhlaups from Fox Glacier. Again, we note that such evidence could exist but has been buried by contemporary aggradation. Davies et al. (2003) attributed jökulhlaups at Franz Josef Glacier to subglacial conduit blockage and a subsequent dam break due to very intense precipitation. Indeed, a compilation of records of jökulhlaups at Franz Josef Glacier illustrate that all such events are associated with some degree of "intense" precipitation (Goodsell et al., 2005). In this respect it might be argued that jökulhlaups at Franz Josef Glacier are climatically driven and perhaps depend on meteorological storm frequency. However, it should be noted that not all intense rainfall periods trigger jökulhlaups (Davies et al., 2003). This suggests an additional glaciological control on Franz Josef Glacier jökulhlaups. Such a control could be related to boulder deposition and water storage within an over-deepening (Davies et al., 2003), as well as to very fast transmission of precipitation to the glacier snout through an efficient crevasse and englacial conduit system. As described in section 1, climatic conditions and glacial geometry at Fox Glacier are very similar to those at Franz Josef Glacier. Fox Glacier has a similar series of ice falls within its ablation area, a similar relief, and given its hypsometry (Fig. 2), presumably a similar mass balance response to climatic perturbations. For jökulhlaup impacts not to be preserved on the Fox Glacier sandur, it could be speculated that englacial and subglacial drainage controls are therefore likely to be important. For example, at Franz Josef Glacier the sub/englacial drainage system is not sufficient to evacuate melt and precipitation efficiently during the early ablation season, leading to outbursts. Thus a difference between discrete and distributed subglacial drainage systems at Fox Glacier (Purdie et al., 2008) and Franz Josef Glacier could explain the contrasts in the two proglacial systems, unless an over-deepening at Fox Glacier either does not exist, or does not become periodically hydraulically blocked due to rapid transmission of intense rainfall through crevasse and englacial conduits.

Summary and Conclusions

Based on the observations of the geomorphology and sedimentology of the Franz Josef Glacier and Fox Glacier sandar we present two fundamentally different proglacial systems that have been produced by responses to the same climate regime. This is our conceptual model. At Franz Josef Glacier, jökulhlaups are the predominant control on sandur character (Davies et al., 2003). These jökulhlaups are episodic pulses of meltwater and sediment that route through the proglacial system, and most likely onto the continental shelf. Locally, these jökulhlaups produce valley-wide boulder deposits, which could act as a suspended sediment trap by encouraging illuviation of glacial meltwater- and hillslope-derived fines into the open-work structure (cf. Boulton and Dent, 1974). This illuviation would change the sedimentary structure. Furthermore, the fact that these boulders form a surface armoring layer also means that underlying sediments are effectively protected from erosion. We therefore suggest that bedload transport will be limited by the glacial meltwater regime, since the active river is restricted by boulder deposits to a single (bifurcating) channel that has minimal capability of lateral migration. Jökulhlaups at Franz Josef Glacier have the capacity and competence to episodically rework supraglacially transported morainic material and also alluvial/debris fan material from tributary gullies and valleys.

In contrast, there is no historical, geomorphological, or sedimentological evidence of contemporary jökulhlaups at Fox Glacier. This means that glaciofluvial discharges across the Fox Glacier sandur are insufficient for transporting paraglacial inputs from valley sidewalls, which are the predominant sediment source to the Fox Glacier sandur. The Fox Glacier sandur is consequently a net aggradation zone (cf. Jordan and Slaymaker, 1991). Paraglacial contribution of sediment comprises debris flows and landslides, which likely occur as a result of rock unloading due to rapid deglaciation, periglacial freeze-thaw activity, and rain-splash and slope-wash processes (Church and Ryder, 1972; Ballantyne, 2002). Such visibly active tributary streams will dramatically increase suspended sediment flux through the proglacial system (cf. Hammer and Smith, 1983; e.g. Warburton, 1990; De Jong, 1990).

We conclude that geomorphological and sedimentological observations of the Franz Josef Glacier and Fox Glacier sandar show that ice-marginal proglacial sediment-landform associations within a tectonically active region with exceptionally high denudation rates are dominated by glaciofluvial and alluvial/debris fan material. More complex combinations of facies assemblages arise due to localized (catchment specific) glacio-fluvial magnitude-frequency regimes and subcatchment geometry.

The Franz Josef Glacier proglacial area is dominated by an active sandur that is the product of episodic glacial outburst floods, jökulhlaups. However, the fluvial regime at Franz Josef Glacier is not exclusively proglacial, since coarse-grained poorly sorted conglomerate facies, which can be indicative of high-magnitude flows and outburst floods, have been reported from many environments and situations.

In contrast, Fox Glacier proglacial area is dominated by alluvial/debris fans from tributary gullies and valleys. In relation to the Franz Josef Glacier proglacial area, this is due to a combination of increased sediment supply due to higher-altitude subcatchments and increased accommodation space on the proglacial area.

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