FINAL REPORT ON RESEARCH PROJECT

Project No. 03/499
Monitoring and effects of landslide-induced aggradation in the Poerua Valley, Westland

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ABSTRACT

The devastating fanhead aggradation that followed the 1999 Mt Adams landslide into the Poerua River catchment, Westland, is a type of hazard that has been previously overlooked. Landslides of this size and greater are expected to result from the anticipated (currently ~ 1% - 2% annual occurrence probability) Alpine fault earthquake, so there is an urgent need to delineate the land areas at risk from this type of aggradation hazard.

Consideration of the impacts of the Mt Adams landslide led to the hypothesis that such events cause anomalously steep, entrenched fanheads to develop at the range front, the young surfaces of which should overlie soils buried between layers of river gravels. This hypothesis was tested using map data, information from a microscale laboratory model and soil stratigraphic investigations of a number of West Coast fanheads; all with positive results. It is concluded that fans with these characteristics reflect the occurrence of large sediment inputs into river catchments. A hazard zone delineation methodology was developed that allows areas likely to be susceptible to fanhead aggradation to be identified. Independent testing of this methodology remains to be carried out.

Monitoring of Poerua River bed elevations suggests that the aggradation episode may be passing its peak, 5 – 6 years after the event. If this is the case, then about 10% of the volume of the Mt Adams landslide has contributed to fanhead aggradation, and the aggradation event is equivalent to about one-twelfth of the total aggraded fanhead volume, suggesting that this is about a 500-year aggradation event. Similar aggradation events are expected to result from the next Alpine fault earthquake.

Frontispiece

The McKenzie farm at the head of the Poerua Valley.

Above: 1986 looking upvalley
(Photo by K. McKenzie)

Below: 2002, looking downvalley

The farm cottage location is visible in both photos (arrowed)

Contents

List of Figures

1. Introduction

The 1999 Mt Adams landslide (Hancox *et al*, 1999, 2000, 2005) deposited 10-15 x 10^6 m^3 of rock debris in the gorge of the Poerua River, Westland (Figs. 1 and 2). This formed a temporary landslide dam (Figs. 3 and 4), which failed some days later (Fig. 5), generating a flood wave that caused deposition (Fig. 6) of mainly sand-sized sediment on parts of the alluvial fan downstream of the gorge exit, together with substantial (but unmeasured) aggradation of the existing river bed (Fig. 7). Subsequently, river reworking of the landslide deposit has caused severe aggradation and avulsion of the river on the fan head (Fig. 8). Prior to the 1999 landslide the Poerua River was substantially incised into the alluvial fan head to the extent that the fan surface was never affected by rainstorm-generated flooding, but the aggradation (of the order of tens of metres) within the gorge and at the fan head has elevated the river bed so that it presently flows (and deposits sediment) across the fanhead. Severe damage has been caused to the farm that occupied the fan (Figs. 9, 10, 11), and the aggradation on the fan is still continuing in mid-2005.

This event was timely in drawing attention to the effects of large mass-movement-derived sediment inputs to West Coast (and indeed other) rivers. Such inputs are expected to occur in a number of river catchments (it is impossible to predict which) on both sides of the Southern Alps as a result of landslides caused by the anticipated Alpine fault earthquake (Yetton, 1998). The progress of the Poerua aggradation event indicates in general terms what to expect, and for how long, in similar locations after this earthquake. In particular, planning for new developments (and for redevelopment after an earthquake) needs to take account of the land areas vulnerable to such aggradation, and its duration. The objective of this project is to analyse the behaviour of the Poerua fan in response to the massive sediment input since 1999, and develop rational inferences regarding the impacts of such events in the future.

The sequence of aggradation and soil profiles observed on the Poerua, and in small-scale controlled laboratory simulations, have led to the general idea that any sufficiently large sediment delivery event, to a fan that is otherwise in long-term dynamic equilibrium with its normal range of water and sediment inputs, will generate an anomalously steep fanhead which will endure as an elevated, incised and normally non-floodable fan surface after the extra sediment has been worked through the river system. The next sufficiently large sediment input will then cause further aggradation of the fanhead. If this is the case, many fanheads in Westland, that presently appear to be out of reach of river flooding, may be vulnerable to aggradation and inundation after large sediment inputs.

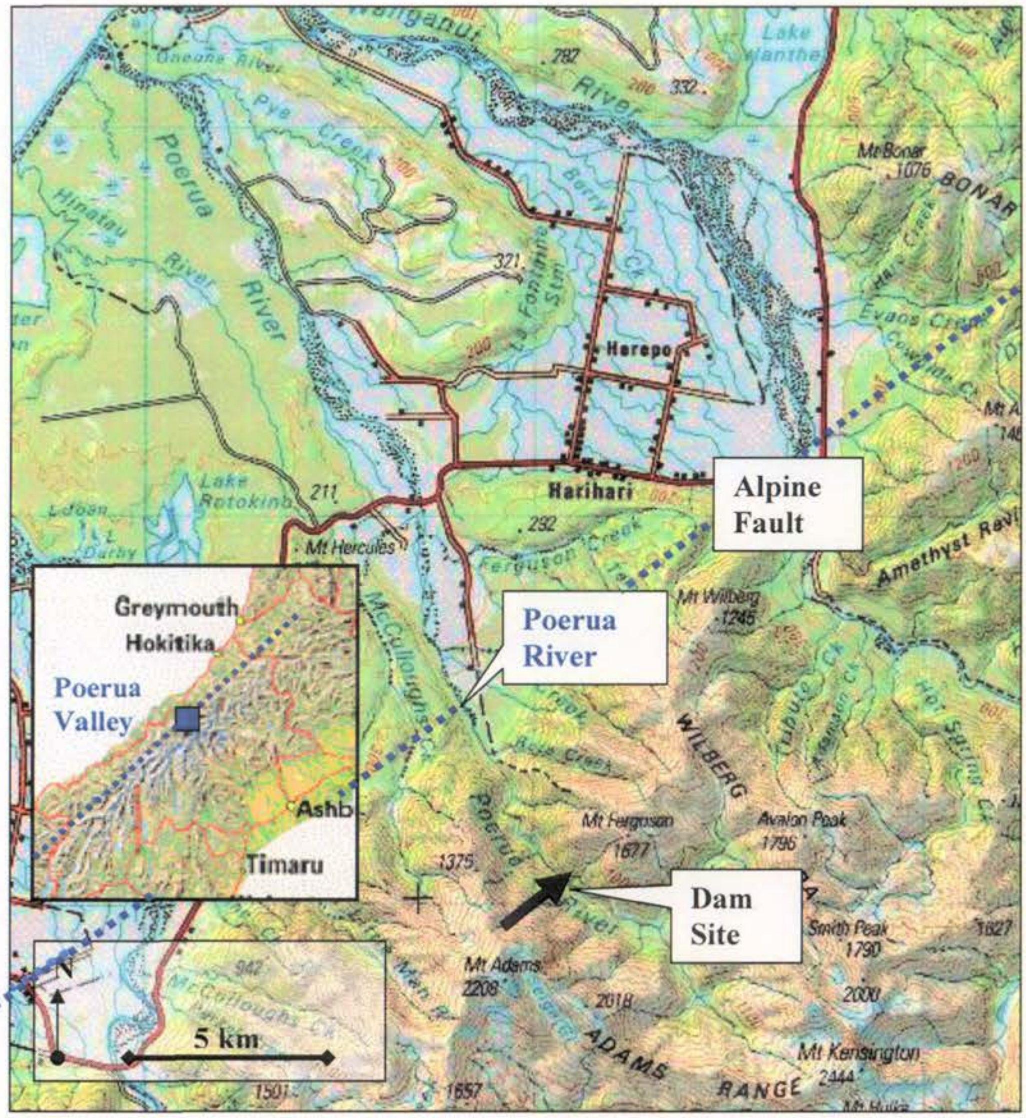


Fig. 1 Poerua valley location map
NZMS 1:250 000 Sheet 12 1997

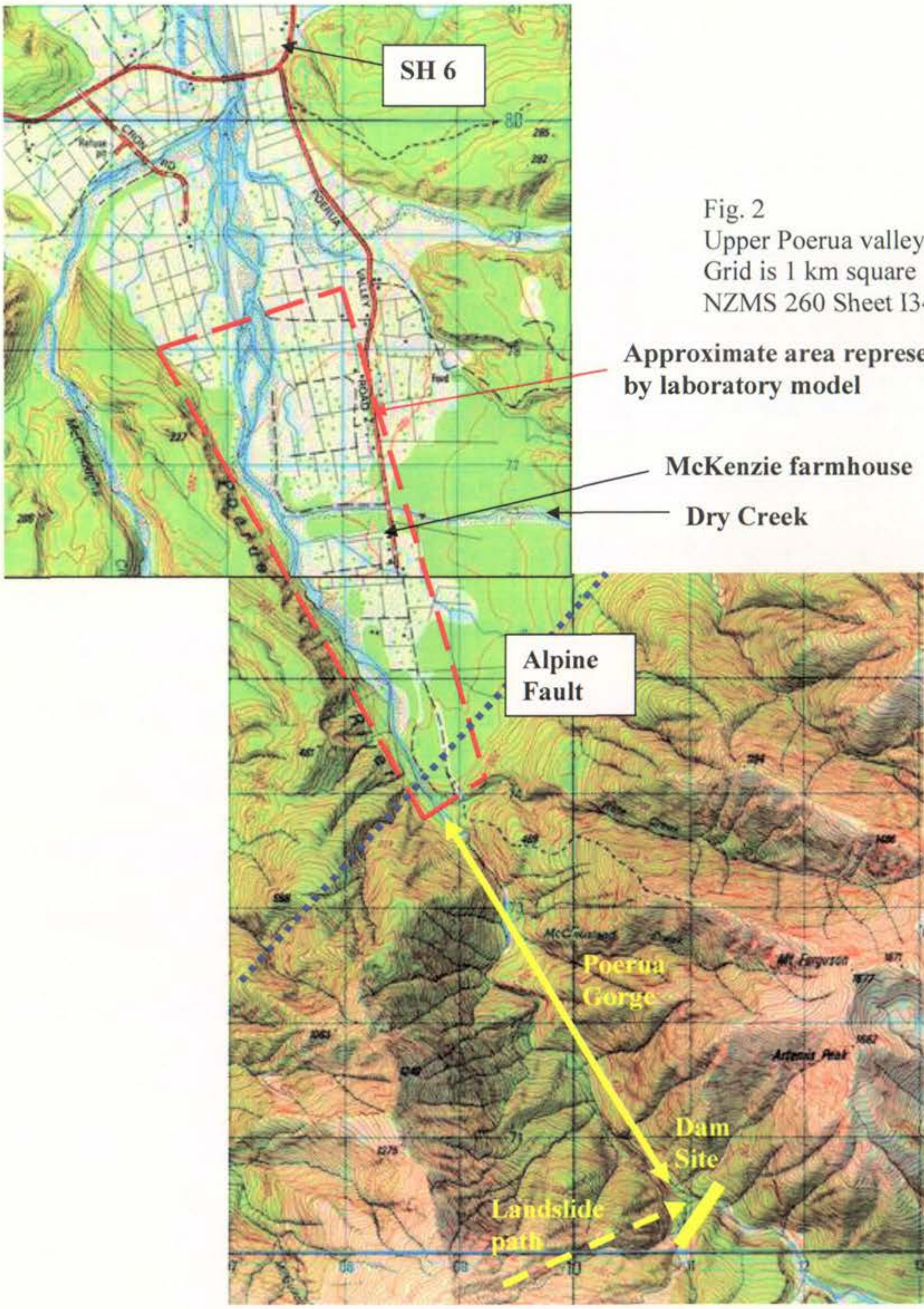


Fig. 2
Upper Poerua valley and gorge
Grid is 1 km square
NZMS 260 Sheet I34 2003

Fig. 3 Poerua landslide dam before overtopping; looking downstream.
(R Daniel Westland District Council)

Fig. 4 Poerua landslide dam after overtopping and before failure; looking upstream
(Hancox *et al*, 1999)

Fig. 5 Poerua landslide dam after failure, October 1999
(Hancox *et al*, 1999)

Fig. 6 Sandy deposits from dambreak flood

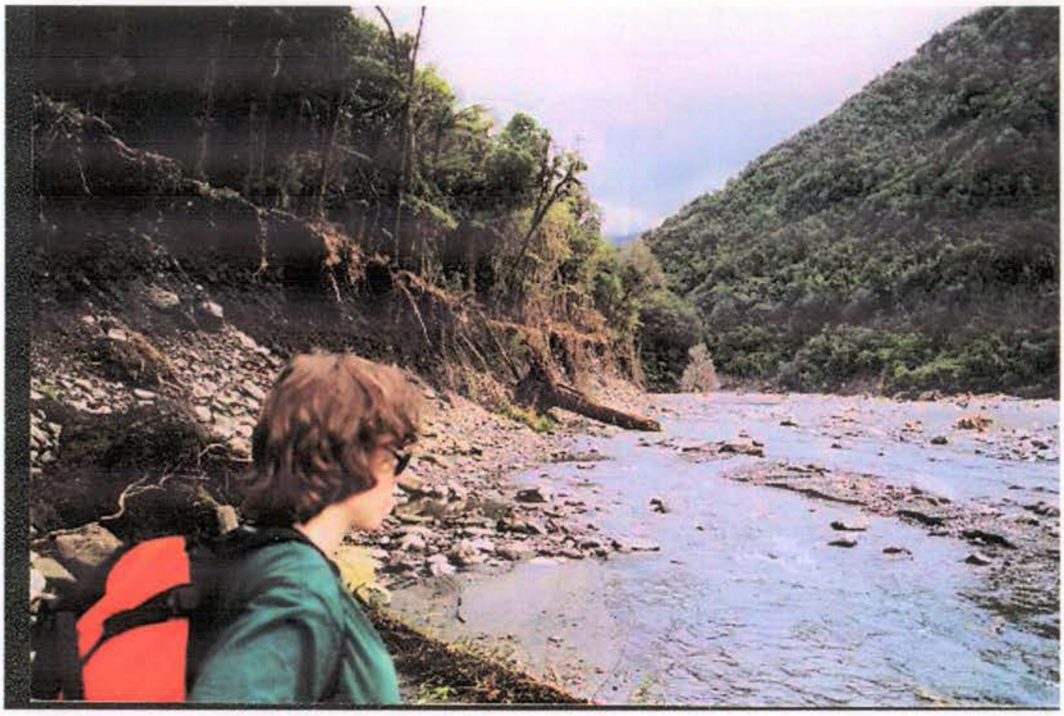


Fig. 7 Gorge exit aggraded by several metres; the riverbed at this location is now higher than the terrace on the left.

Fig. 8 River avulsing over fanhead 2 months after dambreak; flow from left to right.

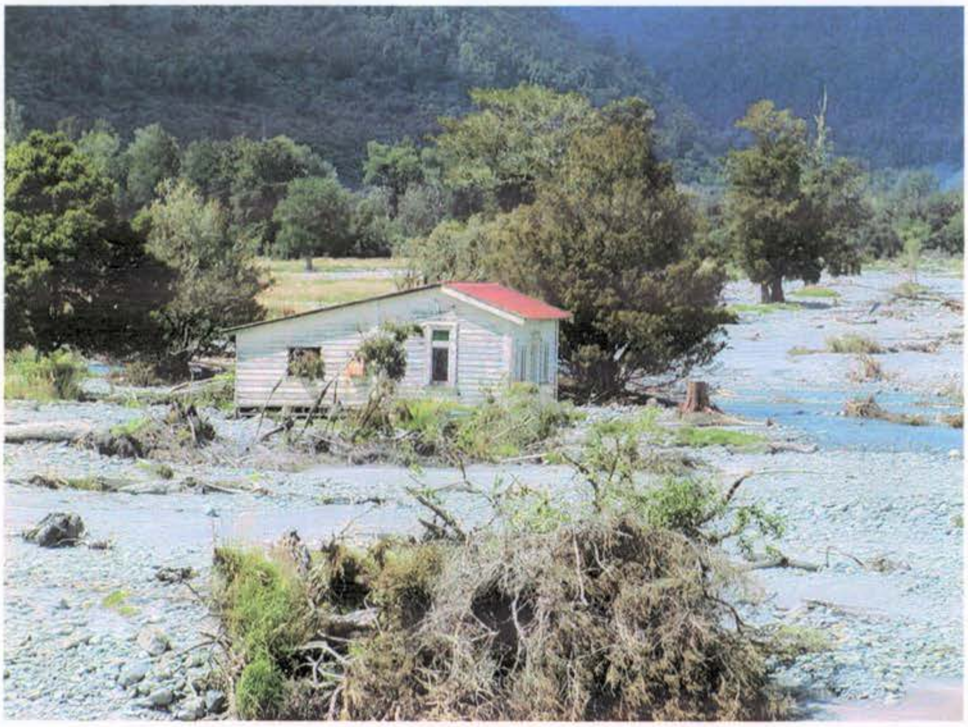


Fig. 9 Cottage surrounded by gravel deposits one year after dambreak

Fig. 10 New milking shed undermined by river eroding into valley-side fan deposit 3 years after dambreak

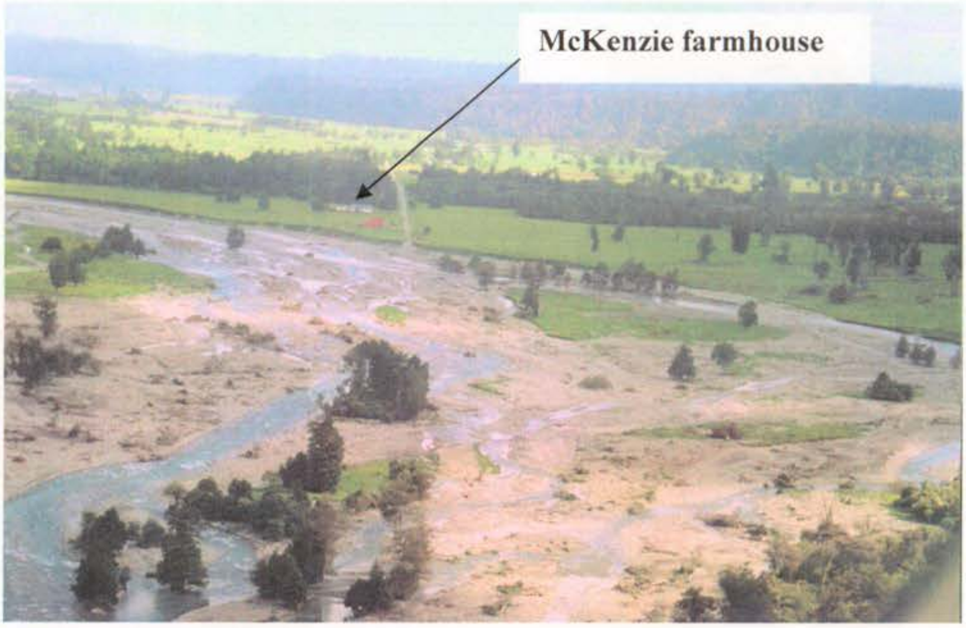


Fig. 11 Devastated farmland on fanhead 3 years after dambreak; looking downstream.

2. Purposes of the research

1. Describe the progress of the aggradation in the Poerua River, Westland, following the 1999 Mt Adams landslide.
2. Assess the likely future progress of the aggradation event.
3. Develop a methodology for delineating the area at risk from river sediment deposition (aggradation) resulting from the input of large volumes of sediment in upstream reaches of West Coast rivers.

This project has continued earlier monitoring of the behaviour of the Poerua River on its fanhead, and has found evidence that this and other fanheads have been affected by similar events in the past. A hypothesis has been developed and tested, associating the origin of the characteristically steep, entrenched fanheads of Westland with the occasional input of large volumes of sediment by landslides in the river catchments. A corresponding method has been developed for identifying fan areas liable to episodic aggressive aggradation, using topographic information and establishing how recently the fan surface has suffered aggradation. A preliminary assessment of areas studied in the present project identifies the extent of aggradation hazards in these areas.

Completion of the present project leaves us in a position to test this methodology, and we propose to do so in the future by applying it to all alluvial fanhead areas in Westland south of Ross township, using existing and new soil and vegetation age information on a GIS platform. A separate study will use published methods to identify those fanheads vulnerable to debris flows (which are a particularly dangerous form of aggradation process).

3. Hypothesis

The hypothesis that this project is designed to test is that:

> Anomalously steep alluvial fan heads with young surfaces, into which the rivers are normally entrenched, are formed by occasional massive (e.g. landslide-derived) sediment inputs to the river system upstream causing rapid fanhead aggradation. Between such inputs the surface of the fanhead is well above river flood level, but successive inputs can cause further increase in the surface elevation of the fanhead.

4. Hazard zone delineation

From this hypothesis follows a principle for identifying land areas at risk of severe aggradation from large landslides into river systems:

> Anomalously steep, entrenched fanheads with young surfaces, which are anywhere underlain by buried soils, are formed by episodic aggradation and are therefore at risk of future aggradation.

The way in which the hazard zone extent resulting from a large, rapid sediment input event is to be defined is to develop a method of recognising in the field the extent of deposits from previous events of the same type. This assumes that everywhere that this particular hazard presently exists, the causative natural event has occurred previously and has left a recognisable geomorphic signature. This signature is hypothesised to comprise a fan head:

- into which the river is distinctly incised;
- which is anomalously steep by comparison with the fan surface downstream;
- the soil profile of which shows evidence of episodic deposition of river gravels interspersed with soil development; and
- the surface age of which is not older than the last aggradation event.

These elements are shown diagrammatically in Fig. 12; the Poerua fanhead is much steeper than the downvalley fan, and there is evidence of episodic soil formation with interspersed aggradation by river gravels. Since the Poerua is known to experience massive sediment inputs (the last two in ~1717 and 1999; Korup *et al*, 2004: Hancox *et al*, 1999, 2005), these features are assumed to be characteristic of such inputs.

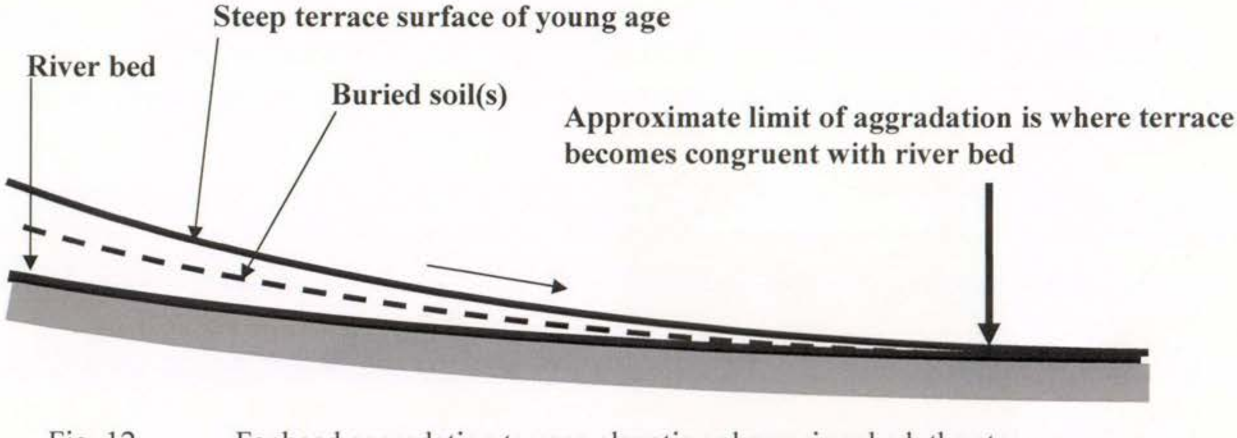


Fig. 12 Fanhead aggradation terrace elevation above river bed; the steeper terrace surface gradient suggests greater concentration of bedload in the flow that formed it.

5. Rationale

5.1 Equilibrium alluvial fans The morphology of an alluvial fan develops in response to the time-series of sediment inputs delivered to the fanhead by water flows, in the context of the nature of the sediment and the topographic constraints on fan planform geometry. The water input rate to the fan depends on precipitation, runoff and routing in the catchment, and the sediment input rate depends on weathering, denudation and storage in the catchment, so the rates of water and sediment input are independent and arbitrarily unsteady.

A particular type of longitudinal constraint on alluvial fan planform geometry is that which occurs when the fan toe is continuously trimmed (by a larger river, or by the sea) to maintain a constant location and base-level over a long time period. Such fans are common on the West Coast of the South Island of New Zealand (Davies & McSaveney, 2000), where a strong longshore ocean current and aggressive wave climate maintain fan toes in positions dictated by the seaward extent of erosion-resistant moraine ridges. These fans are supplied with plentiful water by the very high annual rainfall totals in the headwaters (up to 14 000 mm a^{-1}; Henderson & Thompson, 1999), and with plentiful sediment by the high watershed uplift and denudation rates (both up to ~ 10 mm a^{-1}; Hovius *et al*, 1997; Norris and Cooper, 2000). This means that the fans evolve rapidly, and there is convincing evidence that they are presently in or close to long-term dynamic equilibrium with the inputs, having achieved that state since global sea-levels stabilised about 5000-6000 B.P. (Barrell *et al* 2003). These fans, though laterally confined to become valley-trains, are relatively short; the distance from the main divide of the Southern Alps (~ 3000 m a.s.l.) to the sea is ~ 30 km, about half of which is mountain valley and half (seaward of the rangefront Alpine fault) valley deposit (Figs. 1, 30).

The slope of an equilibrium fan thus depends on the ratio of sediment and water fluxes. Fan size (areal extent) then depends on fan slope and confining topography - i.e. toe and lateral boundary positions. The rate of sediment supply depends on erosion, and therefore on topography and uplift in this dynamic equilibrium landscape (Montgomery and Brandon, 2002; Burbank and Anderson, 2001; Norris and Cooper, 2000). For the same water flux, faster uplift gives rise to greater sediment production and therefore higher sediment concentration and steeper fan slope.

5.2 Episodic fanhead aggradation and entrenchment Here we consider the characteristic morphology that develops at the head of such an equilibrium fan, when, in addition to a time-series of sediment inputs from normal subaerial erosion, it episodically receives substantial sediment inputs from large mass movement events, a large proportion of which can be expected to be soon reworked downstream by the river. This is again the case on the West Coast of the South Island of New Zealand, where the active Alpine Fault runs the length of the western rangefront of the Southern Alps, and is known to rupture catastrophically at intervals of 200-300 years, causing M = 8+ earthquakes, large and numerous landslides and correspondingly large sediment inputs to rivers (Yetton, 1998; Bull, 1996). Aseismic landsides greater than 10^7 m^3 in volume also occur in the Southern Alps – four of them in the 1990s (McSaveney, 2002; Hancox *et al*, 1999). While a fan longitudinal profile is expected to be smooth from head to toe in response to relatively frequent sediment input events from normal subaerial erosion, occasional massive inputs are hypothesised to generate a normally inactive fanhead surface into which the river is normally incised, and which thus has an anomalously steep profile.

Conventional explanations for the existence of entrenched fanheads include rangefront tectonic uplift and long-term reduction in sediment delivery (or increase in water flow) to the fanhead. None of these is satisfactory in the case of the West Coast fans we have investigated, because they all require the inactive surface of the fanhead to be significantly older than the still "active" fan surface downstream of the entrenched reach. The fanhead surfaces we have investigated are consistently of about the same age as the downstream fan surfaces, thus they are formed by recently active processes.

5.3 Poerua fanhead It is considered that the head of the Poerua valley, which is presently being inundated by sediment from the river following the large landslide from Mt Adams in 1999, is not part of the "floodplain" of the river. That is, it is not able to be inundated by major rainstorm-generated floods without massive sediment inputs, nor was it formed by such events. In order to overtop the $\geq$ 5m high banks of the pre-1999 incised channel, which was ~ 200 m wide, a flow of >> 1500 m^3/s^{-1} is needed; this is approximately the 500-year flood for that reach of the river. The fanhead is thus thought to be aggraded only following occasional very large sediment inputs from landslides into the gorge, and is subsequently incised again by the river when the sediment supply decreases to "normal".

This implies that the longitudinal fan surface profile should show a change of gradient between the lower floodplain part and the upper landslide-generated part, corresponding to the difference in formative processes; this is indeed so, and it appears also to be the case for several other West Coast rivers (Figs. 19 - 23). If the steeper part of the fan corresponds to the landslide-generated part, then identifying aggradation-prone areas becomes relatively simple – they correspond to the steeper fanheads.

In order to test this fundamental hypothesis, three procedures were followed:

1. Draw longitudinal profiles of a number of West Coast rivers to identify anomalously steep fan heads. Investigate whether (as with the Poerua) the steep fan head reaches correspond to river incision.
2. Run a microscale laboratory model to test the hypothesis, using the Poerua River as the characteristic prototype. If the model reacts to intermittent large sediment inputs by developing a steep fan head into which the river re-incises itself when the excess sediment input ceases, the hypothesis is supported.
3. Investigate the soil profiles on the steep heads of a number of West Coast fans. If these show evidence of occasional aggradation separated by intervals of soil development, this will support the hypothesis.

If the hypothesis is supported by these tests, it will be sufficiently robust to use for delineation of areas susceptible to aggradation from landslide-generated sediment inputs; these will be anomalously steep fanheads young surfaces and incised rivers that have buried soils alternating with river sediments.

6. Poerua river monitoring

6.1 Aggradation Fig. 13 shows the location of survey cross-sections in the Poerua valley; Fig. 14 shows the evolution of the Poerua valley profile since before the 1999 Mt Adams landslide; and Fig. 15 displays the changes in mean bed level at each cross-section between 1999 and 2005.

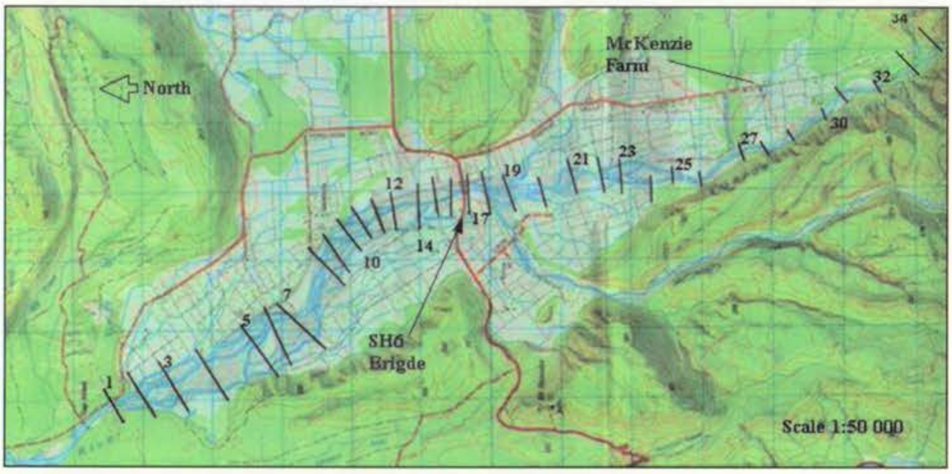


Fig. 13 Poerua River – location of cross-sections

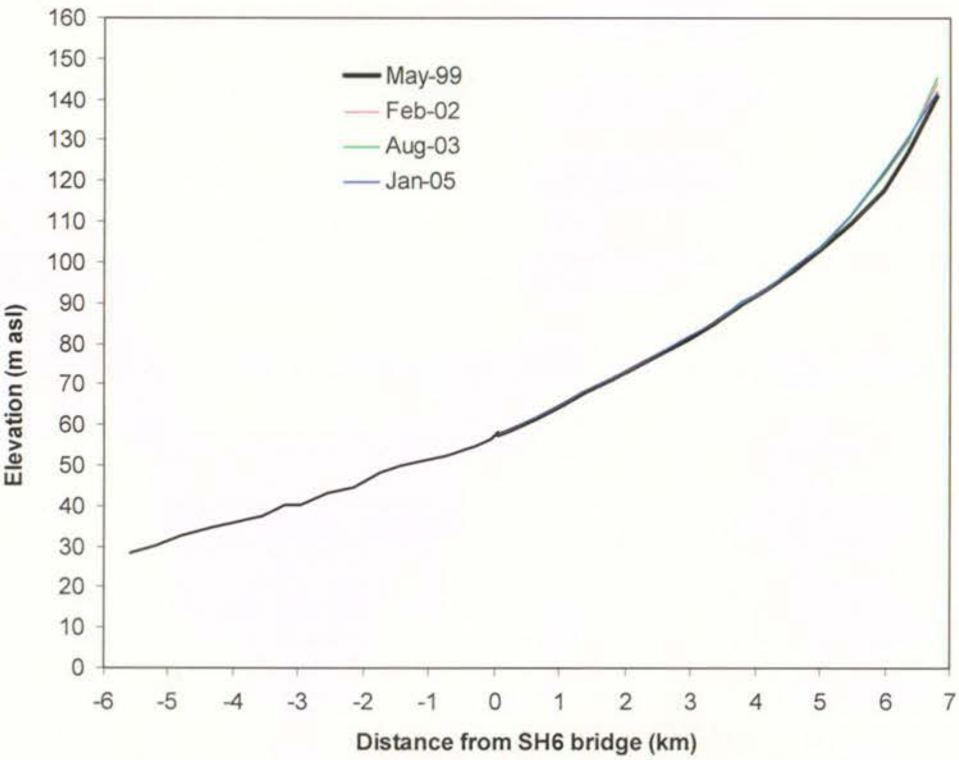


Fig. 14 Poerua River longitudinal profiles 1999 – 2005

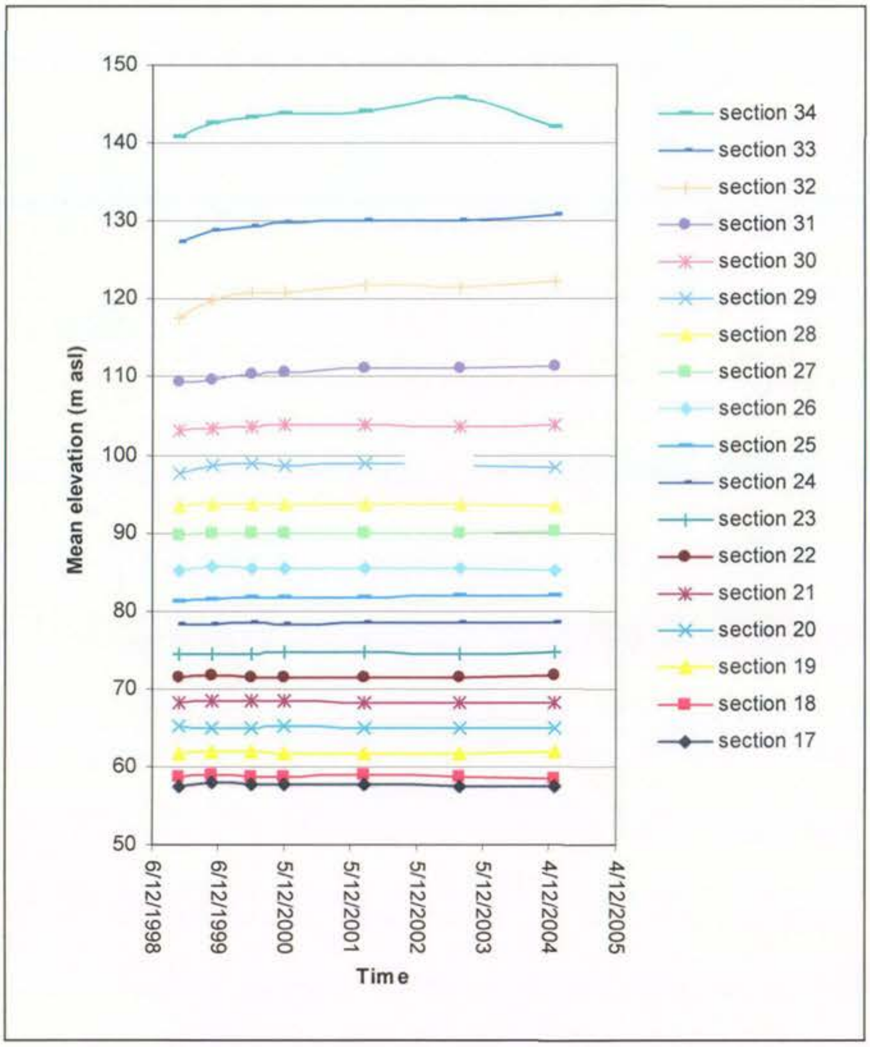


Fig. 15 Mean elevations of cross-sections 1998 – 2005

In order to put the 1999 sediment input into perspective, the "normal" rate of sediment input is estimated. Hovius *et al* (1997) calculated an average rate of denudation of about 10 mm a^{-1} for the western Southern Alps from aerial photographs taken during the aseismic period 1947-1987. This corresponds closely with the estimated rate of tectonic uplift for the region (Norris and Cooper, 2000). Over the 59 km^2 of catchment upstream of the fanhead, this denudation rate translates to about 0.6×10^6 m^3a^{-1}, thus the 1999 Mt Adams landslide was equivalent to about 15 - 25 times the average annual sediment input. This is a significant input, considering that the river before the event had a flow series, cross-section and slope that could transport about 0.6×10^6 m^3a^{-1} of sediment of all sizes farther downstream.

Fig. 15 shows that aggradation was very rapid at all fanhead sections immediately following the dambreak event. The increase of river bed elevation was greatest at the outlet of the gorge, and generally decreased with distance downstream. Although not able to be surveyed, bed elevations upstream of Section 34 increased by considerably more than 10 m (Davies, 2002), and elevations in the gorge itself increased by about 20 m (Korup *et al*, 2004).

The latest survey (January 2005, Fig. 15) suggests that aggradation may have peaked at the farthest upstream section. If this is indeed the case, the addition of volume to the fanhead may be almost complete, and the total volume of sediment added to the fanhead (above Section 28; Fig 13) in this event is then about 1 million m^3. This is ~10% of the total landslide volume; about half of the excess sediment delivered downstream of the gorge since the landslide (Hancox *et al*, 2005); and 1/12 of the estimated total volume of the fanhead above the normal (i.e. not aggraded) river bed level (calculated from Fig. 19). The Poerua River must have achieved its present longitudinal profile at some time following the end of postglacial sea-level rise ca. 6000 BP, so this total above-normal fanhead volume must have accumulated in less than 6000 years, at an average rate of more than two million m^3 per thousand years. The present event has therefore added ~ 500 years' worth of sediment to the fanhead. Perhaps coincidentally, Davies (2002) independently estimated the return period of the Mt Adams landslide to be of the order of 600 – 700 years.

The 1999 Mt Adams landslide was aseismic, but it is likely that many landslides into the Poerua catchment are coseismic. Korup *et al* (2004), for example, reported a date of 295 BP for a high terrace near the gorge mouth (seen in Fig. 7 herein) recently buried by aggradation, and this terrace presumably recorded a previous aggradation event. This seems likely to be associated with the 1717 Alpine fault earthquake. Since ruptures of the Alpine fault occur on average about every 250 years (Yetton, 1998; Bull, 1996), then, assuming that *all* aggradation events are coseismic, the average sediment aggradation on the fanhead in such events is about 0.5×10^6 m^3. The presently-occurring event is assumed to be anomalous in being aseismic; it is however notable that the elapsed time since the last Alpine fault earthquake is ~ 290 years, perhaps suggesting that had the fault ruptured before 1999 a similar landslide may have occurred as a result.

It therefore seems that the long-term "average" catastrophic landslide event in the Poerua is of the order of 5 million m^3, leading to addition of about 10% of this volume to the fanhead, with an average deposit depth of about 0.4 m.

It is not yet possible to estimate the time required for the Poerua River to revert to its "normal" bed incised into the fanhead. Further monitoring will make this increasingly clear. It will depend on the rate of decrease of sediment supply from the dam site. Given that a relatively small volume of sediment has to be removed to incise the river's channel into the fanhead trench, however, it might be expected to occur fairly rapidly (though the entrenching phase may be interrupted by temporary high sediment fluxes, and slowed down by bed armouring).

6.2 Aerial Photographs – Poerua river bed The aerial photographs (Fig. 16 (a) – (e)) show clearly the dramatic avulsion and widening of the riverbed post-1999. The differences between the 1976 and 1987 photos are also interesting, however; there was some bank erosion during this period, indicating that the river was trying to widen its confined bed. It is likely that there was large sediment input to the river during major storms in 1979 and 1982 (Davies and McSaveney, 2000), causing some aggradation and widening, as this effect was also noted on the Tatare and Waiho rivers. There is absolutely no evidence, however, of overbank flows in the Poerua between 1976 and 1987, and this is confirmed by the occupants of the area (K. McKenzie, Poerua Valley,

Fig. 16(a)

Fig. 16 (b)

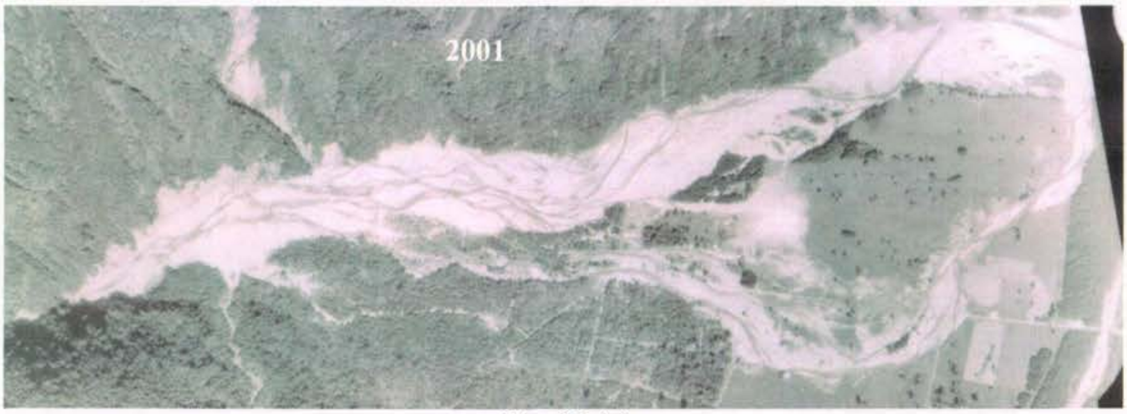


Fig. 16 (c)

Fig. 16 (d)

Fig. 16 (e)

Fig. 16 Poerua river aerial photos 1976-2005

pers. comm. 2005). The progressive increase in the flow to the true right of the fan between 2001 and 2005 is clear, as is the gradual erosion of the true right bank (which is in fact the lower part of the tributary fan of Dry Creek) at the lower part of the fan. This has also occurred in earlier events of this type; the toe of the Dry Creek fan downstream of its confluence with the Poerua is trimmed, and this can only have been accomplished by the Poerua, after it had completely eroded away the lower 1 km of the Dry Creek fan deposit (Fig. 17) existing at the time.

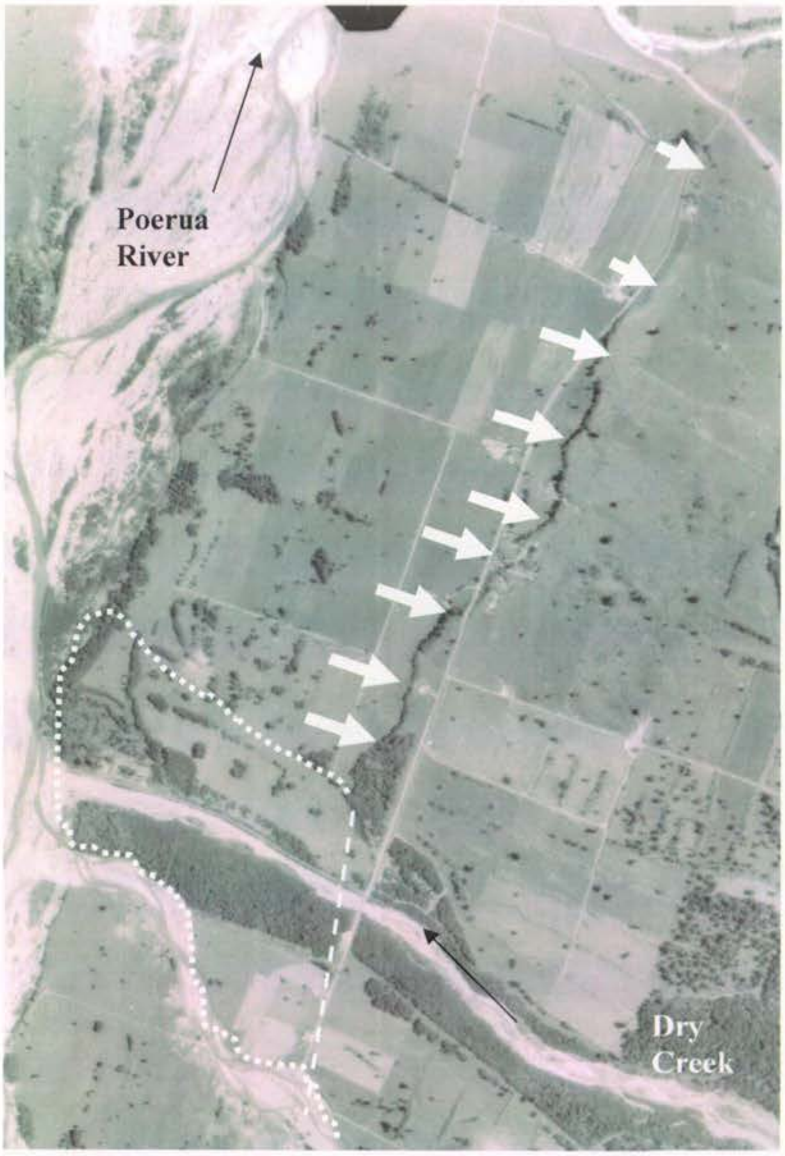
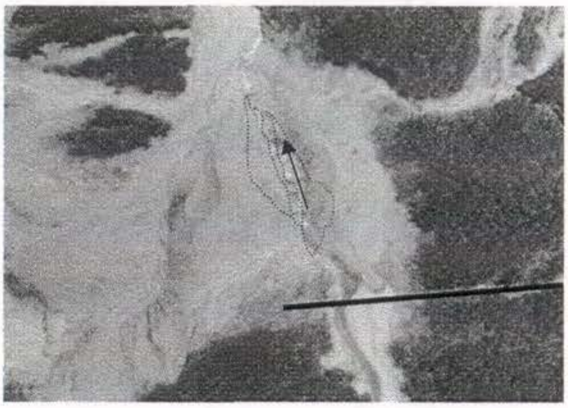


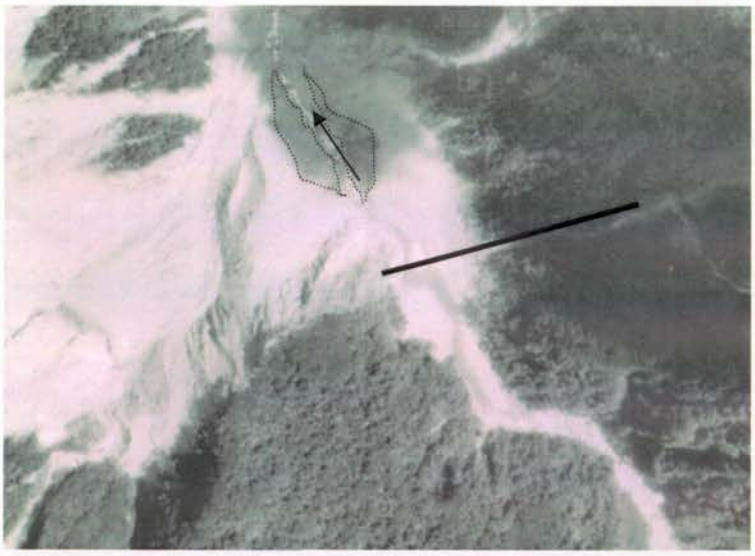
Fig. 17 Ancient terrace edge (arrowed) showing Poerua River erosion before present-day Dry Creek fan (white dotted line) built out into Poerua River. To accomplish this erosion the Poerua had to erode the Dry Creek fan approximately along the dashed line. (2001 photo).

6.3 Aerial photos – landslide dam



(a) 2001

Fig. 18 Erosion of Poerua landslide dam 2001-2005.
All to approximately the same scale – line and arrow are in corresponding place on each photo.
Line is about 500 m long
Dotted lines show approximate extent of dam erosion



(b) 2002

(c) 2005

The dam immediately following the failure is shown in Fig. 5, while Figs. 18 (a) – (c) show the subsequent erosion of the dam and the adjacent deposits.

Hancox *et al* (2005) and Korup *et al* (2004) calculate that about 5 x 10^6 m^3 of material had been eroded from the dam site between 1999 and 2003; the above photos suggest a significant widening of the dam breach between 2002 and 2005, so that about 50% of the emplaced material has now been removed. Hancox *et al* (2005) also comment that some of the deposits in the gorge had been deeply incised by 2003, indicating that sediment supply from the dam was then already decreasing. Note that a large volume of material has been eroded from the deposit on the true left of the dam also.

7. Hypothesis testing

7.1 Fanhead longitudinal profiles: Figs 19 – 23 show longitudinal profiles of some West Coast fans plotted from the 20 m contours on the 1:50 000 scale NZMS 260 map series.

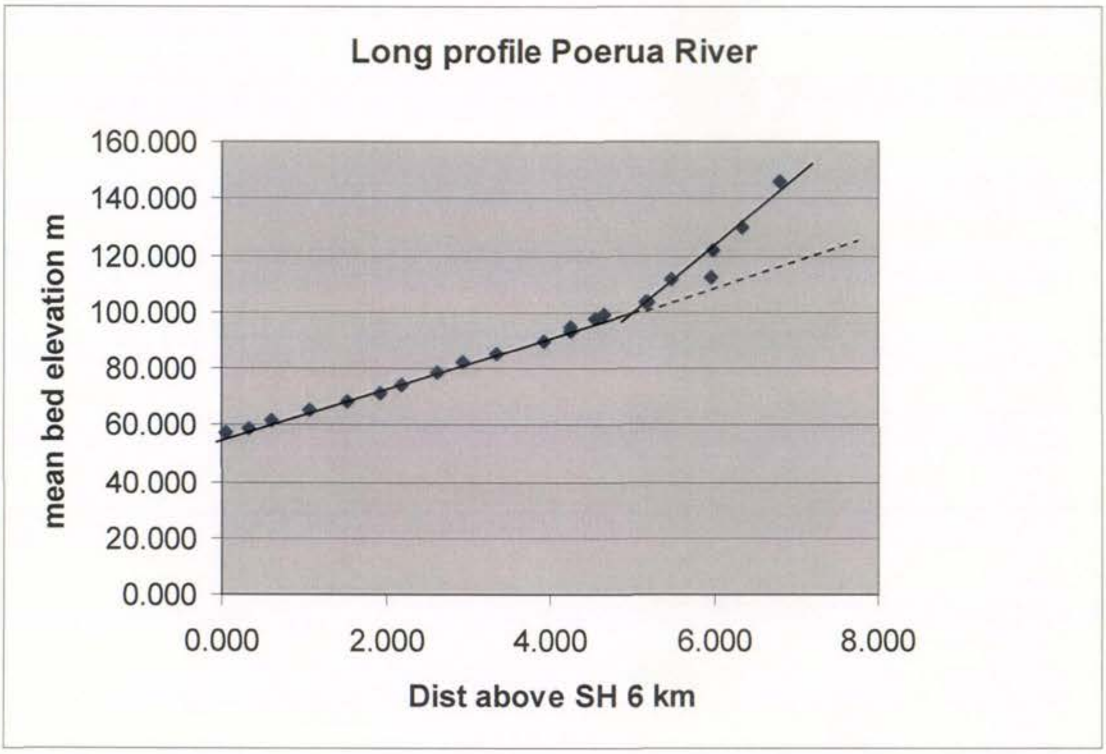


Fig 19 Longitudinal profile of the Poerua River fan surface

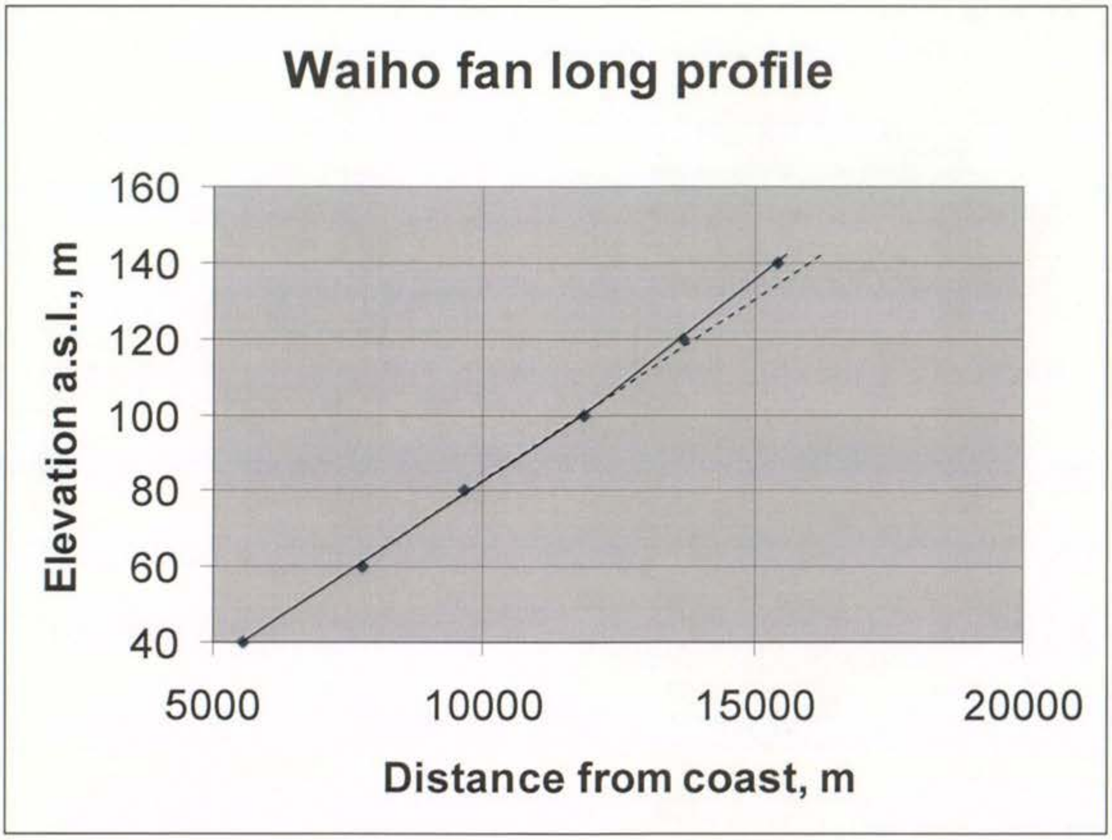


Fig. 20 Longitudinal profile of the Waiho River fan surface

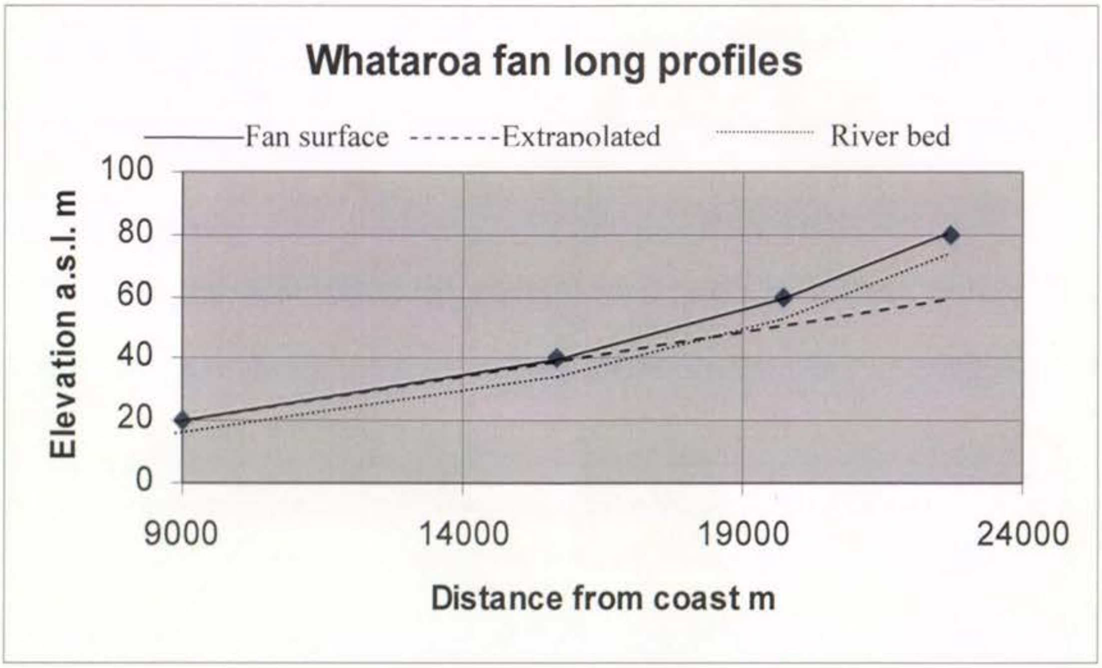


Fig. 21 Longitudinal profile of the Whataroa River and fan surface

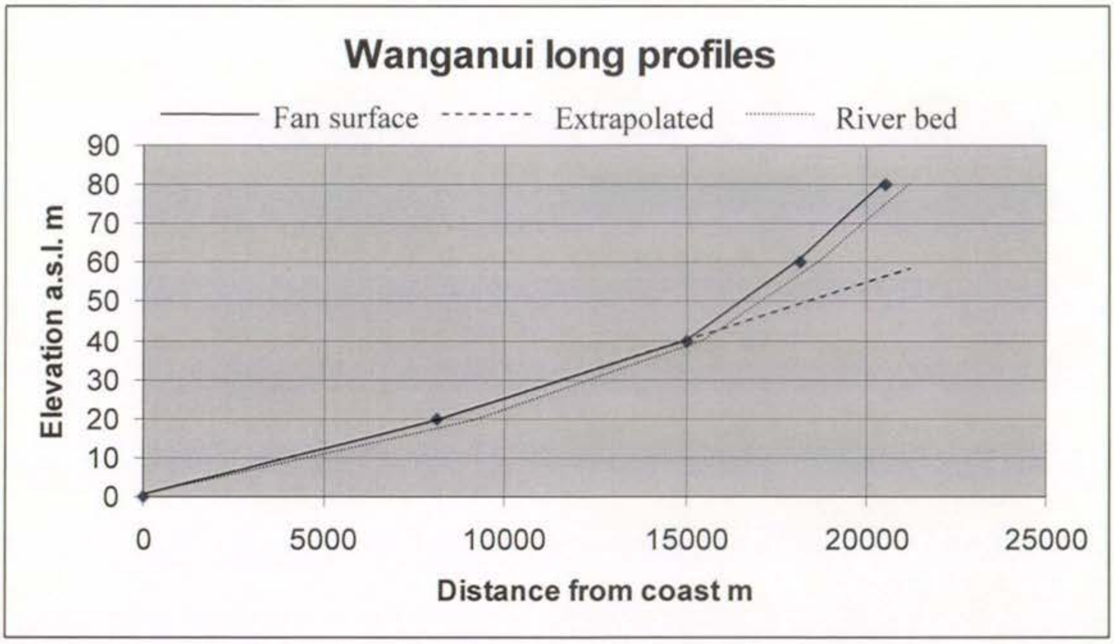


Fig. 22 Longitudinal profile of the Wanganui River and fan surface

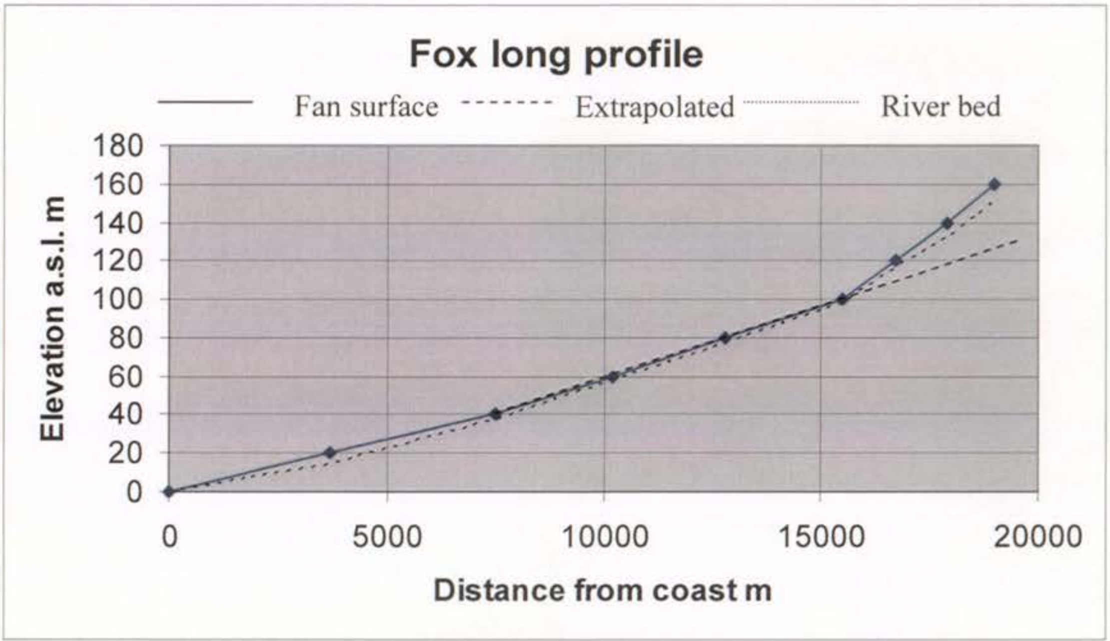


Fig. 23 Longitudinal profile of the Fox River and fan surface

All of these profiles show a steepened fanhead. Most of them also presently have the river incised some metres below the level of the fanhead; the only exceptions are the Waiho, whose fanhead has been aggrading rapidly for several decades as a result of lateral confinement by stopbanks (Davies and McSaveney, 2000; Davies *et al*, 2003), and the Poerua, which is presently in an aggradation episode.

The profiles were drawn from the 20 m contours on the 1:50 000 scale NZMS 260 series maps of New Zealand; except for that of the Poerua, which was drawn from the detailed surveys undertaken for this project. These profiles differ markedly from the more gradual fanhead steepening expected of rivers lacking occasional large sediment inputs; the steeper fanhead profile is itself almost linear, and the upper few kilometres of the profile can in all cases be acceptably described as bilinear. This suggests that the two reaches are formed by different processes, as the present hypothesis suggests. Therefore the field data are interpreted as supporting the hypothesis. It is notable also that the suggested process operates over a wide range of scales and slopes, as the profile axes indicate.

7.2 Laboratory study: A laboratory experiment was carried out to test the hypothesis, that fixed-toe alluvial fans develop steep fan heads as a result of severe aggradation following massive sediment inputs; and that the fanheads keep aggrading as a result of such inputs, even though the downvalley fan surface has achieved dynamic equilibrium with the long-term sediment input series.

A characteristic microscale model (Gaines and Mainord, 2001; Davies *et al*, 2003) was developed, with lateral constraints based on the approximate planform geometry of the upper part of the Poerua fan (Figs. 2, 25 and 26). The downstream limit of the model fan was the equivalent of about 5 km downstream of the head of the fan, and comprised a horizontal free overfall which maintained the fan toe position and level constant. Water and fine sediment were supplied to the fanhead at steady and arbitrary long-term rates, upon which were superimposed independently arbitrary short-term variations. The water input was generated by using a steady inflow to an automatic siphon and reservoir tank; this generated repeated similar hydrographs, between which flow reduced to zero for a short time. The sediment input was generated by allowing sand to avalanche naturally from a conical angle-of-repose sand pile which was supplied with sediment a steady rate; this gave a power law avalanche size distribution (Fig. 24) very similar to that found in nature for landslides of all types (Hovius *et al*, 1997; Malamud *et al*, 2004).

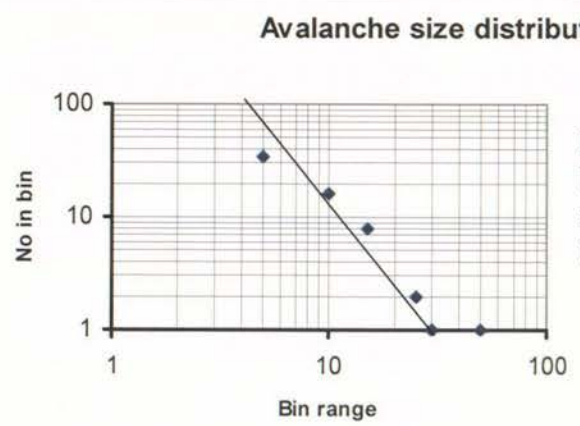


Fig. 24 Distribution of model sediment input avalanche sizes

The model fan was allowed to achieve its dynamic equilibrium profile under the chosen water and sediment input regimes. Then, maintaining these regimes, a relatively and arbitrarily large input of the same sediment was applied in an arbitrarily short time, representing an arbitrary input from a large mass movement. The aggradation resulting from this input was measured, and a further period of normal inputs allowed, followed by another large input. Contour maps before and after each large input were derived from handheld laser scanning, which had a vertical resolution of about 1-2 mm.

A full set of contour maps is included in Appendix 2.

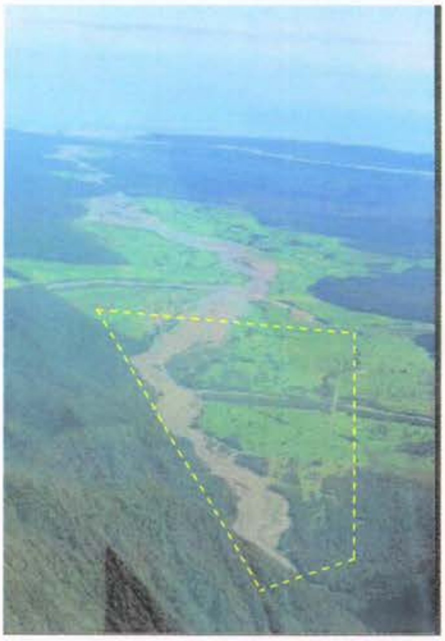


Fig. 25
Poerua River; view downstream; modelled reach outlined

Fig. 26 Laboratory model fan, looking upstream

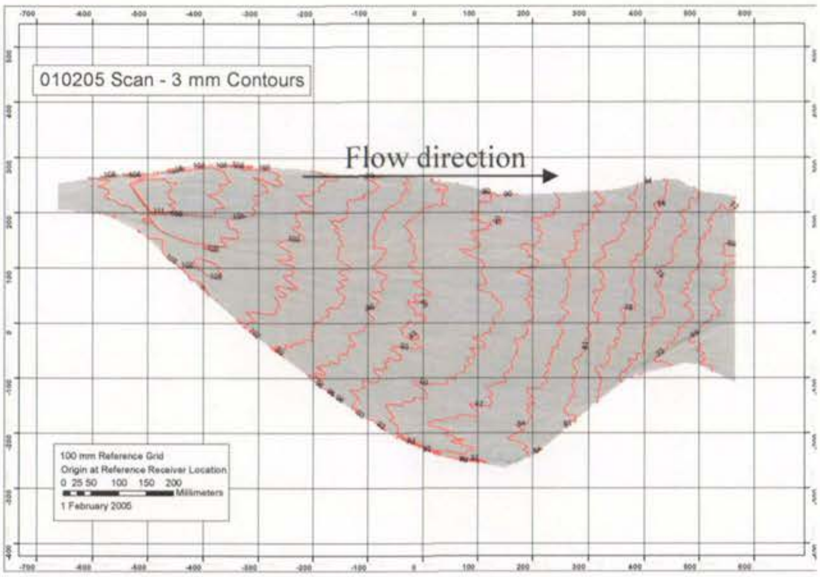


Fig. 27 Contour map from laser scanning

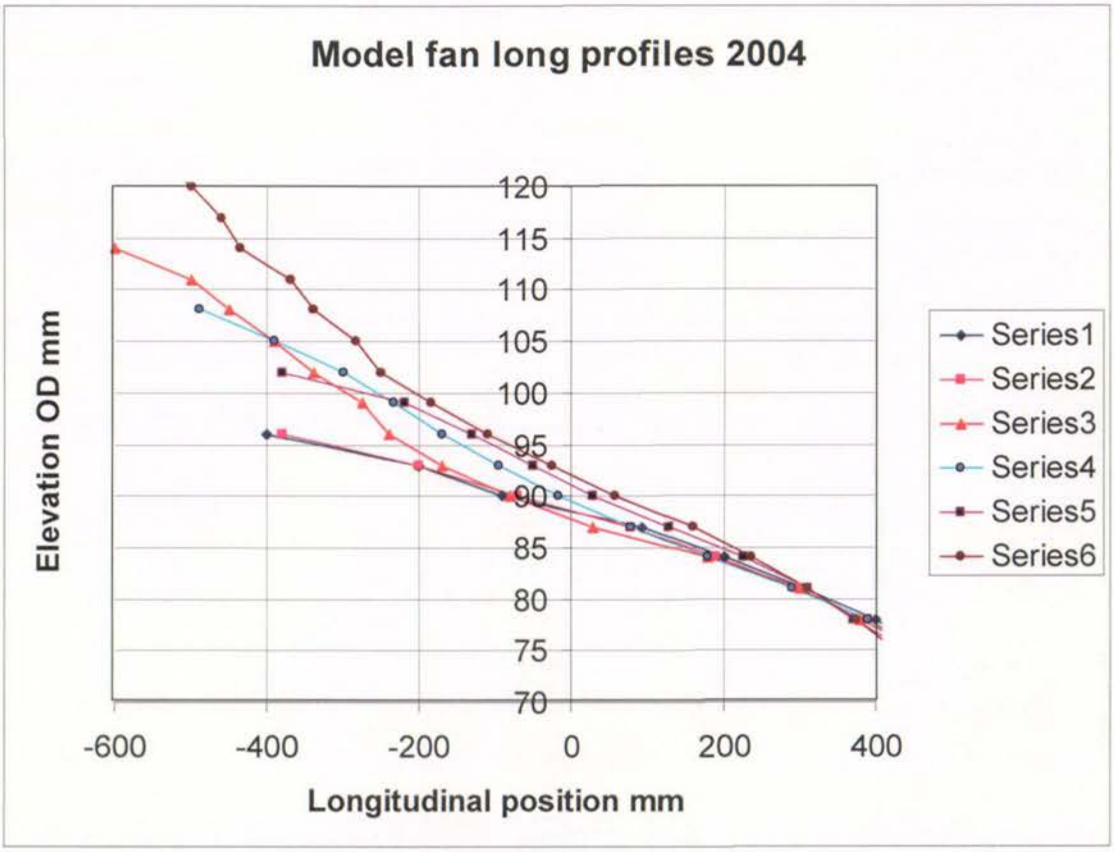


Fig. 28(a) Model fan long profiles - Condition 1
Series 1 = 101104: normal input. Series 2 = 111104: normal input
Series 3 = 161104; mass input. Series 4 = 181104: normal input
Series 5 = 191104: normal input. Series 6 = 241104; mass input

The laboratory tests were carried out under two different sets of conditions, each with arbitrary rates of sediment and water supply. The sequential development of the fan profiles is shown in Figs 28(a) and (b). In Fig. 28(a) the fan evolved to a steady (linear) profile under normally-varied inputs (series 1 and 2). Input of a large sediment volume rapidly led to the development of a steep fanhead (series 3) with an almost linear profile. Upon cessation of the rapid sediment input the stream began to rework the fanhead material downstream (Series 4 and 5) by incising into the fanhead. Upon introducing a further rapid sediment input, of the same volume and rate as the first one, the fanhead aggraded again, but did so more rapidly and to a higher elevation because much of the area of the fanhead was still aggraded from the previous episode.

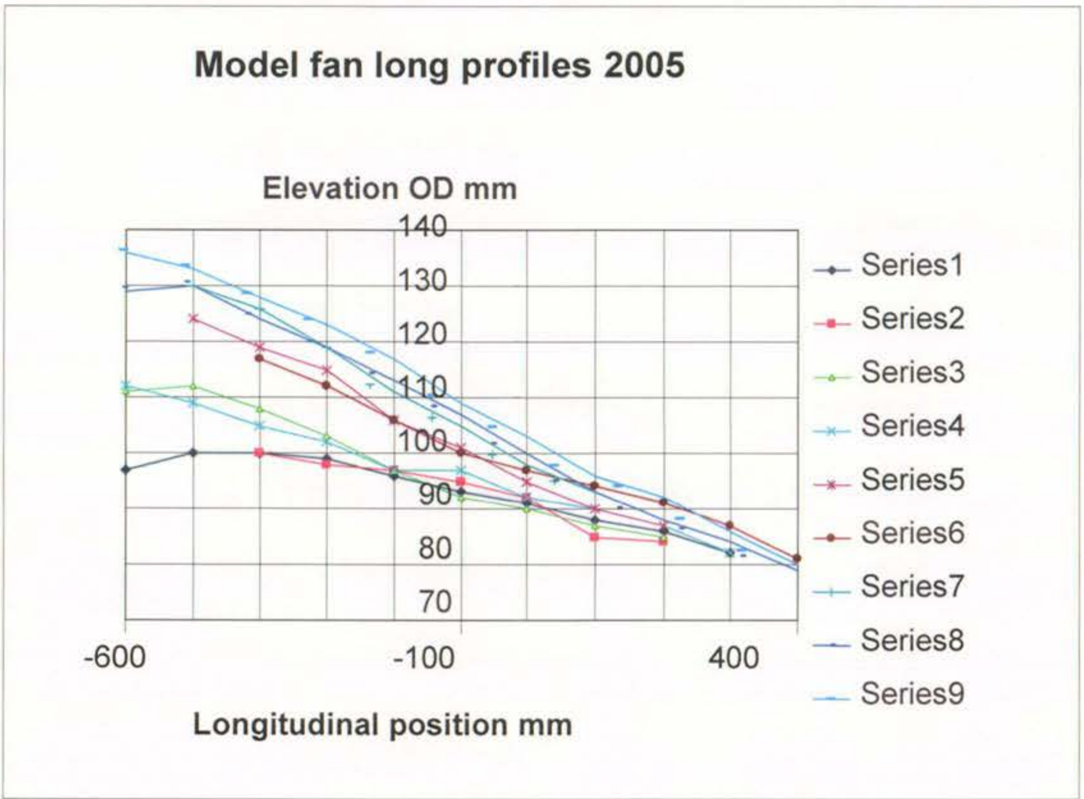


Fig. 28(b) Model fan long profiles - Condition 2
Series 1: 190105 normal input. Series 2: 270105 normal input
Series 3: 310105 mass input. Series 4: 010205 normal input
Series 5: 280205 mass input. Series 6: 110305 normal input
Series 7: 220305 mass input. Series 8: 110405 no sediment input
Series 9: 220405 mass input

Similar behaviour is seen in Fig. 28(b) under quite different input conditions; of note here is the behaviour of series 8, where the aggraded fanhead incised with no sediment input, and developed a deeper, narrower channel then with normal sediment input. The subsequent aggradation (series 9) was rather greater than in other cases, because the deep

Fig. 29 Aggraded fanhead
(2005 Series 3)

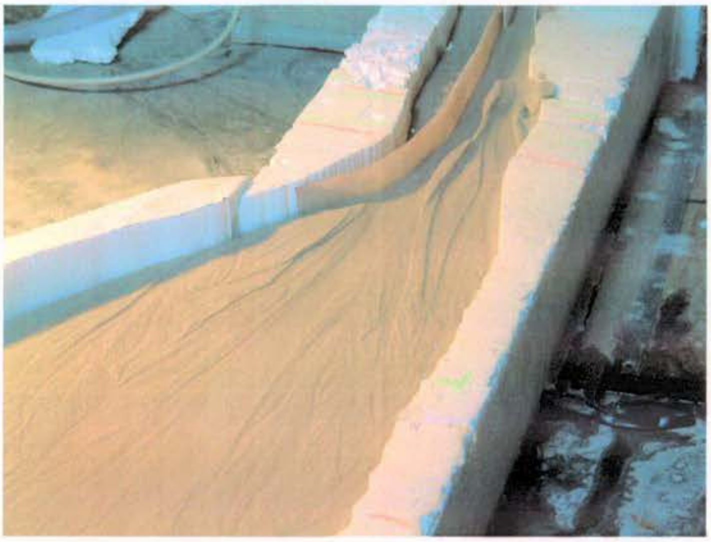


Fig. 30 Incised fanhead
(2005 Series 8)

incised channel was more easily infilled than the wider, less deep channels incised under normal sediment input. Thus successive identical inputs each resulted in build-up of the fan surface, as hypothesised. It is concluded that the laboratory investigation supported the hypothesis of fanhead formation.

Similarity with field-scale processes
Davies *et al* (2003) showed that microscale models of this type are reliable in representing the locations and relative rates of aggradation of field-scale rivers. Since this is the objective of the present tests, we are confident that the aggradation is well represented. One factor that was not well represented in the model was the width of the incising channel following an aggradation episode; this is because in the model the same

sediment was used for both "normal" and "massive" sediment inputs, whereas in the field the "massive" inputs from upstream landslides would almost certainly have larger maximum grain sizes, leading to a narrower incised channel and long-term storage of a greater proportion of the aggraded sediment than is the case in the model. Thus the model is "conservative" in allowing more of the aggraded sediment to be reworked downstream after the aggradation episode, and the field fanhead will in fact aggrade faster, and to a greater elevation, than is indicated by the model. The final incision episode of the 2005 tests was deliberately run with no sediment input to generate a deeper, narrower incised channel than was obtainable with normal sediment input, and this resulted in greater aggradation after the next mass input than occurred with a wider, less incised channel.

Turner and Locke (1998) report the formation and incision of steep fan terraces downstream of the Madison Canyon landslide dam of 1959; this field-scale example behaved in a similar fashion to our model.

7.3 Soil studies A number of localities were selected on the West Coast, where steep fanheads appeared to indicate likely landslide-induced aggradation processes, and where channel conditions upstream suggested the likely occurrence of landslides into a narrow gorge. The chosen sites were the Poerua Valley (f_7 on Fig. 30), the Tatare ($f_{5'}$), the Waiho (f_5), and the Fox/Cook (f_4). Soil pits were dug and the soil profiles described and photographed, and the downstream extent of the landslide-induced aggradation identified from the height of river terraces (Fig. 10). The cut river terraces also provided sites for soil descriptions, as did artificial drains cut in the Tatare fan at the site of a new subdivision in Franz Josef Glacier.

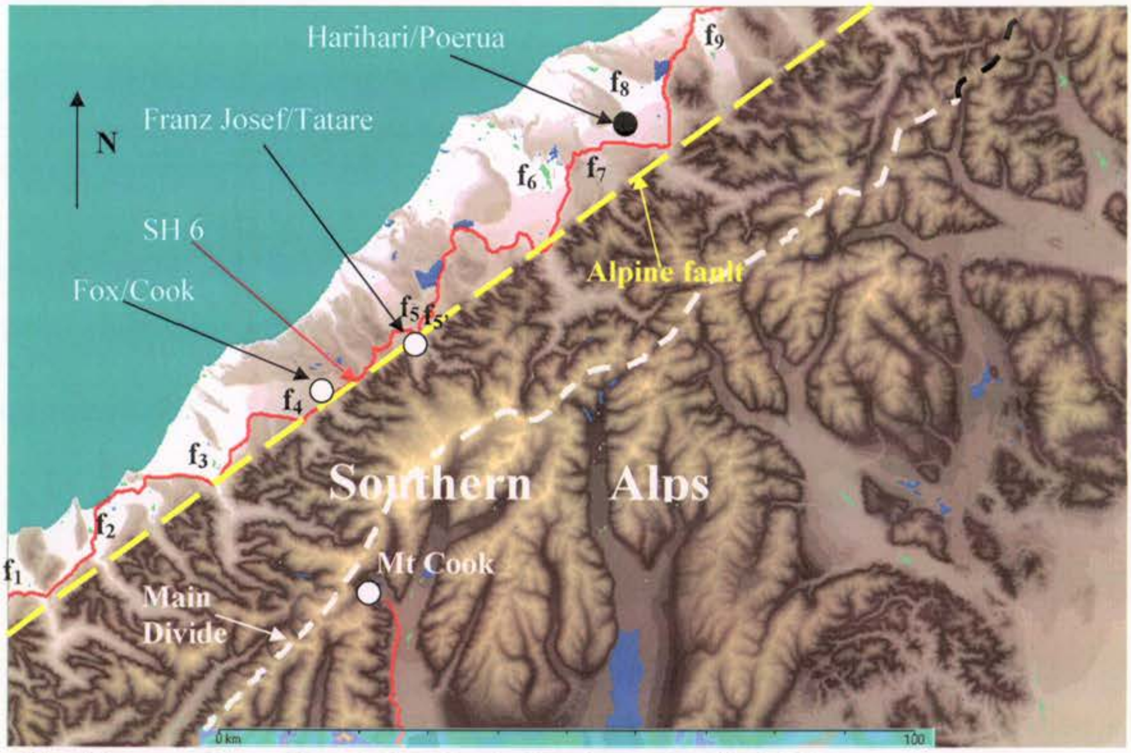


Fig. 30 Part of South Westland, showing main alluvial fans

The detailed site and profile descriptions are in Appendix 1. The soil sequences are illustrated in Figs 31 - 36 below.

At the Poerua site several pits were dug to about 2-3 m depth below the surface of the presently active fan, the achievable depth being limited by rapid ingress of water below the water table. A number of pits yielded no sign of buried soils to a depth of 3 m; this was interpreted as resulting from the most recent aggradation episode causing the pre-existing soil to be removed by erosional flow prior to sediment being deposited. However, in a number of places buried soils were found, mostly in lower-energy environments towards the edge of the fan, although one site in mid-fan yielded two buried soils. Figs 31 - 34 show some of the buried soils at Poerua (indicated by "B"; surface soils are indicated by "S").

Fig. 31 Poerua soil section

Fig 32
Poerua
soil
section

Fig.33 Poerua soil section

Fig. 34 Poerua soil section

Fig. 35 Tatare soil section

At the Tatare site buried soils were exposed in a diversion drainage ditch at the edge of a new residential subdivision. Investigation revealed two soils below the surface soil, with river gravels in between (Fig. 35). This site was at the edge of the Tatare subfan, and of the order of 10 m above present-day river level in the Tatare. The vegetation on the surface soil suggested a surface age of the order of 100-200 years or so.

A pit in the Tatare quarry, just downstream of the SH 6 bridge, was dug to a depth of about 15 m below the surface of the Tatare fan (the river here has excavated a deep canyon as a result of cutting through the Waiho Loop about 2000 years ago). Here we found a deep deposit of medium-fine sands.

At the Waiho River, two pits yielded no sign of buried soils to a depth of about 5 m. Here water ingress was not a problem, possibly due to sealing of the sediments by glacial silt. Both pits showed deposits of medium sand at about 4-5 m that could have been the result of dambreak sedimentation as at Poerua (Fig. 6). One of these contained wood that was dated to 356 ± 33 years (WK 16441), suggesting that it was emplaced between about 1616 and 1682. Either the 1620 or (less likely) the 1717 Alpine fault earthquakes may have been associated with the emplacement and the aggradation that followed it. This ties in with recent dates from the Whataroa fan to the north, where Berryman *et al* (2001) found similar evidence of aggradation associated with the 1620 earthquake (P. Almond, Lincoln University, *pers comm 2005*).

Fig. 36 Fox River bank soil section

Two pits at the Fox River yielded no buried soils to a depth of about 5 m, but again massive sand deposits were found at this depth. However, in the naturally-cut bank of the Fox River a remnant of soil was found buried to a depth of about 1 m beneath the surface soil (Fig. 36).

A pit by the Cook River yielded nothing but large river gravels and boulders, with no sign of buried soils or massive sand deposits.

A consistent feature of all the soil investigations was the young age of the surfaces studied. All were less than a few hundred years old, having formed probably in the interval 1700-1800. This fact has serious implications for development on such fans; the events that formed these surfaces were severely aggradational in nature (like that at Poerua), and the next such events in the future will severely impact any developments on the fan surfaces. An important example is the new residential subdivision immediately west of the Tatare River; this is part of the rapid expansion of Franz Josef township, and is certainly perceived as being without significant risk of flooding or sedimentation. On the contrary, the soil sequence demonstrates unequivocally that the site has been inundated at least twice by several centimetres of river gravels, the last time probably around 1700-1800. On the Waiho fan surface, the last aggradation episode occurred about 1650-1700 and involved several metres of aggradation by coarse river gravels.

It is concluded that the field investigations support the hypothesis that anomalously steep fanheads in Westland are formed by extensive aggradation events, probably resulting from large mass movements (or from clusters of smaller mass movements) into the river systems in their narrow mountain valleys. These can occur as a consequence of Alpine fault earthquakes; but, like the Mt Adams event of 1999, they can also occur without any perceptible trigger event.

8. Hypothesis Testing - Results

The three independent tests of the hypothesis for the origin of steep, entrenched fanheads in Westland have all produced positive results. It is concluded that fanheads of this type are formed by occasional massive inputs of sediment to the upstream river system, usually caused by large landslides or rock avalanches, which may or may not be associated with earthquakes.

These results also confirm the rationale underlying identification of landslide-induced river aggradation hazard zones. Such hazards will be present wherever a fanhead surface is:

1. Noticeably steeper than the downvalley fan surface
2. Of the same age as the downstream fan surface
3. Normally entrenched by the river
4. Underlain *anywhere* by buried soils

9. Hazard Zones and events

The degree of hazard present is related to the age of the fanhead surface, which indicates the last time the fanhead was increased in elevation by river aggradation; if the fanhead surface is young, the last aggradation event was a correspondingly short time ago. Many of the fanheads we have examined were apparently formed no earlier than about 1700-1800. This may indicate association with the last two Alpine fault earthquakes, which occurred in about 1620 and 1717 (though there is also evidence for an earthquake in about 1820, the effects of which have been detected as far north as Franz Josef).

It therefore seems likely that the fanheads we have examined were all aggraded by the 1717 or 1620 earthquakes, which in turn suggests that the *next* major earthquake may have the same extensive effect. In fact, since the elapsed time between the 1717 earthquake and the next one is already much greater than that between the 1420 and 1620, or the 1620 and 1717 events, the accumulated strain is now greater than it was prior to both the 1620 and 1717 events, so the consequences in terms of ground motion and the volume of rock involved in mass movements are likely to be greater. An independent study of parts of the Whataroa fan (Berryman *et al*, 2001; P. Almond, Lincoln University, *pers comm 2005*) has concluded that it is surfaced by soils dating to the 1620 Alpine fault earthquake, which supports this suggestion. Given that the next Alpine fault earthquake has an annual occurrence probability of about 1% - 2% at present (Rhoades and Van Dissen, 1998), the possibility that it will result in severe fanhead aggradation in a number of places is of extreme significance for local authorities, populace and Emergency Management organisations. Risks of damage to structures by earthquakes and wind are considered acceptable only if they are less than 10% in 50 years (Buildings Act 1991, Building Codes), and this seems logically to apply to other natural hazards also, so the 1% - 2% per year probability of damage caused by severe fanhead aggradation is about an order of magnitude greater than the acceptable risk level.

It is therefore of the utmost urgency to carry out a specific study that examines and evaluates this suggestion, and identifies the susceptible sites in Westland. The results of that study could then be applied to all the occupied land on river fans in the Southern Alps.

9.1 Effect of the next earthquake It is useful to speculate about the possible effects of the next Alpine fault earthquake on the Poerua River, based on the present event. The foreseeable scenario is that of an "average" landslide of about 5 million m^3 causing 0.5 million m^3 of fanhead deposition; given that much unstable rock has recently fallen from Mt Adams, this scenario might be less likely than would be the case had the 1999 landslide not yet occurred. The possibility remains, however, that a large (or even a larger) landslide could occur from a different mountain slope – or, of course, a much smaller event, or no event at all, might occur. For planning purposes, it seems reasonable to expect the next earthquake to cause an aggradation event similar in size and effect to the present one. If the earthquake occurs very soon, that is, before the river has re-incised into its bed and while a substantial part of the 1999 dam remains in the river gorge, the aggradation might be both greater and more rapid than the present event. A different scenario, but a not unlikely one, is that the earthquake will cause a large number of smaller landslides in the catchment rather than one large one. The sediment volume generated might be about the same, so the effect on the river might be about the same –

although a large dam is less likely in this case, so delivery of sediment to the fanhead could be faster since less of the sediment may be stored a long way above river level.

Alongside these considerations, which make estimation of the effects of an earthquake very difficult, must be placed the fact that coseismic landslides are often deep-seated (Crozier *et al*, 1995), while aseismic ones are often shallow. The four large aseismic rock avalanches in the Southern Alps in the 1990s – Mt Cook (McSaveney, 2002), two at Mt Fletcher (McSaveney and Downes, 2002) and the Mt Adams landslide – were all shallow relative to their area, whereas coseismic landslides of the same area would probably have been several times more voluminous. In this sense the 1999 Mt Adams landslide may not have been representative of the magnitude of an earthquake-triggered landslide.

Thus, even where we have a great deal of knowledge about the response of a river system to a specific sediment input, this does not allow a very confident estimate of the response of the system to a specified earthquake. However, since only ~ 10% of the landslide volume appears to contribute to fanhead aggradation, the areal extent of this hazard can be confidently delineated; in the case of the Poerua, it will extend to about 5 km upstream of SH 6, or about cross-section 26 on Fig. 10. Farther downstream there will be problems of river aggradation and flooding, but not the devastating deposition of coarse sediment experienced on the fanhead. Instead, finer gravels will build up on the river bed, causing more frequent overbank flooding than normal. In the present event these effects have been managed by individual farmers erecting stopbanks to keep the main river in its normal course, which appears to have been relatively successful (although this may soon cause aggradation problems at the SH 6 bridge that would not have occurred had much of the sediment forced to remain in the river by stopbanking been instead allowed to deposit on adjacent farmland). Attempts to maintain the river in its previous course on the fanhead were utterly unsuccessful because of the great depth of aggradation there. Aggradation is manageable if it is not too great, if the sediment involved is not too large and if it is temporary – in other words, the excess supply of sediment to the river is of limited volume. In the Poerua case, it is because much of the coarse sediment is depositing on the fanhead that the aggradation farther downstream is manageable; had aggradation of the fanhead been somehow prevented, this sediment would have translated farther downstream and been much more difficult to manage there.

The effective duration of the fanhead aggradation episode is determined by the time to peak aggradation plus the time to excavate the fanhead trench to such a depth that the fanhead is no longer susceptible to flooding. As noted earlier, the latter could be fairly short, since only a small volume of sediment needs to be removed to entrench a river to a depth of several metres. For example, the retreat of the Franz Josef glacier in 1999 – 2003 caused degradation of the Waiho River in the upper Waiho Valley to a depth of at least ten metres into very coarse gravels in less than 3 years. Thus, using the Poerua example, if the aggradation has indeed peaked as indicated by Fig. 15, it may take of the order of another few years to develop an entrenched river channel, and the whole aggradation-incision event may be completed in about a decade. Confirmation of this will require continued monitoring.

9.2 Extension to other fanheads This scenario for the Poerua can be applied to other alluvial fans. Of the fans studied in this work, the Fox/Cook and Waiho will be effectively uncontrollable under severe aggradation for several km downstream of their exits from the mountain front. In fact, the fans of these two rivers are so steep all the way to the sea that any sort of management of aggradation anywhere on the fan surface must be dubious. The Tatare fanhead is very close to the exit of the river from the mountain front, and the presence of a recent surface underlain by a number of buried soils suggests strongly that the present surface soil will in turn be buried in the future. The prospects of controlling this aggradation are minimal, due to the steep slope of the fan and the likely depth of deposition close to the river. However, the river bed will take some time to aggrade the ~ 10 m needed to spill onto the fan, so evacuation will be possible even if protecting dwellings is not.

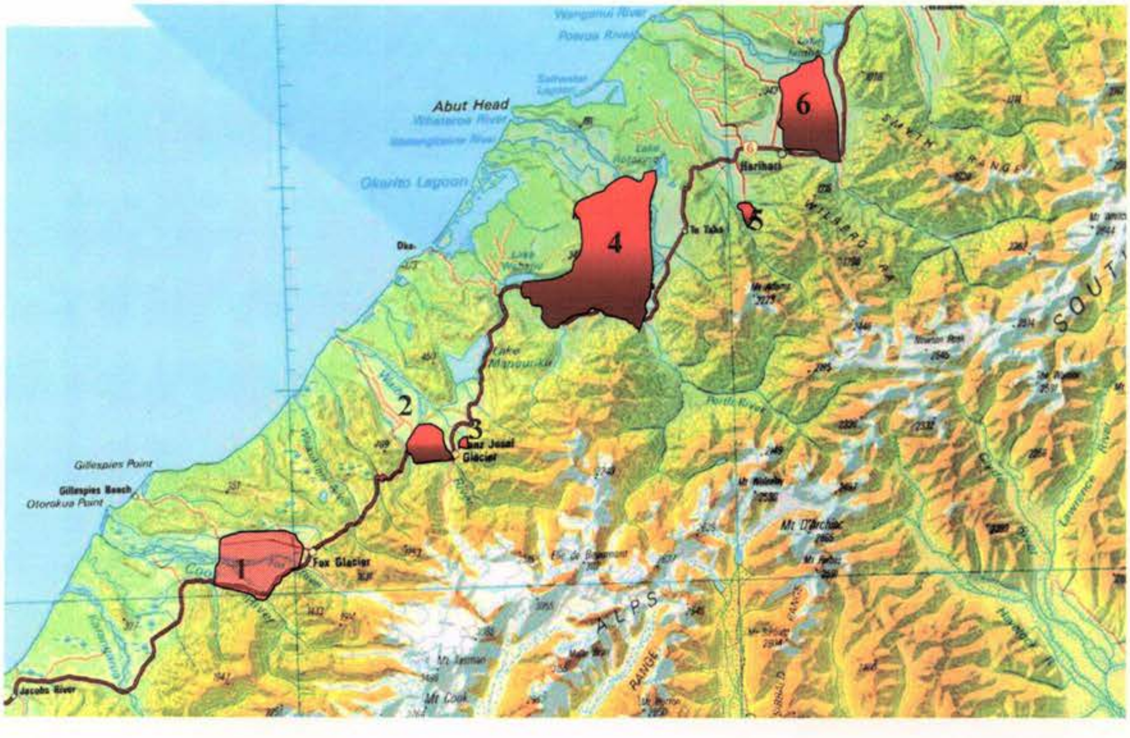


Fig. 37 Areas of the West Coast identified as likely sites of aggradation following large mass movements, based on fanhead steepness, river incision and/or buried soils. 1 = Fox/Cook; 2 = Waiho; 3 = Tatare; 4 = Whataroa/Waitangitaona; 5 = Poerua; 6 = Wanganui

The Whataroa (and by extension possibly the Wanganui too) is a somewhat different situation. Its slope is quite low, and its catchment large, as is its fan, so the progress of aggradation may be fairly slow. This encourages the suggestion that buildings may be able to be protected by ring-banks, a concept that could even apply to townships such as Whataroa and Hari Hari. Protecting the State Highway, however, particularly in the vicinity of the fanheads, will be extremely difficult. In addition, the Waitangitaona River just to the west of the Whataroa is presently in an aggradational phase, having avulsed to flow into Lake Wahapo in 1979 (Griffiths and McSaveney, 1986; Korup *et al*, 2004), and further large volumes of sediment input will exacerbate this aggradation. Fig. 37 shows the areas so far identified as vulnerable to severe aggradation following large volumes of sediment input to the rivers.

9.3 Landslides generated by the next Alpine fault earthquake, and their consequences
Recent research (Keefer, 1994; Malamud *et al*, 2004) suggests that the size distribution of landslides generated by large earthquakes is such that a significant proportion of the total volume of debris is contained in a very small number of large landslides; for example, the 1929 Arthur's Pass earthquake generated a total of about 5.9×10^7 m^3 of debris, 5.5×10^7 m^3 of which was contained in the Falling Mountain rock avalanche alone (Davies & McSaveney, 2005 *in press*). It is sensible to expect that this will be the case in the expected Alpine fault earthquake too. The total volume of debris to be expected in a M = 8 earthquake is of the order of 10^9 m^3 (Keefer, 1994; Malamud *et al*, 2004), while the maximum volume of an individual landslide is expected to be of the order of 2×10^8 m^3 (Malamud *et al*, 2004). Thus one landslide of about a few hundred million m^3, and about four times that volume in lesser landslides, is the sort of scenario to be expected. In addition, aftershocks can be expected to cause further landsliding, of the order of 10% of the total volume due to the main shock (Malamud *et al*, 2004).

This suggests that in a number of catchments (possibly of the order of 10, meaning a few to lots), individual landslides will be large enough ($\sim 10^6$ m^3 or greater) to generate landslide dams giving rise to dambreak flood hazards, and to post-dambreak aggradation hazards of the type experienced at Poerua. Large numbers of smaller landslides will generate a smaller volume of sediment in other catchments; so aggradation can also be expected from these catchments, if there is evidence that it has occurred previously. Since the total sediment volume from small landslides will be smaller than that from the larger landslides, troublesome aggradation from this source will be less widespread. However, the sediment from non-dam-forming landslides can be expected be reworked downriver much more rapidly than that from landslide dams, because dams erode rather slowly after the initial dambreak since much of their sediment is out of immediate reach of the river. A greater proportion of the total volume of sediment from non-dam-forming landslides is immediately accessible by river erosion.

Although we are assuming that a landslide of 10^6 m^3 is sufficiently large to form a dam, this is only the case if the landslide falls into a narrow gorge. Arshad *et al* (2004) identified only 22 sites in Westland where the risk of a large landslide into a river gorge was high, thus it is possible that some larger landslides may not form dams. In these cases, we assume that the sediment still accumulates on the valley floor, and is therefore accessible by the river to be reworked downstream.

The hazard scenario resulting from the next Alpine fault earthquake, assuming an M = 8 event, is thus:

1. Landslide dams and dambreak flood hazards in about 10 (say between 3 and 30) catchments;

2. Landslide-induced fanhead aggradation hazards in many catchments that show evidence of such events in the past.

The dambreak flood hazards can be expected to eventuate rather rapidly (within days or weeks), considering the frequency of heavy rain on the West Coast and the very small number of long-lived landslide dams in river valleys. By contrast, the aggradation hazards will take some time to become fully apparent; the Poerua situation did not become evident until months after the dambreak, and its seriousness was only obvious after about a year. The slow and delayed development of the aggradation hazard, together with its ubiquity, makes it potentially very troublesome, because it may not become apparent until reconstruction of facilities and infrastructure has begun, and this reconstruction may be taking place in areas about to be affected by severe aggradation. If the hazard is foreseen, sediment accumulation in catchments can be investigated and redevelopment can be focused away from vulnerable areas.

Aggradation resulting from sediment inputs in the form of numerous small landslides, or from large landslides that do not form dams, is expected to develop more rapidly than that from individual large events causing landslide dams, but there may still be a significant delay before it becomes apparent. It is also likely that the duration of non-landslide-dam induced aggradation will be less than that caused by landslide dam failure, because the sediment will be able to be reworked faster. For a given sediment volume, the depth of fanhead aggradation from many small landslides is likely to be greater than that from landslide dams, again because sediment delivery to the fanhead is likely to be faster.

It is worthy of note that the aseismic landslide distribution of Hovius *et al* (1997) is very similar in form to that of Malamud *et al* (2004). Thus episodic, catastrophic sediment delivery events are not only associated with earthquakes, but are a more general phenomenon with similar characteristics.

9.4 Reinstating the State Highway State Highway 6 is the vital artery of West Coast life (Fig. 30). It usually crosses alluvial fans in the fanhead area (because the rivers are incised and narrower there), and thus is very susceptible to the aggradation hazards considered herein. Hence it is to be expected that many highway bridges will be affected by aggradation after the next Alpine fault earthquake, and this applies to small as well as large rivers. Reconstruction of bridges damaged by the earthquake is likely to be a high priority to restart the West Coast economy, and it is important that delayed and long-term aggradation is anticipated in planning this reconstruction. In some places (e.g. the Poerua, where the bridge is some kilometers downstream of the fanhead) there may be only relatively minor aggradation; in others (e.g. Waiho, Fox, Whataroa, Wanganui, and many smaller rivers) bridges are sited where aggradation is likely to be greatest. In all cases it is true that the aggradation will be temporary; in due course the river will re-incise into the now higher fanhead. Thus permanent abandonment of fanhead bridge sites appears unnecessary; but alternative crossings will be needed for periods of at least some years, depending on the duration of the aggradation episode.

10. Discussion

The question of whether or not any particular sediment input event can be considered part of the "normal" input series of a catchment or fan depends on its geomorphic effects. By definition, "normal" inputs in the present context are those that do not generate geomorphic signatures outside the "normal" dynamic equilibrium form of the fan. Clearly, the prominent and enduring steep fanheads shown in Fig. 3 do not meet this criterion, so by definition they are generated and further develop under the influence of "abnormal" events. Consequently, any fan that does not show the characteristics of those in Fig. 3 does not experience sediment inputs greater than the "normal" range. There will of course be sediment input events that are marginal in this regard, but from a pragmatic point of view they are unlikely to be sufficiently different from "normal" (i.e. frequent) events to be hazardous; and any fan lacking a fanhead trench is so evidently capable of inundating its fanhead in a major storm event, that one hopes it will be free of vulnerable development.

The present long-term aggradation rate of the Waiho fan is thought to be about 2 mm a^{-1} (Barrell *et al*, 2003) – the same as the present rate of sea-level rise. Thus in fact the "equilibrium" fans we have considered may be slowly aggrading over time. It is likely that the "resistant" LGM moraine ridges at the coast are also slowly eroding, gradually shortening the fans and tending to cause degradation of the fan surface. These two effects compensate each other qualitatively; whether they do so quantitatively is unknown. The net effect, however, is in any case less than 2 mm a^{-1} of aggradation, which is minor by comparison with the metres of aggradation experienced by fanheads even at intervals of centuries. The fact that the steepened fanheads are prominent landscape features shows that slow fan aggradation does not reduce their geomorphic and hazard significance.

The effect of occasional major sediment inputs on the behaviour of non-equilibrium fans (i.e. fans that are "permanently" aggradational) can be inferred from the concepts developed herein. The immediate effect will be the same – a steep fanhead will develop, into which the river will later incise. The gradual aggradation of the whole fan, however, will cause the fanhead to be progressively buried over time, until eventually there is no trace of it remaining. At this stage there is no geomorphic sign that the large sediment input ever occurred. It could only be discovered by digging into the fanhead. On a fan which has developed an incised channel at its head due to long-term reduction in sediment to water ratio, a massive sediment input will again create a steep fanhead, into which the river will eventually re-incise. The long-term morphology will be a fan with two distinct nested and entranched oversteepened fanheads. These complexities show why we have chosen to study the phenomenon in the comparatively simple (but very relevant) context of equilibrium fans.

11. Future work

1. Given the indication from the most recent survey, that the Poerua River fanhead may be starting to degrade, it is vital that the monitoring of river bed elevations continues into the future, at least until the behaviour of the system in response to the 1999 event is fully characterised.

2. The procedure developed herein for identifying areas at risk of severe aggradation needs to be tested and improved by extension to other fans, and to other areas where similar large sediment inputs to rivers can be expected. A survey of small-to-medium sized fans in Westland to determine the age of the fan surface is needed to show how prevalent are the young surfaces found in this study, and thus how reliable are the indicators of aggradation hazard we have developed. We envisage detailed study of both soil stratigraphy and vegetation age on a small number of fans, to establish a correlation between these two factors, and a more extensive survey using vegetation age as a surrogate for soil age. Testing the procedure in the Kaikoura area would also be logical given the presently rapid uplift of the Seaward Kaikoura Range on the Hope fault and the steep, narrow valleys of the Kowhai and Hapuka Rivers.

3. An important factor not discussed in this work is the nature of the aggradation process on a fanhead. Alluvial aggradation, as on the Poerua fan, takes place fairly slowly and sequentially (albeit remorselessly), and there is little resultant danger to human life. However there is also the prospect that, in smaller catchment-fan systems, the aggradation can occur in the form of debris-flows. Debris-flows are sudden events that occur without warning and deliver very large sediment volumes to any part of a fan surface steeper than about 5°; they pose a very serious threat to life (Davies, 1997). Many small fans in Westland are formed at least partly by debris-flow activity (De Scally and Owens, 2004). The potential for debris-flows to affect a fan surface can be determined by catchment and fan morphometric criteria. An investigation is urgently needed to identify areas in Westland vulnerable to the occurrence of debris-flows, so that this information can be incorporated into land-use planning.

12. Conclusions

1. The rate of aggradation of the Poerua River fan has decreased at the fanhead, and appears to be approaching a situation where the river may soon begin to re-incise itself in the fanhead. If this is the case, the duration of the aggradation-incision event may be of the order of a decade; continued monitoring is needed to confirm this.

2. Alluvial fanheads in which rivers are entrenched, and which have young surfaces and buried soils, result from, and are therefore subject to, episodic sediment deposition when sufficiently large sediment inputs cause substantial river aggradation.

3. Such fanheads can be identified by:
   - Anomalously steep surface gradient
   - Incised river channel
   - Young surface soils overlying coarse river sediments
   - Buried soils (found most easily in low-energy environments)

4. A number of fans have been identified in Westland that appear to be at risk from aggradation caused by mass movements entering the upstream watercourse. These are the Wanganui, Whataroa, Poerua, Tatare, Waiho and Fox fans. Other fans probably have the same risk; this needs to be further investigated.

5. A severe earthquake is likely to generate very large mass movements in a number of catchments in Westland, with consequential aggradation on downstream fans; however, earthquakes are not the only cause of such aggradation episodes.

6. Fanhead aggradation from non-dam-forming mass movements is likely to develop more rapidly, and be higher, than that from dam-forming events, for the same volume of sediment.

13. Acknowledgements

We gratefully acknowledge the laboratory facilities and support – in particular the work of Warwick Hill - provided by Natural Resources Engineering, Lincoln University.

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University of Canterbury provided accommodation at their Harihari Field Centre for field work.

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Appendices

1. Soil stratigraphy investigations
2. Model fan contour maps 2004
3. Model fan contour maps and long profiles 2005

Appendix 1

Soil Stratigraphy of the fans of the Poerua, Tartare, Waiho, Fox and Cook rivers, South Westland

Report to Dr Tim Davies
Department of Geological Sciences, University of Canterbury

P. C. Almond
Soil and Physical Science Group
Agriculture and Life Sciences Division
Lincoln University

Tuesday, 12 April 2005

Table of Contents

Soil Stratigraphy of the fans of the Poerua, Tartare, Waiho, Fox and Cook rivers, South Westland

1- *Brief*

The aim of the work described in this report was to investigate the soil stratigraphy of the heads of the fans of three major rivers (Poerua, Waiho and Fox-Cook rivers) and a smaller stream (Tartare stream) in South Westland (Fig. 1) to test the hypothesis that these landforms have experienced episodic aggradation. Buried soils within a stack of alluvial sediments are evidence of periods of landscape stability and soil formation punctuating episodes of sedimentation. Lack of a soil stratigraphy in the sediments is evidence that the hypothesis should be rejected. Where a soil stratigraphy is present it can be interpreted in terms of past river behaviour: buried soils correspond with times of river incision and minimal channel migration, whereas sediment packages correspond to times of river aggradation and channel instability.

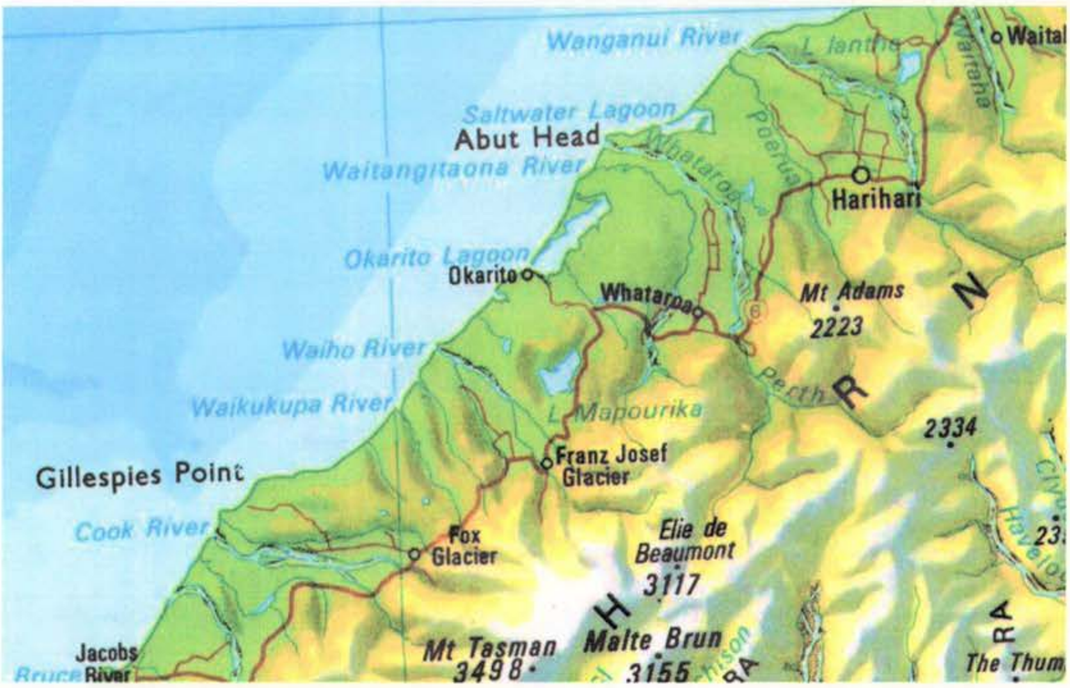

Figure 1. Location of river systems discussed in the text.

From a number of soil chronosequence studies carried out in Westland (see Tonkin and Basher, 1990) it is possible to calibrate the extent of soil development in terms of soil age. The major emphasis is placed on the development of the B horizon, as expressed by its colour and depth. Soil B horizons become progressively brighter and redder in colour the longer soil processes, principally weathering and oxidation, have had time to act. If a number of buried soils occur in a stratigraphic sequence the average recurrence interval for the aggradation events that buried them can be made. The buried soils' morphologies can be related directly to soil ages, which equate to the durations of intervals between aggradation events.

2- *Methods*

Soil stratigraphy was examined from pits dug by a machine excavator and from existing exposures, and described according to the soil horizon nomenclature of Milne(1995) All descriptions are presented in the Appendix. Sites for examination were located mostly near the axes of the fans but also on the fan margins.

3- *Results*

Poerua Fan Head

The Poerua river fan head has been affected severely by aggradation since a large landslide in 1999 from Mt Adam deposited 10-15 million m^3 of sediment in the river valley, temporarily damming the river (Hancox et al., 1999). Prior to the landslide the region of the fan head examined was covered in pasture and free of any alluvial activity. Of the five sites examined (Fig. 2), one (PO2) exposed very recent weakly stratified alluvial gravels within a channel, three (PO1, PO4, and PO5) on an interchannel islands showed recent, dominantly fine sandy overbank sediment over a buried soil, and one (PO3) on an interchannel island exposed a well developed soil beneath a large totara tree.

The stratigraphy is consistent with a stable land surface, represented by the soil at PO3 and the buried soils in PO1, PO4, PO5, having been buried by the 1999 aggradation event. The B horizon of the soil beneath the older land surface has a colour of 2.5Y 4/2 and varies between 10 and 60 cm deep. This level of B horizon expression equates to a few hundred years of soil development.

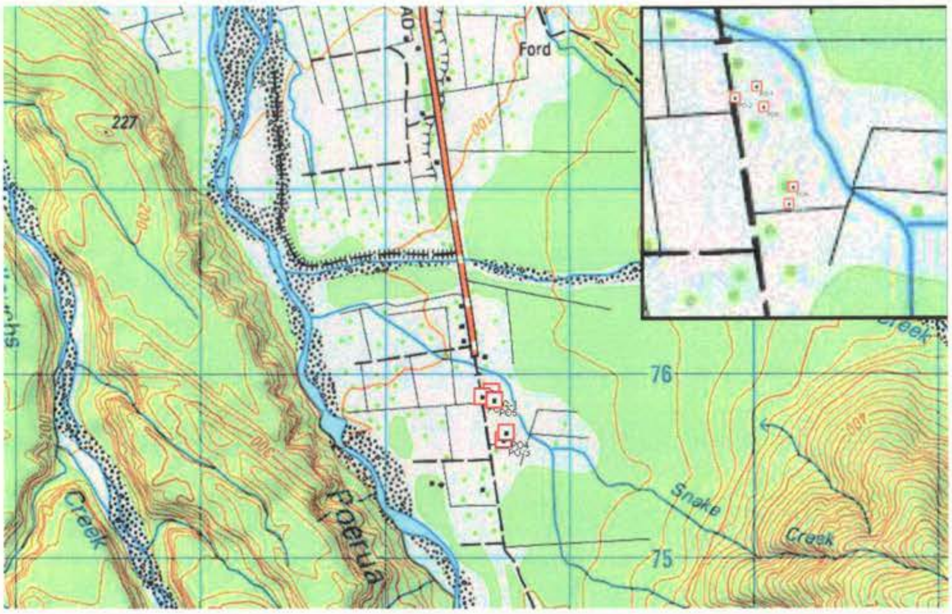

Figure 2. Sites on the Poerua river fan (Inset: details of site locations).

Tartare Fan Head

Two sites were examined on the fan of the Tartare stream: the first, site TT1, was exposed in a drain at the back of a new subdivision behind Franz Josef township, and the second, site TT2, was in a quarry immediately downstream of SH6 near the bridge over Tartare stream (Fig. 3). Site TT1 showed unequivocal evidence of episodic aggradation of generally fine-textured sediment. The most recent episode produced 33 cm of silty, sandy and fine gravelly material in which the surface soil has formed. The soil is very rudimentary showing only A horizon development. The first buried soil occurred between 33 to 53 cm depth in silt loam and sandy loam sediment and included a 16 cm thick olive-coloured B horizon. This soil represents a few hundred years of landscape stability. The second buried soil occurred below 112 cm in more loamy material. The soil was only recognisable on the basis of a 4 cm thick buried A horizon. The absence of a B horizon indicates the brevity of the period (perhaps <250 years) between initiation of soil development and the subsequent aggradation episode, which forms the parent material of the first buried soil.

Figure. 3. Sites on the Tatare stream and Waiho river fans.

At site TT2 a buried soil with an 18 cm thick dark greyish brown B horizon occurred under about 11.5 m of schist-dominated very gravelly and stony medium sand. .The sediments immediately above and below the buried soil are generally fine-textured and indicate that the river was depositing overbank sediment in this location before the phase of soil formation and immediately afterwards. The soil appears to be accretionary in nature indicating that some overbank sedimentation was occurring during the period of soil development.

Waiho Fan Head

Two exposures, WA1 and WA2, were examined from deep pits dug in the Waiho Fan (Fig. 3). WA1 was very close to the axis of the fan and less than 100 m from the present Waiho river channel. WA2 was about 2 km to the west in a direction normal to the fan axis. The surface soils exposed at both sites showed relatively weak soil development. At WA1 12 cm of fine textured material in which was developed a thin A horizon (6 cm) and a thin (6 cm) gleyed B horizon overlay a 12 cm thick horizon of oxidised gravelly sandy loam. Below 24 cm to the base of the pit at 3.2 m the alluvial material was very coarsely textured ranging from gravelly to bouldery with no soil stratigraphy. At WA2 the surface soil had a thicker fine-textured upper part than WA2 (43 cm) but the level of soil development was similar. A thin A horizon (8 cm) overlay gleyed silty and sandy material to a depth of 43 cm. Some thin horizons within this material were weakly oxidised to colours of 2.5Y 5 or 4/3 (light olive brown). Below 43 cm the alluvial material was dominantly gravelly to bouldery coarse sand with some pockets of pure coarse sand. There was no evidence for any significant breaks in the accumulation of this material. A piece of wood at 240 cm depth was collected for radiocarbon dating.

The soil at WA1 is very similar to the Stage IX soil of the chronosequence of soils in the Franz Josef valley studied by Stevens(1968). He estimated this soil to be 250 years old.

Cook River Valley

Four exposures were examined in the Cook river valley, three on the fan head of the Fox river near the town of Fox Glacier's oxidation ponds (FX1, FX2, FX3), and one on the fan head of the Cook River (FX4) (Fig. 4). Exposures FX1 and FX2 came from deep pits dug into a former channel and adjacent bar, respectively, next to the ponds, and FX3 was exposed in the river bank about 200 m to the south west. Site FX1 in the channel had about 30 cm of fine-textured material over very bouldery alluvium extending to the bottom of the pit at 4.00 m. The soil in the fine textured upper material was reduced and gleyed because of the local drainage conditions. The lower bouldery material showed some weak stratification related to variation in clast size, the degree of sorting, and the extent of silt plugging, but no soil stratigraphy. Site FX2 on the channel bar had only 25 cm of fine-textured material in which was formed a thin A horizon (9 cm) and a 16 cm-thick weakly oxidised (colour 5Y 4/3) BC horizon. The underlying bouldery alluvium was extremely hard to excavate and was exposed to a depth of 2.00 m only. It showed no soil stratigraphy or stratification. The extent of soil development at these two sites is rudimentary and suggests that the river abandoned this area no more than 200-300 years ago.

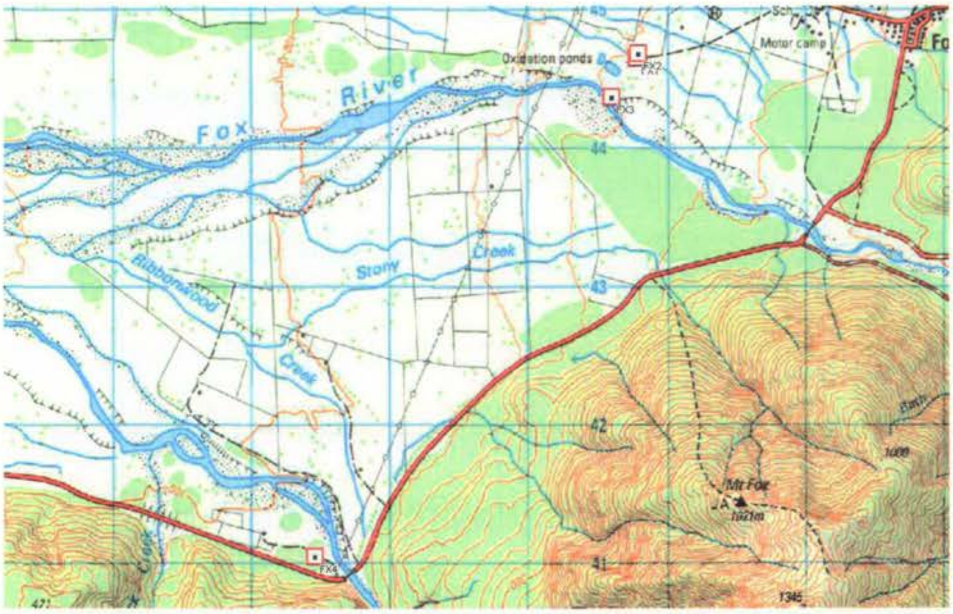

Figure 4. Sites on the Fox and Cook river fans.

The river bank section at FX3 showed 5 m of coarse-textured alluvium clearly separable into distinct packages that varied in clast size, sorting and coherence. The surface soil was not exposed at this site. The upper 1.7 m-thick gravel package was loose whereas all the underlying packages were tight and coherent. This difference suggests that the upper package is somewhat younger than those below. The absence of buried soils beneath the upper package or anywhere in the section, however, prevents any interpretation of the duration of time between the accumulation of the alluvial packages.

Site FX4 was exposed in a pit 300 m to the west of the present channel of the Cook river and very near the fan axis. The upper 1.8 m of the pit was an upward fining sequence from stony and gravelly coarse sand to loamy medium sand at 20 cm depth. The upper 20 cm was very gravelly. This package is dominated by schist clasts and suggests a local stream source. Below 1.8 m to the base of the pit at 3.8 m clasts were dominantly greywacke sandstone, which originates close to the main divide of the Southern Alps and therefore must have been carried by the Cook river. The extent of soil development in the surface soil is rudimentary. The colour of the B horizon is similar to that of the soil at WA1 although it is slightly less red and therefore the age of the land surface at this site is estimated to be no more then 250 years. There was no soil stratigraphic evidence for episodic aggradation at this site.

4- *Discussion*

At only one site, TT1 on the Tartare stream fan, is there unequivocal evidence of multiple episodes of aggradation on the fans examined. At this site the surface soil and two buried soils are evidence of three aggradation episodes separated in time by at most a few hundred years and at least by less than an estimated 250 years. Wood taken from a buried soil at 11.5 m depth in the section exposed at site TT2 will date the most recent aggradation in the lower part of the fan.

On the Poerua fan there was clear evidence of aggradation related to the 1999 landslide on Mt Adam burying a former land surface that had been stable for a few hundred years. There was, however, no evidence from our excavations for similar episodes prior to the most recent.

Sites WA1 and WA2 on the Waiho river fan and sites FX1, FX2, and FX4 on the Fox and Cook river fans all pointed to activity on the fans within the last few hundred years but no evidence of episodic aggradation. At site FX3 on the bank of the Fox river at least two distinct gravel packages suggest multiple aggradation events but the absence of any buried soils makes it impossible to be sure whether the gravels represent distinct episodes of aggradation or merely events within a single aggradation episode.

The clear evidence for episodic aggradation on the Tartare stream fan and not on any of the other fans is probably due to the differences in fluvial characteristics of the Tartare stream compared to the other rivers. The Tartare stream has much smaller catchment area, smaller discharge, and finer bedload sediment. As a consequence the aggradation packages are much thinner and the stream flows carrying them far less erosive. The lack of evidence for episodic aggradation on the larger rivers may relate to either (1) too great-a-depth of sediment so that the buried land surfaces were not seen in the holes we dug; or (2) the soils formed on those land surfaces were eroded away in the early stages of the subsequent aggradation episode leaving similar gravels stratigraphically juxtaposed.

5- *Conclusions*

From soil evidence the fans of the Tartare, Waiho, Fox and Cook rivers have been active within the last few hundred years, and the fan of the Poerua river is currently aggrading in response to sediment delivered to the river by the 1999 landslide on Mt Adam. Only on the head of the fan formed by the small Tartare stream is there clear evidence for multiple aggradation episodes. The larger rivers may also behave in this manner but the stratigraphic evidence is lacking, possibly because fluvial erosion at the early stage of aggradation episodes removes the soils formed on the pre-existing landscape. Alternatively, aggradation packages may be so thick that the machine-dug and natural exposures we used did not extend deep enough for the stratigraphy to be seen.

6- *References*

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Soil Descriptions

Profile code: PO-1

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Grassy island within Poerua River floodplain on Keith McKenzie's farm

Grid Reference: NZMS 260 2308578 5775899
Date described: 2/2/2005
Authors: PJT, FLS
Site notes:

C1	0 - 8 cm	medium sand to loamy fine sand; 2.5Y 5/1 (grey to greyish brown); loose soil strength, massive; sharp smooth boundary.
bA	8 - 9 cm	loamy medium sand; 2.5Y 3/1 (very dark grey); weak soil strength, massive; sharp broken boundary.
bC1	9 - 13 cm	medium sand; 2.5Y 5/1 (grey to greyish brown); loose soil strength, single grains; abrupt smooth boundary.
bC2	13 - 19 cm	loamy fine sand; 2.5Y 5/1 (grey to greyish brown); weak soil strength, massive; abrupt smooth boundary.
2bA	19 - 20 cm	loamy sand; 2.5Y 3/1 (very dark grey); weak soil strength, massive; sharp broken boundary.
2bC1	20 - 32 cm	loamy fine sand; 5Y 4/1 (dark grey); weak soil strength, massive; abrupt smooth boundary.
2bC2	32 - 36 cm	loamy sand; 5Y 4/1 (dark grey); weak soil strength, massive; abrupt smooth boundary.

Profile code: PO-1

2bC3	36 - 41 cm	loamy sand; 5Y 4/1 (dark grey); weak soil strength, massive; sharp smooth boundary.
3bA	41 - 49 cm	sandy loam; 2.5Y 3/1 (very dark grey); weak soil strength, weak fine and medium nutty structure; clear smooth boundary.
3bBw(g)	49 - 55 cm	sandy loam; 2.5Y 4/1 (dark grey to dark greyish brown); many medium faint 2.5Y 4/2 (dark greyish brown) mottles; weak soil strength, massive; clear wavy boundary.
3bBw	55 - 60 cm	sandy loam; 2.5Y 4/2 (dark greyish brown); weak soil strength, massive; clear broken boundary.
4C	60 - cm	bouldery, sandy gravel; 2.5Y 4/1 (dark grey to dark greyish brown); ; Note: This material is the only bedload material in the profile, material above is overbank sediment.

Profile code: PO-2

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: In the middle of a channel deposit on the Poerua Floodplain, Keith McKenzie's farm

Grid Reference: NZMS 260 2308530 5775874
Date described: 2/2/2005
Authors: PJT, FLS
Site notes:

C	0 - 21 cm	thinly horizontally bedded medium sand (mm to cm thick); N 4 (dark grey); loose soil strength, single grains; sharp irregular boundary.
2C	21 - 93 cm	bouldery sandy fime and medium gravel; N 4 (dark grey); loose soil strength, single grains; clear irregular boundary.
3C	93 - 160 cm	horizontally bedded mm to cm thick laminations of medium and coarse sand; N 4 (dark grey); loose soil strength, .

Profile code: PO-3

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Adjacent to a large Totara tree that survived recent channel cut and fill, Poerua floodplain, McKenzie's farm
Grid Reference: NZMS 260 2308647 5775640
Date described: 2/2/2005
Authors: PCA, FLS
Site notes:

A	0 - 4 cm	sandy loam; 10YR 3/2 (very dark greyish brown); weak soil strength, moderate fine granular structure; abundant medium and coarse roots; gradual boundary.
Bw	4 - 90 cm	slightly bouldery, stony sandy loam; 2.5Y 4/2 (dark grey ish brown); common medium distinct 7.5YR 4/2 (brown) mottles; weak soil strength, moderate medium nutty structure; abundant medium and coarse roots; .
bA	90 - 100 cm	gravelly, stony sandy loam; 7.5YR 3/2 (dark brown) and 2.5Y 5/1 (grey to greyish brown); common medium distinct 5YR 3/4 (dark reddish brown) mottles; weak soil strength, weak fine and medium nutty structure; abundant medium and coarse roots; clear wavy boundary.
bBw	100 - 112 cm	moderately stony, gravelly sandy loam; 2.5Y 4/2 (dark greyish brown); weak soil strength, weak fine blocky structure; clear wavy boundary.
bC1	112 - 215 cm	very bouldery, stony, gravelly coarse sand; 5Y 4/1 (dark grey); loose soil strength, single grains; .

Profile code: PO-3

bC2	215 - 240 cm	stony, gravelly coarse sand; slightly firm soil strength, .
bC3	240 - 260 cm	open network stony gravel; .
bC3	260 - 290 cm	bouldery, stony gravel; .

Profile code: PO4

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Along side a 60 cm dbh matai tree

Grid Reference: NZMS 260 2308658 5775678
Date described: 2/2/2005
Authors: PCA, FLS
Site notes:

C	0 - 55 cm	fine gravelly coarse sand; N3/1; loose soil strength, single grains; sharp smooth boundary.
bA	55 - 64 cm	sandy loam; 5Y 4/2 (olive grey); weak soil strength, massive; abrupt wavy boundary; Note: A hint of reduction is showing below the A horizon.
bBw	64 - 125 cm	sandy loam with some medium sand lenses; 5Y 4/2 (olive grey); massive; abrupt smooth boundary.

Profile code: PO5

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Beside a buried fence post on a grassy island

Grid Reference: NZMS 260 2308593 5775854
Date described: 2/2/2005
Authors: PJT, FLS
Site notes:

C	0 - 15 cm	fine sand; 2.5Y 4/1 (dark grey to dark greyish brown); loose soil strength, single grains; abrupt wavy boundary.
bA	15 - 17 cm	loamy fine sand; 2.5Y 4/1 (dark grey to dark greyish brown); weak soil strength, weak fine granular structure; clear smooth boundary.
bC	17 - 37 cm	medium and fine sand interlayered (5 cm thick layers); 2.5Y 4/1 (dark grey to dark greyish brown); loose soil strength, single grains; abrupt smooth boundary; Note: lower boundary looks erosional.
b2C(f)	37 - 45 cm	loamy fine sand; 5Y 3/1 (very dark grey); few fine distinct 10YR 3/3 (dark brown) mottles; massive; sharp wavy boundary.
2b3A	45 - 54 cm	sandy loam; 2.5Y 4/1 (dark grey to dark greyish brown); weak soil strength, weak fine blocky and coarse granular structure; clear wavy boundary.
2b3Bg	54 - 63 cm	loamy sand; 2.5Y 4/1 (dark grey to dark greyish brown); few medium distinct 7.5YR 4/6 (strong brown) mottles; weak soil strength, massive; abrupt wavy boundary.
2b3Bw	63 - 83 cm	fine gravelly coarse sand; 2.5Y 4/2 (dark greyish brown); few fine faint 10YR 4/2 (dark greyish brown) mottles; loose soil strength, massive; abrupt wavy boundary.

Profile code: PO5

2b3C	83 - 114 cm	fine gravelly coarse sand; 10YR 4/1 (dark grey); loose soil strength, single grains; ; Note: varies to bouldery gravelly coarse sand.

Profile code: TT1

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: On the side of a drain behind Kamahi Heights subdivision in Franz Josef

Grid Reference: NZMS 260 2282193 5754456
Date described: 3/2/2005
Authors: PCA, FLS
Site notes:

spoil	-40 - 0 cm	.
A1	0 - 1.5 cm	humic slightly gritty sandy loam; 7.5YR 3/1; abrupt smooth boundary.
A2	1.5 - 5 cm	sandy loam; 10YR 4/1 (dark grey); weak soil strength, massive; clear wavy boundary.
C	5 - 26 cm	layered coarse sand and fine gravel; 5Y 5/2 (olive grey); weak soil strength, massive and single grains structure; sharp wavy boundary; Note: erosional lower boundary.
2C	26 - 33.5 cm	loamy silt; 5Y 5/2 (olive grey); semi-deformable failure, massive; clear smooth boundary.
3bA	33.5 - 37 cm	silt loam; 5Y 5/1 (grey); weak soil strength, semi-deformable failure, weak medium blocky structure; abrupt wavy boundary.
3bBw	37 - 53 cm	fine sandy loam; 2.5Y 5/3 (greyish brown to light olive brown); weak soil strength, brittle failure, weak medium blocky structure; gradual boundary.

Profile code: TT1

4bC	53 - 68 cm	coarse sand; 2.5Y 4/2 (dark greyish brown); weak soil strength, single grains; abrupt wavy boundary.
5bC(f)	68 - 80 cm	very gravelly loamy coarse sand; 10YR 4/4 (dark yellowish brown); moderately coherent soil strength, single grains; abrupt smooth boundary.
6bC	80 - 95 cm	very gravelly coarse sand; and 5Y 4/3 (olive); loose soil strength, single grains; sharp wavy boundary; Note: erosional lower boundary.
7bC	95 - 112 cm	medium sand; 5Y 4/1 (90%) and 10YR 4/3 (10%); weak soil strength, brittle failure, massive; abrupt smooth boundary.
8b2A	112 - 116 cm	loamy silt; 10YR 4/1 (dark grey); weak soil strength, massive; abrupt smooth boundary.
9bC	116 - 150 cm	loamy fine sand to medium sand with occassional pods of fine gravel; 5Y 5/2 (olive grey); massive; .

Profile code: TT2

Survey: South Westland fan stratigraphy study

Region:

Location: Tartare fan, south side to the west of SH6. Excavation into the floor of a gravel quarry cut back into the edge of a terrace

Grid Reference: NZMS 260 2281700 5756370

Date described: 6/2/2005

Authors: PJT

Site notes: A partly decayed portion of a rimu? tree trunk and root taken for radiocarbon dating most likley come from the equivalent of the 1177-1192 cm increment. This wood was excavated by backhoe from a similar stratigraphic position at an earlier date by Tim Gibb of Franz Josef.

C	0 - 1150 cm	stony, gravelly medium sand; loose soil strength, single grains; abrupt smooth boundary.
2C	1150 - 1177 cm	silt loam; 2.5Y 4/2 (dark greyish brown); many fine distinct 5YR 4/6 (yellowish red) mottles; slightly firm soil strength, massive; abrupt smooth boundary; Note: mottles are tubular.
3bA	1177 - 1192 cm	fine sandy loam; 2.5Y 4/3 (dark greyish brown to olive brown) and 2.5Y 5/1 (grey to greyish brown); slightly firm soil strength, massive; abrupt wavy boundary; Note: macropores filled with loamy medium sand.
3bBw(g)	1192 - 1210 cm	fine sandy loam; 2.5Y 4/2 (dark greyish brown) and 2.5Y 4/1 (dark grey to dark greyish brown); few medium distinct N6 mottles; slightly firm soil strength, weak fine blocky structure; clear smooth boundary.
3bBC	1210 - 1224 cm	fine sandy loam and loamy fine sand; 7.5Y 4/1; slightly firm soil strength, massive; abrupt smooth boundary; Note: fine laminations of fine sandy loam and loamy fine sand.
4C	1224 - 1242 cm	loamy fine sand; 7.5Y 4/1; weak soil strength, massive; clear boundary.
5Cg	1242 - 1256 cm	sandy loam; 2.5GY 4/1 and 10YR 4/2 (dark greyish brown); few fine distinct 7.5YR 4/4 (brown) mottles; slightly firm soil strength, massive; abrupt boundary.

Profile code: TT2

6C	1256 - 1270 cm	slightly gravelly coarse sand; 2.5Y 4/1 (dark grey to dark greyish brown); loose soil strength, single grains; .

Profile code: WA1

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Franz Josef Holiday Park now abandoned

Grid Reference: NZMS 260 2281221 5753468
Date described: 3/2/2005
Authors: PCA, FLS
Site notes:

A	0 - 6 cm	silt loam; 10YR 3/2 (very dark greyish brown); weak soil strength, weak coarse granular structure; clear smooth boundary.
Bg	6 - 12 cm	slightly fine gravelly sandy loam; 10YR 4/1 (dark grey); few medium distinct 7.5YR 3/4 (dark brown) mottles; weak soil strength, weak medium blocky structure; clear wavy boundary.
BC	12 - 24 cm	slightly stony, fine gravelly sandy loam; 7.5YR 3/3 (dark brown); weak soil strength, weak coarse granular structure; gradual wavy boundary; Note: organic/Fe coatings around clasts.
C1	24 - 55 cm	slightly stony, gravelly coarse sand; 10YR 4/3; loose, but slightly coherent soil strength, single grains; diffuse boundary.
C2	55 - 95 cm	slightly stony, gravelly coarse sand; 5Y 4/1 (dark grey); loose soil strength, single grains; clear wavy boundary; Note: a weak imbrication in the clasts.
C3	95 - 175 cm	stony, bouldery gravel; 5GY 5/1 (greenish grey); loose soil strength, single grains; clear smooth boundary.
C4	175 - 320 cm	silty slightly stony, bouldery very gravelly coarse sand; N5 (grey); loose soil strength, ; Note: silts and fines plug gravels.

Profile code: WA2

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: Lavender farm, south side of the Waiho River

Grid Reference: NZMS 260 2279675 5753849
Date described: 3/2/2005
Authors: PCA, FLS
Site notes:

A(f)	0 - 8 cm	silt loam; 10YR 3/2 (very dark greyish brown); common fine distinct 7.5YR 3/4 (dark brown) mottles; weak soil strength, moderate medium granular structure; clear wavy boundary.
AC(g)	8 - 16 cm	loamy silt; 5Y 3/1 (very dark grey); few medium distinct 5B 5/1 (bluish grey) mottles with common fine distinct 7.5YR 3/4 (dark brown) secondary mottles; weak soil strength, brittle failure, weak coarse blocky structure; abrupt smooth boundary.
2C(f)	16 - 20 cm	loamy sand; 10Y 5/1; common coarse distinct 2.5Y 5/3 (greyish brown to light olive brown) mottles; weak soil strength, massive; abrupt irregular boundary.
3C(f)	20 - 25 cm	loamy silt; 10Y 6/1; common coarse distinct 2.5Y 5/3 (greyish brown to light olive brown) mottles; slightly firm soil strength, brittle failure, massive; abrupt wavy boundary; Note: hackley fabric suggests this may be a buried A horizon.
4bBC	25 - 31 cm	loamy fine sand; 2.5Y 5/3 (greyish brown to light olive brown) and 7.5YR 4/6 (strong brown); weak soil strength, brittle failure, massive; abrupt wavy boundary; Note: 7.5YR 4/6 is an incipient iron pan.

Profile code: WA2

5b2C(f)	31 - 37 cm	loamy fine sand; 5GY 5/1 (greenish grey); few coarse prominent 7.5YR 4/6 (strong brown) mottles; weak soil strength, brittle failure, massive; abrupt wavy boundary; Note: hackled broken surfaces, possibly another buried A horizon.
6b2BC	37 - 43 cm	fine gravelly sandy loam; 2.5Y 4/3 (dark greyish brown to olive brown); weak soil strength, weak granular structure; diffuse boundary; Note: patchy incipient iron pan 7.5YR 4/6, transition below 55 cm is a bit more yellow.
6b2C	43 - 85 cm	stony, gravelly coarse sand; 5GY 4/1 (dark greenish grey); loose soil strength, single grains; clear boundary.
7bC	85 - 200 cm	bouldery, stony, gravelly coarse sand; 10GY 4/1; loose soil strength, single grains; clear boundary; Note: open network gravels at upper boundary, fabric looks chaotic, no silt plugging
8bC	200 - 240 cm	slightly stony, gravelly coarse sand; loose soil strength, single grains; clear boundary; Note: From 200 cm there is a gradual change to coarse gravelly with few boulders to 245 cm then slightly stony coarse sand lenses 10-20 cm thick and fine gravelly coarse sands to 280 cm. A piece of wood at 240 cm was retrieved for radiocarbon dating.

Profile code: FX1

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: In a former channel near the oxidation ponds on the Cook River flats

Grid Reference: NZMS 260 2266768 5744661
Date described: 4/2/2005
Authors: PCA, FLS
Site notes:

A	0 - 15 cm	silt loam; 2.5Y 4/2 (dark greyish brown); weak soil strength, deformable failure, turfy structure; abrupt smooth boundary.
Cr	15 - 28 cm	silt with medium sand and fine gravel as fine lenses; 5BG 4/1 (dark greenish grey); common medium prominent 5YR 3/4 (dark reddish brown) mottles; weak soil strength, massive; abrupt wavy boundary; Note: silt coatings up to 1 cm thick on upper and lower surfaces of clasts.
2C	28 - 70 cm	slightly bouldery, stony silty gravel; 10BG 5/1 (greenish grey); moderately coherent soil strength, single grains; gradual boundary.
3C	70 - 150 cm	bouldery, stony silty gravel; 10BG 5/1 (greenish grey); moderately coherent soil strength, single grains; sharp boundary.
3Cfm	150 - 151 cm	bouldery, stony silty gravel; 7.5YR 2.5/1 (black); moderately coherent soil strength, weakly cemented; massive; sharp boundary.

Profile code: FX1

4C	151 - 300 cm	silty bouldery, stony gravel; 10GY 3/1 (very dark greenish grey); moderately coherent soil strength, single grains; clear boundary; Note: sorting is better than horizons above.
5C	300 - 400 cm	coarse sand grading to stony bouldery gravel across the pit; 5B 4/1 (dark bluish grey); loose soil strength, .

Profile code: FX2

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: On a bar of previous channel on Cook River Flats near the oxidation ponds

Grid Reference: NZMS 260 2266779 5744693
Date described: 4/2/2005
Authors: PCA, FLS
Site notes:

A(g)	0 - 9 cm	sandy loam; 10YR 3/2 (very dark greyish brown); few medium faint 10YR 4/1 (dark grey) mottles with common medium distinct 5YR 3/4 (dark reddish brown) secondary mottles; weak soil strength, weak medium nutty structure; clear wavy boundary.
BC	9 - 25 cm	loamy medium sand; 5Y 4/3 (olive); weak soil strength, massive; clear wavy boundary.
2C	25 - 200 cm	bouldery, stony, gravelly coarse sand; 5Y 3/1 (very dark grey); loose soil strength, single grains; ; Note: some iron staining in places, poorly sorted chaotic (no imbrication), below 80 cm silt plugging occurs beneath big clasts, amphibolite schist is oxidised and significantly weathered.

Profile code: FX3

Survey: South Westland fan stratigraphy study
Region: South Westland
Location: North bank of the Cook River adjacent to the oxidation ponds

Grid Reference: NZMS 260 2266586 5744383
Date described: 4/2/2005
Authors: PCA, FLS
Site notes: Mature totara trees grow above the section

0 - 120 cm	bouldery, stony, gravelly coarse sand; loose soil strength, abrupt boundary; Note: surface soil not seen.
120 - 140 cm	gravelly coarse sand; abrupt boundary.
140 - 170 cm	medium sand on loamy sand; abrupt boundary; Note: loamy sand unit may be a buried soil, at the lower boundary there are oxidised gravels.
170 - 320 cm	gravelly, stony coarse sand; slightly coherent soil strength, ; Note: poorly sorted.
320 - 400 cm	coarse bouldery stony gravelly coarse sand with some silt plugging; ; Note: a line of boulders marks a stratigraphic break.
400 - 550 cm	weakly stratified stony fine gravelly coarse sand; very coherent soil strength, ; Note: silt plugged throughout.

Profile code: FX4

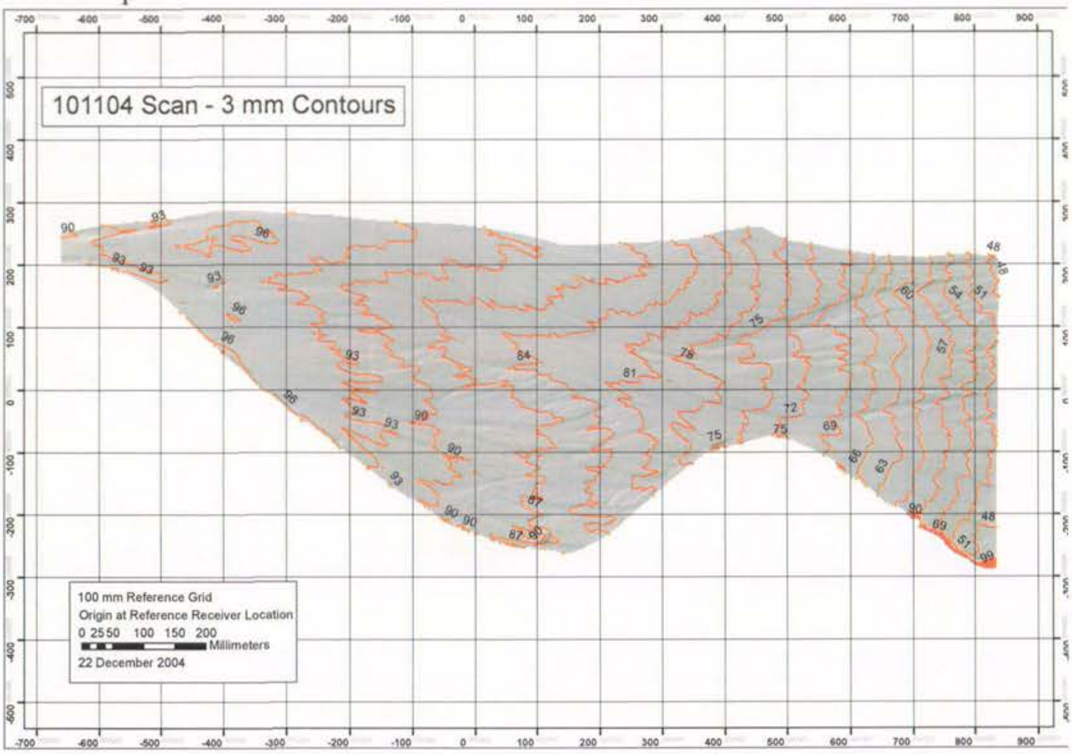
Survey: South Westland fan stratigraphy study
Region: South Westland
Location:

Grid Reference: NZMS 260 2264451 5741062
Date described: 4/2/2005
Authors: PCA, FLS
Site notes:

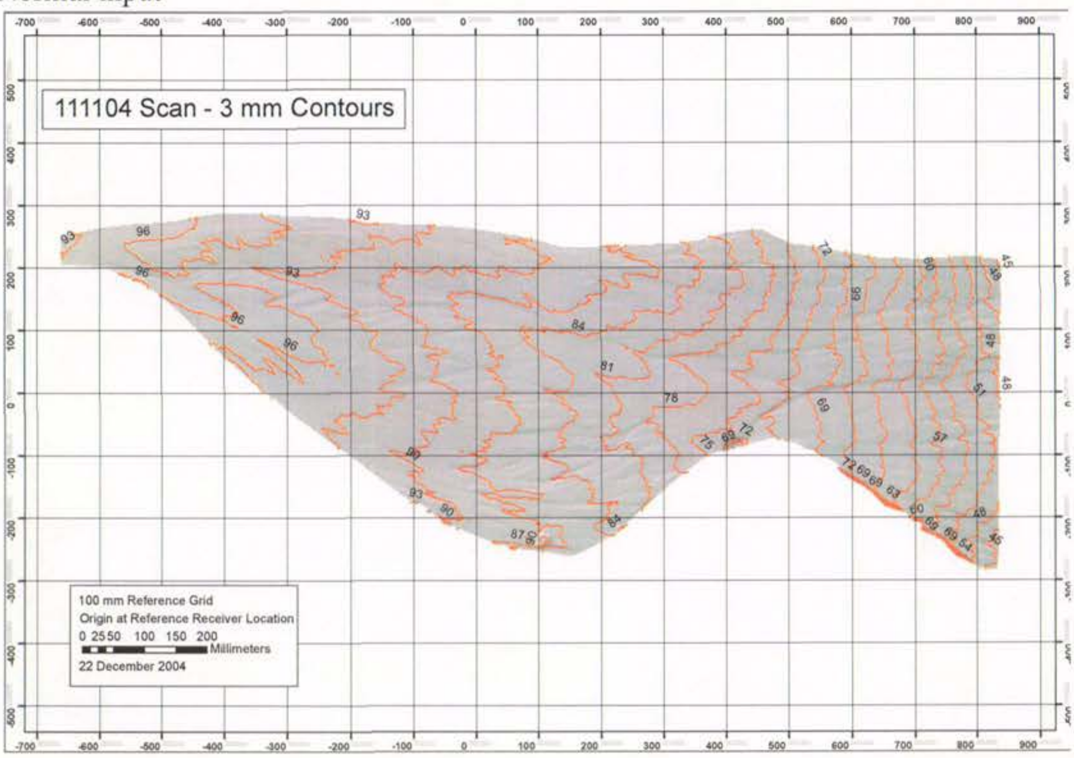
A	0 - 6 cm	very gravelly sandy loam; 10YR 3/2 (very dark greyish brown); weak soil strength, moderate coarse granular structure; abrupt wavy boundary.
BC	6 - 21 cm	very gravelly coarse sand; 10YR 3/3 (dark brown); loose soil strength, single grains; abrupt smooth boundary.
2C	21 - 31 cm	loamy medium sand; 2.5Y 5/3 (greyish brown to light olive brown) and 5Y 5/1 (grey); weak soil strength, massive; abrupt wavy boundary.
3C	31 - 80 cm	slightly stony, gravelly coarse sand; 10Y 5/1; loose soil strength, single grains; gradual boundary.
4C	80 - 180 cm	slightly stony, gravelly coarse sand; 5GY 4/1 (dark greenish grey); loose soil strength, single grains; gradual boundary.
5C	180 - 380 cm	bouldery, stony silty fine gravel; 5GY 5/1 (greenish grey); loose soil strength, single grains; .

Appendix 2 – 2004 model scan maps Condition 1

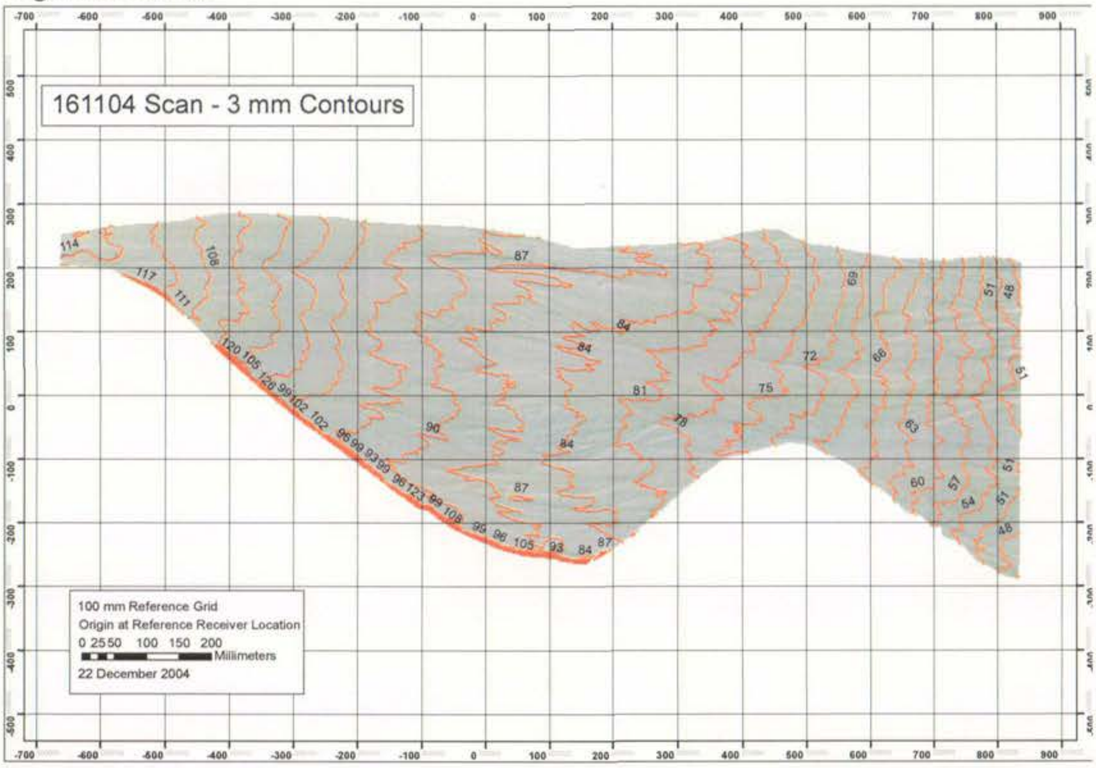
Normal input



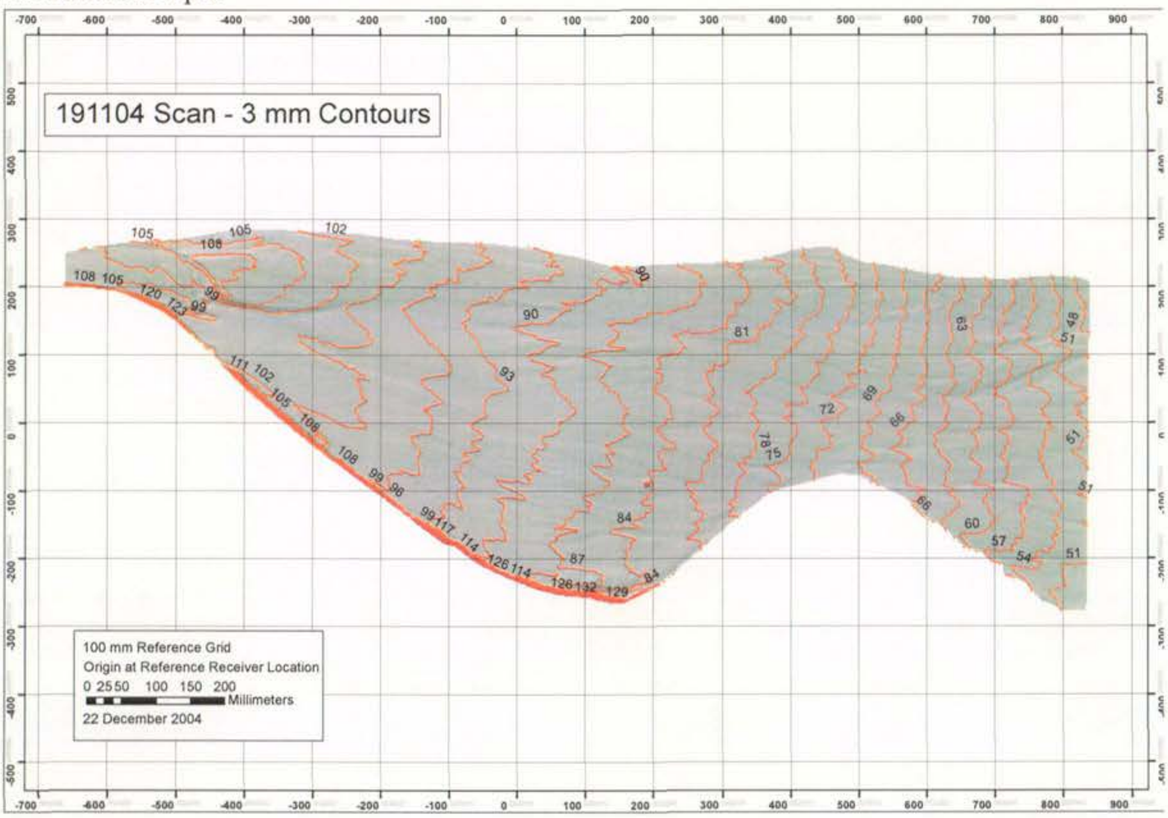
Normal input



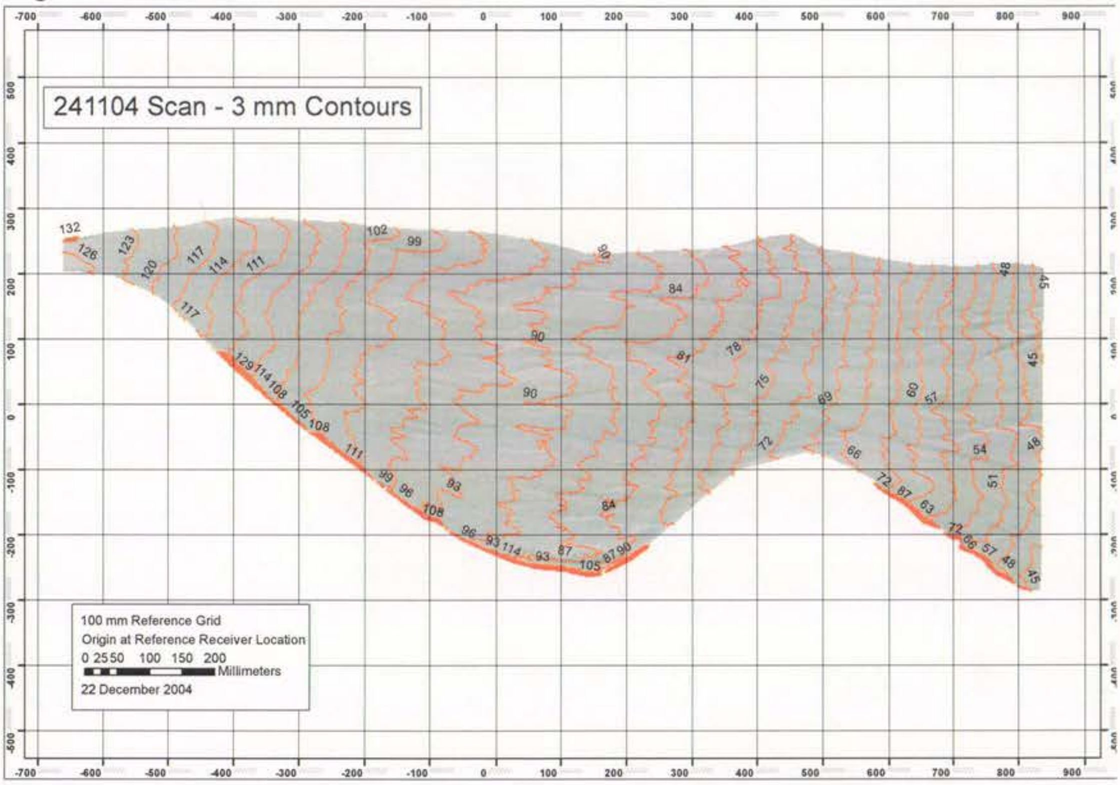
2 kg in in 33 min



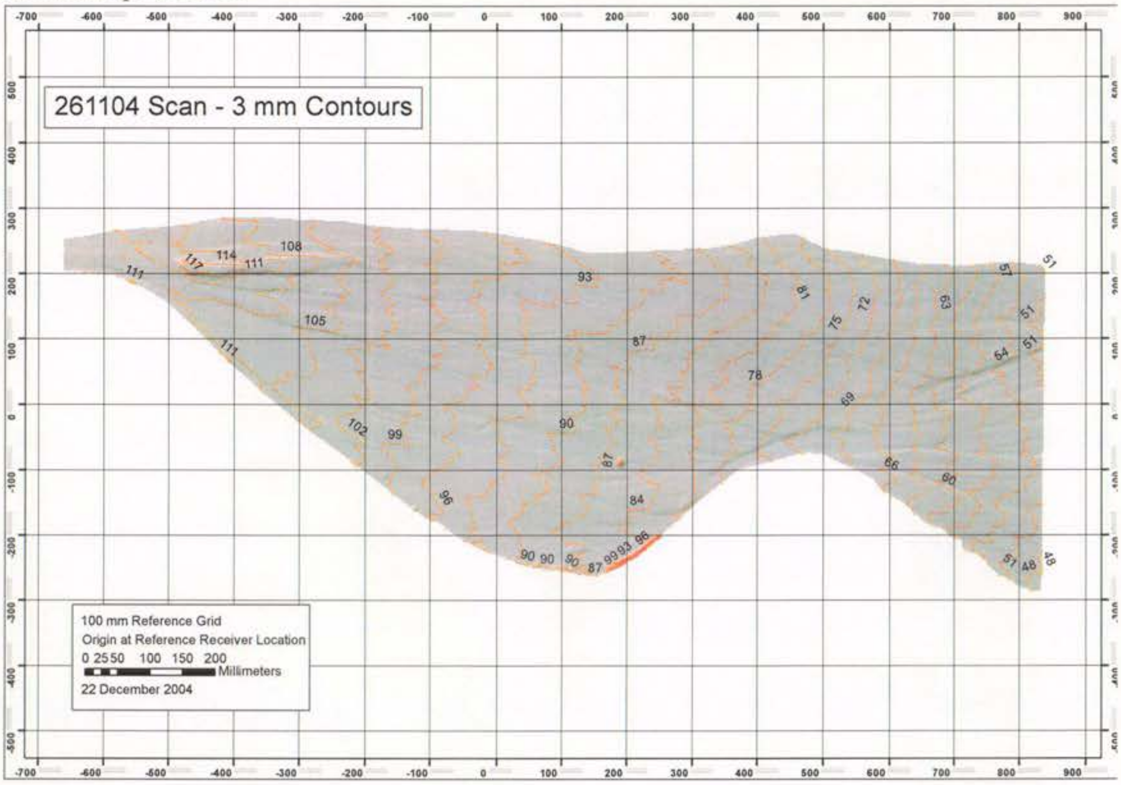
2 hrs normal input



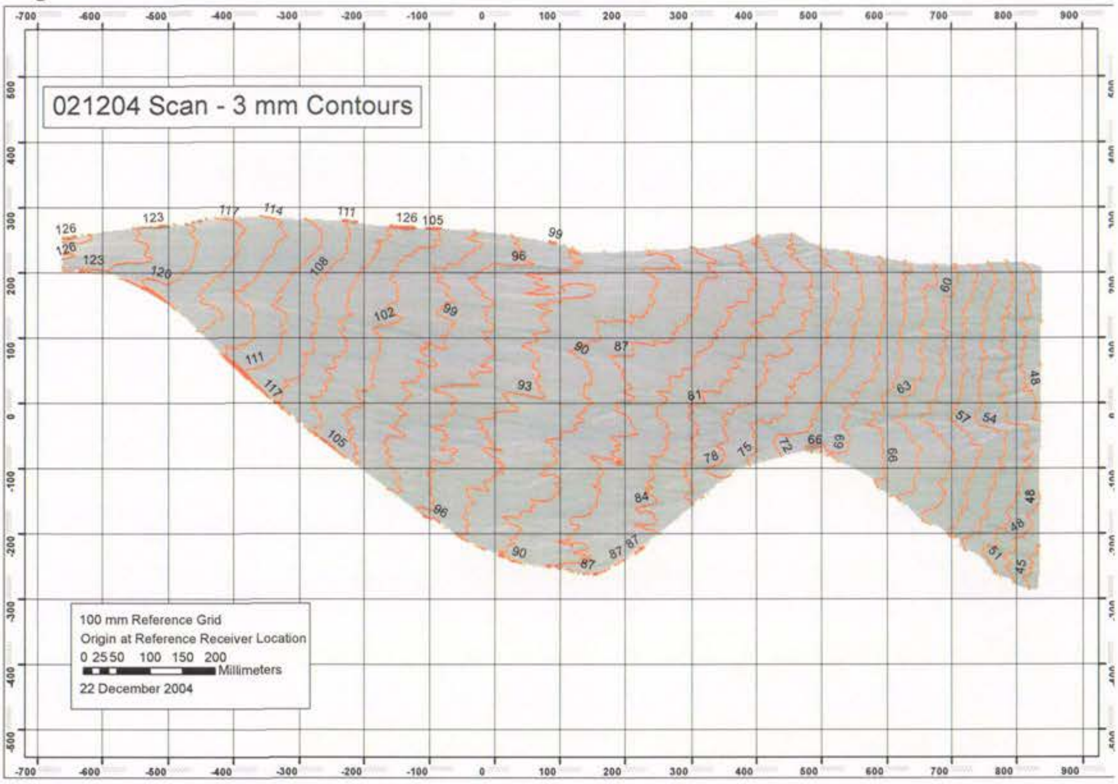
2 kg in in 33 minutes



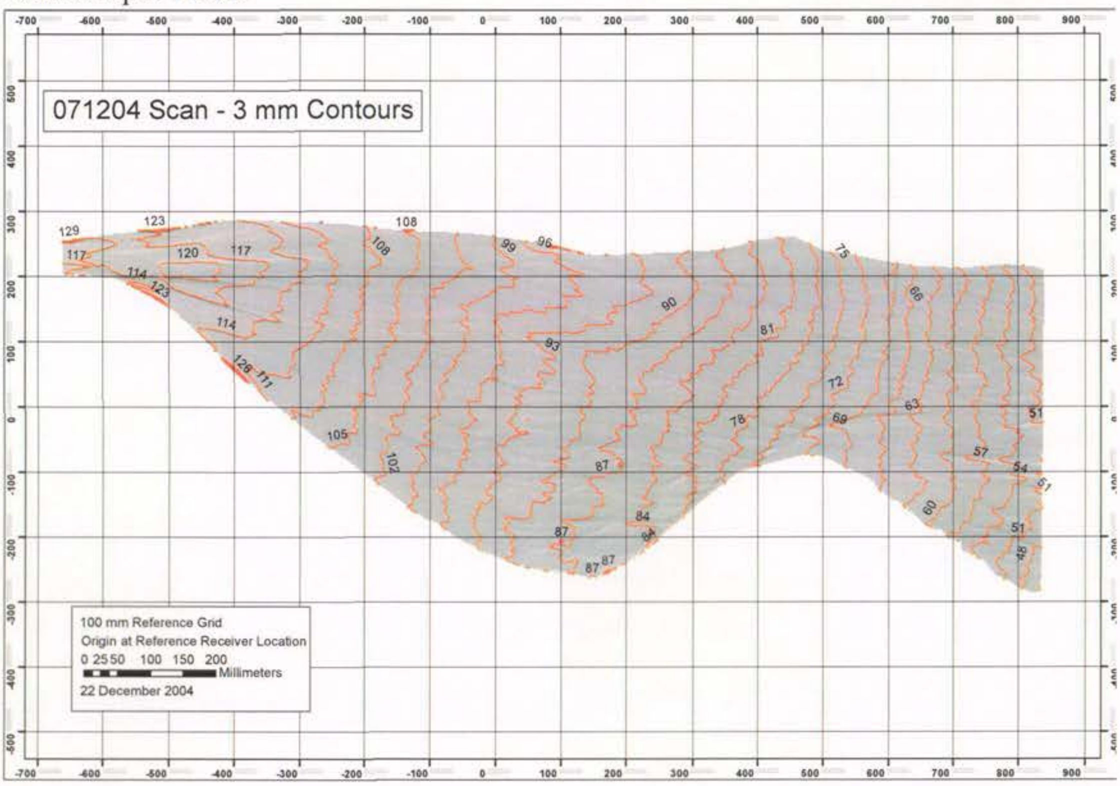
Normal input 1 hour



2 kg in in 33 minutes

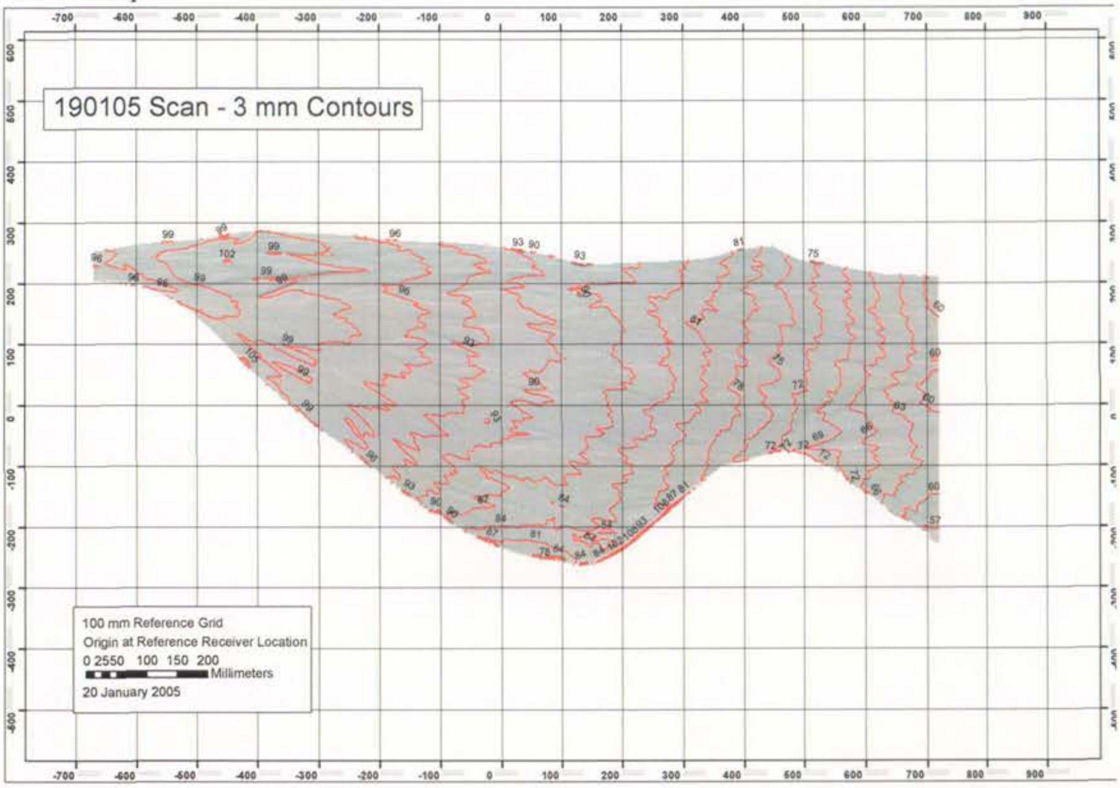


Normal input 1 hour

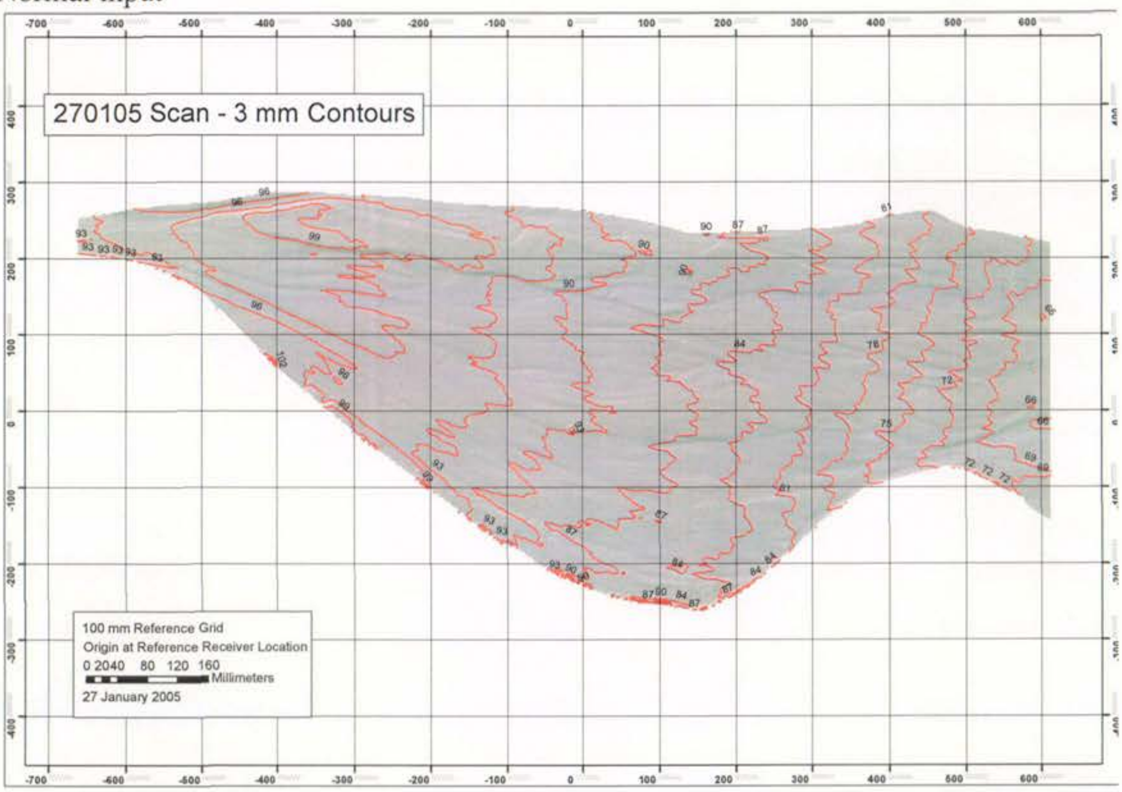


Appendix 3 – 2005 model scan maps Condition 2

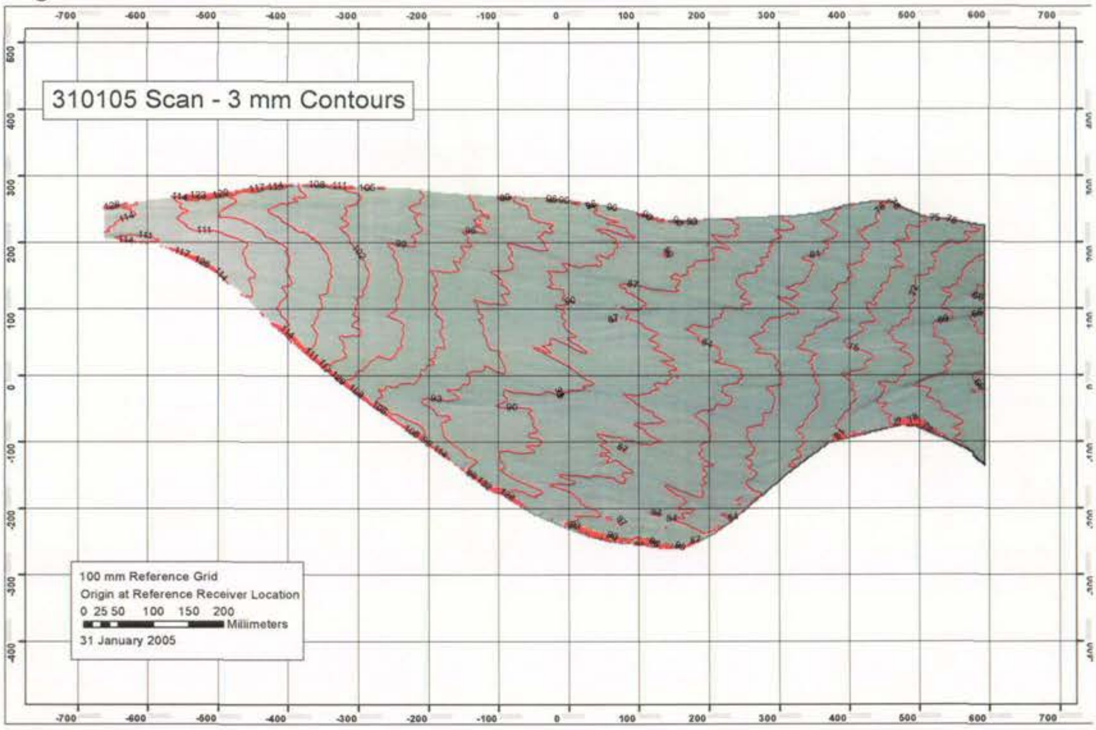
Normal input



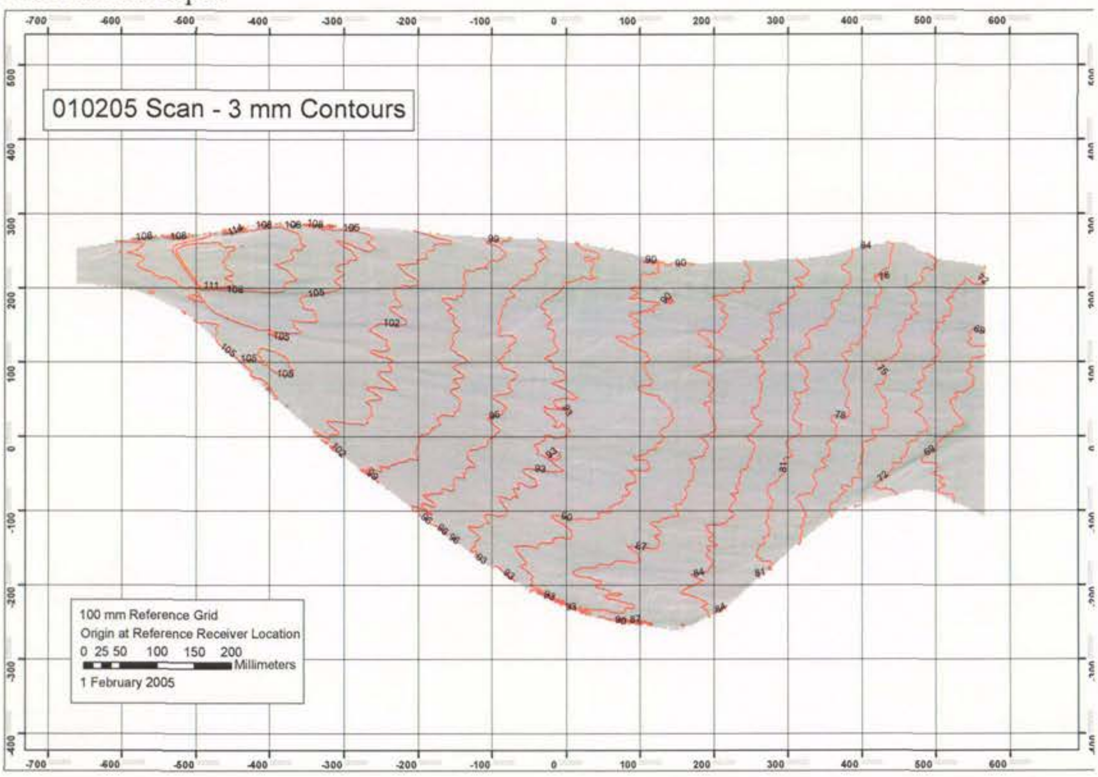
Normal input



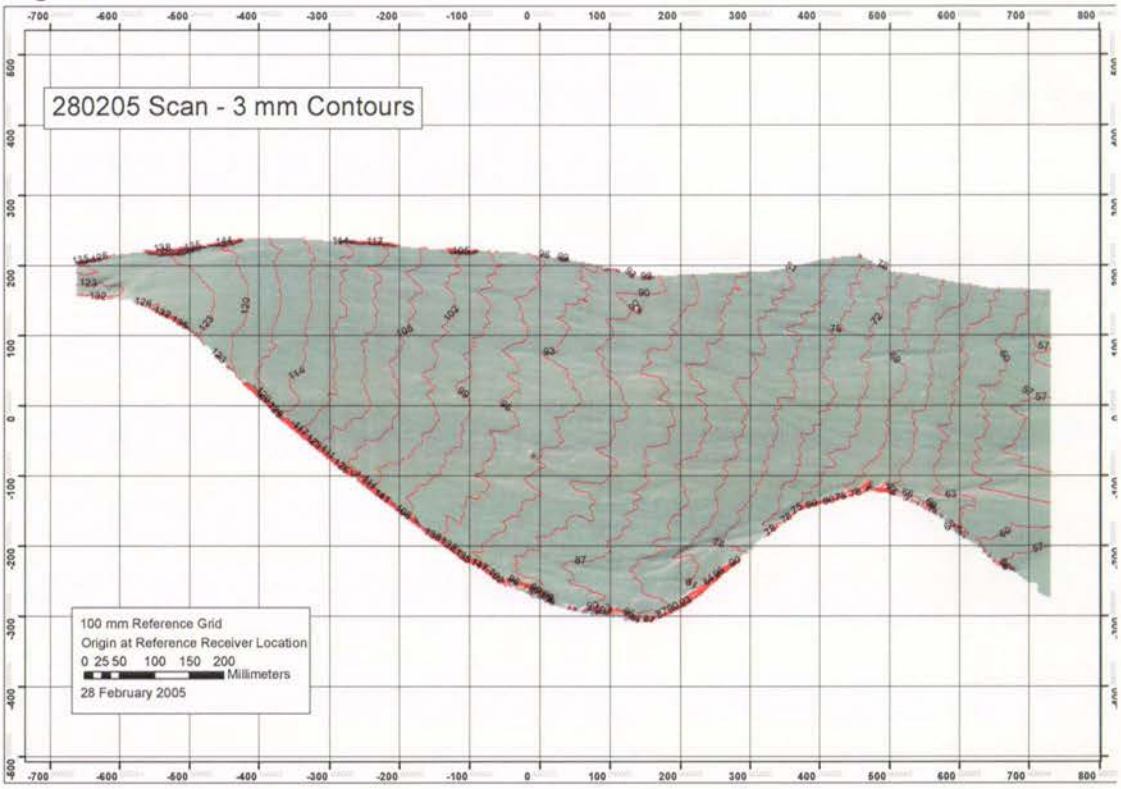
2 kg in in 91 in



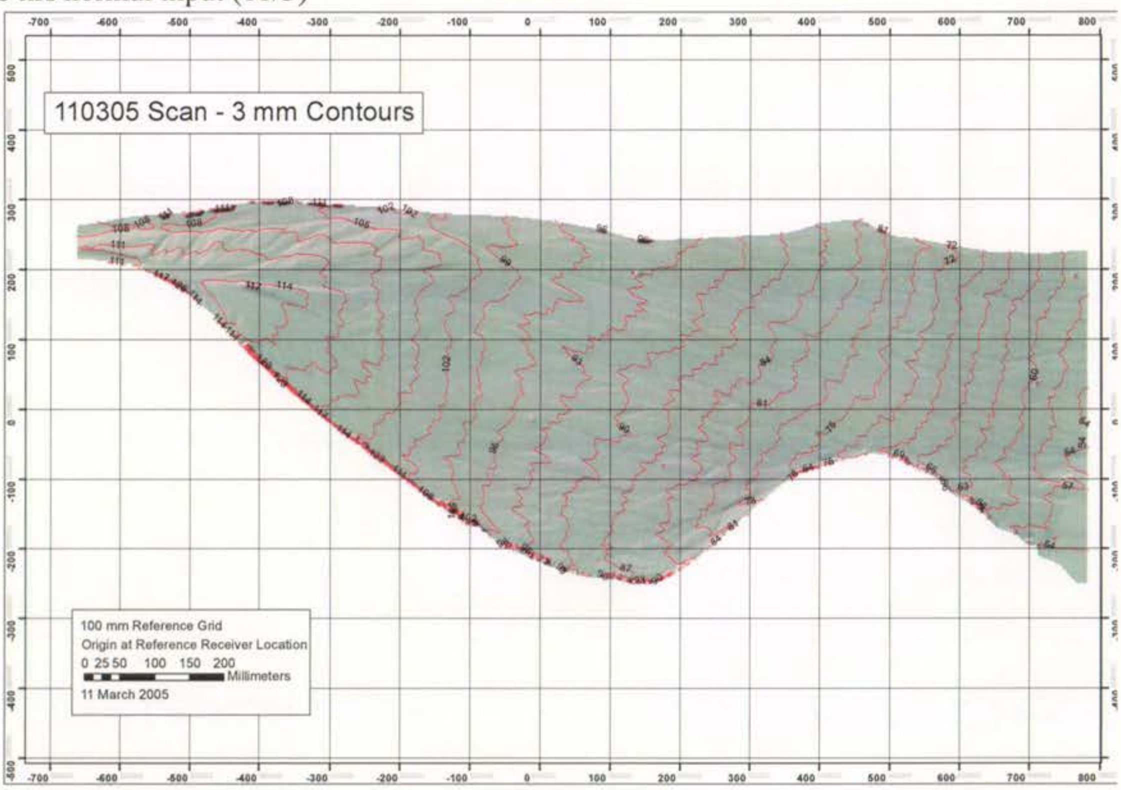
6 hrs normal input



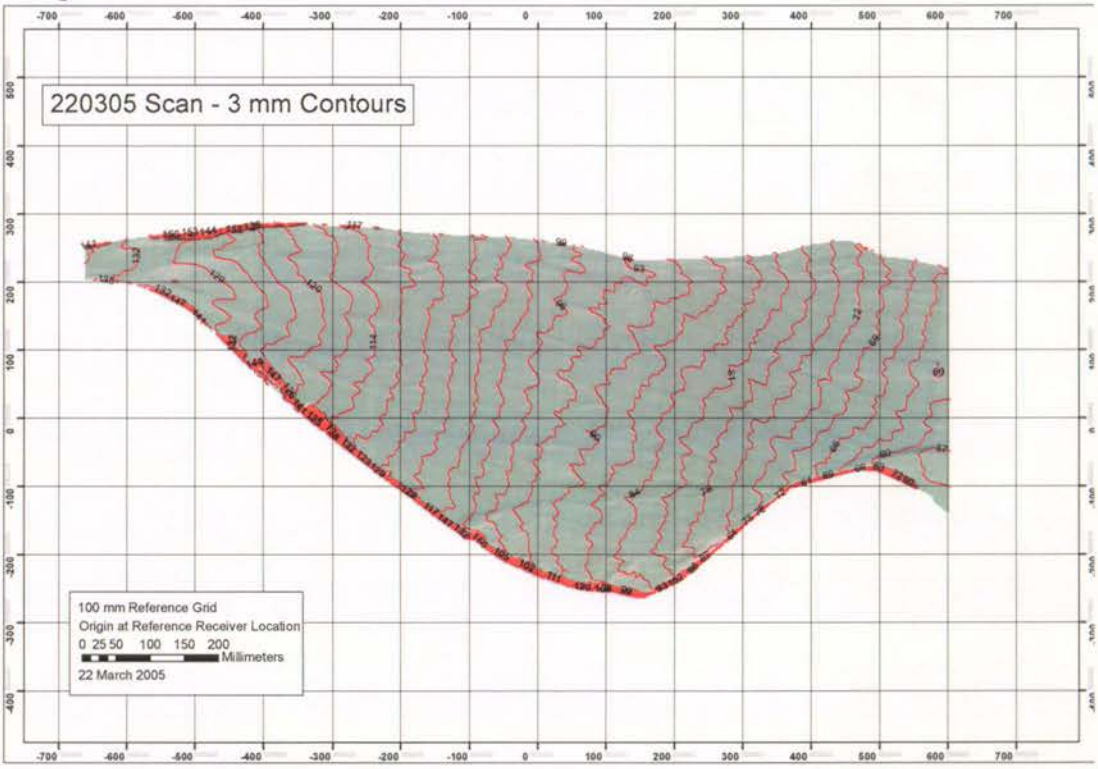
2 kg in in 95 min



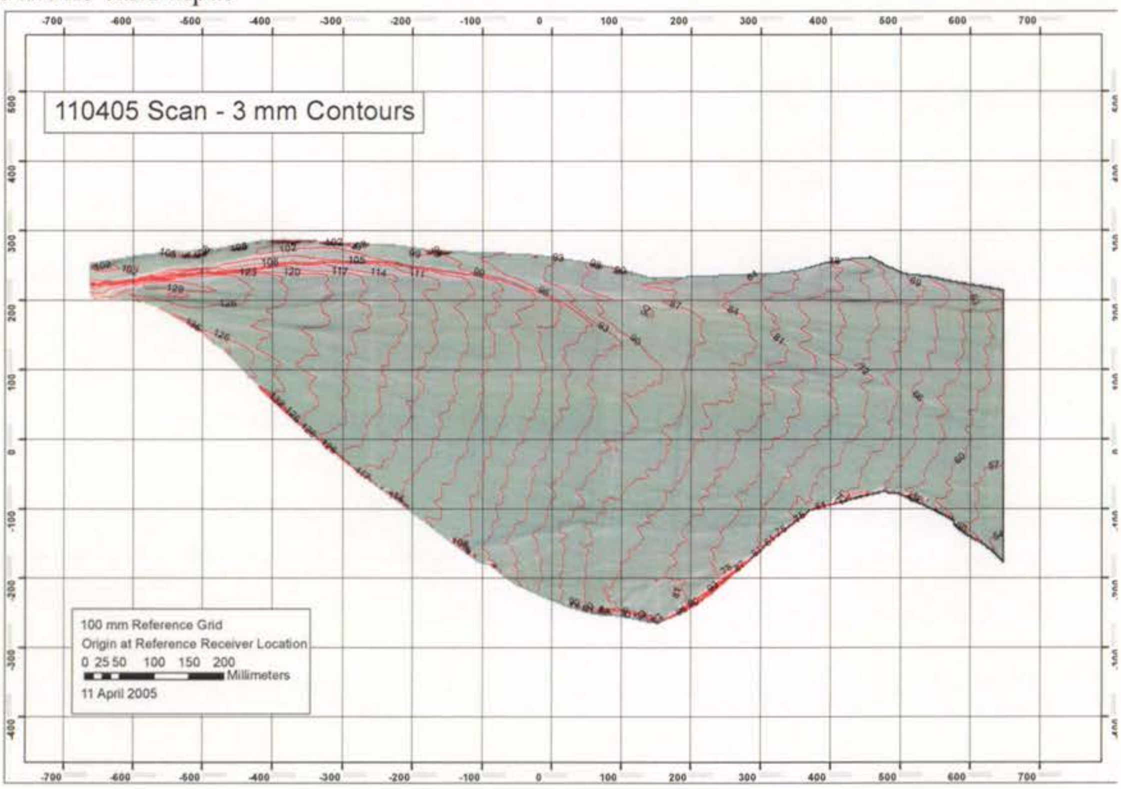
8 hrs normal input (11/3)



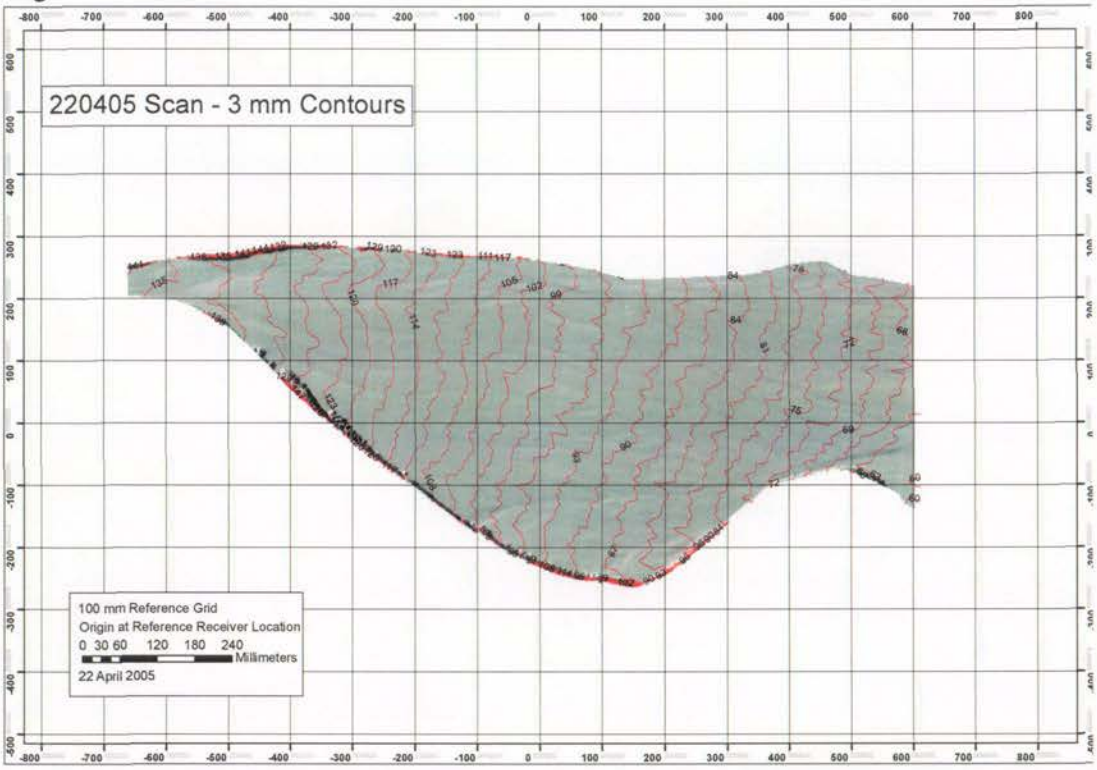
1.3 kg in in 60 min



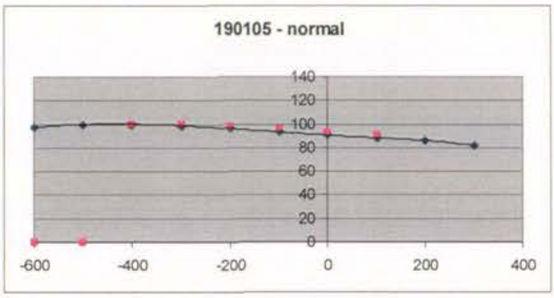
6 hrs no sand input

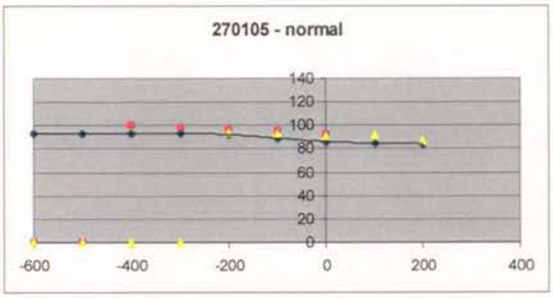


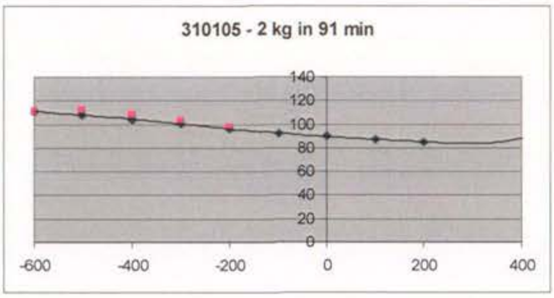
2 kg in in 95 min

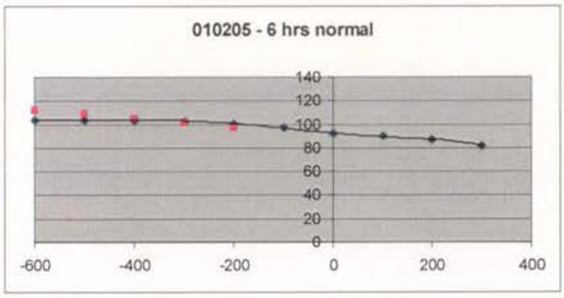


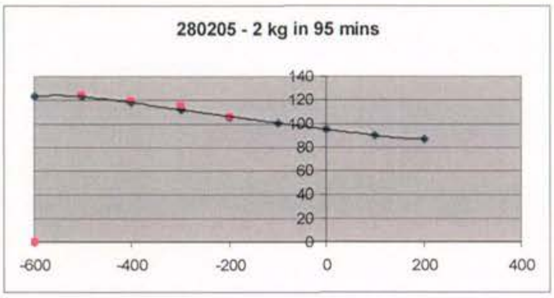
2005 runs – fan long profiles

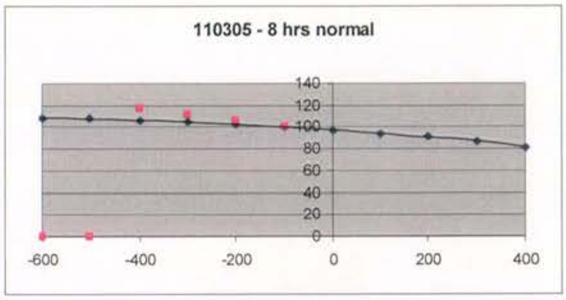


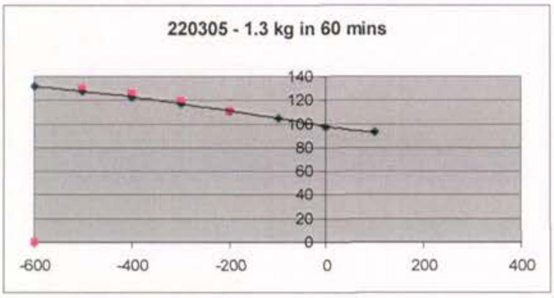


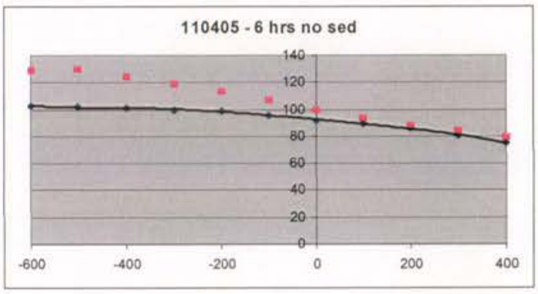


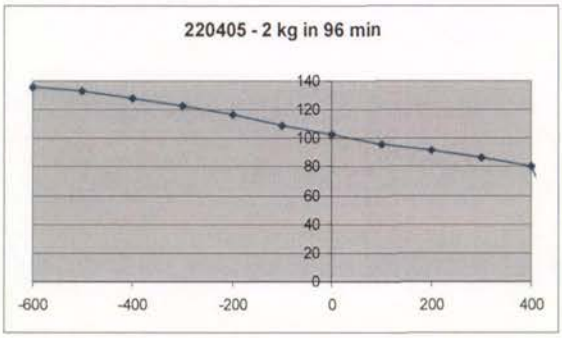












Key:
Blue diamonds with line = channel profile
Mauve squares, yellow triangles = fan surface