Activity of the landslide Te Horo and Te Koroka fan, Dart River, New Zealand during January 2014

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Frontispiece: Overview of the Te Koroka/ Slip Stream debris-flow fan damming Dart River at Dredge Flat (Image: Vladka Kennett, 15 Jan 2014).

ABSTRACT

The landslide Te Horo lies on the eastern side of Cosmos Peaks, Dart Valley, Otago. It as an active compound rock and debris slide with ancillary debris topples and debris flows commencing from its toe. Te Horo has an area of 0.9 km^2 with a steep toe area that is rapidly eroding on its southern lateral margin to feed 10^5 – 10^6 m^3 of sediment annually onto a debris-flow fan on the valley floor. Debris flows in 2013 and January 2014 crossed the fan and entered Dart River, impeding flow, and impounding a lake which grew from 0.47 km^2 to 1.48 km^2 between December 2013 and January 2014. Between 5 and 15 January 2014, a continually surging debris flow added about 1–2 x 10^5 m^3 of sediment to the toe of the fan, but the main surge appears to have occurred on 4 January after heavy rain in the area. The lake is expected to persist for decades as the landslide continues to supply debris. The lake level and extent will fluctuate. There is no downstream danger of a catastrophic lake outburst flood. The landslide-derived sediment is redistributed downstream by Dart River, to Lake Wakatipu. Known as Te Koroka to Iwi/Māori, the locality is significant as a source of Pounamu (nephrite/greenstone) and is recognised and managed as a special Topuni area in the Mount Aspiring National Park with entry by permit only.

KEYWORDS

Landslide, Slip Stream, Debris flow, Dart River, Dam, Lake, Te Koroka, Otago

1.0 INTRODUCTION

On Sunday 5 January 2014, GNS Science was notified by the Department of Conservation (DoC) Glenorchy Field Office of concern about the Te Horo (Slip Stream) landslide in the Te Koroka Tōpuni area of Dart Valley. During a helicopter flight the previous evening DoC staff had noticed that a lake on Dart River at the base of Te Horo had greatly enlarged following heavy rainfall and enhanced activity on the slip. First formed in 2013, the lake covering the full width of the Dart valley floor has now extended about 3 km upstream from the slip and at the time of field observation was still rising. Part of the Rees-Dart tramping circuit was submerged beneath the lake at Dredge Flat and the track was also cut by slope collapse at Sandy Bluff. There were many people on the popular circuit which was in its peak-use period. Also, the lower Dart River is used for commercial and private boating, fishing and picnicking and there was concern about a possible flood hazard if the dam were to fail suddenly. Through the GeoNet programme, GNS Science maintains a rapid-response capability for landslides in New Zealand and can mobilise knowledgeable people to provide advice and gather data following any major landslide. Given the threat of flooding following the landslide, the many people potentially at risk, and cultural significance of the Te Koroka Tōpuni, GNS Science initiated an immediate science response to investigate the landslide.

Simon Cox (GNS Science, Dunedin) mobilised from Dunedin to Queenstown, where he collected Mauri McSaveney (GNS Science, Avalon) on arrival from Wellington. They met Mark Rattenbury (GNS Science, Avalon – in the area on annual leave), Richard Kennett (DoC Glenorchy) and Callan Grimmer (Dart River Safari Jets) in Glenorchy and conducted an aerial inspection from 6–8.30 pm courtesy of Glacier Southern Lakes Helicopters (Brendan Hiatt pilot). On Monday 6 January 2014, Drs Cox, McSaveney and Rattenbury returned for a more detailed ground inspection of the lower slopes of the landslide after a brief but appropriate Karakia at the landing site. During the following weeks, the site was examined on vertical aerial, satellite and oblique images from 2010 to 2014 in completing an assessment of the most recent activity.

This report details the situation as at 27 January 2014, as well as outlining landslide activity that had occurred since documented in an earlier investigation (Thomas & Cox 2009). It provides an overview of processes occurring at Te Koroka (Slip Stream), with expectations for the future and implications for users and management.

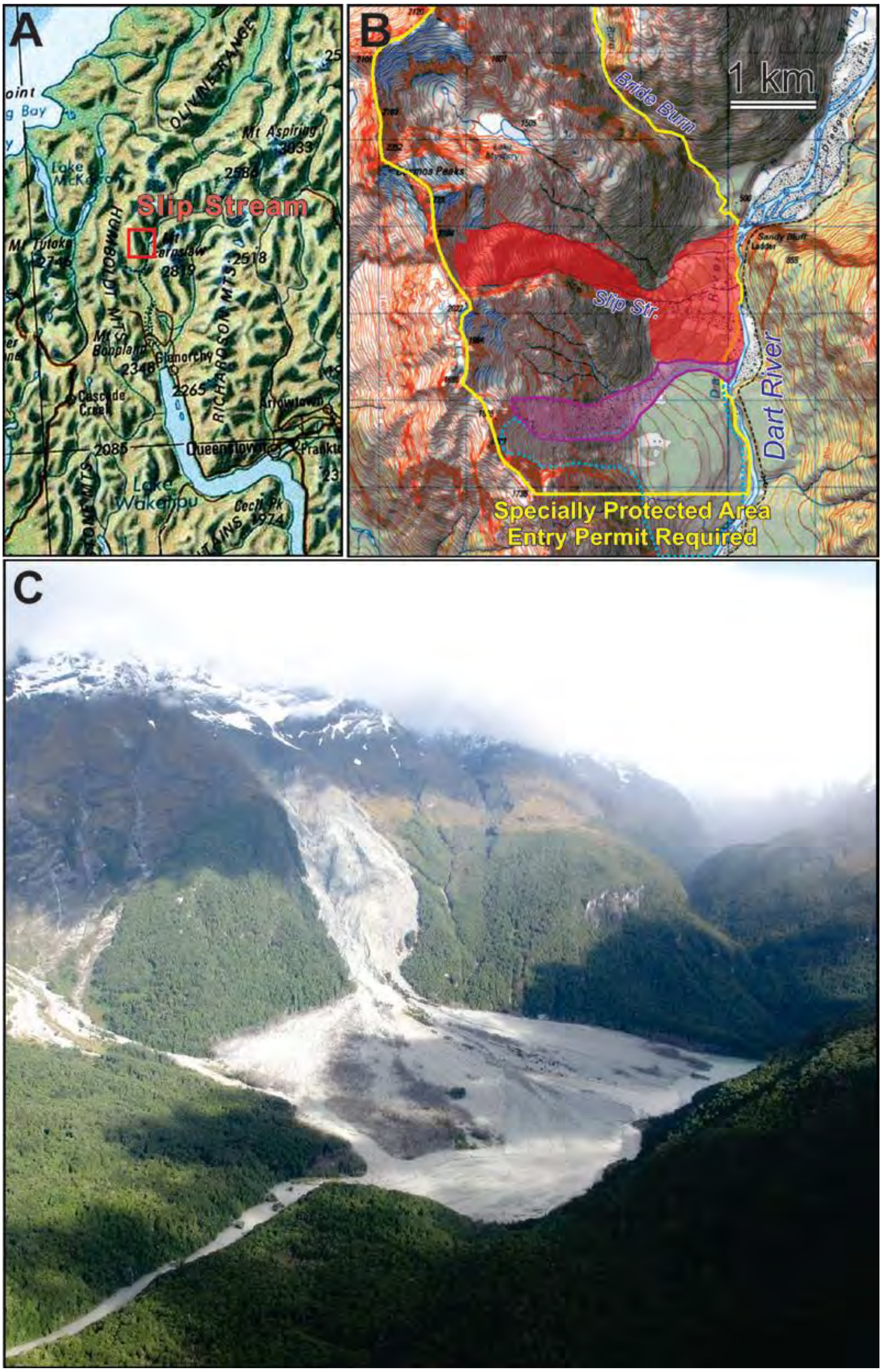


Figure 1 (a) Location of Te Horo and Te Koroka/ Slip Stream in Dart Valley at the head of Lake Wakatipu. (b) Map of the landslide and fan (red), showing the extent of the protected area for which entry requires a special permit. In the catchment south of Slip Stream there is an active landslide (pink shading) commonly mistaken for Te Horo, and possibly a much older landslide (blue dashed outline). (c) Overview of the landslide and fan (Photo S. Cox, 6 Jan 2014).

2.0 GENERAL DESCRIPTION OF LANDSLIDE AND ACTIVITY

2.1 SETTING

Te Koroka/Slip Stream is located on the eastern side of the Cosmos Peaks in Dart Valley (Figure 1), where a 0.9 km^2 landslide known as Te Horo stretches from the ridge crest to the valley floor. There is a second landslide in the unnamed adjacent catchment about 1.5 km further south in the Dart Valley. This catchment also drains the east face of Cosmos Peaks, and the landslide is commonly mistaken for Te Horo.

A detailed landslide description and history of rainfall-induced debris flows and fan aggradation between 1966 and 2008 is provided by Thomas & Cox (2009). In the revised Varnes classification of landslides (Hungr et al., 2013) the landslide is a large, very slow, reactivated compound rock and debris slide with ancillary rapid debris topples, rock falls and debris flows. The head scarp roughly follows the 1840 m contour between peaks 2104 and 2027. The main body of the landslide lies between 1600 and 1200 m, where slopes are ~18–30° (Figure 2). Steeper (30–46°) unvegetated slopes occur between 1200 and 800 m, where the landslide mass overlies slightly steeper bedrock. The landslide-toe area is now asymmetric: its northern side has large precarious boulders and active talus overlying weakly consolidated, poorly sorted, chaotic, landslide debris; whereas its southern side is deeply incised by channels, with much of the landslide material now removed. Boulders spontaneously ravel from the toe slopes during dry weather, and during 5–6 January 2014 (between rainstorms) the landslide was continuously supplying sediment-lasden water to a narrow, deeply incised canyon cut in bedrock. In the channel, the muddy torrent was bulking up episodically to deliver surging debris flows to the valley below. The landslide has an estimated volume of about 56 million m^3 based on a mapped area of about 0.93 km^2 and an assumed average thickness of 60 m (40–80 m, Thomas & Cox, 2009).

A 1.4 km^2 debris fan has accumulated at the base of Te Horo, forcing the Dart River channel against Sandy Bluff, and causing its bed level to rise against the bluff. Fan slopes range from ~16° at the fan head to 2° at the river. The fan was mostly vegetated in 1966, but it has since been completely covered by fresh debris, ranging in particle size from giant boulders to fine silt. Nearly all of the former vegetation on the fan has been killed in the last few years, or is dying. The fan thickness is not known, but it is inferred to have been deposited over glacial outwash alluvium over the last 18,000 years, and has an estimated volume of ~ 10^8 m^3 (i.e., 100 million m^3) (Thomas & Cox, 2009). During January 2013, debris flows on the northern side of the fan reached and partially blocked Dart River, impounding a 0.13 km^2 lake (Bryant, 2013). After disappearing over winter, the lake covered 0.47 km^2 by December 2013, and grew to 1.4 km^2 in the first week of January 2014. Earlier, prehistoric development of the fan had impeded the river flow to form Dredge Flat, but we have found no historic or geomorphic record of previous lakes there.

Local bedrock is greyschist with minor greenschist - metamorphosed sandstone, mudstone and volcaniclastic rock of the Caples Terrane (Turnbull, 2000). These rocks have an internal weakness formed by mica growth (schistosity and foliation) which, on the east face of Cosmos Peaks, is nearly parallel to the hillslope (Fig 2). Pounamu (New Zealand jade or greenstone) is found associated with small slivers of ultramafic rock (principally serpentinite) faulted within the schist.

Te Koroka/Slip Stream is an important Pounamu collection area for southern Māori, and the distinctive semi-nephrite and nephrite can be recognised in archaeological collections from sites throughout New Zealand (Beck et al., 2010). The Māori name for the area is Te Koroka (or Koloka) and the slip is known as Te Horo. The area is now, and was in traditional times, held under a Tapu (supernatural condition) by Māori until an appropriate Karakia (incantation) and ceremony has been performed to permit access for retrieval of the taonga (treasure) pounamu. A "Specially Protected Area" was gazetted within the Mount Aspiring National Park in 1973, which includes the landslide and the fan on the true-right side of the river below (Figure 1B). A Tōpuni (symbolic cloak of protection) was placed over the area as part of the Ngāi Tahu Deed of Settlement Act 1998, as recognition of its cultural and archaeological significance. All pounamu is the property of Te Rūnanga o Ngāi Tahu and can only be removed with special authorisation. Entry to the area requires a special permit from the Department of Conservation, in consultation with Te Rūnanga o Ngāi Tahu.

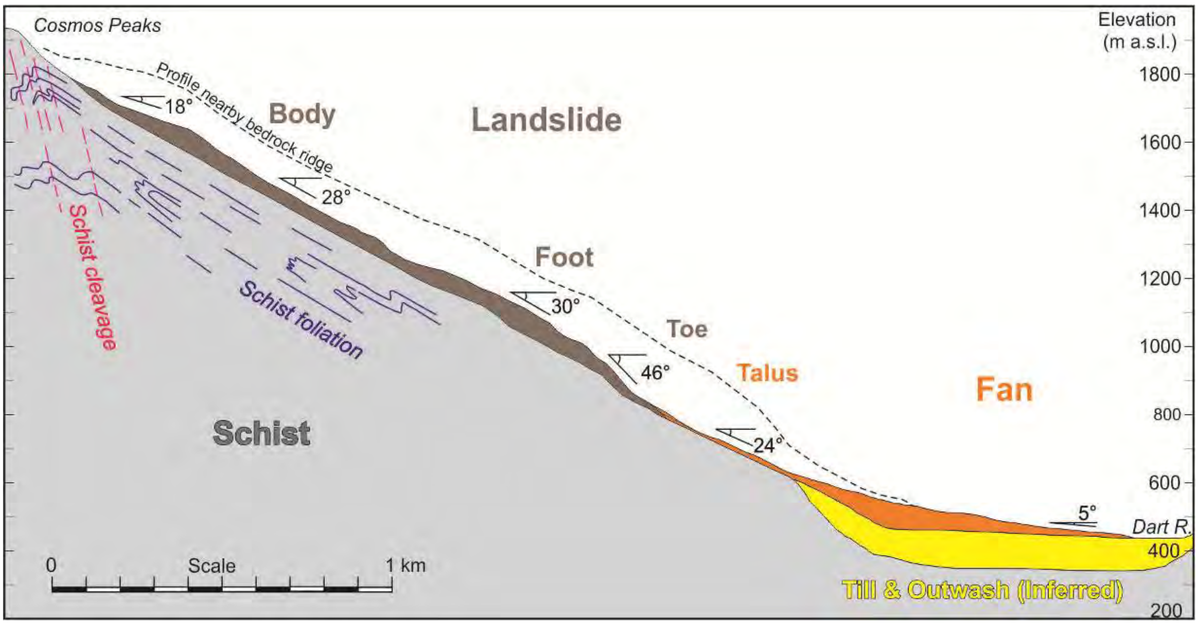


Figure 2 Profile (cross-section) of Te Koroka/Slip Stream and Te Horo landslide (after Thomas & Cox 2009).

2.2 PHASES OF LANDSLIDE ACTIVITY

A prehistoric period (or periods) of heightened landslide activity of Te Horo landslide can be inferred from the 100 million m^3 of post-glacial debris stored in a once-forested fan below a 56 million m^3 landslide, which require that the Te Horo landslide was once much larger than 156 million m^3 (a substantial quantity of sediment has been carried away by Dart River over the last 18,000 years) and is now reduced to less than a third of its original volume

A brief history of depositional events on the Te Koroka/Slip Stream fan is recorded by aerial photographs, satellite imagery, oblique photographs and field visits between 1966 and 2009 (Thomas & Cox, 2009). Based on areas of vegetation damage, Thomas and Cox interpret that the landslide has episodically fed 10^4–10^5 m^3 and smaller volumes of rock debris downslope onto the fan. Thomas & Cox (2009) produced a figure of changes based on aerial photographs, culminating in a map based on 2007 colour aerial photography. In 1966–1979 newly deposited debris covered 15% of the fan, with activity continuing over the next 30 years affecting 65% of the area. Whilst debris flows during the 1966–2009 period have all been initiated during rain, it was unclear which of total storm-cycle precipitation or localised peak rainfall intensity have been the more important factor in initiating debris flows. Thomas and Cox suggested Te Horo is one of the more active landslide sites in Otago region.

Evidence suggests that the activity level of Te Horo has increased since 2009. The Te Koroka/Slip Stream fan is now completely covered by fresh debris and the southern side of the landslide above it is now deeply incised. Observations and interpretations of changes on the landslide and fan since 2009 (Table 1) have been compiled from visits, photographs, and imagery. The major changes are depicted in Figure 3.

Table 1 List of field visits, photographs, imagery and data sources used in preparing this report, with summary of geomorphic observations for the landslide, fan and Dart River areas.

Date	Source	Landslide Area	Fan Area & Dart River
10 Feb 2010 7 April 2010	Field visits and photographs by Southern Kaitiaki Pounamu Working Group, Te Rūnanga o Ngāi Tahu, and GNS Science.	Debris-flow channels from front slopes, northern side of toe.	Fresh debris covers large area on northern side of the fan. Area of bush and grass still present on central fan. Insufficient clarity to map extent of debris flows.
8 Jan 2011	Geoeye-1 imagery, available on Google Earth.	Debris-flow channels from front slopes, of toe. 24,000 m^2 evacuated area northern side. Other small channels initiating from line of springs/seepage areas in toe. Minor activity in channel southern side landslide. Local areas of surface disturbance by rockfalls. Growth in height of some scarps on the landslide surface.	Deposits of 420,000 m^2 in two separate lobes cover central fan and northern side. A further 78,000 m^2 is downstream spread over river bars and in the Dart River. Average thickness appears ≤0.5m, based on vegetation, implying volume ~ 2 x 10^5 m^3. Small 29,000 m^2 area of channel/debris-flow on south fan.
14 March 2012	Aerial oblique photographs by Don Bogie, supplied by DoC.	Prominent channel from front slope, southern side of toe. Potential for some debris to have been delivered from channel on south side of landslide.	Narrow debris channels on central fan reach Dart River, delivering sufficient sediment to divert main channel eastward. Deposit area 157,000 m^2 and appears thin (thought to be <0.5 m). Redistributed sediment, if any, is undefined.
1 April 2012	Field visit and photographs by Southern Kaitiaki Pounamu Working Group, Te Rūnanga o Ngāi Tahu.	Small debris flows on the main body of the landslide. Deep channels cut on south-side of landslide.	Most debris appears to have fed onto central and upper south parts of fan. Insufficient clarity to map/ confirm extent of debris-lobes.
21, 28 Jan 2013	Aerial and ground photographs supplied by DoC (taken 21 Jan, Richard Kennett) and Otago Regional Council (taken 28 Jan by Jeff Bryant) See Bryant (2013).	Removal of material from 68,000 m^2 area between 900-1200m elevation, southern side and rear of landslide toe. Growth in height of some retrogressive scarps above the landslide toe area.	Two lobes covering 532,000 m^2. Earlier lobe on central fan covers last remaining grass and vegetation, reaching river. Later lobe covers entire the northern side of fan. 81,000 m^2 of redistributed sediment deposited downstream. Thickness reaches ~1m (Bryant, 2013), suggesting debris volume ~ 6 x 10^5 m^3. Impounded lake 134,000 m^2.

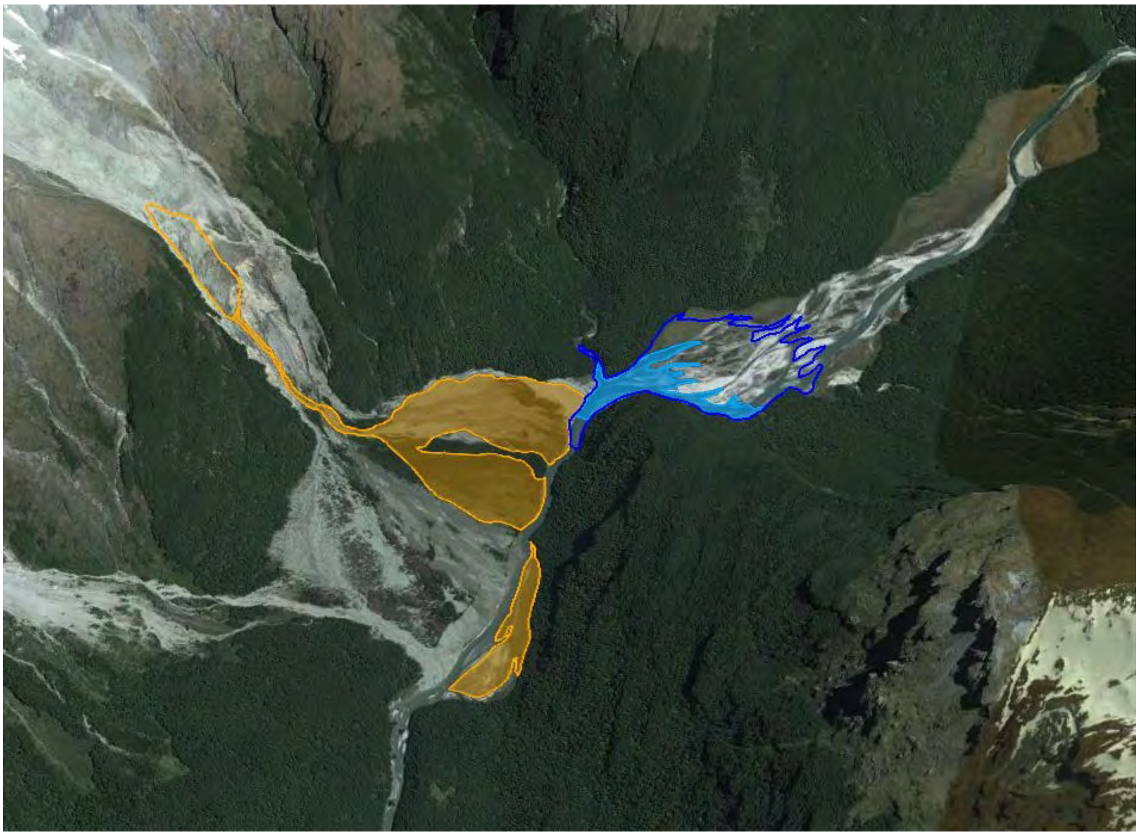
Date	Source	Landslide Area	Fan Area & Dart River
Dec 2013	Photographs supplied by DoC (taken 11, 17, 18 Dec by Richard Kennett).	Fresh debris flows on central fan, appear to be derived from channels draining southern side of landslide.	Impounded lake increased in size to 474,000 m^2. Slopes below Sandy Bluff eroded by river, compromising tramping track. Dart River incising and dirty downstream of central fan, but clear further upstream.
5–6 Jan 2014	GNS Science visit. Photographs and field observations by M. McSaveney, S. Cox, M. Rattenbury, supplemented with photographs from DoC (John Roberts) and Otago Daily Times (taken 9 Jan by Tracey Roxburgh).	Removal of material from 107,000 m^2 area between 1000–1350m elevation, lower part of main landslide body. Area of intense new fracturing suggests pending unravelling of 96,000 m^2 between 1200-1470m.	Debris flows cover 265,000 m^2 of central fan in a direct path from landslide to river. Sediment redistributed downstream covering an area of 124,000 m^2. Lake Wakatipu discoloured 75 km from landslide (9 Jan). Ground observations suggest deposit locally >1m. Debris volume possibly reaches 4 x 10^5 m^3. Impounded lake 1,484,000 m^2.
15 Jan 2014	Photograph supplied by DoC (taken 15 January 2014 by Vladka Kennett)		Debris flow cover expanded area of central fan. Lake covers slightly larger area
27 Jan 2014	Photograph taken 27 January 2014 by P. Johnston, Landcare Research.		Debris flow active to immediate south of central part of fan, and no longer entering Dart River at lake crest.
15 minute “continuous” data	Monitoring of Dart River flow/stage/rainfall at the Hillocks, and rainfall at Paradise. Data supplied by Otago Regional Council, also available on http://water.orc.govt.nz/WaterInfo/	Rainfall at Paradise assumed to correlate approximately with rainfall on the landslide, although a multiplier of up to 2 might apply to the Cosmos Peaks area.	Recordings of anomalous low flows, attributed to impounding Dart River behind debris on the fan. Seen intermittently through the weeks of Jan 2014, but not Jan 2013.

Figure 3 See following pages. Vertical views of Te Horo and Te Koroka fan, overlain on imagery from 8 Jan 2011 in Google Earth, with coloured polygons showing the extent of the debris-flow channels and deposits, redistributed sediment and impounded lake. Source area polygons are hollow. (A) Late 2010-early 2011 phase of activity = purple; (B) Early 2012 phase of activity = yellow; (C) Jan 2013 phase of activity = orange, with smaller January lake (shaded light blue) and larger December lake area (dark blue outline); (D) late 2013 – Jan 2014 phase of activity = green, with blue lake. The pink outline shows an area of intense fracturing thought to be a likely future source area.

A Late 2010-early 2011

B Early 2012

C Jan 2013



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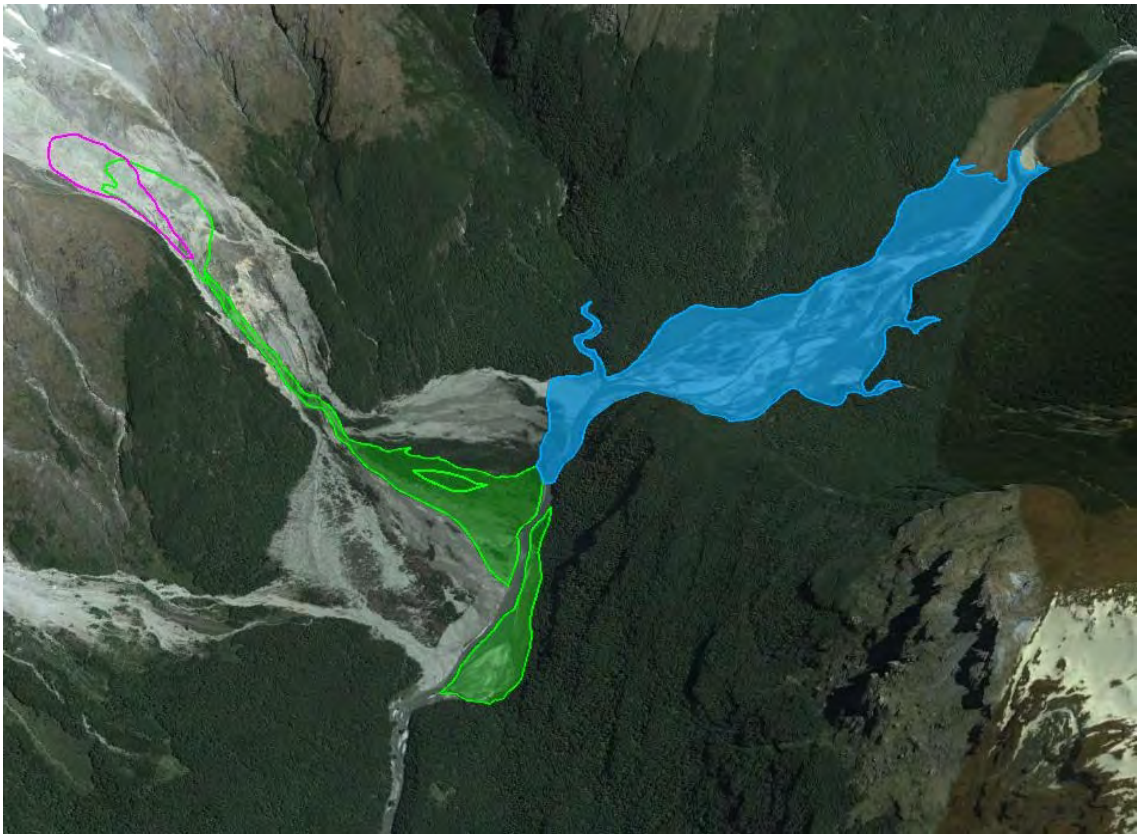

There have been at least four, and possibly five, phases of enhanced landslide activity since 2009. These appear to be triggered by heavy rain (and ice melt) during the Spring-Summer periods:

- During a field visit on 9 February 2010 it was evident that debris flows had recently occurred along the northern edge of the fan, just reaching as far as the Dart River/Bride Burn confluence. Trees were still splashed with mud at the time of the visit. We could not clearly delineate the source area and full extent of debris lobes in available photographs.
- Geoeye-1 imagery of 8 January 2011 (viewed on Google Earth, January 2014) is very clear, showing dark, very fresh looking (still wet) debris-flow deposits in the central and northern parts of the fan. These came from a number of small areas between ~800–900 m elevation on the front of the landslide toe. Debris reached and entered Dart River, and was remobilised downstream to be deposited on gravel bars. The source, debris and remobilised sediment are depicted in Figure 3A.
- Photographs in early 2012 indicate that debris flows had recently been active at mid-altitude (1200 m) on the main body of the landslide, but may not have continued as far as the lower slopes. Some debris was mobilised from between 850–900 m elevation on the south side of the landslide toe, travelling across the central fan to Dart River, where it displaced the channel eastward. Colour of the debris suggests that it was dry when photographs were taken, implying that the phase of activity illustrated pre-dates photography by weeks. An inferred source area and debris flow path are shown in Figure 3B but are not as well defined as other phases.
- The landslide was particularly active during January 2013, and debris mobilised from the upper toe reached all the way across the fan to the river. A lake of some 0.13 km^2 was impounded at the downstream (south) end of Dredge Flat. The debris flows are thought to have been initiated by rainstorms on 1–2 and 8–9 January 2013 (Bryant, 2013). The January 2013 source area, debris, remobilised sediment and lake are depicted in Figure 3C.
- In December 2013, there was fresh debris transported directly from the landslide across the centre of the fan into Dart River and the lake had grown to 0.47 km^2. Whilst there were numerous storms in October 2013, November and December had been relatively dry, so it is possible that groundwater base flow or snow melt contributed to the activity.
- In January 2014, heavy rainfall occurred late on 2nd and appears to have brought much further debris to Dart River, restricting the flow and increasing the lake to 1.48 km^2. The 4 January 2014 source area, debris, remobilised sediment and lake are depicted in Figure 3D. The frequent occurrence of flow blockage in clear weather inferred from the Hillocks records of rainfall and Dart River discharge confirms that debris-flow activity is being supplied with water from groundwater fed springs in the landslide.

With the exception Dec 2011–Jan 2013, when the area and thickness of added fan debris appears to have been relatively small (<10^5 m^2), our observations indicate annual debris-flow volumes of 10^5-$10^6 m^3$. The source of debris, initially from the toe of the landslide, has now switched to the southern side of the landslide, with failure retrogressing to progressively higher altitudes. An area of 96,000 m^2, immediately upslope from the January 2014 source area has extensive, open cracks which suggest that the failure process is continuing.

When the debris flows have avulsed to new channels, they have left very soft, wet, deposits that eventually dry to a non-cohesive (silty) deposit that is easily deflated by wind. Rain appears to quickly modify the deposits, washing the finest material from the surface, cutting channels and leaving a lag of pebbles and cobbles.

The Geoeye-1 image of 8 January 2011 also shows two other recently active landslides on the Cosmos Peaks range south of Te Horo. The larger of these is in the adjacent catchment 1.5 km south of Te Horo, albeit with smaller debris flows presently not reaching the river. A very much smaller landslide is a further 1200 m south along the range. They are both compound rock and debris slides, and they head at similar elevations to Te Horo. The larger of these slides has some large and prominent rock topples at its head, while the smaller one is simply a reactivated retrogressive rock and debris slide.

3.0 PROCESSES

3.1 LANDSLIDE PROCESSES

Te Horo is a large, very slow, reactivated, compound rock and debris slide with ancillary rapid debris topples, rock falls and debris flows (in the revised Varnes classification of landslides, Hungr et al., 2013). There is some geomorphic evidence (in the form of extensive areas of freshly exposed debris on the landslide surface) to suggest that Te Horo has moved more in the last few decades, than in the previous century or so. Although rates of movement have not been measured they probably have remained slow to very slow (using Hungr et al., 2013). The larger mass of Te Horo is not expected to ever move rapidly, because rapid movement would be very uncharacteristic of this type of landslide.

The movement in transferring mass from the upper landslide area to the lower landslide area, has caused the toe and flanks of the landslide to become higher and steeper, on average. More areas of the landslide toe and flanks are now at the angle of repose for loose debris. As a consequence, loose rocks and debris tumble from these areas as rapid rockfalls more often than they used to. In addition, cracks are opening wider in the landslide debris above the steep faces, as large masses of debris topple outward from the top of the toe of the landslide. These will eventually fail as rapid debris topples; some have already done so. There are also areas where retrogressive failure of the landslide debris is occurring. Although as yet unmeasured, some past motion of Te Horo may be able to be determined retrospectively from analysis of appropriate historical satellite imagery (cf. Thomas & Cox 2009).

Collapses of loose debris into gullies in December and January have frequently temporarily blocked flow of Te Koroka/Slip Stream. Debris flows have been initiated in the processes of clearance of these ephemeral blockages. On 7 January 2014, such ephemeral blockages were forming and breaching several times each hour, to send fresh debris-flow pulses down to Dart River. Between rainfalls, flow of Te Koroka/Slip Stream is maintained by springs in the landslide debris mass, and these springs appear to supply enough water to have allowed a continuously pulsing debris flow to reach Dart River throughout January and the first half of February 2014. In less active times without debris flows, Te Koroka/Slip Stream is ephemeral in the lower channel reaches on the fan.

3.2 LANDSLIDE MOVEMENT

To investigate past motion of the Te Horo landslide, 29 radar images acquired by the European Space Agency's Envisat satellite between January 2004 and 2010 were examined using Satellite Radar Interferometry (InSAR) (Massonnet & Fiegl, 1998). In a first step, we formed multiple interferograms which minimised the temporal and spatial separation between acquisitions. In order to boost the signal to noise ratio and to correct topographic errors, the interferograms were processed with a r esolution of 90 m. The relatively small area of the landslide and problems with incoherence in many of the InSAR pairs resulted in failure to detect any displacements over the landslide. For Envisat, a look angle of 23° to the vertical, and a near -polar orbit limits the sensitivity for detecting displacements to the vertical and east-west directions.

We attempted to overcome some of these issues by subsequently processing the interferometry data using a Permanent or Persistent Scatterer (PS) technique. Originally outlined by Ferretti et al. (2000, 2001), PS-InSAR exploits the existence of isolated point scatterers which have coherent scattering characteristics through time. For the Te Horo landslide, PS processing was done using Stamps (Hooper, 2004, 2007). Using the PS method, we identified scatterers located in the vicinity of the landslide, but found no evidence of motion during the observation period (2004–2010) (Figure 4). It is likely that there were too few data points available to resolve any motion of the landslide. Radar images acquired over New Zealand in the past have generally been s poradic which limits the number of interferograms that can be reliably processed. This limit should disappear with the launch of ESA's sentinel-1 satellite during April 2014, which will routinely acquire images within a tightly controlled orbit enabling the formation of regular interferograms.

3.3 DEBRIS-FLOW PROCESSES

In steep mountain torrents with abundant granular material available to be m oved in the channel, the normal processes of stream bedload transport of sediment by rolling and saltation in the water can be supplanted by massive bed instability. The switch from the water causing some sediment to move, to the sediment moving the water, can be sudden, with a dramatic increase in speed and volume of the moving fluid mass. A flowing mass of water-saturated debris is called a debr is flow, and can move very fast. Debris flows are capable of moving much larger boulders that would be moved by flood water in the stream channel.

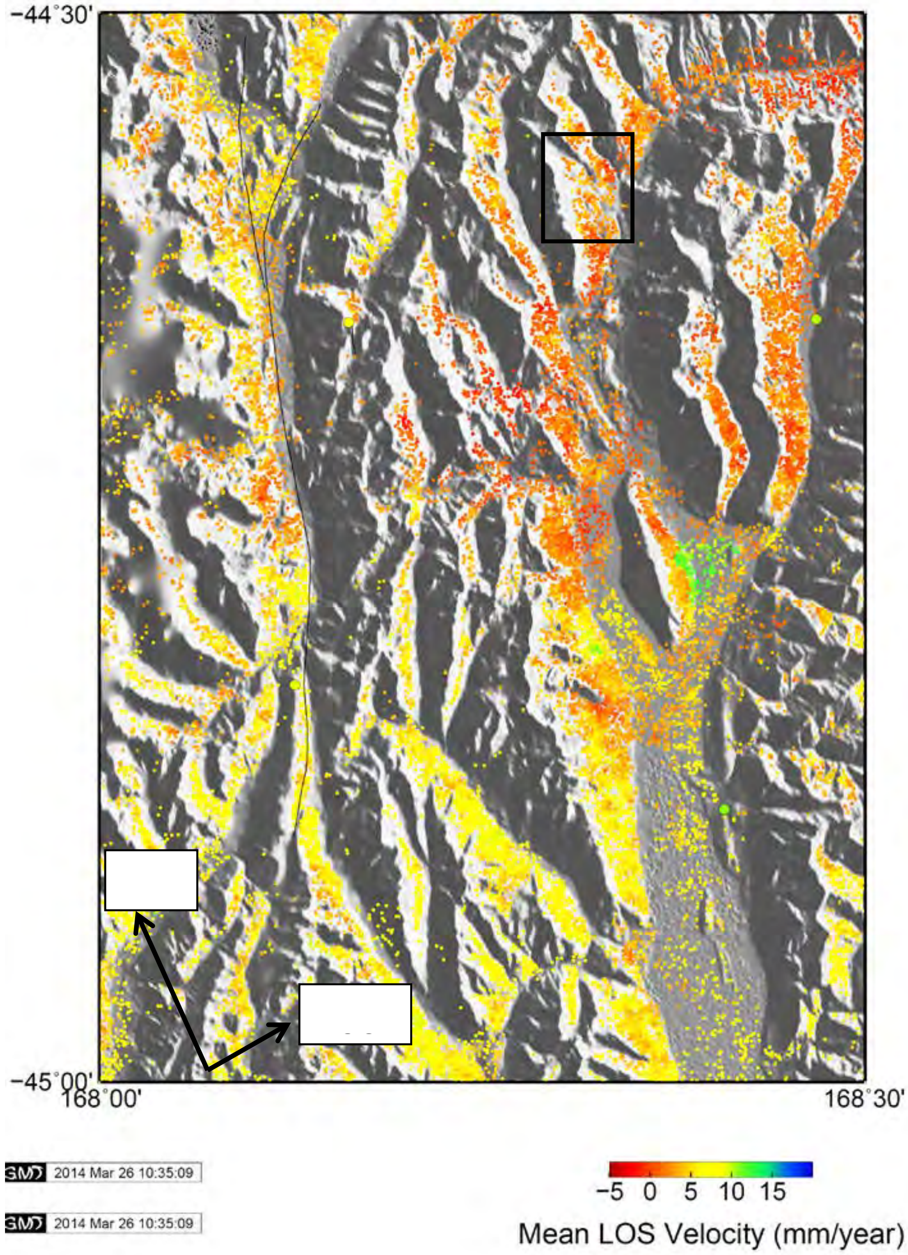

Figure 4 Permanent Scattering points detected using InSAR superimposed onto a 90 m DEM. Positive Line-of-site (LOS) velocities indicate motion towards the Satellite. Arrows show the satellites flight (Az) and look (LOS) direction. A black rectangle shows the area of Figure 1B, in which the landslide is located.

When we were present on 6 and 7 January 2014, Te Koroka/Slip Stream was alternating between flowing as a very muddy stream (hyperconcentrated flow), to flowing like freshly prepared concrete pouring from a concrete mixer, with all gradations in between. A short video clip of the debris flow can be viewed at http://youtu.be/Y6vs_InBqwY. A probably much larger debris flow had occurred around the middle of the day on 4 January (following heavy rain on 2–3 January). As large flows reached Dart River, they were progressively raising the level of the lake.

Figure 5 Aerial view of a portion of the Te Koroka/Slip Stream showing various levels reached by debris-flow surges as they passed by on their way to Dart River. A small lobe of debris has spilled out of the channel to reach the young Mountain Beech tree on the right (true left of channel). The larger boulders in the channel are several metres across. (Photo: M.McSaveney).

Figure 6 View of a distributary channel of the 5 January debris flow on the Te Koroka/Slip Stream fan. The boulder lodged in the fork of the mature nothofagus tree has a diameter of about 0.5 m. The flow was inactive at the time of photography (7 January) (photo: S. Cox).

Figure 7 View of inactive debris-flow distributary on Te Koroka/Slip Stream fan. A sample of the debris for particle-size analysis (Fig. 8) was randomly taken from the debris perched atop the log behind the pack (photo: M. McSaveney).

Figure 8 Texture of recently drained debris-flow deposit (two days after deposition). The non-plastic, matrix-supported deposit is an extremely poorly sorted muddy gravel (photo: M. McSaveney).

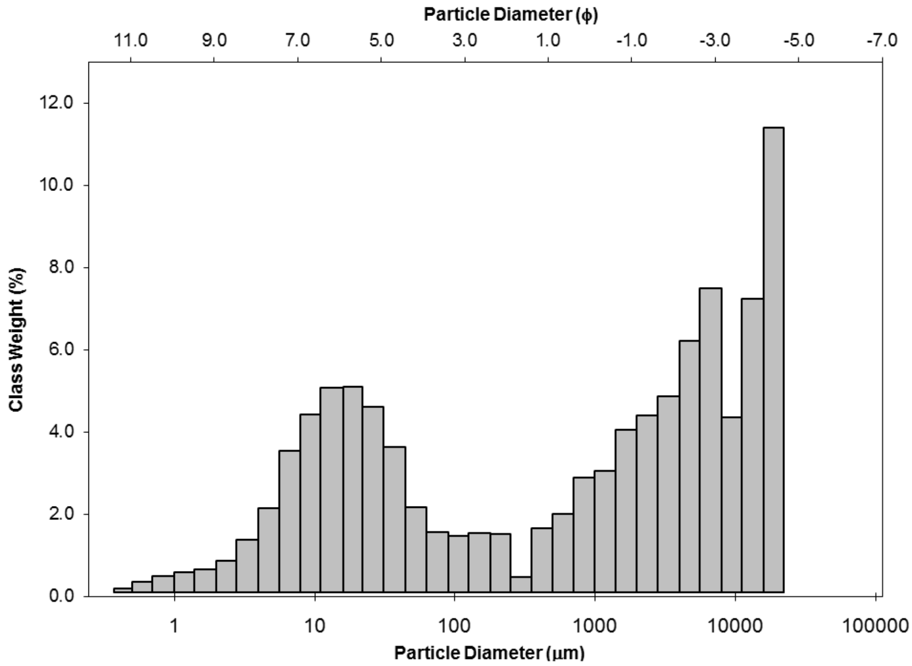

Figure 9 Particle-size histogram of the Te Koroka/Slip Stream debris-flow grab sample, showing the fine silt mode and the truncated coarse debris mode. The coarse debris mode was biased by having to sample at a safe site (an overbank lobe) and consequently material >2 cm up to boulders 4 m across observed in the main channel are not represented.

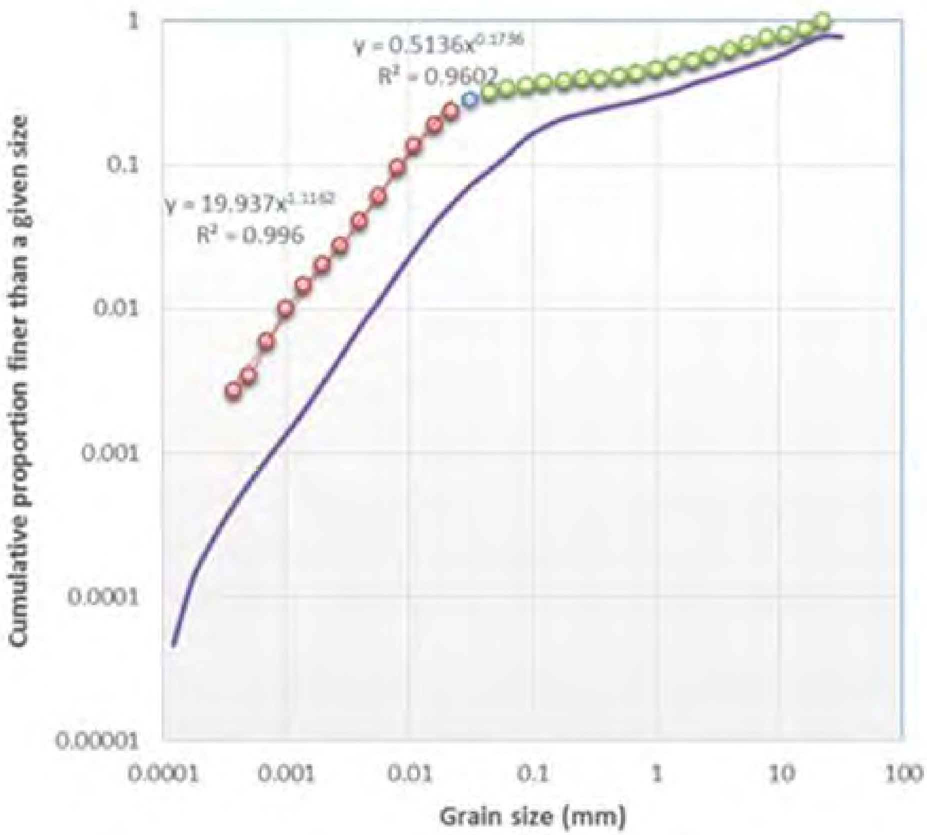

Figure 10 Grain-size distribution of a random sample of debris from a fresh, but inactive debris flow deposit onTe Koroka/Slip Stream fan. Power-law curves are fitted to two sections of the distribution. Also shown in the solid purple line, is a grain-size distribution from a debris flow that occurred in January 2002 in the headwaters of nearby Rees River valley (McSaveney and Glassey, 2002)

Safety considerations precluded sampling of the main channel of the active debris flow on 7 January. Instead, a grab sample was taken from an inactive overbank flow lobe probably deposited on 5 January (Figure 7 and Figure 8). The saturated matrix-supported deposit (Figure 8) is a bimodal muddy gravel (Figure 9), with the coarser mode significantly truncated (by our selection of sampling site). The material was readily liquefied when disturbed at the drained field water content and was non-plastic.

The fine and coarse modes appear to form separate fractal distributions (Figure 10) which is remarkably similar to what was found in the Cleft Peak debris flow of January 2002 which occurred in the headwaters of nearby Rees River (McSaveney and Glassey, 2002). The fractal nature of the sediment distribution results from the fragmentation and abrasion of phyllosilicate-rich, schist-derived rocks during transport in the debris flow. The silt and sand fraction is rich in phyllosilicates, including more than trace amounts of talc that probably was originally associated with serpentinite.

For most of January, the debris flow on the upper fan was confined in a single deep channel, but mid-fan it was less and less able to move large boulders on the lower gradients and was less incised. As boulders stopped against other obstacles, forming stable clusters of boulders, the debris flow sometimes diverted into other channels. On the gentle slopes of the lower fan, the debris flow was not in a defined channel, instead, there was a wide, smooth, low-gradient section of a cone. Across this section, streams of fluid debris glided at generally slow speeds which varied with the debris thickness and viscosity, but with no static areas between flow streams. Some of these streams carried widely scattered boulders up to several metres across, but most of the solids in the debris-flow solid were in the coarse sand to fine silt sizes (Figure 8 to Figure 10).

We can only speculate on when the January 2014 debris flow began, because the event which blocked the river at Te Koroka/Slip Stream sometime on the morning on 4 January, may not have been the beginning of debris-flow activity. Activity may have begun about the time of the peak in rainfall shortly before midnight on 2 January. During periods of increased water flow following rain, further blockages of the river presumably by debris flows at Te Koroka/Slip Stream occurred, but only late in the recession from peak flow (see Section 3.4). We, however, witnessed debris-flow activity on the fan on 7 January that did not modulate Dart River discharge. Also, some other known debris flows in January 2013 could not be recognised in Dart River discharge record at the Hillocks. Hence we are aware that blockage may not occur (or be recorded) at high flows, and that not all debris flows are recorded as diminished Dart River flows.

Along the northern sector of the fan, debris was flowing directly into the formed lake in early January. We have only viewed this situation when there was little wave action on the shore, and little turbulent mixing of the two fluids. We presume that the debris mostly slows as it enters the lake and increases in thickness due to the reduction in effective shear stress caused by water immersion. In ten days between 5 and 15 January 2014, the debris-flow fan prograded some 50 m into the lake, eventually constricting the lake outflow on the north-eastern edge of the prograding fan.

A different situation arises where the debris enters the active river channel. This is discussed in the section 3.3. By 27 January 2014, the Te Koroka/Slip Stream debris flow had avulsed to a more southerly channel across the lower fan, to enter Dart River downstream of the dam crest where it was not blocking flow. Flow-blocking debris-flow activity, however, is inferred from the Dart River flow record at the Hillocks site in the late afternoon of Friday 31 January. This is interpreted simply as episodic avulsion of the debris-flow channel on the surface of the fan, through debris-flow deposition caused by the low gradients of the lower fan.

3.4 DART RIVER CHANNEL

The Dart River channel was displaced eastwards approximately 20 metres between 4 and 6 of January 2014. The river had cut and eroded the eastern bank and created 16-metre high cliffs in alluvial gravels in a terrace remnant (Figure 11). Trees had been undermined and fallen into the river. The Dart River track which locally follows the terrace was also lost in several places when undermined by river erosion. Downstream of the Te Koroka/Slip Stream fan, aggradation of the Dart River channel had also locally flooded another section of the Dart River track

There are at least two ways that a minor side stream can block a major river such as has occurred on Dart River at Te Koroka/Slip Stream: the side stream can bring to the river boulders too large for the river to carry away; or the side stream can bring too much sediment for the river to carry away. Both ways can occur at the same time. In January 2014, although some boulders in excess of a metre in diameter were seen moving slowly across the lower fan near the river channel, no large boulders were seen armouring the bed of the Dart River channel. We concluded that Dart River was dammed in January 2014 because Te Koroka/Slip Stream was delivering more sediment than Dart River was able to carry away.

When inflow of sediment from Te Koroka/Slip Stream diminishes, and Dart River cuts deeper into the fan toe, we speculate that a lag deposit of very large debris-flow boulders will form in the river bed from the accumulated large boulders that have reached the river, and that this will stop further incision of the lake outlet. No large boulders however, have yet appeared in the Dart River bed, despite the constant erosion of the debris-flow deposit and its transport down river.

In the absence of development of a bed armour, a capacity load of sand and gravel is being eroded from the fan and carried as bedload beyond the dam crest by the river on a channel gradient of 0.004–0.005. The river channel immediately downstream of the debris-flow input is heavily braided, where formerly it flowed in a single thread. This change in channel form is a result of the increased bedload due to the increased activity on the fan. Previously most of the bed load of up-valley Dart River was transported passed Te Koroka/Slip Stream from Dredge Flat and beyond. With the lake present, this up-valley component of Dart River bedload has been eliminated by its deposition at the head of the lake.

The process by which the debris-flow discharge into Dart River is impounding water in the lake is uncertain, and complicated by a number of constantly irregularly varying parameters. The varying factors are:

- debris-flow discharge (flux) into the river;
- ratio of solids to water in the debris flow (debris rheology);
- debris entry point(s) into the river channel;

- width of debris-flow entry;
- width of river channel;
- river-channel bed elevation;
- presence and nature of channel armour;
- lake water-surface level;
- lake inflow;
- lake outflow.

Most of these are largely independent variables, or can vary independently, although the lake water surface must be highly correlated with the lake inflow and outlet bed elevation.

Figure 11 View of the dam crest from low on Te Koraka/Slip Stream fan on 7 January 2014. Lake is to left. The very low gradient, and still moving debris flow forms the foreground. Debris-flow deposition has elevated the bed of the river against the eastern wall of the Dart River valley. A terrace remnant of ancient Dart River alluvium has been undercut and collapsed into the river, taking with it a portion of the Dart River access track.

Debris-flow discharge takes place at varying rates across a wide front. On 5-6 January 2014 the front was about 600 m wide; on 15 January it was about 800 m wide. About 200 m of this front discharged into the lake and the remainder into the river channel. The debris-flow thickness at the river bank is unknown, but is expected to vary laterally and in time from a few decimetres, to about a metre or so.

Direct growth of the debris-flow fan into the lake does little to change the height or extent of the lake. The Dart River channel across the toe of the fan, however, has been significantly narrowed by growth of the fan into the channel. Fan growth into the channel appears to occur repeatedly as the river discharge drops from above-normal flow. Whenever the lake outlet was photographed from the air through January, the river could be seen to fit the channel to bankfull, regardless of the stage of the river. We interpret this to indicate that as river stage decreased, the saturated debris-flow deposit forming the channel bank was narrowing the channel and continuing to limit river flow.

At higher river flows, when the river is flooded onto debris-flow deposits, the deposits are likely to be eroded very rapidly, to be carried off as wash and bed load. The excess of the winnowed coarser bed-material load is building up the floor of the channel for many kilometres downstream (see redistributed sediment, Figure 3). Although the debris making up the dam contains very little material incapable of being moved by Dart River, the material present has been in such quantities that the river has been incapable of shifting it quickly along the existing channel gradient. Based on extrapolation of the larger grain-sizes in the distribution shown in Figures 9 and 10, and our observation that the larger boulders are not carried to the base of the fan, probably much less than 1% of the volume of sediment delivered to the Dart River bank at the toe of the fan is of a size beyond the capacity of Dart River to move as bedload, and possibly as much as a third of the sediment volume is capable of being carried as washload into Lake Wakatipu.

When the amount of debris-flow sediment reaching the river diminishes, Dart River can be expected to slowly incise into the toe of the fan, and the lake level will slowly drop. The lake is unlikely to disappear entirely in the short term, because at some point in the incision process, the Dart River bed is likely to become armoured with larger boulders at the dam crest. In the longer term, the lake will probably disappear by infilling of the lake with Dart River bedload arriving from upstream. The lifespan of the lake, however, is indeterminate, because it is dependent on Te Horo activity and the mode of transport of debris across the Te Koroka/Slip Stream fan. The only certain features are that the lake level can be expected to fluctuate widely and frequently, but the lake can be expected to persist for decades. There is no downstream danger of a catastrophic lake outburst flood.

An ancient analogue of the long-term future behaviour of Dart River at Te Koroka/Slip Stream can be found on nearby Rees River at the Muddy Creek fan (-44.696S, 168.465E). There, Rees River flows across an extensive braid plain upstream of Muddy River, but flows in a single-thread, white-water channel across a boulder bed past the toe of the Muddy Creek fan. No lake is now present upriver of the fan, and any evidence that there may once have been an ephemeral lake has long disappeared.

3.5 LAKE HISTORY

A lake first appeared on Dredge Flat in January 2013, when water was impounded behind the aggrading fan to cover 0.13 km^2 of the upstream flood plain. DoC staff informed GNS Science that the lake disappeared for a short period during winter 2013, but by December 2013, it had re-grown to 0.47 km^2. During this time, the Dart River flow record at the Hillocks river gauge, 24 km downstream from the landslide, did not show any unusual or anomalous flows that we can confidently attribute to landslide (debris flow) damming of the river.

On 6 January 2014, the water level of the lake and a former higher water level indicated by flotsam were measured by handheld GPS, with multiple readings taken along the shore against Te Koroka fan to decrease uncertainty. At 3 pm Monday 6th January the lake level was 445.4 ± 1.5 m (based on an average ± 1 standard deviation, n=12). Deposits of leaves, wood and hare scat marked a previous high level at 447.7 ± 1 m (n=19) at approximately the position photographed at 7 pm on the evening of Sunday 5 January. At its high level, the lake was 3.5 km long, covering 1.48 km^2. We attempted to derive a depth and volume of lake water from the difference between 447.7 m elevation and a 10 x 10 m digital elevation model generated from NZMS260 digital topographic contours, but these contours are not sufficiently accurate to define the shape of the valley floor and provide a useful answer. Comparison of images of the eroded terrace edge suggests that the river is now about 15 m higher than it was in January 2013. If it is assumed that the average lake depth is between 7.5 and 10 m (the lake varies from 0 m deep at the upstream end and is perhaps 15–20 m deep at the dam) then the volume of the lake is constrained between 11 and 15 million m^3.

The Hillocks river gauge indicates Dart River departed from a normal (negative exponential) flood recession curve at 12:00 on 4 January, with a rapid drop to anomalously low flow (Figure 12). We attribute the rapid drop in flow to the river being blocked by a large debris flow from the landslide. Flow resumed to its expected recessional level after the river overtopped the dam shortly before 01:00 on 5 January.

Another drop in recessional flow between 01:00 and 08:00 on 8 January probably also relates to larger debris flows reaching the river. The integrated "missing" (i.e., below-normal) volume of water flowing past the Hillocks gauge on 4–5 January is about 4 x 10^6 m^3, dependent on the recession curve selected, and about 1.3 x 10^6 m^3 on 8 January. Such flow volumes would increase the depth of lake by around 3 m and 1 m, respectively, which is commensurate with the size of shoreline fluctuations observed in the field.

Dart River flow at the Hillocks was still exhibiting episodic anomalous flow behaviour over a week later (Figure 13) when compared with neighbouring Matukituki River, indicating that a lake was still present and being dammed by recurrent debris flows.

The expected long-term evolution of the lake after the debris-flow activity dies away is for the outlet to become armoured with large boulders leaving a smaller lake to persist until it is infilled with sediment arriving from upstream.

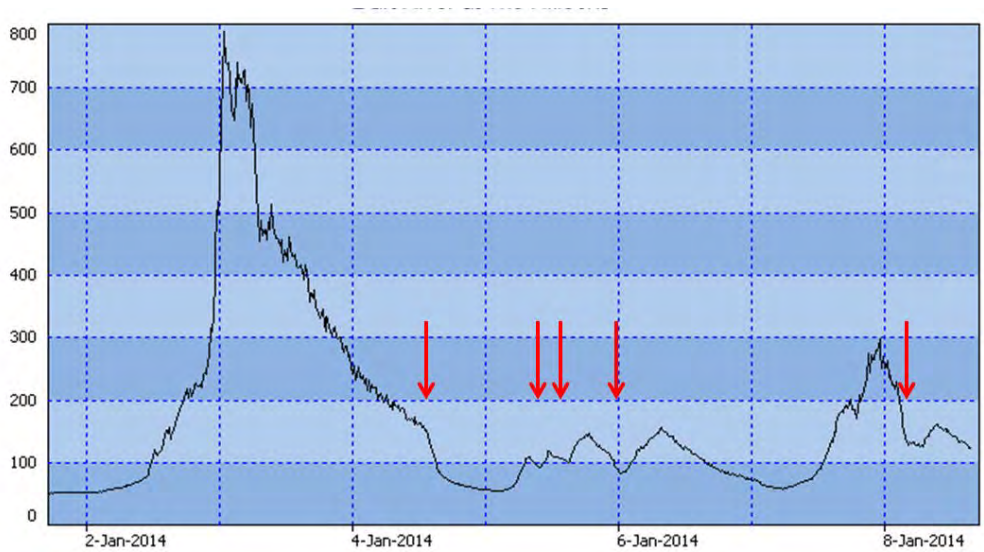

Figure 12 Dart River discharge (cubic metres per second) at the Hillocks river gauge, 24 km downstream from Te Koroka/Slip Stream. River discharge began behaving anomalously (arrowed) when it rapidly decreased from 160 to below 90 cubic metres per second after mid-day on 4 January 2014. Episodic discharge decreases (arrowed) have occurred irregularly through January 2014 (see also Figure 12). Data covering the period 2–8 January 2014 from Otago Regional Council (http://water.orc.govt.nz/WaterInfo/).

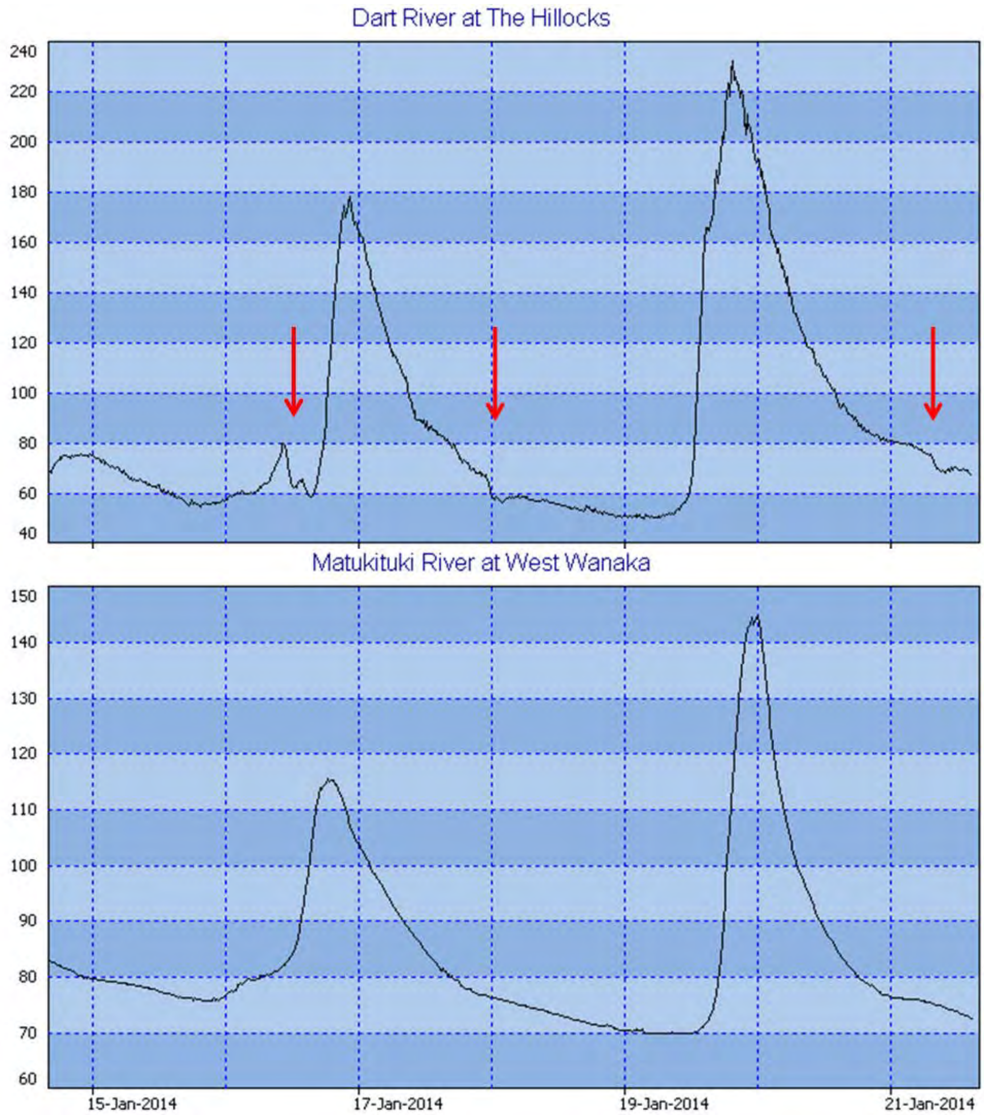

Figure 13 Anomalous discharges (arrowed) of Dart River with respect to Matukituki River are apparent on 16, 18 and 21 January. Discharge is in cubic metres per second. Data covering the period 15–21 January 2014 from Otago Regional Council (http://water.orc.govt.nz/WaterInfo/).

4.0 SUMMARY

The ~50 million cubic metres Te Horo landslide is in a remote unpopulated area of Dart Valley, at the head of Lake Wakatipu in the Southern Alps. Although the landslide is not continually monitored, a history of its most recent activity is provided through a punctuated record of photographs, satellite imagery and field visits. The landslide presently delivers between 10^5-10^6 m^3 of sediment debris annually to the valley floor. There has been an increase in activity to that recorded prior to 2009, when larger events involved 10^4–10^5 m^3 and smaller movement of debris. Enhanced phases of rainfall-induced activity seem to occur in spring-summer, and can continue throughout periods between rainstorms, hinting that the contribution from groundwater baseflow is important.

The Te Horo landslide episodically delivered very viscous slurries of boulder- to fine-silt-sized sediment in wet-concrete-like debris flows downslope across the gently sloping toe of Te Koroka fan to Dart River. Starting as a silt-laden mountain torrent from springs high on Te Horo, the torrent has episodically increased in bulk and dens ity by eroding sediment along its path, transforming into surging debris flows travelling at velocities of ~1 to 10 ms^{-1}, flattening and burying vegetation, ultimately slowing and thinning where the slope decreases. Phyllosilicate-rich, schist-derived rocks have been fragmented and abraded during transport. The initially boulder-rich debris flows become increasingly silt- and pebble-dominated in their lower reaches as boulders are deposited along the channel. The flows leave very soft, wet, deposits that eventually dry out and def late. Rain appears to quickly modify the deposits, eroding fine-grained material from the upper surface, cutting channels and leaving a lag of pebbles and cobbles.

During January 2014, most debris flows travelled the entire 1 km distance down the fan to reach Dart River. A delicate interplay there exists between the flux of sediment delivered, and the river's ability to carry this predominantly fine sediment away and r ework and redistribute the sediment in its flow. A small (0.13 km^2) lake first developed at the upstream end of the fan during January 2013, and had evolved to 1.48 km^2 in January 2014 with an estimated volume of 11 to 15 million m^3. Periods of anomalously low river flow and recovery were recorded at a river gauge 24 km downstream. The debris-flow flux and river discharge have varied largely independently of one another, continually varying the balance between debris supply and removal. At times when an excess of supply over removal has occurred at the dam crest, downstream flow has decreased and the lake level has risen. For much of the time during January and early February 2014, the debris flows did not enter Dart River at the dam crest, but entered the lake north of the outlet, or Dart River south of the outlet. When the debris flows have not entered at the dam crest, the river has eroded the lake outlet channel, lowering the lake level.

A lake will persist for some time after the current debris-flow episode ceases, because river-channel erosion is expected to expose enough large debris-flow boulders to armour the lake outlet. The remnant lake ultimately will fill with Dart River sediment from upstream.

A large amount of sediment and woody debris is being washed down Dart River below the lake. As a result, the river has continually appeared dirty as if in flood-like conditions, but at all flows. Close to the landslide dam, the river channel was shifted east to cut through forest. Trees and riverbank sediment have been falling into the river. Visitors to the area need to be wary of changes in channel position, areas of very soft sediment, wood and rock debris, and periods of anomalous and slow changes in river flow (up or down) with no apparent cause.

The landslide dam is broad and the river channel across it has a very low gradient. No abnormally high flows should be expected below the dam, other than those that would be expected from the amount of rain falling in the upper catchment. In our view, the landslide-related debris flows and the lake currently add no additional hazard to the lower Dart River below the dam. There is no downstream danger of a catastrophic lake outburst flood. The upper slopes of Te Koroka fan and Te Horo landslide currently are areas of heightened risk to visitors and should be avoided.

The debris-flow source areas on the landslide have progressed retrogressively upslope: being ~800-900 m on the front of the toe from 2010–2012; ~900–1200 m on the southern side/rear of the toe in 2013; to ~1000–1350 m in the main body of the landslide in 2014. The landslide is intensely fractured upslope, and the area between 1200–1470 m is thought likely to provide a ready source for debris flows into the near future. Until such a time as sediment delivery from the landslide reduces radically, the *status quo* of episodic debris-flow surges, river-channel restriction, an impounded lake and downstream sediment redistribution is unlikely to change.

5.0 ACKNOWLEDGEMENTS

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APPENDICES

APPENDIX 1: SELECTED IMAGES OF TE HORO AND TE KOROKA/SLIP STREAM, JANUARY 2014

Figure A1 Aerial oblique view (to west) of the Te Koroka/Slip Stream fan below Te Horo. Dart River in foreground (Photo: S. C. Cox, 6 January 2014).

Figure A2 Aerial oblique view to west of the debris-flow catchment of Te Koroka/Slip Stream and the Te Horo landslide (Photo: M. J. McSaveney, 6 January 2014).

Figure A3 View of the Te Koroka/Slip Stream debris-flow channel, upper fan, and T e Horo landslide (Photo: M. J. McSaveney, 6 January 2014).

Figure A4 View of fresh debris-flow deposit of 4 January on the Te Koroka/Slip Stream fan. Te Horo is in the background (Photo: M. J. McSaveney, 6 January 2014).

Figure A5 A debris flow in the incised channel of Te Koroka/Slip Stream (Photo: S. C. Cox, 6 January 2014).

Figure A6 A debris-flow surge pours like wet concrete down the Te Koroka/Slip Stream channel (Photo: S. C. Cox, 6 January 2014).

Figure A7 Aerial oblique view (to west) of the upper Te Koroka/Slip Stream fan with debris flow in channel (Photo: S. C. Cox, 6 January 2014).

Figure A8 View of a debris flow moving past a 2-m diameter boulder on the Te Koroka/Slip Stream fan. Flow rate was at a fast walking speed (Photo: S. C. Cox, 6 January 2014).

Figure A9 View of the waning stage of a debris-flow surge on the Te Koroka/Slip Stream fan. Flow rate was at a fast sprint (Photo: M. J. McSaveney, 6 January 2014).

Figure A10 A debris flow in Te Koroka/Slip Stream (Photo: S. C. Cox, 6 January 2014).

Figure A11 Recently deposited debris-flow lobe of 4 January on the Te Koroka/Slip Stream fan (Photo: S. C. Cox, 6 January 2014).

Figure A12 A debris-flow surge in Te Koroka/Slip Stream. Flow rate was at a f ast running speed (Photo: S. C. Cox, 6 January 2014).

Figure A13 Partially buried trees (from January 2013 debris flows) on the Te Koroka/Slip Stream fan surrounded by 4 January 2014 debris flow deposit (Photo: S. C. Cox, 6 January 2014).

Figure A14 Partially buried trees (from January 2013 debris flows) on the Te Koroka/Slip Stream fan surrounded by 4 January 2014 debris flow deposit (Photo: S. C. Cox, 6 January 2014).

Figure A15 Partially buried trees (from January 2013 debris flows) on the Te Koroka/Slip Stream fan surrounded by 4 January 2014 debris flow deposit (Photo: S. C. Cox, 6 January 2014).

Figure A16 View of a freshly deposited debris flow on the Te Koroka/Slip Stream fan (Photo: M. J. McSaveney, 6 January 2014).

Figure A17 Aerial oblique view (to north) of the Te Koroka/Slip Stream fan and active debris-flow channel (Photo: S. C. Cox, 5 January 2014).

Figure A18 Aerial oblique view (to south) of dam crest on Dart River and the toe of Te Koroka/Slip Stream fan. Lake is in the left foreground (Photo: S. C. Cox, 5 January 2014).

Figure A19 Aerial oblique view (to south) of the toe of Te Koroka/Slip Stream fan and dam crest (Photo: S. C. Cox, 5 January 2014).

Figure A20 Aerial oblique view (to south) of the toe of Te Koroka/Slip Stream fan and braided Dart River (Photo: S. C. Cox, 6 January 2014).

Figure A21 Aerial oblique view to south of the toe of Te Koroka/Slip Stream fan and braided Dart River. Note transition in river turbidity from foreground to background (Photo: M. J. McSaveney, 6 January 2014).

Figure A22 Aerial oblique view to south of the crest of the debris-flow dam, Dart River. The very slowly moving debris flow at the toe of the fan forms the right foreground and middle ground in the image (Photo: M. S. Rattenbury, 5 January 2014).

Figure A23 Aerial oblique view (to north) of the active debris flow at the dam crest on Dart River (Photo: S. C. Cox, 6 January 2014).

Figure A24 Aerial oblique view (to north) of the active debris flow on Te Koroka/Slip Stream fan where it enters the lake (Photo: S. C. Cox, 6 January 2014).

Figure A25 Aerial oblique view (to east) of the toe of Te Koroka/Slip Stream fan and dam crest on Dart River (Photo: S. C. Cox, 6 January 2014).

Figure A26 Aerial oblique view to north of Te Koroka/Slip Stream fan and lake, Dart River. Dam crest is formed by an active debris flow in the image. Note the silt-laden braided Dart River channel downstream of the dam in right middle ground (Photo: M. S. Rattenbury, 5 January 2014).

Figure A27 Aerial oblique view to south of the Te Koroka/Slip Stream fan. The landslide in the right background is often mistaken for Te Horo (Photo: M. J. McSaveney, 6 January 2014).

Figure A28 View to north of the Te Koroka/Slip Stream fan and lake. This area of the fan was active in January 2013 (Photo: M. J. McSaveney, 6 January 2014).

Figure A29 Aerial oblique view (to north) of the Te Koroka/Slip Stream fan and lake. This area of the fan was active in January 2013 (Photo: S. C. Cox, 5 January 2014).

Figure A30 View to north of the Te Koroka/Slip Stream fan and lake. Trees buried in January 2013 (Photo: M. J. McSaveney, 6 January 2014).

Figure A31 Aerial oblique view (to north) of the Te Koroka/Slip Stream fan and dammed Dart River (Photo: S. C. Cox, 6 January 2014).

Figure A32 Aerial oblique view to north of the Te Koroka/Slip Stream fan and braided Dart River channel downstream of the dam (Photo: M. S. Rattenbury, 5 January 2014).

Figure A33 Aerial oblique view (to north) of the lake on Dredge Flat (Photo: S. C. Cox, 6 January 2014).

Figure A34 Aerial oblique view (to north) of the head of the lake on Dredge Flat (Photo: S. C. Cox, 6 January 2014).

Figure A35 Aerial oblique view to south of the new lake on Dredge Flat. The Te Koroka/Slip Stream fan is in the background (Photo: M. J. McSaveney, 6 January 2014).

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