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Evidence for a rock-avalanche origin for 'The Hillocks' "moraine", Otago, New Zealand

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ABSTRACT

A landform in Otago, New Zealand, previously interpreted as a glacial deposit, has been investigated, described and reinterpreted as a rock avalanche deposit. 'The Hillocks' is a conspicuous cluster of small conical hills on the Dart River floodplain. The landform is protected under a local bylaw because of its identification as an outstanding example of a glacial kame deposit. However, the geological and geomorphological setting, and the deposit morphology, sedimentology and lithology, suggest that it was formed by a large (c. 22.5×10^6 m^3) rock avalanche subsequent to glacial retreat, and that the deposit temporarily dammed the Dart River valley. Relative age dating evidence suggests that it is at least several hundred years old but younger than ca 7500 B.P. This work highlights the problem of paleoclimatic reconstructions using 'moraines' as indicators of regional climate events. Despite similarities in form and, in some cases, sedimentology, by applying an understanding of landslide initiation, runout and depositional process, we demonstrate that it is possible to distinguish the deposits produced by landslides from those produced by glacial deposition.

1. Landslides and glacial deposits

Misinterpretation of glacial landforms has recently been highlighted as a pertinent issue in glacial-geomorphology and for paleoclimate reconstructions (Larsen et al., 2005; Tovar et al., 2008; Deline, 2009; Deline and Kirkbride, 2009; Shulmeister et al., 2009; Winkler and Matthews, 2010). Misinterpreting depositional landforms is a particular problem because of the long-standing use of glacial deposits as indicators of past climate. The problem lies in distinguishing between glacier deposits that represent regional climatic events; those that represent localised (or regionalised) non-climatic events; and deposits of non-glacial origin (Orombelli and Porter, 1988; Hewitt, 1999; Tovar et al., 2008).

Landslide phenomena have been especially problematic for glacial-geomorphology and paleoclimate reconstructions. Erosional landforms created by landslides, such as cirque-like basins, have received conflicting interpretations (e.g. Shakesby and Matthews, 1996; Turnbull and Davies, 2006) but landslide deposits have been even more problematic; like glacial-deposits, landslide deposits often have hummocky morphology and occur in similar mountain valley locations. Supraglacial landslide debris that undergoes little glacial reworking before final deposition can exhibit similar sedimentary characteristics to that of the rock avalanche carapace material as well as similar morphology (Tovar et al., 2008; Vacco et al., 2010). Examples of landslides misinterpreted as having a glacial origin include numerous deposits in the Karakoram Himalaya (Hewitt, 1999), and several in the European Alps such as the famous Fernpass (Prager et al., 2009) and Flims rock avalanches (Ivy-Ochs et al., 2009). In New Zealand there have been similar misinterpretations (Thomson, 1994; Porter, 2000), and some remain controversial (Tovar et al., 2008; Vacco et al., 2010). Glacial deposits have also been mistakenly identified as landslides, for example McSaveney and Whitehouse (1989) reinterpret a previously described landslide deposit as being moraine. It appears that although some criteria have been established for distinguishing between deposits of glacial and mass-movement origin (e.g. Hewitt, 1999), difficulties remain in distinguishing between the deposits produced by these very different processes.

'The Hillocks' in the Dart River valley, Queenstown Lakes District (Fig. 1), is one such example of a landform of debatable origin. It is a collection of small, mostly conical, hills on the Dart River floodplain (Fig. 2), formerly known as 'The Hillocks'. It is a protected landform under the Queenstown-Lakes District Council Plan due to its listing in the New Zealand Geopreservation Inventory, which describes it to be: "A kame field that formed when the Dart glacier extended this far…" and was classified therein as an "extremely well defined landform of scientific/education value" and given an importance status of Class B; "a site of national scientific, educational or aesthetic importance" (Kenny and Hayward, 1993). An expectation of glacier deposits in the glaciated valley and the hummocky nature of the deposit, appear to be the reasons it has received a glacial-origin interpretation. Following

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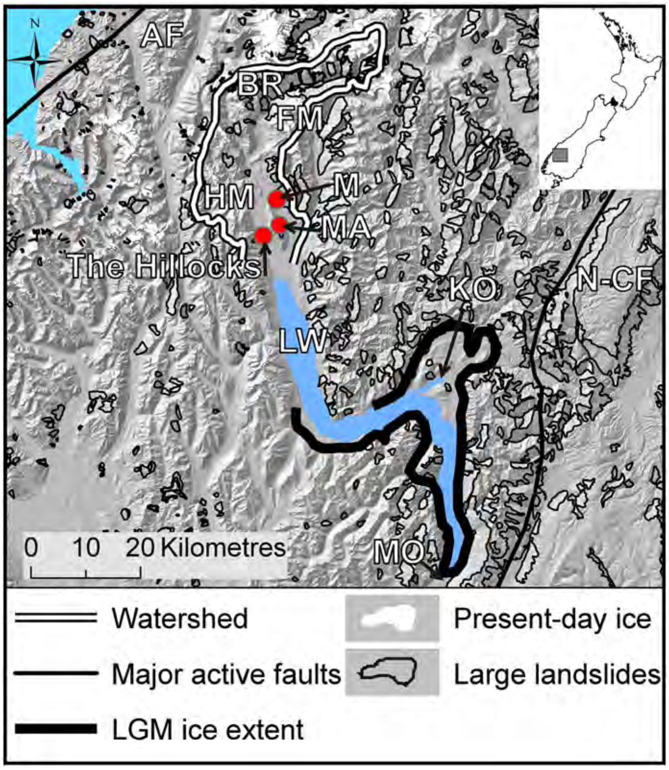

Fig. 1. The Hillocks and Dart River Catchment. LGM = c. 20 ka. Present-day ice distribution sourced from the Land Information New Zealand. Landslide distribution sourced from Turnbull (2000) and GNS Science Large Landslide Database. DEM is 25 m cell size, from Landcare Research. AF = Alpine fault; N–CF = Nevis-Cardrona fault; BR = barrier range; FM = Forbes Mountains; HM = Humboldt Mountains; M = moraine near to The Hillocks; MA = Mt Alfred; LW = Lake Wakatipu; KO = Kawarau outlet; MO = Mataura outlet.

investigation of the deposit sedimentology, lithology, morphology and geographical setting, details of which follow, we interpret the deposit to be of rock avalanche origin.

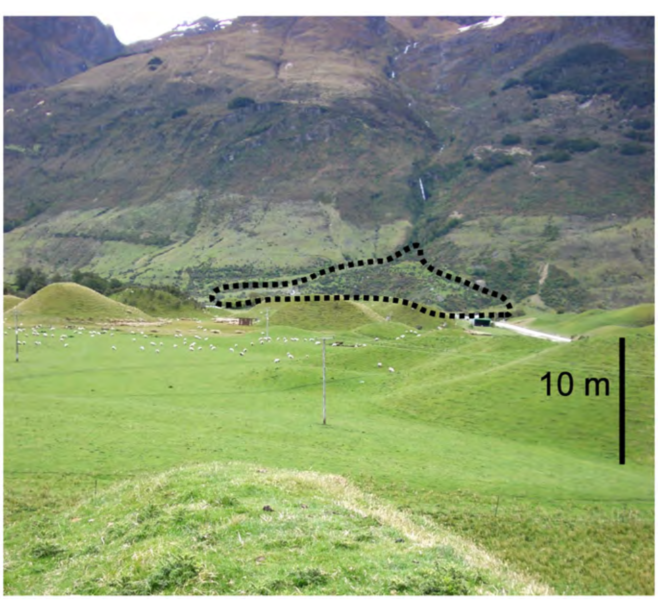

Fig. 2. The Hillocks, looking west with debris fan (dotted outline) mapped by Turnbull (2000) visible in back-ground. Landslide source area is just out of the picture at top right.

2. Geology and geomorphology of the Dart Catchment

The Dart Catchment lies within the Mesozoic Haast Schist Group in the Southern Alps, a region of metamorphosed greywacke (Turnbull, 2000) (Fig. 3). Weakly foliated volcaniclastic Caples terrane is predominant to the west in the Humboldt Mountains, while higher-grade schists (chlorite zone IIB and IV with well developed foliation and alteration) of the Caples and Rakaia terranes compose the Barrier Range and Forbes Mountains to the north and east, making up the greater part of the Dart Catchment. Elevations in the area range from c. 300–2300 m above sea level. Regional seismicity is high with the active Alpine and Nevis–Cardrona faults within 60 km of the study area (Fig. 1) and with major earthquakes of up to Richter Magnitude 8 on the Alpine Fault every 250–500 years (Berryman et al., 1992; Sutherland et al., 2006). Based on a regional probabilistic hazard model, Stirling et al. (2002) estimate a peak ground acceleration of 0.7 G for a 475 year return time for the Hillocks area.

Landsliding is a dominant form of erosion in the Wakatipu region, and within a 50 km radius of The Hillocks ~700 landslide features – source areas, deposits, areas of gravitational deformation – have been identified and mapped (GNS Science and Turnbull, 2000) (Fig. 1). Much of the landsliding occurs in the structurally weak schist but numerous landslides have been mapped in the less foliated rock.

Glaciations have helped to shape the landscape and form the characteristic large lakes in the region. The Dart glacier, the present day terminus of which lies some 50 km up-valley of the Hillocks, was once part of a much larger glacier that formed Lake Wakatipu (Fig. 1). The glacial history of the Otiran and earlier glaciations is reasonably well known for the Wakatipu area (Barrell, 1994; Turnbull, 2000) but is poorly known for the late-Glacial and Holocene time. The Hillocks and a moraine 5–6 km up-valley (Fig. 1) are speculated to be from an early Aranuian (present interglacial) advance (pers. comm. Royden Thompson) but there are no age-date data to support this. The level of Lake Wakatipu has fluctuated above and below its present level since its formation, in response to changes in drainage configuration (Barrell, 1994; Thomson, 1996).

3. Methodology

Topographic contours (20 m), Google Earth 3D, and the Wakatipu QMAP 1:250 k regional geology sheet and mapping by Kawachi (1974) were used for the identification and mapping of a likely source area for the landslide. Identifying the source areas in the field was not possible because of the difficult terrain.

A combination of satellite imagery (Google Earth), oblique photographs taken from Mt Alfred (1375 m.a.s.l.; Fig. 1), and a Garmin GPSMAP 60CSx were used to map the location of the hillock features remotely and on foot. Where groupings of hillocks displayed a predominant orientation, or formed approximately linear groupings, lines were traced over them to indicate the orientation.

Deposit sedimentology and lithology were examined and described at outcrop and hand-specimen scale at several exposures cut by the Dart River and Stockyard Creek (Fig. 4). Several large boulders exposed in the river and on the surfaces of some hillocks were examined.

4. Results

4.1. Landslide source area and locality

It is likely that a landslide large enough to form the Hillocks occurred in this locality. Other large rockslides and slope failures have been identified in the Humboldt Mountains (Fig. 1). Landslide debris adjacent to The Hillocks (Figs. 2 and 4) was mapped by Turnbull (2000) but hitherto a source area for this deposit had not been identified. The upper part of the slope above the deposit has a conspicuous concave profile and bowl-shape (Fig. 5). Such bowl-shaped depressions are often formed at the top of steep slopes by

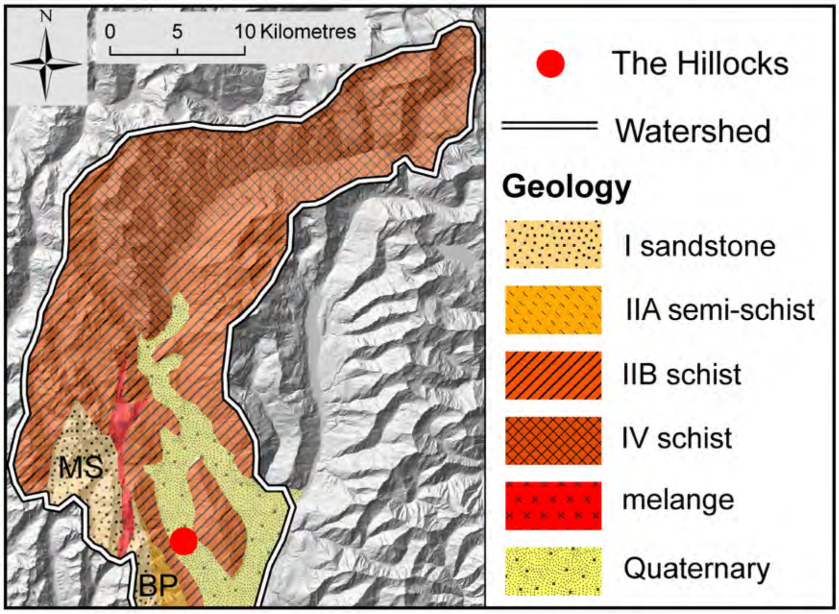

Fig. 3. Geology of the Dart River catchment simplified from Turnbull (2000). The prefixes I, IIA, IIB and IV denote the textural zone of the schist. See Fig. 1 for the geographic location of the catchment. DEM is 25 m cell size, from Landcare Research. BP = Bold Peak formation; MS = Momus Sandstone formation.

deep-seated coseismic rock slope failures (*cf*. Turnbull and Davies, 2006; Bazgard et al., 2009). We have mapped the extent of this source area and calculated a minimum volume of 22.5 million m^3, conservatively assuming a planar pre-failure surface.

The geology of the source area has been mapped as Bold Peak unit, a predominately weakly metamorphosed sandstone of the Caples terrane (Turnbull, 2000) (Fig. 5). The degree of metamorphism probably ranges from weak to moderate foliation, within textural

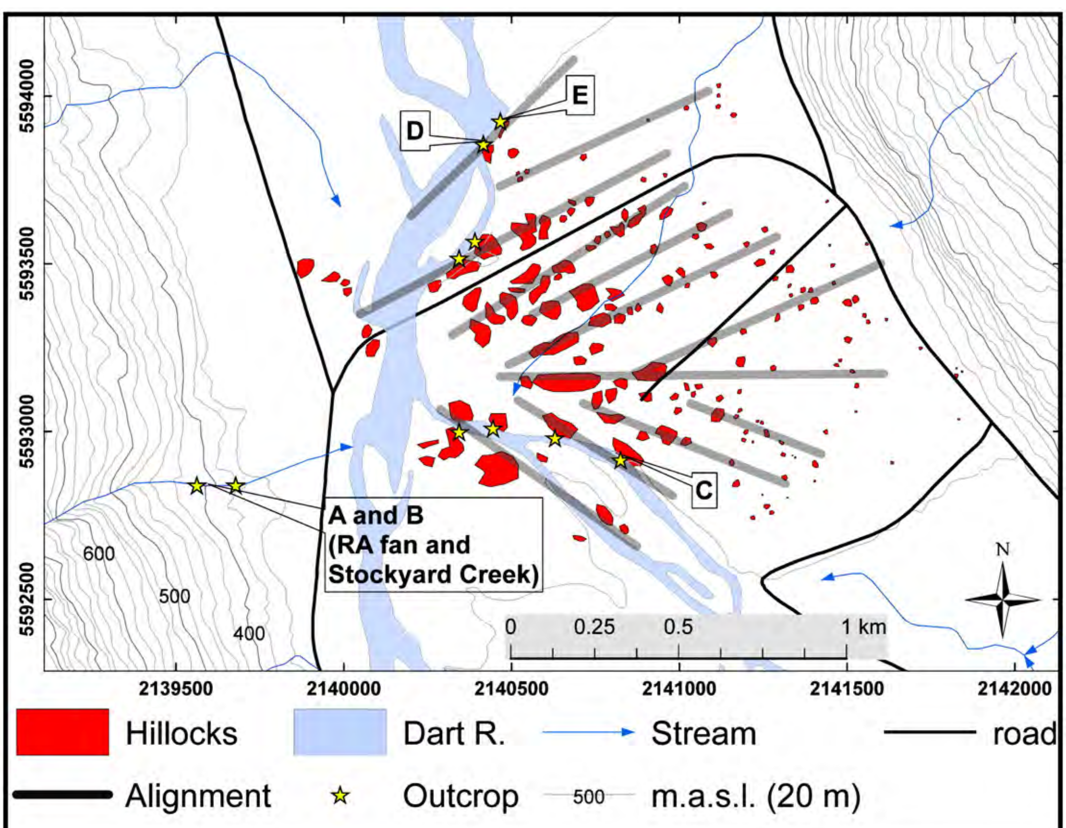

Fig. 4. The Hillocks, showing the distribution of hillocks and alignments and localities where exposures of hillocks were observed. The rock avalanche (RA) fan is indicated by the widely spaced contours at the base of Stockyard Creek. Letters A–E relate to Fig. 7 photograph locations. Contours (20 m) from Land Information New Zealand, data projected in Geodetic Datum 1949 with New Zealand Map Grid, 500 m grid spacing.

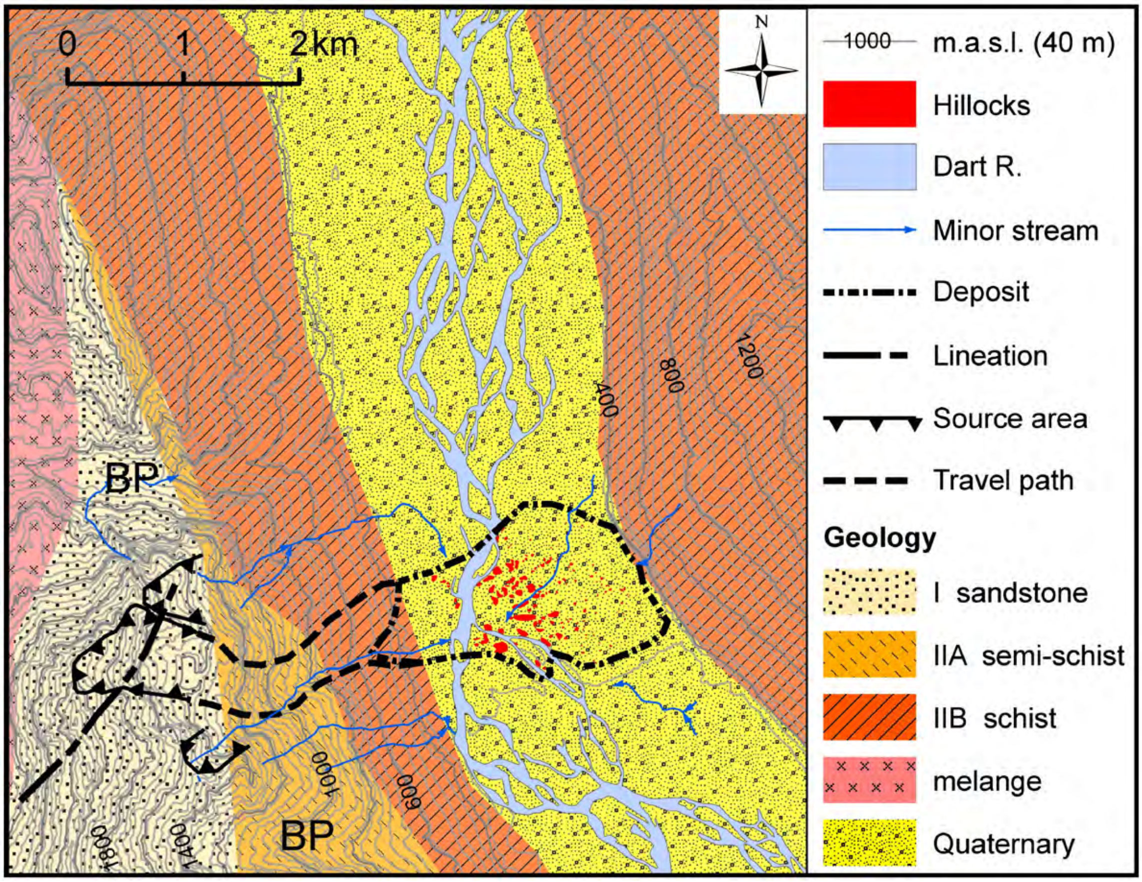

Fig. 5. Geomorphology and geology of the Dart Valley at The Hillocks, showing our preferred landslide source area, suggested runout path and deposit area. Contours (40 m) from Land Information New Zealand. BP = I and IIB textural zone Bold Peak Formation.

zones I to IIIa (Kawachi, 1974; Turnbull, 2000). We identify an unmapped structural lineation running through the proposed source area (Fig. 5) and suggest that it is a zone of weak rock, possibly a fault, that may have contributed to the failure.

The elevation difference (H) between the top of the source area (2040 m.a.s.l.) and the Dart River floodplain (340 m.a.s.l.) is 1700 m. The horizontal distance (L) from the back of the source area to the distal down-valley hillock is 5300 m. This gives a travel angle of $\tan^{-1}(H/L) = 18°$, which is of the normal order of magnitude for a rock avalanche of this volume (e.g. Legros, 2002).

4.2. Deposit morphology

A prominent feature of the floodplain deposit is the numerous conical hills (Figs. 2, 4 and 6). We have mapped c. 160 individual hillocks, with planform areas between 6 m^2 and almost 10,000 m^2 and with heights ranging from about 1 to 15 m above the floodplain surface. While most of the hillocks are conical, several in the more proximal part of the deposit are elongate. These elongate hills, as well as alignments of the conical hills, form a quasi-radial distribution converging towards the western side of the valley (Fig. 4). The course

Fig. 6. Panorama of The Hillocks from Mt Alfred (1375 m.a.s.l.) looking west. The <10 m wide semi-sinuous channel forms crossing the flat pasture are best observed right of the road. df = debris fan at Stockyard Creek. Black bar on road is 900 m long.

of the Dart River appears to be controlled by the distribution of the hillocks—the braided river is forced to narrow and travel westwards around the main cluster of the hillocks (Fig. 4). The size of the hillocks (both area and height) decreases from west to east. The area between the hillocks is a flat surface of uniform elevation but with small (<10 m wide), shallow (<1 m) palaeo-channels etched onto it (Fig. 6). The non-dendritic channels are approximately aligned in the direction of the valley long axis and are slightly sinuous.

On the true-right of the Dart River, below our suggested source area, a fan builds out from Stockyard Creek gully towards the floodplain hillocks at a slope angle of about 16° (Figs. 2 and 4). It has been dissected by up to 5 m by Stockyard Creek. Turnbull (2000) mapped this fan as landslide debris.

4.3. Deposit sedimentology and lithology

Three distinctive sedimentary facies were observed (Fig. 7). Facies 1 is most abundant and was identified in all of the exposures investigated, which included several locations where the Dart River has dissected hillocks, and the dissected fan at Stockyard Creek (Fig. 4). Facies 1 consists of tightly interlocking angular to sub-angular clasts that range from fine gravel to boulder size, with some boulders >4 m in diameter, and with fine-grain to coarse sand and silt matrix. The gross coarseness of the deposit is variable with the debris fan at Stockyard Creek being slightly finer than the other exposures in the hillocks. Facies 1 is homogenous without stratification. The rock type in each exposure is monolithic and across exposures it varies from non-metamorphosed to weakly foliated

Fig. 7. Sedimentary facies of The Hillocks (see Fig. 4 for photograph locations). A) and B) facies 1 in fan deposit showing coarse angular monolithic clast-supported material with matrix of fine gravels and sand. C) Coarser grained facies 1 in hillock exposure with extremely large boulder (10 m) overlaying (*cf.* Fig. 9B) (hammer in centre is 325 mm long). D) Contacts between (a) angular greywacke of facies 1, (b) rounded mixed lithology river gravels of facies and (c) facies 3 loess. E) Rounded mixed lithology river gravels of facies 2 positioned in an exposure between two hillocks.

sandstone with thin black mudstone lenses. Higher-grade schist (above textural zone IIIa) was not identified but low-to medium-grade schists (textural zone IIa and IIb) were found occasionally. Facies 1 appeared to control the overall shape of the hillocks. A lower contact for facies 1 was not observed but the facies was observed to be at least 5 m thick.

Facies 2 comprises well-sorted and well-rounded clasts of gravel to cobble size. It was found sometimes as a thin (<0.2 m) layer overlaying facies 1 on the lower parts of several hillocks (e.g. Fig. 7D) and as a thicker (0.5 to >2 m) stratified deposit between individual hillocks (e.g. Fig. 7 E). The gravels were a mix of lithology that included high-grade schists and quartz gravels, similar to the mixed gravels observed in the present-day Dart River channel.

A third facies identified was a soft well-sorted fine-grained (loess) deposit mantling many of the hillocks, up to several metres thick in places. It lacked obvious stratification; however, many of the exposures of this material had been affected by post-depositional reworking.

4.4. Deposit age

No quantitative age-dating has been done but several observations provide an indication of age. The source area does not appear fresh and substantial amounts of debris from rockfall and debris-flow processes have accumulated within the bowl-shaped source area. While the region was most likely deforested for farming by the 19th century, some trees remain on the slopes below the source area. These trees are in the path of the rock avalanche so they must post-date the avalanche, as would the few trees on and around some of the hillocks. The substantial mantling of the hillocks by fluvial and aeolian deposits, together with moderate soil development indicates that substantial time has passed since emplacement. Substantial time is also required for both the incision of the fan deposit by the small Stockyard Creek and the erosion of hillocks in the present Dart River channel, as indicated by clusters of well-rounded very-large boulders in the channel. It is also possible that a Maori Pa (village) was established here (pers. comm. Simon Cox, GNS Science, Dunedin), which would be consistent with Maori occupation of landslide generated hillock-features elsewhere in New Zealand (e.g. Mt Taranaki debris avalanche, Fig. 8A).

5. Discussion

5.1. Evidence for rejecting a glacial origin for The Hillocks

Before considering evidence that supports a landslide origin, we discuss evidence that we have used to reject a glacial origin for The Hillocks.

5.1.1. Glacial origin without landslide input

A dominance of coarse monolithic angular material precludes the possibility of a glacial origin not involving significant landslide input. Glacial till from basal and terminal ice melt, without a significant supraglacial landslide debris component, would be a matrix-supported diamicton accompanied by fluvially sorted and rounded outwash material. Further, it would have a mixing of different lithologies, including high-grade schist, sourced from the entire Dart River catchment. Glaciofluvial depositional processes, which would favour down-valley sorting and arrangement of sediments, seems unlikely to have formed either the quasi-radial alignment distribution of the hillock features or created the across-valley decrease in the hillock size. The localised extent of the hillock features, as opposed to their widespread occurrence throughout the catchment, is a further indicator that a purely glacial origin for The Hillocks is unlikely.

5.1.2. Supraglacial landslide origin

A supraglacial landslide farther up the catchment, with subsequent glacial transport to the present site, is a highly unlikely origin for The

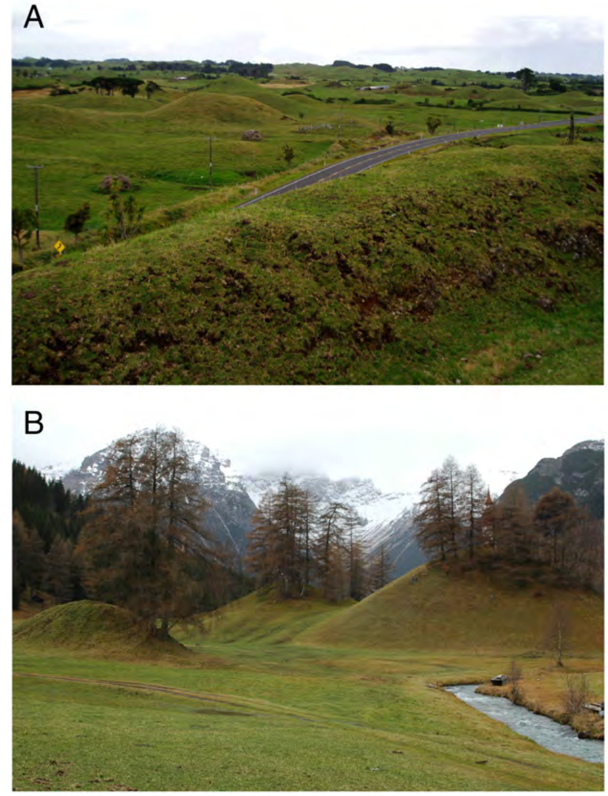

Fig. 8. Hummocky morphology of other unequivocal rock avalanche. A) Mount Taranaki volcanic debris avalanche deposit, New Zealand. Photo is taken from the trench of an ancient fortified Maori Pa (village) atop one of the hillocks. 8 m high power-poles give scale. B) Obernberg rock avalanche deposit, Austrian Alps. Trees provide scale (photo courtesy of Marc Ostermann).

Hillocks. It would require a large landslide source area of weakly-metamorphosed rock, and a process of deposition from the glacier surface that can create or preserve the pattern of hillocks.

5.1.2.1. Source areas. The only substantial sources of weakly-non metamorphosed rock in the Dart Catchment are the Bold Peak Formation and Momus Sandstone (Fig. 3). There is no sufficiently large landslide source area further up-valley in the Bold Peak unit. There is an apparent landslide scar immediately north-east of the source area we have identified that occurs in the Bold Peak unit (Fig. 5), however we judge that its outline is too small and ambiguous to confidently assign it as a source area for The Hillocks rock avalanche. The Momus Sandstone occurs in tributary catchments 10–15 km up valley from The Hillocks. No landslide features have previously been mapped in the non-metamorphosed Momus Sandstone Formation further up valley within the Dart River catchment (GNS Science & Turnbull, 2000), and no new ones have been identified in this study.

5.1.2.2. Emplacement and reworking. If the landslide from our suggested source area was emplaced onto the Dart Glacier, we would expect that the deposit would have been offset from the source area above Stockyard Creek by glacial transport, especially if the debris cover caused an advance (see McSaveney, 1978; Deline and Kirkbride, 2009; Shulmeister et al., 2009; Vacco et al., 2010). That the deposit was not transported by glacier flow suggests that, if emplacement was indeed onto the Dart Glacier, it must have been emplaced on to 'dead' ice being no longer capable of transporting it, which then melted to form the hillocks. It is unlikely that the distribution of the aligned and distally thinning hillocks would have been either formed by, or preserved during, this process. It is even less likely that such a pattern would have been preserved if the landslide source area was further up the valley, especially in the non-metamorphosed Momus Sandstone. Even if this was the case, it could be expected that during transport and final deposition by the glacier, significant reworking of the landslide debris with other glacial and glaciofluvial sediments would have occurred. There is no evidence for this.

5.2. Evidence for a landslide origin for the Hillocks

5.2.1. Source area and failure mechanism

We propose that The Hillocks formed with the emplacement of a large rock avalanche sourced from the bowl-shaped depression identified in Fig. 5. Given the deep-seated nature of the failure surface and its extension to the ridge-crest, a co-seismic trigger is probable (Turnbull and Davies, 2006). Other triggering mechanisms, which may include rainfall, snowmelt, snow loading, or a critical reduction in strength are less likely to have developed a deep-seated concave source area shape. The three largest (>10 M m^3) historical aseismic rock avalanches in New Zealand have involved failure of a prominent spur or rock slab (Owens, 1992; Hancox et al., 2005; Massey et al., 2008). In contrast, the coseismic Falling Mountain Rock Avalanche of 1929 left a large hole in the mountain (McSaveney et al., 2000).

5.2.2. Runout

The Hillocks rock avalanche would have travelled rapidly down the steep (30°) valley-side slope before spreading out onto the flat floodplain below. The travel angle of 18° is in the upper range of typical values reported by others for rock avalanches of this size (McSaveney et al., 2000; Smith et al., 2006; Strom and Korup, 2006; Devoli et al., 2009). A longer runout distance may have been prevented by the opposite valley wall (Mt Alfred) but no evidence for *brandung* runup is observed. It is likely that the runout distance has been underestimated because of burial or erosion of the deposit.

5.2.3. Sedimentology

The sedimentology of The Hillocks corresponds clearly to that of unequivocal rock avalanche deposits elsewhere. A rock avalanche generally comprises a thoroughly fragmented mass of monolithic, fractally-graded, angular clasts from sub-micron to boulder sizes, with a carapace of less-fragmented coarser rocks (McSaveney and Davies, 2006) (Fig. 9). We suggest that the deposit exposed in the Stockyard Creek fan represents internal rock avalanche debris whereas the material exposed in the hillock features is coarser carapace overlaying buried internal and basal debris.

5.2.4. Depositional environment and post-depositional processes

It is probable that at the time of emplacement the floodplain surface was lower than today, as evidenced by the absence of an observable lower contact for facies 1. Further, for the estimated source area volume of 22.5 million m^3 to approximately equal the deposit volume, an average deposit thickness of 9.5 m is required. This is ignoring any bulking factor but it is also using a minimum areal deposit extent based on the present distribution of hillocks. In any case, the visible (unburied) volume of sediment contained within the hillocks (<1 million m^3) is considerably less than the source volume. The deposit must be substantially buried, which is consistent with our interpretation in 5.2.3 above.

We suggest that the deposit blocked the Dart River because the hillocks extend to the opposite valley wall (Mt Alfred). The breach of the landslide-dam is likely to have been non-catastrophic; fluvial deposits (facies 2) between the hillocks indicate that the river flowed through the entire width of the deposit for some time. The river cut its present course through the western side of the deposit and appears to remain confined there by the remaining deposit. That the river cut through the western (proximal) side of the deposit, is not unexpected.

Fig. 9. Internal and carapace structure of other unequivocal rock avalanche deposits. A) basal exposure of the 1929 Falling Mountain rock avalanche, Arthur's Pass National Park, New Zealand, displaying a typical fragmented mass of angular greywacke sandstone in a matrix of finely comminuted rock. B) exposure of one of the hillock features (e.g. Fig. 6) of the Obernberg rock avalanche, Austria. The coarsely fragmented and angular rock, in this case dolomite, forms a typical carapace on the top of the rock avalanche deposit (photo courtesy of Marc Ostermann).

Debris of primary rock avalanches, *sensu* Strom (1996), travel as a single mass, of which most arrests towards the distal end of the runout path. The Hillocks rock avalanche can therefore be classed as primary because of the absence of hillocks on the western side of the Dart River (see Fig. 4) and the almost complete evacuation of debris from the source area. The Dart River would have cut through towards the western side of the valley because the deposit surface was most likely lower there. Subsequent progradation of the Dart River delta into Lake Wakatipu and the corresponding aggradation of the Dart River at The Hillocks is likely to be responsible for the partial burial of the deposit.

If the landslide occurred sufficiently early for Lake Wakatipu to have been at a higher level, it could have fallen into the lake water. Thomson (1996) suggests that prior to ca 7500 B.P. Lake Wakatipu drained into the Mataura River at the southern end of the lake (Fig. 1), with a surface level at about 355 m.a.s.l. This is ~15 m above the *present* Dart River level at The Hillocks; since that time the drainage switched to the Kawarau River, which is inferred to have degraded gradually to its present level. There is no evidence to suggest that the rock avalanche fell into a lake; neither lacustrine deposits on top of the debris nor splash deposits have been observed.

5.2.5. Morphology

The radially-aligned and conical appearance of The Hillocks is a well-known form in landslide geomorphology. Indeed hummocky terrain is one of the diagnostic features of landslide deposits, including those from rock avalanche, volcanic debris avalanche, and debris flow (Fig. 8) (Hewitt, 1999; Dufresne and Davies, 2009). Post-emplacement stream erosion or sediment mantling of a landslide deposit is more likely to produce channels and ridges that align down the valley axis rather than across the valley as observed here. Dufresne and Davies (2009), on the other hand, explain that rock avalanche flow dynamics can produce such features.

Dufresne and Davies (2009) explain that ridges develop from lateral instabilities in a granular flow (i.e. in a rock avalanche), especially one involving angular material travelling rapidly over an erodible substrate. These conditions are met by the suggestion that the Hillocks are a rock avalanche deposit emplaced onto river gravels. Dufresne and Davies (2009) also suggest that radially aligned hillocks are remnants of granular flow ridges that have begun to separate as the distal end of the ridge decelerates. Further, scattered hummocks may form when the lateral velocity of the flow is similar to the longitudinal velocity of the flow, as might happen when the flow becomes unconfined on a floodplain. We suggest that longitudinal ridges developed when the debris travelled onto the floodplain, and that lateral spreading as well as deceleration caused the breakup of ridges to create the approximately aligned divergent distribution of hillocks that we record. Post-emplacement sedimentation has partly masked any ridge structures and enhanced the conical appearance of the hillocks. The maximum height of the hillocks, which appears as 15 m above the present surface, would be greater if not for post-emplacement burial. Hillock features in other unequivocal rock avalanche deposits have been observed to be of a similar height up to tens of metres high (e.g. Fig. 8).

5.2.6. Hillocks age

The exact date of the event is yet to be determined but based on vegetative growth and possible Maori occupation, a minimum age of some 200–300 years can be assigned. Based on post-event modification of the source area and deposit the authors judge that the event may be closer to some thousands of years old. It must be considerably younger than the Last Glacial Maximum (~18–22 ka) when ice extended to the end of Lake Wakatipu some 90 km down valley (Barrell, 1994; Turnbull, 2000) (Fig. 1) and is probably younger than the drainage capture by the Kawarau River, i.e. younger than c. 7500 B.P.

We note that in many parts of the world, clusters of large coseismic rock avalanches date to the late-Glacial to mid-Holocene (e.g. Hormes et al., 2008; Agliardi et al., 2009; Hancox and Perrin, 2009; Sanchez et al., 2010). The timing we suggest for The Hillocks rock avalanche in the late-Glacial to mid-Holocene would be compatible with this pattern.

5.3. Implications and further work

The misidentification of landslide deposits as glacial moraine has two serious implications. First, it omits events from landslide records, therefore concealing the real likelihood of future landslide hazards—because landslides are more likely to occur in areas where landslides have occurred in the past. Besides The Hillocks, there are probably other landslide deposits in New Zealand that may have been misinterpreted, as is the case elsewhere in the world. 'Knobs Flat' in the adjacent Eglinton valley, also recorded in the New Zealand Landform Inventory as a glacial deposit, is one such example that requires further investigation. The perceived landslide risk at such sites may be dangerously low if the deposit has been misidentified.

Second, because of the longstanding practice of reconstructing past climates from glacial deposits, misinterpretation of origin leads to misinterpretation of past climate. The ongoing debate about inter-hemisphere climate synchroneity and the presence of a Younger Dryas event in New Zealand is complicated by such misinterpretations (Vacco et al., 2010; Ivy-Ochs et al., 1999; Schaefer et al., 2006; Tovar et al., 2008; Schaefer et al., 2009; Shulmeister et al., 2009; Winkler and Matthews 2010).

There is an urgent need for a systematic review of existing interpretations, and an improved methodology for distinguishing between the landforms and sedimentological characteristics that each process (landsliding and glacial sedimentation) produces.

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