

## ***Interactive comment on “Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss” by Douglas I. Benn et al.***

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Thank you for these detailed and constructive comments. We have revised the text and Figures to take the comments into account, as detailed below.

1. Part of the justification for the study (lines 63-71) is that we still know relatively little about englacial conduit formation, and specifically the relative importance of the three processes previously described in the two Gulley et al., 2009 papers and summarised in Benn et al., 2012. Although not stated explicitly, the subsequent analysis here suggests that cut-and-closure is the dominant, or even exclusive, mechanism, at least on Ngozumpa. Given that the argument against NG-01 to NG-03 being structurally con-

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trolled (lines 308-311) could be invoked for most conduits running parallel to flow, and that to my knowledge there have been no direct observations of hydrofracture here or in the wider region, some actual discussion of their relative importance would be an interesting addition to the manuscript. Based on their additional analysis, do the authors now believe that cut-and-closure is the dominant mechanism for these debris-covered glaciers, or does it just happen to prevail at Ngozumpa? Or is it paired, in that cut-and-closure forms the conduit in the first place, and then the relict channels provide the dominant structural control thereafter? Or some combination of these? Some clarification in the revised text would be a good addition.

A paragraph has been added (L 610-17) to clarify these points.

2. The least-well constrained element of the paper is the analysis of the existence or otherwise of a subglacial hydrology, understandably so. In the absence of any direct observations, the velocity proxy provides some evidence for subglacial water in the upper ablation area, but if the authors are correct in their interpretation of this, what happens to it then? I'd be interested to see some further discussion of the lower ablation area – if as stated (line 507) all of the water leaving the glacier passes through Spillway Lake, do the authors propose that the subglacial waters from the upper ablation area pass through the lower ablation area and are then elevated at the terminus under pressure? Some direct measurement of the discharge would give an indication of whether it is at least the correct order of magnitude for a glacier of this size, but in the absence of this some discussion of whether it might go to deep groundwater, or shallow groundwater and then emerge further down-glacier, would fill this gap. The hollow that drains the supraglacial channels (line 384) is also important in this regard – it hints at a direct surface-to-bed connection but there is no further information given – can any more light be shed on where these waters go?

Although we lack sufficient data to answer these questions, we have added speculations (L381 & 505-8) to address the issue of water routing.

C2

3. The interpretation that hummocky closed basins cannot support a supraglacial hydrology is believable, but there is a spatial mismatch between the analysis shown in Figure 9 and the observations shown in Figure 8, which detracts from the argument. If this is the dominant control on supraglacial water (and the interpretation in Figure 13 hangs on it being so) then can the analysis in Figure 8 be extended up so we can see if it prevails in the upper ablation area too? Or at least see some morphological/topographic differences between c) and d) in Figure 8.

There is indeed a gap between areas where channels are visible on the glacier surface and area where surface basins can be reliably mapped. We have addressed this mismatch by identifying a 'transitional zone', now discussed in the text (L 411 ff.), and shown on Fig. 9 (previously Fig. 8) and a new Figure 3.

L86: 7922 m here but 7952 m in Figure 1.

>The true elevation is 7952 m, and this has been corrected in the text.

L95: I suggest stating that it is 'effectively' stagnant, since it is probably deforming at some rate, just not detectable by the satellite analysis.

>The change has been made

L130 and elsewhere: just a note that the terms pond and lake are used interchangeably – I'd have a preference for using the former for the majority, which are perched and relatively small, and saving the latter for Spillway Lake, which is not.

> Done as suggested.

L158-167: can you add some more detail on the masking/filtering that is evident in Figure 7? And what is the threshold of 'detectable flow' referred to in line 95 – I guess that should be mentioned here too.

> No masking or filtering was applied. A note on the definition of 'detectable motion' has been added in L171.

### C3

L331: Length of stagnant zone - this is 7 km earlier in the manuscript.

> This has been changed to 6.5 km in both cases.

L351: should these artifacts not be masked as per Fig 7a? As it stands, it looks like you have greater confidence in the speed-up data than the annual pair measurements, which can't be right since you derive the former from the latter.

> Neither the absolute nor differenced velocity maps have been filtered, and the existence of velocity difference data in areas of no apparent absolute annual displacement is simply a result of the scales used. A note has been added to the caption of Fig. 7 to point out the lack of masking and filtering.

L364-366: there's some contradiction with the Figure caption here – the text says there are only crevasses in the upper part of the clean ice tongue (c), but the caption states they are only in (a)?

> The text has been corrected.

L371-373: this is the only hint at what happens to the subglacial water after it descends from the upper ablation area – can you offer any insight into where it may go then? Lines added to 375, and 491 ff, to speculate on fate of subglacial water.

> We have added the speculation that the subglacial water is drained via the sub-marginal channels.

L382-385: this hollow is quite an important part of the picture, particularly if it shows the surface is connected to the bed directly – is it the same hollow that Horodyskuj monitored? Is it a moulin? Can you offer any further information on it?

> This is not the same hollow, as is now made clear in the text. We have no evidence that direct surface to bed drainage occurs in any of these basins, and decline to speculate about this issue.

L396: Figure 9 does not extend sufficiently far up-glacier for us to be able to verify this

### C4

is true – can you extend the analysis to make this argument more robust?

> Basins cannot be reliably delineated any further upglacier. Text and a new figure have been added to explain this in terms of a 'transitional zone'. (see reply to Point 3 above)

L402-415: the number of basins etc is interesting here but the upper boundary of the analysis seems arbitrarily defined. Why not cover the whole of the debris-covered area? That way others can repeat the analysis for future time periods and quantify the change.

> see previous comment

L410: Figure 9 doesn't show any full drainage events, unless these are lumped into the < 1000 m2 category? Shouldn't they be shown as 'empty'?

> Empty basins in any one year are indicated by 'missing' coloured circles - The caption has been modified to explain this.

L425: do they have to be relict, necessarily?

> 'relict' has been changed to 'active or relict'

L425-427: as above, I can't see the evidence for 35 drainage events – can you make this a bit clearer?

> see comment on line 410.

L424-427: can you add an acknowledgement that there is a seasonal signal in these data?

> We do not have a good enough data series to reliably identify a seasonal signal.

L439: they're probably underlain by thick sediment too, inhibiting bottom melt.

> We do not have any data on pond bottom sediment thickness, so decline to comment.

L456: this disparity between the number of basins on the west and the east sides merits

C5

some further comment – does it reflect the dominant englacial drainage pathway? Or debris-thickness? It's a stark contrast when looking at Figure 9.

> This is indeed striking, but the reason is unknown. We think that speculation neither justified nor helpful.

L460: missing 'the'

> added

L471: Horodyskuj (2015) is not in the reference list.

> Added

L507: can you be sure that all of the water passes through Spillway Lake?

> A sentence has been added to qualify this statement.

L518-521: can you bring this into line with the six elements stated in the abstract?

> Done.

L528: 3° gradient.

> A statement about glacier gradients (line 105) and a new Figure 3 has been added to clarify this issue.

L543-544: it'd be better to show these basins superimposed on Fig 14b, rather than repeating the channels on both figure panels.

> The figure has been redrafted to make the evolution of this part of the glacier clearer.

L545: can you indicate where these elongate ponds are on the figure for clarity?

Done.

L546-549: the figure referred to here doesn't relate to the text. Do you mean figure 10 instead? clarify

C6

This has been corrected.

L553: where does this thickening debris cover come from?

> Text has been added to explain this.

L557: note cut-and-closure is hyphenated in some places but not in others.

> Changed to 'cut-and-closure' throughout

L589: section numbering jumps one here.

> The numbering has been corrected.

L626-627: remove the bracketed text since it is clear already?

> Bracketed text has been removed.

L662-664: interesting that the Khumbu ponds also follow what might be a sub-marginal channel.

Agreed. This is something for others to investigate in detail.

L666: this sentence implies that Ngozumpa is in a more advanced stage of recession than others in the region – is this what you mean? I'm not sure it is much different to others except for Spillway Lake?

> Not all others - for example, Imja and Trakarding have large base-level lakes. Base level lakes do not yet exist on Khumbu Glacier. Spillway Lake is an important example of a transitional stage.

L669: maybe 'interpretation' is better than 'view' here?

> Changed as requested.

Figure 7 (now 8): mentioned above too, but how can b) have more coverage than a) given that it is derived from a)?

C7

> The difference map also depends on the winter velocities (not shown). Also, the velocity scale in a) fades to grey, so small velocities (which can contribute to velocity differences) are not visible. Text has been added (L 358) to point out that the small changes indicated on the lower glacier are below the margin of error.

Figure 8: what are the coloured dashes here?

> They delineate the areas identified by the letters.

Figure 11 (now 12): are there no better data than these TM images? Only because they're poor resolution. Do the 2010 and 2012 data you have not cover these areas? At least could you superimpose your interpreted pond boundaries?

> Pond boundaries superimposed to make the figure clearer.

Figure 12 (now 13): maybe add that the reader should see the text for explanation of the annotations?

> Text added to caption

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