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RE: RC C1120

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We write in relation to the manuscript 'Glacier-like forms on Mars' submitted for publication in The Cryosphere. We thank reviewer 2, Matthew Balme, for their expert comments and summarise our response to each suggestion that was raised below.

Comment (unedited)	**Response**
Reviewer 2 (RC C1120 Matthew Balme):	
The only major question I have is whether the case studies provided are sufficient, in and of themselves, to support a research article. This lack of weight is seen in the summary, in which most of the bullet points reference "review" aspects. However, having said that, the forward looking part of summary is extremely useful, and so with a bit of 'beefing up' of this section the paper would be improved.	We agree with the reviewer that this contribution includes elements of both a review and a research paper. It has been necessary to combine these two elements in order to bring this information to the attention of the broader cryospheric community. We also follow the reviewer's advice and have inserted references to the data or case studies presented herein to the appropriate statements in the paper's Summary (p. 2977 lines 5-24). Amended text is as follows: *"– Many GLFs were previously more extensive and thicker than at present, possibly now representing the remnants of former large ice sheets. In Section 2.2.1 (above) we identify a distinctive proglacial zone some 3 km wide surrounding a GLF located in Phlegra Montes. This zone, bounded along its distal edge by moraine-like ridges is interpreted as having been recently deglaciated and is likened to a similar proglacial region bounding Midre Lovénbreen, Svalbard, on Earth.* *– GLFs flow slowly downslope through a combination of ductile and (less common) brittle deformation. In Section 2.3.3 (above) we identify and interpret four slightly contrasting sets of crevasses located on two martian GLFs in terms of variable strain regimes. These crevasses are also shown to range from being relatively fresh in appearance, implying a correspondingly young age, to appearing blunt and degraded, implying earlier formation and possibly a relict current condition.* *– GLFs have the ability to transport debris, forming large bounding moraines and depositing boulder trains extending for several kilometres along-GLF. In Section 2.4.1 (above) we identify an extensive supra-GLF debris train which we interpret in terms of passive transport from specific ice-marginal supply points. Reconstructing boulder transport distances since GLF formation (over the range 5.0 to 0.5 Ma ago, with a best estimate age of 2.0 Ma) yields an equivalent provisional GLF surface velocity range of 3 - 30 mm a^{-1}, with a best estimate of ~7.5 mm a^{-1}.*

	– GLFs currently show little influence of liquid water, confined to postulated intermittent surface melting which is insufficient to form coherent supra-GLF drainage. In Section 3.1.1 (above) we illustrate that such supra-GLF incised channels occur on several GLFs and are not confined to the single instance at which they have hitherto been reported. However, more extensive former GLFs, and/or their predecessor ice masses, may have been partially wet-based."
P 2959 line24. What types of images were examined? What percentage of the global surface area was observed?	The survey was completed with CTX imagery and covered ~25% of the martian surface. For clarity this sentence has been amended to: '*In their inventory of Mars' GLFs, Souness et al. (2012) inspected >8,000 CTX images, covering ~25% of the martian surface, and identified 1,309 individual forms, reporting the location (Fig. 2) and basic morphometry of each.'*
P 2960, line 1-3. Distribution of GLFs. Were these numbers normalised by (1) total area observed (i.e. is the coverage the same in both hemispheres (2) by surface area (i.e. higher latitudes have small surface area in a given latitude band)? If not, can this be done? This is specifically important for the discussion of clustering – does this reflect true clustering, or just a concentration of images? Without such normalisation, the results are not so compelling	The reviewer is correct in pointing out that the coverage of 'parent' images reported by Souness et al. (2012) was not spatially uniform, and that inferred GLF clustering (which was not normalised) could therefore be to some extent an artefact of image clustering. That said, with over 8000 images, spatial coverage is good for the latitudinal bands investigated in both hemispheres and – although not statistically proven by Souness et al. (2012) - it is clear from inspection of Figure 2 that GLFs are spatially clustered. Since we only report these data as background review information (clearly attributed to Souness et al. (2012)) we choose not to revisit these data and attempt a statistical normalisation here. Instead, we amend the text to point explicitly to the raw nature of the data we report by amending the sentence on p. 2960 line 4-8 to: *"Although Souness et al. (2012) did not normalise their GLF count to (spatially variable) image coverage, inspection of Figure 2 strongly suggests that GLFs are locally clustered in both hemispheres, for example along the so-called "fretted terrains" (Sharp, 1973) of Deuteronilus Mensae, Protonilus Mensae and Nili Fossae in the north and around the Hellas Planitia impact crater in the south."*
P 2960 Line 19. How do we know the regolith is dust-rich?	This raises an interesting point. This surface layer is generally assumed to be dust-rich, but there is some evidence to indicate that this surface material is at least easily deformed and boulder-poor. Evidence for the former is provided by incisions left behind boulders that have rolled onto the GLF's surface (see for example Fig. 5a in Hubbard et al. (2011)), while the latter boulders would be seen in HiRISE images (resolution ~25 cm), from which they are notably largely absent (as evidenced by Section 2.4.1 of this contribution). Nonetheless, we cannot be sure the surface regolith is 'dust' rich and we amend the adjective to 'fine-grained' where appropriate.
P 2961 Line 9-11. According to the Laskar model results, (Laskar, J., A.C.M. Correia, M. Gastineau, F. Joutel., B.	We agree that as written the section could cause confusion relating to short and medium scale orbital fluctuations. For clarity the section has been replaced with the following: *"While it is thought that Mars' last major ice age ceased when martian*

Levrard, and P. Robutel. 'Long Term Evolution and Chaotic Diffusion of the Insolation Quantities of Mars'. Icarus 170, no. 2 (2004): 343–64.) mean obliquity decreased about 5 Ma BP and has been stable at around 25 ◦ for ∼ 3 Ma. There have been numerous cyclic obliquity excursions since then, which might have triggered 'ice ages'. In the time period specified here, the obliquity was much more variable than in the preceding 0.5Ma, changing from nearly 15 to nearly 35 degrees on very short (∼100ka) timescales. As written, this section appears to mix up these two concepts.	*obliquity changed from ~35^o to ~25^o between four and six million years ago (Laskar et al., 2004), evidence of a subsequent, late-Amazonian ice age has been proposed (Head et al., 2003). It is thought that during periods of short term obliquity cycles (~100 ka) between ~2 Ma BP to ~0.5 Ma BP, obliquity still exceeded 30^o. During these intermittent periods increased solar radiation led to the melting of Mars' polar caps, the release of moisture into the atmosphere and its precipitation as snow or condensation above or within the ground at lower latitudes (e.g. Forget et al., 2006; Hudson et al., 2009; Schon et al., 2009)."*
P2965 Line 6. Is the Smooth Terrain type related at all to GLFs?	We do not have evidence to evaluate this possibility – but the smooth terrain does appear to be ice-rich and older (from a visibly higher crater density). Evaluation of large-scale regional glaciation in this and other sectors is beyond the scope of this submission, but remains to be evaluated as more images become available.
P2965 Line 17. The MLRs are all contained within each other. Does this lack of transgression tell us anything? Do any MLRs record transgressions across a terminal moraine by more recent glacier activity?	We know of no examples on Mars of moraines crossing each other, indicating a later advance taking a different path from an earlier one. This is to be expected since GLF growth would closely follow the geometry of the existing terrain, leading to advances of similar morphometries. Without any dating constraint, all we really can say from these nested moraine-like ridges is that (i) recession was punctuated and (ii) the innermost ridges were formed later than the outermost ridges.
Page 2967 Line 1. Does this 'model restriction' to 2 dimensions make any difference? This is the sort of thing where planetary science can really learn from terrestrial expertise. Can the authors expand on what the benefits (if any) are of using a more	Yes it does. Although pioneering and valuable, the model used was in fact one dimensional (not 2-d; we have corrected this in the revised text) and restricted to a point analysis of the strain anticipated on the basis of local stress under a typical range of VFF conditions. This non-spatially-distributed approach showed that VFF flow could occur at the rates and timescales expected, but it did not consider the spatial distribution of stresses present throughout the geometry of an actual VFF. In contrast, a spatially-distributed implementation of such a stress-strain relation considers the spatial arrangement of stresses (locally in a 'first order' model and inherited from elsewhere in a 'higher order' model). Once developed and applied to a given VFF/GLF geometry, such a

complex model?	model can be used to investigate both its steady-state condition and its response to imposed environmental changes. Clearly, the development and application of such a spatially-distributed model would therefore represent a major glaciological advance. To correct, clarify and expand slightly we amend the revised text (p. 2966 line 21 to p. 2977 line 3 to: *"In an effort to shed some light on the likelihood of GLF motion, Milliken et al. (2003) applied the multi-component constitutive relation of Goldsby and Kohlstedt (2001) to typical ranges of VFF temperature, slope and (assumed) ice grain size. … Although the application of this stress-strain relationship to martian VFF conditions represented a major advance, the model was not distributed spatially and was not therefore applied to, nor considered, any particular VFF geometry."*
Page 2968 Line 12. Does it have to be exposed by excavation, it could be caused by a lack of regolith deposition in this area?	We agree, and amend the revised text accordingly to: *"Crevassing therefore occurs, or is at least more readily visible (i.e. exposed by the absence or excavation of supraglacial regolith), in these specific areas."*
Page 2971 Line 1. Why is the erosional headwall similar to a depositional lateral moraine? This needs to be explained more fully.	This statement makes reference to the work of Hubbard et al. (2011) as background information, preceding the case study in Section 2.4.1. The original text is clear in this ("These authors likened this 'incised headwall terrain' to ice-marginal lateral moraines on valley glaciers on Earth"). Nonetheless, it is an interesting point as to why this GLF's headwall is sediment-rich and therefore visually similar to terrestrial medial moraines. It could well be that higher-up the headwall is eroded into rock and lower down into deposited sediment. In this case we do not amend the text as the distinction is a small one (and possibly be read as unnecessarily confusing if made), while the text is accurate (stating the interpretation of the earlier published work).
Page 2973, line 10. It would be relatively simple to estimate the error on this velocity, or at least provide a realistic range in which the actual number would sit. This should be done. Without the acknowledgment that this is not a precise measure, this number could end up being used in future models etc without question.	Although we do describe our method and assumptions in the text, we also agree that a 'hard' figure such as this should come with some caveat. Since the boulder travel distance is fairly well fixed the likely error involved comes from our original assumption – clearly stated – that the GLF's age is 2 Ma. In line with general consensus we now amend the calculation to consider a range of ages from 0.5 to 5.0 Ma, with a centre 'best estimate' of 2 Ma based on the onset of the proposed late Amazonian ice age (see revised Section 1.1.3 and response to C1120 comment above). We amend this text (and elsewhere, where appropriate) accordingly to: "*In the absence of any firm age constraint on this particular GLF, we adopt a 'best estimate' age for its formation of 2 Ma, at the onset of the proposed 'late Amazonian' ice age, and a likely age range from 5 Ma - the middle of the last major ice age on Mars - to 0.5 Ma - the end of the proposed 'late Amazonian' ice age (Section 1.1.3 above). Thus, if boulder transport was initiated at the time of GLF formation from point "I." on Fig. 8c it follows that, for those*

	boulders to have been transported passively to the distal end of Population G, GLF #498's minimum centreline velocity was within the range of 3 – 30 mm a^{-1}, with a best estimate value of 7.5 mm a^{-1}." We also amend references to these figures in the Summary (see response below) and Abstract accordingly.
Section 3.1.1. The evidence presented for these channels is the weakest part of the paper. It is very hard to differentiate between the background pattern of fractures and potential channel-like forms. In the sketch elements of fig 10, perhaps only the most convincing ones should be shown, and the matching features marked with arrows in the image? Also, use of the term "strongly indicate" seems to be overly confident	We take the reviewer's point entirely in this case. The problem, we believe, lies not in the evidence for the channels – which appear fairly clear on high-resolution screen images – but in illustrating them as small panels within a figure of limited resolution. We therefore amend Figure 10 to include only one additional case (panels a – c of the original Figure), and re-align them vertically to allow expansion.
Section 3.2. Could the authors discuss possible evidence for possible pro-glacial channels systems too? Do any GLFs have channels 'downstream' of them?	As far as we know, there is no evidence of pro-GLF fluvial activity (the martian equivalent of pro-glacial streams). This is stated in the original text at the start of Section 3.2 (p. 2975 lines 13-14) as follows: "… *present-day GLFs show little or no sign of the presence or influence of liquid water. For example, no evidence of pro-GLF fluvial activity has been reported*…"
Section 4. The 'current unknown aspects' part of the paper is very important, and the authors have identified some useful points. I think that they could expand upon each point to say which aspects could be determined using current (or planned future) data, and how. Thus, rather than just being a 'wish list', this part of the paper would read more like a	We thank the reviewer for this insightful recommendation and have amended several of the itemised pointers for unknown aspects to include a brief indication of how they might be addressed. We have deliberately kept these pointers brief and general to avoid appearing at all prescriptive; there will almost certainly be cryospheric researchers with novel methods that we are not aware of but which are appropriate to address these issues. The revised text is as follows: *"– It is not known whether GLFs are currently active or whether they are decaying relics of previously active forms. Diagnostic indicators of such activity would include any indication of motion (addressed below) and for a GLF to have a surface profile that is in balance - as indicated by a spatially-distributed numerical model of GLF flow - with current climatic conditions.* *– The previous extent of GLFs, and their putative parent ice sheets, is still only*

roadmap.	*poorly understood. This requirement could be addressed through additional field mapping at a variety of spatial scales, based on CTX or High Resolution Stereo Camera (HRSC) images at the regional scale to HiRISE images at a local scale. Such mapping could be targeted at identifying markers of former ice extent such as specific surface terrains, subglacial deposits and ice-marginal moraines.* *– The thermal regime of former GLFs is unknown, and the possibility of partial wet-based conditions remains unproven and their extent unevaluated. This could be evaluated empirically or theoretically, ideally through a combination of both. Empirical evidence could include the identification of indicators diagnostic of wet-based conditions (e.g., bedforms such as mega-scale glacial lineations) or of subglacial drainage (e.g., meltwater channels or eskers). Theoretically, former thermal regime could be estimated from the application of a thermomechanically-coupled ice-flow model to reconstructed former ice mass geometries under realistic climatic conditions for the time.* *– The basic mass-balance regime of GLFs is unknown. Whatever the spatial expression of this regime, there is no compelling climatological reason for it to comply with the common terrestrial valley-glacier model of net accumulation at high elevations gradually giving way to net ablation at low elevations. This is possibly the most challenging unknown GLF property to elucidate, and would likely require several lines of evidence to be combined. Central to these might be a regional evaluation of GLF extent in the light of corresponding regional variations in meteorological conditions. A modelling approach may also shed some light of the mass-balance regime of GLFs, for example, through comparing modelled GLF geometries and flow with empirical data under a variety of modelled mass-balance patterns.* *– The 3-D geometry and internal structure of GLFs is unknown. Although SHARAD radar data are available and capable of mapping ice thickness, the data are of fairly coarse resolution and have limited spatial coverage. Very little information is therefore available to allow the basal interface of GLFs to be identified and mapped. This property is also critically important because spatially-distributed models of ice mass flow depend sensitively on accurate bed geometry. In this case, new and existing SHARAD data could usefully be mined to locate intersections with known GLFs – providing a first approximation of bed profiles. Further to that, modelling-based sensitivity analyses (to GLF depth) could also be used to constrain likely bed geometries.* *– Mechanisms of GLF motion are poorly known and, apart from the estimate of 3 – 30 mm* a^{-1} *presented herein (Section 2.4.1 above), it has not yet been possible to measure surface velocities on any martian GLF. Further research based on indicators of surface displacement – such as the boulder analysis presented herein – could usefully be used to refine the range we propose. As the period of time between repeat HiRISE images of certain GLFs increases it may also become possible to identify contemporary GLF motion on the basis of feature or speckle tracking. Indeed, a single such measurement would provide a major advance in our understanding of the dynamic glaciology of martian GLFs*

	– particularly if the GLF concerned could also be modelled. *– GLF-related landforms such as lineations, drumlin-like forms, surface cracks/gullies and possible eskers remain largely unexplored and their basic morphometric characteristics are unreported. Targeted mapping from HiRISE images remains the best way to identify and evaluate such landforms. The online inventory accompanying Souness et al. (2012) would provide a suitable starting point for identifying candidate regions of interest.* *– Although considered to be rich in water-ice, the internal composition of GLFs remains unknown, despite these material properties having important implications for GLF dynamics and our ability to model GLF behaviour accurately. Apart from direct sampling in the future, which is unlikely in the near-term, SHARAD data analysis may be combined with numerical modelling to further constrain the internal composition of GLFs. Opportunistic images, for example shortly following a meteorite impact, may also continue to yield information relevant to GLF sub-surface conditions*."
Page 2958, Abstract, line 2. "Visually similar…being composed of…". Referencing 'visual similarity' and 'composition' makes the sentence confusing as written, just needs a tweak in structure.	We agree and amend the sentence to: "*These GLFs are predominantly composed of ice-dust mixtures and are visually similar to terrestrial valley glaciers, showing signs of downhill viscous deformation and an expanded former extent*."
Page 2960 Line 13. How were the mean bearing calculated?	Souness et al. (2012) calculated the mean bearing as that from the centre pixel at the head of each GLF to the centre pixel at its terminus. Since we are summarizing the results of previous research here we do not add an explanation of this method to the revised text.
Page 2964 Line 1. "much-contested sinuous ridges". Presumably, this means that their formation mechanism is still hotly debated. If so, more detail is needed to explain what the debate consists of. Alternatively, this could be deleted as it doesn't add much here anyway.	We have deleted this statement from the revised manuscript as it is tangential and unnecessary to the argument.
Page 2967 Line 6. "relatively unambiguous, universal diagnostic indicator" is a contradiction.	We agree and have altered to: *'Fracturing is a universal diagnostic indicator…'*

Fib 7b. The contrast could be improved on this figure, and arrows added to show the features of interest. The same applies to several other figures, where features should be identified with arrows or labelled in some other way.	Agreed and, as well as Figure 10 (see comment above), Figures 7 and 8 have been amended to improve clarity.
Page 2973 Line 18. The idea that Mars was both significantly warmer and significantly wetter in the past is still debated. Suggest toning down this statement, or add reference to the alternate point of view.	We agree and have toned the text down and added reference to an alternative viewpoint as follows: *"Although still debated (see Ehlmann, 2014; Robert, 2014), early Mars appears to have been both warmer and wetter than at present (Kargel, 2004). Current surface conditions are relatively cold and dry (see Section 1 above), and are consequently no longer conductive to the survival of surface water."*
Page 2973 Line 23. Earlier, more fundamental RSL papers than Stillman (2014) exist. Suggest these should be cited too/instead.	We agree and have altered the reference to McEwen et al. (2011).
Page 2974 Line 1. Is there a reference for the gullies eroded into pro-GLF material?	Yes, we have added reference to Hubbard et al. (2011).

Please do not hesitate to request any further information you might need. I look forward to hearing from you.

Kind regards,

Bryn Hubbard (corresponding author)