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Interactive comment on "Timing of exotic, far-travelled boulder emplacement and paleo-outburst flooding in the central Himalaya" *by* Marius L. Huber et al.

Anonymous Referee #2

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Review of Huber et al. "Timing of exotic, far-travelled boulder emplacement and paleo-outburst flooding in the central Himalaya" – ESurf, April 2020.

Huber et al. examine a series of large boulders in the central Himalaya. The lithologies of these boulders suggest that they are sourced from further upstream, over 40 km in some instances, implying they have undergone significant transport to reach their current location. Using cosmogenic radionuclide exposure dating of the boulders, Huber et al. find their ages tend to cluster, with the most notable clustering in ages being around the Early Holocene Climatic Optimum, ~5 ka. They infer that these boulders have been transported by large glacial lake outburst floods (GLOFs), which may have

been more prevalent in the region at this time as climate transitioned into more arid conditions that would have promoted widespread glacier retreat. Using digitized topographic maps to determine valley-cross sections and gradients, peak discharge values that would have been required to mobilise these boulders were calculated using 3 different methods. The authors conclude that the magnitude of flow to transport these boulders is larger than what could be achieved by modern monsoonal discharges, but comparable to other documented GLOFs. The authors comment on the wider importance of this work in terms of the interactions between large, infrequently mobilized boulders and bedrock incision patterns and longer-term landscape evolution, as well as understanding climatic controls on lake outburst flood frequency and magnitude.

In general, the manuscript is well written and presents a very interesting story – it is not uncommon to find these large boulders dotted around the Himalaya so it is nice to finally see an analysis of how and where they have come from. It also serves as an important contribution to understanding how rare but large magnitude discharge events contribute to landscape evolution, and how this may link to broader patterns of climate change. I do feel that the manuscript would benefit from a few additional clarification and considerations, and I hope the comments below help generate some discussion.

General comments:

One aspect that was/is not obviously clear to me is where these boulders have originated from. Are these deposits which would have been sat in the valley of their source lithology (e.g. delivered from local hillslope wasting) and then transported by large flows? Or are these boulders that would have been glacially eroded and then exposed during glacial retreat and subsequently flushed out? I would have thought the latter would be less likely as subglacially sourced rock would be highly fractured. If there had been some CRN accumulation on the valley floor prior to entrainment, this may help explain some of the spread in boulder ages. Looking at Figure 4, there is still a reasonable spread around a series of boulders (~2.5-6 ka) which are suggested by the authors to have been transported by a single event. While some of that spread can be attributed to error, some could also be explained by pre-transport accumulation, or a whole range of other factors (e.g. intermittent transport by a series of events rather than a single one). I felt this discussion was lacking from the main text.

Figure 1 would help tie a lot of this information together better if it had 1) the different lithologies mapped out, 2) the corresponding boulder lithologies shown, 3) best-guess of where paleo-ice limits would have been. Perhaps even make this as a separate figure zoomed in.

I'm curious as to why we don't see any boulders relating to older glaciations/climatic changes, if this is the proposed mechanism of transport. Have these boulders been buried? Was this most recent event so large that it flushed everything else through – and are there more boulders further downstream? One aspect I'm struggling to visualize is the local valley conditions in which these boulders are deposited – are they typically found in regions of local valley widening for example, where you may feasibly be able to temporarily store/bury larger clasts. Some details may be helpful.

One additional comment here would be whether boulder emplacement could be by debris-flows, which in theory could raft very large particles a considerable distance. A number of moraine dam failures in Clague and Evans (2000) resulted in debris flow initiation, transporting boulders several kilometers, despite relatively modest initial discharges from the lakes. If the boulders represent the coarsest material within a much older deposit that has reset the CRN clock, finer material may have been washed away leaving a layer of surficial boulders (almost like a deflation layer I guess?) with potentially quite similar ages. Presumably these valleys have gone through considerable phases of aggradation and incision? This reminds me of one particularly large boulder further downstream on the Koshi just south of Chatara – lat 26.813896, lon 87.152834. The boulder is maybe 5-6 m in diameter and sat in the middle of a sand-bed river – it must have been transported several km (over a very low gradient) to get there, yet there are no other deposits nearby. Is it just the remnants of an ancient mass flow deposit that spilled out of the mountain front and everything else has been washed away?

Given the large transport distances of some of these boulders – would some abrasion/fracturing have occurred during transport? Presumably boulders would have been moving/saltating on the bed which is likely to produce quite high rates of abrasion/mass loss, so initial boulder sizes may have been a good chunk larger. Some comment to that effect may be helpful. If these boulders are of glacial landscape origin, this may also explain the absence of glacial features/signatures on their surface.

Flow estimates – To transport boulders of the sizes you have, how long would these flows need to persist in order to transport the minimum distances? I'm just looking at Figure 3a – you'd need a peak discharge sustained for nearly an hour or two to transport some of those boulders the required distances. Is that reasonable (I have no idea!)? Or is it more likely that these boulders would have been moved progressively (and potentially rotated)? An estimate or rough calculation of paleo-lake size to generate a discharge of that magnitude may be useful here. I'm not hugely familiar with the characteristics of proglacial lakes, but how big do moraine-dammed lakes tend to be in comparison to ice or landslide dammed ones? The magnitude of discharges you predict here are large – could you feasibly hold that much water behind a moraine-dammed proglacial lake?

Specific comments:

P1L11: First line of abstract 'commonly linger in Himalayan river channels'

P1L23: Why is this counter-intuitive? If climate is warming (as you state) then you'd expect more melt? You later mention that past large phases of glacier retreat have been suggested to increase GLOF frequency, so it doesn't seem especially counter-intuitive! It seems the only mention of increased temperature is in the abstract – so which is happening/more important – increased temperature (+ more melt) or aridity? Presumably, a case simply of increased aridity doesn't necessarily mean increased melt unless accompanied by some change in temperature. Some further explanation in the text further down may help. How exactly – is it simply that there are more moraines exposed so more damming of the usual meltwater?

P1L31: Earthquakes are pretty common in the Himalaya – specify the sizes/magnitudes that are of importance.

P2L39: Worth noting that not all proglacial/landslide dammed lakes drain catastrophically so there are probably more of these lakes than there are catastrophic events.

P2L46: How far back do these records go?

P3L76: What about even older glaciations? Just a quick comment to say how they fit in.

P4L127: Why was boulder diameter measurement from Google Earth as opposed to field measurements? What is the uncertainty/resolution/error? I'm confused about how you get an intermediate axis from a satellite image of a boulder where some of the boulder may be buried – it's hard enough on a high resolution photo. More details are needed.

P5L131: What is the vertical spacing of the contours on these maps…50 m? Does this give better valley geometry than any of the available DEMs? Is there information relating to the modern channel from any of the DHM stations which could be used to help improve (at least a part of) these cross-sections?

P5L135: Were any of these calculations done for valley geometry further upstream near the source lithologies, where the boulders were actually entrained? Presumably if everything has been calculated using digitized maps this could have been looked at – so for the same discharge in the upstream valley geometry, what size boulder could have been transported/motion initiated, does it match? I'm also curious about where the biggest source of uncertainty comes from in the paleo-discharge calculations. You comment on this in section 5.2, stating that the channel geometry is probably one of the biggest uncertainties. Are the results more sensitive to uncertainties in slope or cross-sectional area, for example? Even if paleo valley estimates were available, there

is still no constraint on how the bed or valley floor may have evolved during the event.

P7L213: Could these abrasion marks also have been generated while the boulder has sat in-situ during subsequent high flows where the boulder has been submerged/partially submerged? If this is a possibility, have any of the exposure ages been corrected for post-depositional erosion? Some comments on this and potential effects on exposure ages would help.

P11L345: Yes, but not all earthquakes will generate LLOFs – on the flip side, presumably a modest earthquake at the right time in the right place could also generate a LLOF?

Figure 2: I find the red text quite hard to read – could you put a white box behind?

Figure 6: Do you see boulders within ∼50 km of the moraine deposits in any of these other catchments?

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