Solid Earth Discuss.,
https://doi.org/10.5194/se-2018-132-AC1, 2019

Solid Earth
Discussions

Interactive comment on "Regional Pliocene Exhumation of the Lesser Himalaya in the Indus Drainage" *by* Peter D. Clift et al.

Peter D. Clift et al.

pclift@lsu.edu

Received and published: 24 February 2019

We thank reviewer one for their insightful questions and are grateful for the chance of being able to reply to them in detail. The reviewer notes that the Inner Lesser Himalaya appear to have cooled rapidly without having been widely exposed until after 1.9–3.0 Ma. We agree that this would require rapid erosion of the Greater and/or Tethyan Himalaya, although not necessarily the Outer Himalaya, which were also largely buried at this point of time (Webb, 2013). Contrary to what is stated the record provided in this study does provide evidence for this erosion because there is a steady increase in erosion of Greater/Tethyan Himalayan material since the Miocene, accelerating after 5.7 Ma, as shown by the drift to more negative ïĄěNd bulk sediment values. The zircon U-Pb ages are dominated by Greater/Tethyan Himalayan grains throughout the record,

also indicative of such erosion. The deep sea fan record is quite compatible with the record of Najman et al. (2009), in that the initial pulse of Lesser Himalayan zircon appears after 8.3 Ma, not long after the erosion shown by this earlier work after 9 Ma. Neither the submarine fan or the Siwalik records directly relate to fault motion, only to exposure of units to erosion. In this respect the data are "plausibly consistent" with the bedrock thermochronology data as the new study does not deny cooling of the Lesser Himalaya in the Late Miocene, 6–10 Ma (Caddick et al., 2007), only the lack of regional exposure and erosion.

The Siwalik record considered by Najman et al. (2009) reflects the erosion history in that particular part of the foreland basin, likely a paleo-Beas River, but does not constrain other regions of the Indus catchment. The Jhellum, Chenab, Ravi and most notably trunk Indus Rivers would never have flowed through this part of the basin as the regional topography forces them to flow to the SW away from the range front. This means that the Lesser Himalaya could have been exposed in the paleo-Beas valley but not to much extent in other parts of the basin.

Regarding Nanga Parbat as a possible source of the Lesser Himalayan zircon grains seen in the submarine fan we argue that this is unlikely because only $\sim$16% of the zircons in the modern trunk river downstream of Nanga Parbat are >1500 Ma and of Lesser Himalayan affiliation. We do not ignore the erosion of Nanga Parbat and our results are compatible with the recent cooling noted by Koons et al. (2002). As noted in the manuscript the shift in bulk Nd isotope since the Miocene appears to be 35% caused by Nanga Parbat and 65% by the rest of the Lesser Himalaya. Nanga Parbat is too small and its erosion is insufficient to drive all the observed changes by itself.

Regarding the role of recycling of older sediments from the Siwalik Group as a source of the Lesser Himalayan material, we do not agree that the "Lesser Himalaya Series is the nearest bedrock to the foreland basin it follows that its detritus makes up a significant proportion of the immediate foreland basin". Tectonic juxtaposition does not transfer material into the sedimentary record, only unroofing and erosion can do that. Unfortunately, there is no zircon U-Pb dating of the Siwalik Group within the Indus catchment so any estimate of its influence is based on data from Nepal where the stronger monsoon rains may have driven faster erosion. There are indeed >1500 Ma zircons in the Nepalese Siwaliks, but a mass balance of these drainages by Lavé and Avouac (2001) indicated that only ∼15% of the net erosion could be from Siwalik sources. Furthermore, an isotope-based mass balance for the Ganges catchment placed the influence of the Siwaliks at <10% (Wasson, 2003). Similar modest values would seem appropriate in the western Himalaya too, as the zircon U-Pb populations of the major modern rivers are quite diverse and are largely consistent with the bedrock geology of their mountain catchment, especially in the wetter southern parts (Alizai et al., 2011), implying that the Siwalik Group is not a major buffer on the zircon population. In any case, if the Lesser Himalaya had been exposed earlier and had been supplying >1500 Ma zircon to the foreland basin then these materials should also have been seen in the fan at that time.

Regarding the detailed comments We rephrase Page 1, line 13 as suggested.

Page 1 Line 14 - Our argument was badly phrased. It is not the increase in >300 Ma zircons that disproves drainage capture but rather the fact that there are large volumes of such zircons throughout the section, which in turn requires continuous sediment supply from the Himalaya, thus precluding any former drainage pattern that excludes much of the Himalaya-draining rivers. The abstract is edited to reflect this.

Page 1 Lines 16-19 – Yes, the change in the provenance we see is relative and could be caused by slowing of Karakoram erosion in the other sources, including the Greater Himalaya. However, the sediment budget of the Indus Fan implies increased total erosion rates in the Pleistocene compared to the Pliocene making this scenario extremely unlikely.

Regarding lag times between exhumation and deposition we now add a note concerning the work of Blöthe and Korup, (2013) and provide details about recently published

information concerning buffering in the upper Indus catchment from Jonell et al. (2017). We also note that zircon travel times in the Indus River are estimated to be 7–14 ky since the Last Glacial Maximum (Clift and Giosan, 2014), thus precluding these processes from influencing the interpretation of the erosion record presented here.

Page 1 Line 25-27 – The question of the nature of the foreland basin record stored in the Siwalik Group was questioned. The sedimentary section at Jawalamukhi analyzed by Najman et al. (2009) lies in the east of the Indus Basin and would sediments deposited in the foreland in front of the range in this area that were then accreted into the thrust stack. In the present day this means sediment from the Beas and Sutlej Rivers, and possibly the Yamuna in the past when this used to flow west into the Indus (Clift et al., 2012). The geometry of the foreland basin means that the Himalayan tributaries must have flowed SW in the geologic past too {Burbank, 1996 #45}. The trunk Indus River is essentially pinned on the western edge of the foreland, as also shown by studies of the Siwalik Group in that area (Chirouze et al., 2015). The Indus mainstream has never flowed eastwards along the foreland basin to join the Ganges as far as anyone is aware. Thus, the section at Jawalamukhi and similar locations would never preserve sediment derived from the Indus and so only be able to reconstruct the flux in the Beas/Sutlej ± Yamuna.

Page 1 Line 28-32 – We agree that our sedimentary record of Lesser Himalaya erosion needs to be compatible with the bedrock thermochronology. We emphasize that we are looking at erosion, which is the final stage of exhumation. Most bedrock thermochronology does a poor job of constrain final unroofing. Lesser Himalayan thermochronology in the Indus catchment suggests rapid cooling at 6–10 Ma based on high temperature U-Pb monazite dating (Caddick et al., 2007), but this still predicts that the Inner Lesser Himalaya now at the surface were at ∼550ËŽC, 4.5 kbar depth (∼15 km) at 6 Ma. Apatite fission track dating of the Lesser Himalaya in the Sutlej Valley shows much younger ages of 1–2 Ma (Vannay et al., 2004), implying rapid uplift of 3–5 km since that time. However, these methods can only constrain the cooling of the rocks now exposed. We have no way to tell from the bedrock alone how much Lesser Himalaya erosion has taken place in the past, or what used to cover the presently exposed units. The bedrock thermochronology does not preclude final unroofing after 1.9 Ma and indeed structural reconstructions are consistent with late stage unroofing in the Indus catchment (Webb, 2013).

Page 2 Lines 10-15 – The reviewer was concerned about the short duration of the zircon erosion record (largely <8.3 Ma) compared to thrusting and cooling of the Lesser Himalaya after 10 Ma. Clearly we can't say anything about erosion at or before 10 Ma without sediment of that age but the data we present are not incompatible with this model. Exhumation of a given unit does not require its unroofing, as explained above. In fact, erosion of bedrock into sediment is almost the only way to track that final stage in the exhumation history. The rocks eroded in the pulse we see after 1.9 Ma did probably start to exhume after 10 Ma. The data we present doesn't constrain when the source started to exhume, so we can't say anything about that process.

Page 2 Lines 25-35 – As suggested we change the title of the "Provenance Methods" section to "Background and Prior Studies", but these lines are a discussion of prior studies more appropriate in a background section than a methods section.

Page 5 Line 5 – The reviewer was concerned that we overemphasize the drift to positive ïĄěNd values from 17 to 9.5 Ma. We now change the text to note that the change is modest. Nonetheless, the total change is greater than the ± 1 uncertainty, so we consider the slight drift to be real.

Page 5 Lines 10-30 – The reviewer wanted to see a figure showing the rivers discussed in this section, but their modern courses are shown in Figure 1, which is called out in this section too. We further add a comment concerning longshore currents in the region as requested.

Page 5 Lines 38-42 – The reviewer was concerned about the Lesser Himalayan contribution from the granites of Nanga Parbat. As detailed above, and in the manuscript,

we discuss this possibility and suggest that Nanga Parbat is responsible for 35% of the provenance change but cannot be the only cause of the change in bulk isotope composition.

Page 6 Line 30-35 – The reviewer was concerned about rapid exhumation of the most proximal foreland basin deposits rather than preferential erosion of the LHS to explain the provenance change in the fan. The arguments against this are provided above, namely that the estimated flux is small in volume and that there is no evidence that the Siwaliks in the NW Himalaya have many of the right aged zircons, as all existing data is from Nepal.

Page 7 Line 26-30 – The reviewer is concerned at the lack of evidence for an exhumation event in the K2 region of the Karakorum, as well as at Nanga Parbat, and thinks that the fan dataset cannot be interpreted as a complete record of western Himalaya exhumation. We argue that the erosional record in the submarine fan is providing an averaged record of western Himalayan exhumation. No matter how dramatic a tectonic event might be locally if it does not result in a large erosional flux then this will not be noticed in the fan record. As far as K2 is concerned, it is far from clear how much of the Karakoram this represents as its motions are largely governed by the Karakoram Fault which does not influence most of these ranges. Moreover, around half the sediment from K2 is transported north into the Tarim Basin. The lack of impact from K2 and Nanga Parbat is simply reflection of their small size relative to all the other sources.

Page 8 Line 30-33 – The reviewer is again concerned about reconciling bedrock thermochronology with the erosional data, especially the zircon (U-Th/He) data of Colleps et al. (2018). As explained above, and in the manuscript, these data describe exhumation but not unroofing and are not inconsistent. The rocks studied by Colleps et al. (2018) do not lie in the Indus, but even if they are representative of equivalent rocks in that catchment, rapid cooling after 11 Ma in the Lesser Himalayan rocks now exposed does not mean that the same unit was exposed at that time.

References

Alizai, A., Carter, A., Clift, P.D., VanLaningham, S., Williams, J.C., Kumar, R.: Sediment provenance, reworking and transport processes in the Indus River by U-Pb dating of detrital zircon grains. Glob. Planet. Change, 76, 33-55, doi:10.1016/j.gloplacha.2010.11.008, 2011.

Blöthe, J.H., Korup, O.: Millennial lag times in the Himalayan sediment routing system. Earth Planet. Sci. Lett., 382, 38-46, 2013.

Caddick, M.J., Bickle, M.J., Harris, N.B.W., Holland, T.J.B., Horstwood, M.S.A., Parrish, R.R., Ahmad, T.: Burial and exhumation history of a Lesser Himalayan schist: Recording the formation of an inverted metamorphic sequence in NW India. Earth Planet. Sci. Lett., 264, 3–4: 375–390, doi:10.1016/j.epsl.2007.09.011, 2007.

Chirouze, F., Huyghe, P., Chauvel, C., van der Beek, P., Bernet, M., Mugnier, J.-L.: Stable Drainage Pattern and Variable Exhumation in the Western Himalaya since the Middle Miocene. J. Geol., 123, 1–20, doi:10.1086/679305, 2015.

Clift, P.D., Carter, A., Giosan, L., Durcan, J., Tabrez, A.R., Alizai, A., Van Laningham, S., Duller, G.A.T., Macklin, M.G., Fuller, D.Q., Danish, M.: U-Pb zircon dating evidence for a Pleistocene Sarasvati River and Capture of the Yamuna River. Geology, 40, 3: 212-215, doi:10.1130/G32840.1, 2012.

Clift, P.D., Giosan, L.: Sediment fluxes and buffering in the post-glacial Indus Basin. Basin Res„ 26, 369–386, doi:10.1111/bre.12038, 2014.

Colleps, C.L., McKenzie, R.N., Stockli, D.F., Hughes, N.C., Singh, B.P., Webb, A.A.G., Myrow, P.M., Planavsky, N.J., Horton, B.K.: Zircon (U-Th)/He thermochronometric constraints on Himalayan thrust belt exhumation, bedrock weathering, and Cenozoic seawater chemistry. Geochem. Geophys. Geosyst., 19, doi:10.1002/2017GC007191, 2018.

Jonell, T.N., Owen, L.A., Carter, A., Schwenniger, J.-L., Clift, P.D.: Quantifying episodic

erosion and transient storage on the western margin of the Tibetan Plateau, upper Indus River. Quat.Res., 89, 1: 281-306, doi:10.1017/qua.2017.92, 2017.

Koons, P., Zeitler, P., Chamberlain, C., Craw, D., Meltzer, A.: Mechanical links between erosion and metamorphism in Nanga Parbat, Pakistan Himalaya. American Journal of Science, 302, 9: 749-773, 2002.

Lavé, J., Avouac, J.P.: Fluvial incision and tectonic uplift across the Himalaya of central Nepal. J. Geophys. Res., 106, 26,561–26,592, doi: 10.1029/2001JB000359, 2001.

Najman, Y., Bickle, M., Garzanti, E., Pringle, M., Barfod, D., Brozovic, N., Burbank, D., Ando, S.: Reconstructing the exhumation history of the Lesser Himalaya, NW India, from a multitechnique provenance study of the foreland basin Siwalik Group. Tectonics, 28, TC5018: doi:10.1029/2009TC002506, 2009.

Vannay, J.-C., Grasemann, B., Rahn, M., Frank, W., Carter, A., Baudraz, V., Cosca, M.: Miocene to Holocene exhumation of metamorphic crustal wedges in the NW Himalaya; evidence for tectonic extrusion coupled to fluvial erosion. Tectonics, 23, TC1014: doi:10.1029/2002TC001429, 2004.

Wasson, R.J.: A sediment budget for the Ganga–Brahmaputra catchment. Current Sci., 84, 3: 1041-1047, 2003.

Webb, A.A.G.: Preliminary palinspastic reconstruction of Cenozoic deformation across the Himachal Himalaya (northwestern India). Geosphere, 9, 572-587, 2013.

Interactive comment on Solid Earth Discuss., https://doi.org/10.5194/se-2018-132, 2018.