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Interactive comment on "Clast imbrications in coarse-grained sediments suggest changes from upper to lower flow regime conditions" *by* Fritz Schlunegger and Philippos Garefalakis

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We are grateful for this third review by McLelland as it allows us to clarify some important questions. The major point of this review addresses two issues: (i) the mismatch between experimental results and our inferences, and related to this, (ii) the lack of a clear explanation of the possible processes and mechanisms for imbrication. We fully acknowledge that we have not considered these aspects with sufficient care in our original manuscript, and we also note that the same critique, though with a different nuance, has been formulated by R. Hodge and P. Carling. We address both issues by adding a new section referred to as 'The formation of imbrications in ex-

periments' where we discuss the outcome of experiments, and how this relates to our observations and to possible mechanisms for imbrication. Interpretations of the possible linkages between experiments and natural systems are complicated because of the contrasts in scales. Despite these limitations, it was possible to reproduce the formation of clast imbrications in subcritical flumes (Carling et al., 1992), or at least in the absence of any change in flow regime in many experiments. For instance, Qin et al. (2013) quantified the imbrications that resulted from the experiments by Aberle and Nikora (2006) where flows have been stationary. Carling et al. (1992) additionally showed that the shape of a clast has a strong control on the thresholds for incipient motion, the style of motion, and the degree of imbrication. A similar arrangement of clasts was formed in the experiments by Powell et al. (2016) and Bertin and Friedrich (2018), who reproduced imbrications with low Froude numbers between c. 0.55 and 0.9. Powell et al. (2016) additionally showed that the material can be entrained with φ-values as low as 0.03. Johansson (1963) reported particle vibration before entrainment either through rolling or sliding. He noted that imbrication was formed at conditions, which corresponded to the lower flow regime during the flume experiments. Finally, based on field observations, Sengupta (1966) reported examples where imbrication was most likely initiated by the development of current crescents around pebbles that were embedded in sand, and that these processes possibly occurred during lower regime flows. Such eddies preferentially develop at the upstream end of pebbles, which then leads to preferential winnowing of the fine grained sand at the upstream edge and the tilting of this particular clast. Additional sliding, pivoting and vibrating of these sediment particles might then result in the final imbrication. If this process occurs multiple times and affects the sand-gravel interface at various sites, then an armored bed with imbricated clasts can establish without the necessity of supercritical flows and changes in flow regimes, as experimental results have shown (Aberle and Nikora, 2006; Haynes and Pender, 2007). They may even form in response to prolonged periods of subthreshold flows, as summarized by Ockleford and Haynes (2013). Finally, using flume experiments in a 0.3 m-wide, 4 m-long, recirculating tilting channel flume, Brayshaw

(1984) was able to reproduce cluster bedforms with imbricated clasts during subcritical flows (F-values between 0.03 and 0.07). We will fully acknowledge these studies in our revised manuscript and we will present such a summary of these experiments in the revised text. However, inspections of photos illustrating the experimental set up reveal that the surface grains are either flat lying on finer-grained sediments before their entrainment (Figure 3 in Powell et al., 2016), occur isolated on the ground (Figure 2.1b in Carling et al., 1992), or have a low degree of interlocking (Figure 3a in Lamb et al., 2017). In all experiments, the surface morphology of the sedimentary material is flat and lacks topographic variations, which we found as reach-scale alternations of riffles, transverse bars and pools in the field. The low φ-values of 0.03, which appears to be typical of bed surface conditions that develop in laboratory flumes (Ferguson, 2012), as summarized by Powell et al. (2016), could possibly be explained by these limitations. Furthermore, and probably more relevant, the lengths of the experimental reaches are generally less and range between e.g., 4.4 meters (Powell et al., 2016), 15 meters (e.g., Lamb et al., 2017) and even 20 meters (Aberle and Nikora, 2006). We find it really hard to upscale some of the results associated with these experiments to our natural cases where standing waves of 1 m, and even between 5 and 8 meters lengths may occur, which are not reproducible in the experiments. In addition, while winnowing of fine grained material, tilting of clasts and subsequent bed armouring might be a valuable mechanism for the explanation of imbrications during low stage flows in experiments, we consider it unlikely that these results can be directly translated to our field observations. We base our inference on two closely related arguments. First, we consider that the observed imbrications have resulted from selective deposition of large clasts because they form cluster bedforms, In contrast, experiments on bed armoring return imbrications that result from selective erosion of fine-grained material surrounding the larger clasts. Second, observations (Berther, 2012) and calculations (Litty and Schlunegger, 2017) have shown that effective sediment transport in these streams is likely to occur on decadal time scales (and most likely much shorter; van der Berg and Schlunegger, 2012), at least for subaquatic bars. Sediment transport is then likely to

occur over a limited reach only. This means that a large fraction of the shifted material per flood has a local source situated in the same river some hundreds of meters farther upstream where bars are also well armored. This calls for relatively large thresholds for the removal of clasts (Brayshaw, 1985). In addition, on subaerial bars, waning stages of floods result in the deposition of fine-grained material and not in the winnowing of sand, as our observations have shown. Accordingly, while low φ-values and thus a lower flow regime might be appropriate for predicting the entrainment of the sediment particles in experiments, greater thresholds and thus larger φ-values are likely to be more appropriate for our natural examples for the reasons we have explained in above.

Reviewer:

Comments by line (I've avoided repeating comments already made by others): 50: The diagram suggests that hydraulic jumps occur at a grain-scale (as shown in Figure 1 and later in Fig 5)? Is this a representative of realistic situations?

Our response:

Yes, it is. We have mentioned this in the revised version.

Reviewer:

169: It's not clear why sediment structures are associated with 'channel forming floods'. As experiments have shown, bed structuring can take place as mobile or static armours develop which may be just high flow events rather than channel forming events.

Our response:

This relates to the same comment by A. Wickert. We have corrected the text accordingly.

Reviewer:

288: Are these groups of imbricated clasts cluster bedforms or are they just embedded in the bed structure? It would be useful to distinguish whether or not your structures are clusters both in terms of the moderns streams and stratigraphic record.

Our response: These are indeed cluster bedforms. We have specified the text accordingly.

Reviewer:

355: You use D/d in text, but D84/d in equations. 373: Equation 1 does directly related to flow depth (d) or D84

Our response:

Both address the same point. We have corrected the text accordingly.

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