Interpreting fluvial hydro-morphology from the rock record: large river peak flows leave no clear signature

Appendix S1

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BRIEF REVIEW OF PAOLA-BORGMAN THEORY AND NEW TESTING OF THE APPLICABILITY OF THE LECLAIR-BRIDGE MODEL

Introduction

The Paola-Borgman theory (1991) proposes a probability distribution function of set thicknesses to reconstruct random topography from preserved stratification. The theory considers the stochastic variability in scour distribution as the main control on the formation of sets, e.g., due to the migration of successive bedforms. Even without bed aggradation this control is sufficient to create superimposed sets, whose thickness distribution is related to the probability that the deepest scour could be related to the passage of the first bedform, or the second, etc. Bridge and Best (1997) adapted the theory to depositional conditions for upper-stage low-relief bedwaves, and Leclair (2000, 2002) further compared the Paola-Borgman theory with data from experimental aggrading and non-aggrading dune beds. Of course, a trivial observation would be that coset thickness is greater with than without sediment aggradation, but the distribution of set thickness does not vary systematically with aggradation rate. The terms 'set' and 'cross-set' are used herein in a general and specific way, respectively, because the present figures show cross-sets, i.e. alongstream oblique stratifications instead of across-stream trough-cross (see Allen 1982, his Fig.9-1 for definition); flow direction or bedform shape (2-D versus 3-D) are irrelevant to the application of the theory, which is based on mean and variance of elevation data.

This appendix presents unpublished data from Leclair's experimental investigation on dune preservation, in addition to results from a new analysis of selected data from Leclair (2002).

The experiments were conducted in two flumes (Binghamton University, NY and St.-Anthony Falls Laboratory, University of Minnesota, Fig. S1) in order to get flow depths up to 0.9 m (Table S1). Maximum aggradation rate in Leclair (2002) was 0.014 mms^{-1}, i.e. higher than 0.002 mms^{-1} estimated from data for one of the world's largest and most sediment loaded rivers, the Jamuna River in Bangladesh Ashworth et al. (2000). Bed elevation was measured with an ultrasonic depth profiler accurate to 0.1 mm (mounted on a motorized carriage at BU, Fig. S1A). The flume was drained at the end of each run, at least three 1-m long box cores were taken of the deposit, and sediment peels were made (Picture files S1A-E).

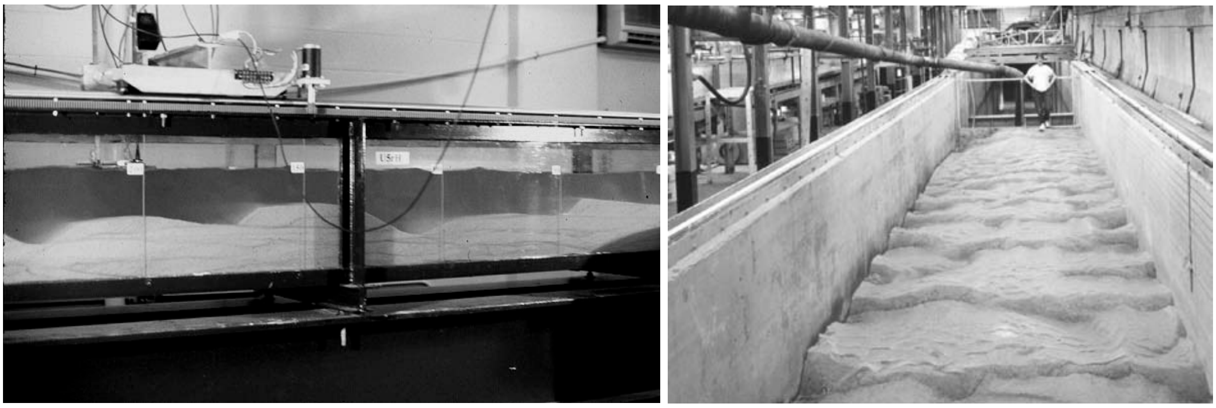

Figure S1. View of experimental dunes in flumes at A) Binghamton University and B) St.-Anthony Falls Laboratory.

Table S1. Experimental flow and sediment conditions of selected runs from Leclair (2002)

Run	**9**	**10**	**11**	**12**	**14**	**15**	**16**	**17**	**18**	**19**	**21**	**22**	**23**	**24**	**32**	**34**
* **d**	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.53	0.9
U	0.5	0.5	0.5	0.5	0.6.	0.6	0.6	0.6	0.6	0.6	0.75	0.75	0.75	0.75	0.8	0.6
r	N	L	H	H	N	N	L	L	L	H	N	L	L	H	N	N

*d = mean flow depth (m), U =mean flow velocity (m/s), and r= aggradation rate (N=none, L=Low range 0.002-0.005 mm/s, and H= High range 0.009-0.014mm/s).

Experimental results produced distributions of matching dune height, trough scour depths below mean level, and set thickness from at-a-point time series of bed elevation. Set thickness was also measured from sediment peels. The Paola-Borgman theory is clearly illustrated with graphs of time-series of bed height at a given point drawn at the same scale as the sediment deposit and next to that point (Leclair, 1997, 2006; Fig. S2A). As suggested by Paola and Borgman (1991), a Gamma function was fitted to distributions of dune height, while their theoretical equation was applied to the distribution of cross-set thickness from the peels. As stated in the theory, both distributions are related by parameter *a* of their probability density function (Fig. S2B).

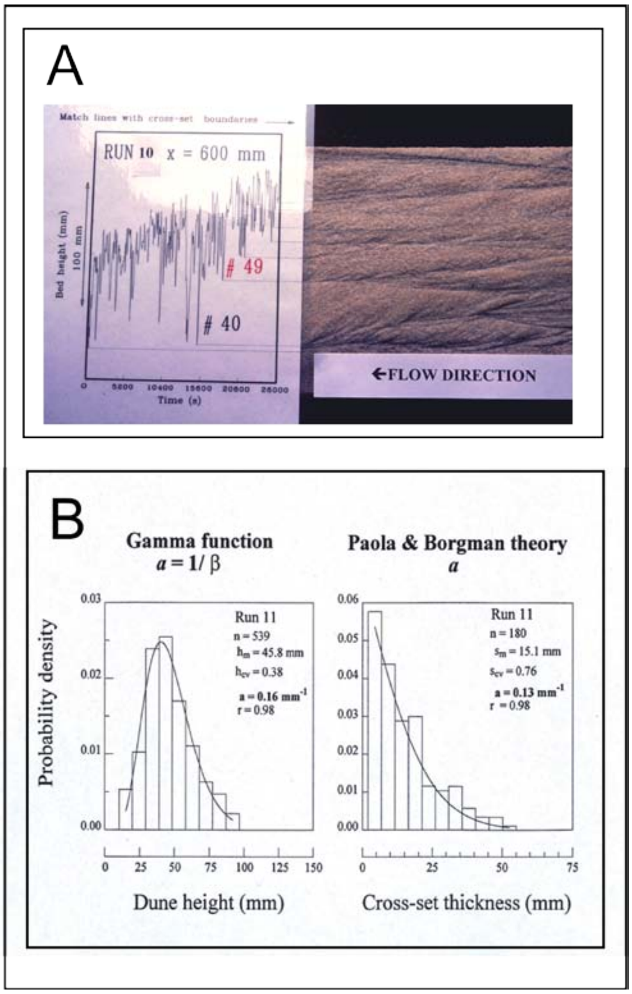

Figure S2. A) Time variation in bed elevation at a point controlling the vertical sequence of cross-set thicknesses. The same principle applies without sediment aggradation. B) Distribution of experimental dune heights and cross-set thicknesses from Leclair (2000), with respective functional parameter ‘*a*’ illustrating the Paola-Borgman theory (1991).

The equation on the links between mean set thickness and formative bedform height distribution is:

$$1.6445 /2a \qquad \text{(S1)}$$

Paola and Borgman (1991) assumed that the height of bedforms spreads evenly above and below mean bed level (hence the factor 2 in Eq.S1), which is not the case in reality (see Fig S2A or Bridge 2003, his Fig. 4.29). Leclair and Bridge (2001) therefore slightly modified the Paola-Borgman theory in order to consider the natural variability of dune height and scour depth elevation below mean bed level as dunes migrate, and proposed a simple method for estimating mean dune height (h_m) from mean set thickness (s_m):

$$h_m = 2.9\ (\pm\ 0.7)\ s_m \qquad \text{(S2)}$$

Equation S2 is based on the <u>mean</u> set thickness and it would be erroneous to make estimations from only the thickness of the larger set(s) of a distribution, or from a single set; all sets in a coset should be counted (yet thin sets are hard or impossible to recognize). The preservation ratio (mean set thickness over mean formative dune height (s_m/h_m) of experimental dunes averaged 0.3 (Leclair 2002; Table S2), which is in good agreement with the value in Equation S2 (computed independently). Yet, the preservation ratio of any individual dune can take any value (Leclair et al. 1997; Bridge 2003). In the experiments, apart from the fully preserved overtaken dunes, no individual preservation ratio more than 0.72 was observed, and this high value was mostly associated with the largest dunes. Consequently, dune height computed with Equation S2 and applied only to the thickest set(s) will likely be overestimated. The case of the single preserved set still represents the probability that the deepest scour was the next to last one (Paola and Borgman 1991). A single set, however, may not be from a dune in a train of dunes, but from a unit bar (e.g. a tributary mouth bar), and it practically only provides a lower estimate for the height of one bedform of the distribution.

The Leclair-Bridge model has been used to interpret dune deposits in the rock record (e.g., Adam and Bhattacharya 2005, Holbrook et al. 2006, Pontén and Plink-Björklund 2007), but yet there is still a critical question that was not brought up during the initial investigation. The theory was developed and applies when the initial set-thickness distribution has been fully preserved. In flume experiments, a run simply ended and the entire record (a complete coset) was analysed. However, in natural systems, most fluvial-dune cosets are typically eroded on their tops**,** and hence, only a sub-sample of the original distribution of set thicknesses will be available (bottom of coset) for computing a mean set thickness and interpreting the formative mean dune height. The issue then is to evaluate the reliability of such a sub-sample of the original distribution of preserved sets, and to provide practical guidelines for interpreting field data.

Testing the theory for the interpretation of partially preserved cosets

Testing how the theory applies to a partially preserved coset can be achieved by reconsidering the experimental data set of Leclair (2002), and assuming that only part of the deposit was preserved. These sediment deposits consist, for each of the 16 runs selected for this analysis, of at least three 1-m long epoxy-resin or latex sediment peels, and hard copies of 1:1 scale outlines of bed surface and cross-set boundaries as observed on the peels. The dune and cross-set geometrical characteristics for the 16 selected runs are presented in Table S2.

The analytical method was the following: 1) the mean deposit thickness for each run was computed from the difference between the mean bed-surface level and the mean lowest-boundary elevation (Fig. S3, upper and lower straight lines); 2) the lower 50%, 30%, and 10% of the total deposit thickness was successively considered (Fig. S3) and; 3) the thickness of cross-sets below each datum was measured, ignoring anything above the selected reference line, along vertical sections 50 mm apart, as in Leclair (2002), for at least 60 vertical sections per run. This approach resulted in a large number of measurements for statistical analysis. The mean and coefficient of variation of the cross-set distributions where 50%, 70%, and 90% of the original deposit was missing (hereafter named ‘observed’ cross-set thickness) were computed and compared to original values from the experimental deposit. The discrepancy between observed and original values was computed and presented as an error percentage.

Table S2. Experimental dune and cross-set geometrical characteristics from Leclair (2000).

		Dune geometry *				Cross-set geometry**	
Run	h_m	h_{sd}	ts_m	ts_{sd}	h_{sd} / ts_{sd}	s_m	s_{cv}
9	43.2	16.9	21.7	21.6	0.78	17.9	0.62
10	50.2	19.1	29.5	22.8	0.84	16.6	0.67
11	45.8	17.5	23.3	15.3	1.14	15.1	0.76
12	53.1	16.9	31.2	19.4	0.87	17.4	0.56
14	54.9	24.6	38.3	24.6	1.0	15.1	0.64
15	48.4	18.9	24.0	21.1	0.9	.16.6	0.63
16	47.5	21.6	29.2	20.7	1.04	17.2	0.58
17	51.3	19.4	23.6	21.4	0.91	18.3	0.58
18	52.7	22.5	24.1	24.5	0.92	21.6	0.59
19	48.1	22.5	28.3	22.6	1.0	16.1	0.58
21	48.2	21.0	31.0	23.2	0.91	23.4	0.69
22	50.5	20.1	32.9	20.7	0.97	16.9	0.57
23	49.7	20.6	31.2	22.2	0.93	15.3	0.57
24	56.4	20.4	39.9	24.3	0.84	21.9	0.69
32	115	45	62	44	1.0	20.0	0.55
34	121	56	112	60	0.9	37.0	0.68

* h_m and ts_m = mean dune height and mean trough scour depth below mean bed level (mm), respectively; h_{sd} and ts_{sd} = standard deviation
** s_m and s_{cv} =mean cross-set thickness and coefficient of variation (mm), respectively.

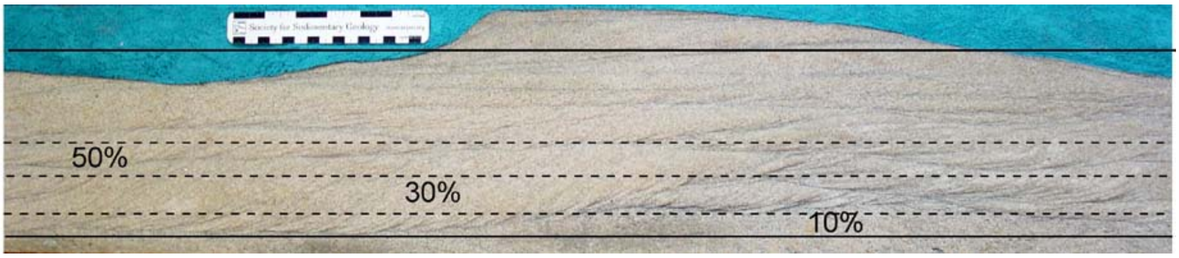

Figure S3. Methodological approach for testing the Leclair-Bridge model. Upper and lower lines define the average deposit thickness. Dashed lines are reference datum for measuring cross-set thickness of deposits representing only 50%, 30%, and 10% of the original deposit.

Results show that in several cases, the mean cross-set thickness (of all vertical sections) observed on 50% and 30% of the initial deposit is very close to the original value, and the error is no more than the natural variability itself observed in the 34 runs of Leclair (2001; 2.9 ± 24%, from Eq. S2); most estimates from measurements made on 10% of the initial deposit depart markedly from the original value (Table S3). All (but one) values of observed cross-set thickness that do not show good agreements with the original values are systematically underestimated.

Table S3. Percentage of error between original mean cross-set thickness and observed value from selected partial deposits.

Portion of original	**Run :**	**9**	**10**	**11**	**12**	**14**	**15**	**16**	**17**	**18**	**19**	**21**	**22**	**23**	**24**	**32**	**34**
		Error relative to original cross-set thickness (%)															
50%		-2	-5	-3	-22	-9	-25	2	-12	-14	-17	-28	0	-2	-20	-9	-5
30%		-16	-12	-9	-20	-26	-33	0	-24	-35	-11	-37	-3	-22	-25	-7	-2
10%		-19	-20	-21	-38	-31	-34	-2	-47	-51	-27	-44	-24	-22	-44	-22	16

The systematic underestimation of many results (Table S3) is explained by the comparative analysis of the histograms describing the distributions of trough-scour depth for dunes of runs that show little (Runs 16 and 22) or more (Runs 23 and 24) % error in the estimate of mean cross-set thickness (Fig. S4). The % error increases as the proportion of dunes with deep trough increases in the distribution (all cases for 30% of the initial thickness).

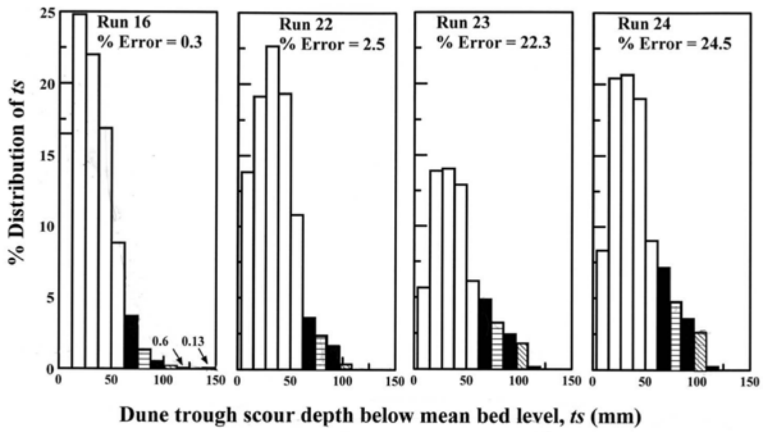

Figure S4. Relative distributions of trough scour depth below mean bed level, *ts*, of individual dunes.

Mean cross-set thickness from individual at-a point vertical sections are not reliable if the deposit is not fully preserved. In the example provided here (Fig. S5; Table S4), the error increases as 50% and 30% of the original deposit are considered. In addition, in theory as in experiments, it is understood that the uppermost dune should not be used in the computation (as it is not a true set, Paola and Borgman 1991), but in a natural deposit it is not known if the set below an erosion contact was at the top or not of the coset. If the remaining thickness of this top bedform is included in the computation of mean set thickness at a section, the results will be overestimated proportionally to the specific preservation ratio of this bedform.

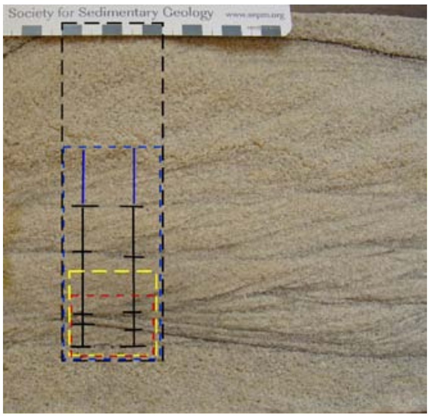

Figure S5. Illustration of the various cross-set distributions considered in an at-a-point vertical section in a partially (or completely) preserved coset. Examples from Run 10 (Leclair, 2002).

Table S4. Percentage of error between original mean cross-set thickness on sediment peel from Leclair (2000, 2002) Run 10, and observed value from selected partial deposits from at-a-point sections as they would be observed in a core depending on their preservation.

	Cross-set thickness (mm)							
	Original (16.6 mm)		**30% of original**		**50% of original**		**With top cross-set**	
							29	29
	23	26					23	26
	31	28	9	9	21	20	31	28
	6	9	6	9	6	9	6	9
	11	9	11	9	11	9	11	9
Mean	**18**	**18**	**9**	**9**	**13**	**13**	**20**	**20**
% Error	**4%**	**6%**	**-48%**	**-46%**	**-26%**	**-24%**	**17%**	**19%**

Effects of dune migration patterns on cross-set boundaries

The first step in the quantitative interpretation of river dune deposits is the correct identification of a distinct coset. Individual dunes have a few typical migration patterns (climbing and overtaking the downstream dune, and eroding the bed at their trough) that determine the path of cross-sets boundaries and create cross-set internal features, all of these possibly being interpreted erroneously as coset boundaries. This section describes dune migration patterns, provides examples of sedimentary structures solely due to each of these patterns, and provides guidance (or warning) for identifying cosets and cross-sets in outcrops and cores.

Dune climbing up the back of the downstream dune is the most recognized migration pattern and cause of set formation (e.g., Rubin and Hunter 1982). Experimental results showed that dune climbing occurs frequently and even in the absence of sediment aggradation. As a dune starts climbing, it typically decreases in height and finally disappears on the back of the downstream dune, which suddenly becomes longer (Video S1). In the deposit, dune climbing produced upward-inclined lower cross-set boundaries at the angle of the downstream dune stoss slope (Fig.S6A, showing stacked cross-sets of successive climbing dunes). Figure S6B and S6C illustrate how these cross-sets would show in a 5-cm wide core, among other cross-sets produced under the same steady flow conditions.

A **B** **C**

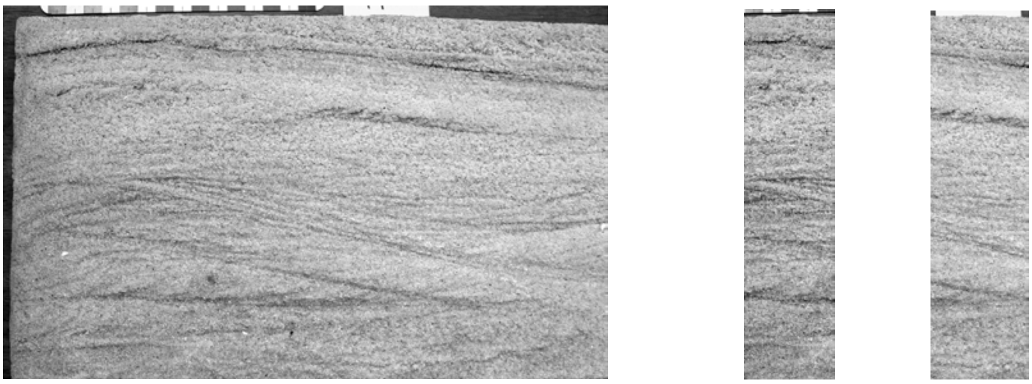

Figure S6. Experimental deposit showing cross-set boundaries due to dune climbing as seen A) in a 2D view, or B) and C) in cores. Scale is in centimetres (see video S4; more examples can be found on Picture files S1A-E). Video S1 is from Run 12; distance between flume sections (dark frame) is 1.5 m.

The overtaking of a dune by a superimposed, faster dune (Video S2**)** was observed by Gabel (1993). In experiments, the occurrence of this migration pattern was not related to flow velocity nor aggradation rate; it happened in all flume runs but it was not a common pattern (Leclair 2002). In the deposit, the lee face of an overtaken dune is entirely preserved and its trough is filled with strata from the overtaking dune (Fig. S7). Dune overtaking and the complete preservation of the overtaken dune can be erroneously interpreted as a reactivation surface (as in Collinson 1970) The avalanche face of the overtaken dune indeed stops migrating for a few seconds as the faster dune approaches the crest (see Video S2) and the lee face 'reactivates' during the overtaking, but flow conditions remain the same.

A **B**

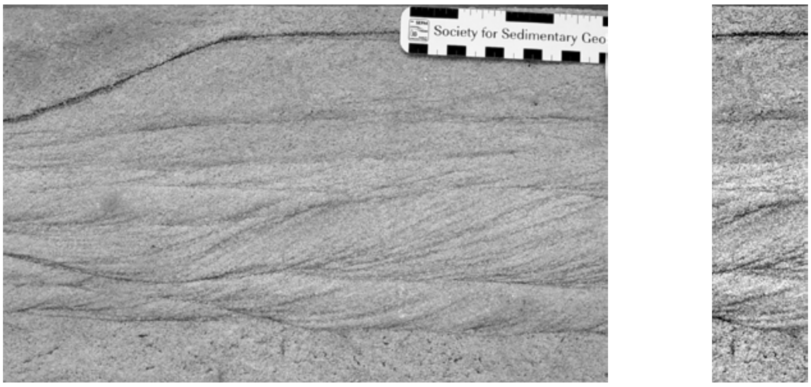

Figure S7. Experimental deposit showing cross-set boundary due to dune overtaking as seen A) in a 2D view or B) in a core. Scale is in centimetres. See video S2 from Run 16.

Trough scouring refers to the erosion of the bed by a dune that is migrating increasingly deeper relative to mean bed level. This pattern is the main process by which dunes increase in height (Leclair 2002; Video S3A). Also, it is the essential process by which an incipient bedform becomes a dune (Video S3B). Because changes in dune geometry have rarely been measured relative to a reference datum (cf. Nordin, 1971), this migration pattern has not been considered before Leclair (2000, 2002. In deposits, lower boundaries defined by trough scouring are most often a low-angle, down-dipping contact (e.g. lower part of Fig. S8A; see also example in Bridge and Demicco 2008). However, because trough scouring can be sudden, rapid, and vigorous (Video S3A), the lower cross-set boundary can dip steeply over a short distance, intersecting the cross-sets below and hence controlling their alongstream extent (Fig.

S8A, upper part). Figures S8B and S8C illustrate how these cross-set boundaries would look in a core. The interpretation of a scour contact as evidence of the passage of larger dunes from more powerful flows would lead to splitting what is actually a coset.

A **B** **C**

Figure S8. Experimental deposit showing cross-set boundaries due to dune scouring as seen A) in a 2D view, or B)and C) in cores. Scale is in centimetres (Videos S3A and Video S3B are from Run 14 and Run 17, respectively)

See main text for references.