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# BED-LEVEL CHANGE OVER INDIVIDUAL SWASH CYCLES ON SAND AND GRAVEL BEACHES

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This paper describes two large field campaigns designed to obtain the most comprehensive dataset to date of morphodynamic change in the swash zone and the associated hydrodynamic processes. Experiments were undertaken at a sand and gravel beach to provide complimentary data from contrasting beach types. An initial analysis of the data revealed that relatively large bed-level changes (1 – 2 cm) were observed to occur in response to individual swash events. Indeed, it was found that the net morphological changes over a 2-hour section of data were not caused by the gradual accumulation of small bed-level changes, but in fact the morphological response was dominated by a small number of large events which had the same order of magnitude as the overall bed-level change during the entire time-series.

## INTRODUCTION

The swash zone marks the transition between the submerged surf zone and the dry beach and can be loosely defined as the region where the beachface is intermittently submerged by wave runup, over time-scales ranging from a few seconds to a few minutes. Along tidal coasts, the swash zone translates landward-seaward across the intertidal profile.

Seas, swells and breakpoint- or swash-driven infragravity energy, cause water to rush up and back across the beachface, resulting in the destabilisation and movement of sediment. It is the integration of this wave-by-wave sediment movement that causes beaches to erode or accrete, over time-scales ranging from a few minutes to a single tide cycle, and from individual storm events to chronic and longer-term coastal erosion. Some significant differences exist in sediment dynamics between the swash zone and the adjacent surf zone, and these differences have inhibited direct application of existing surf zone sediment transport models to the swash zone. Several recent reviews (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006) have assisted in clarifying the dominant hydrodynamic and sediment transport processes that occur in the swash zone of natural beaches, and the degree to which these may differ from the adjacent surf zone.

Fundamentally, beachface erosion is characterised by a general flattening of the profile, and is sometimes accompanied by the rapid formation of vertical erosion ‘scarps’ up to several metres in height. During calmer periods,

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steepening of the beachface often occurs, caused by the accumulation of sediment to form a 'berm' above the high-tide still water line. In general, hydrodynamic models tend to be able to reproduce the velocity and depth variations in the swash zone quite well (e.g. Raubenheimer, 2002; Raubenheimer et al., 2004). In contrast, large-scale morphodynamic models, used in both research and industry to predict the evolving nearshore morphology, are less successful at predicting the flattening and steepening of the beachface. Indeed, in the majority of operational models the swash zone is usually excluded, with the land-ocean boundary represented numerically by a vertical 'wall' at the shoreline. More advanced treatments include predictions of long-wave swash motions only, with short-wave swash energy and asymmetries being estimated from (untested) surf zone parameterizations.

It is generally acknowledged that our understanding of swash zone sediment transport processes lags equivalent knowledge of the surf zone and must be improved. To meet this challenge, in September 2004 the '$1^{st}$ International Workshop on Swash Zone Processes' (Puleo and Butt, 2006) was held, to coincide with the 29th International Conference on Coastal Engineering (McKee Smith, 2005). The purpose of this benchmark meeting was to bring together key research groups working in the swash zone, to discuss ideas, share concerns and to formulate future directions for research. At the conclusion of the meeting it was highlighted that in-situ and continuous beachface bed-level measurements at the fundamental time-scale of individual uprush-backwash events were yet to be achieved. The meeting participants identified the need to measure swash zone morphology on a swash-by-swash basis, to quantify the relative contributions of suspended and bedload transport, and to examine the net effect of sediment transport patterns (Puleo and Butt, 2006).

Previous studies of bed-level change in the swash zone have been undertaken, but such measurements are fairly sparse and generally not at sufficiently high frequency to characterise wave-by-wave bed-level change. The methods employed in these studies have included manual measurements of a series of stakes with a graduated rule (Sallenger & Richmond, 1984; Howd & Holman, 1987; Horn & Walton, 2004; Weir et al., 2006), the use of video to measure bed elevations against a series of stakes (Larson et al., 2004) and capacitance probe techniques (Waddell, 1976; Waddell, 1980). These studies suggest that considerable morphological changes can be observed in the swash zone on relatively short timescales. However, significantly more detailed information with corresponding measurements of the processes that drive morphodynamic change (sediment transport and hydrodynamics) are needed.

The work reported herein describes two separate field programmes that were undertaken at a sandy beach in France and a gravel barrier beach in England to provide unique simultaneous measurements of bed-level change and hydrodynamics on two contrasting beach types. To demonstrate the nature of the data obtained from these experiments we then go on to present some initial analysis of two short time-series from the sandy beach experiment. Future work will go on to compare the similarities and differences in swash zone processes for the two different beach types. Additional measurements were also made at prototype scale in the large-scale Delta Flume facility in the Netherlands, which will be reported elsewhere.

## FIELD SITE AND INSTRUMENTATION

### Le Truc Vert – Sandy Beach Field Programme

The first set of field data was obtained at Le Truc Vert beach, France over 27 tidal cycles between 19th March and 4th April, 2008. The experiment was undertaken within the structure of the multi-institutional ECORS project (Senechal et al., 2008) and forms part of a large collaborative swash zone research project between the Universities of New South Wales and Plymouth. Le Truc Vert is an exposed beach located on the Atlantic Coast of France to the west of Bordeaux (Figure 1). The beach experiences a mixture of high-energy Atlantic swell and locally generated wind-waves with an average significant wave height of 1.3 m. During the experiment, the significant offshore wave height varied in the range 0.9 m to 4.1 m. The beach is macrotidal, with a spring tidal range of 4.3 m and a beachface gradient of approximately 1:18. The median sediment size $D_{50}$ is approximately 0.35 mm.

**Figure 1 – Aerial photograph of Le Truc Vert beach, and map showing the location of Le Truc Vert on the Atlantic coast of France.**

High frequency bed-level data were recorded using a large array of 45 ultrasonic bed-level sensors sampled at a rate of 4 Hz. The sensors were mounted on a large scaffolding rig approximately 1 m above the bed in 3 cross-shore lines with a spacing of 1.9 m (Figure 2). The bed-level sensors are described by Turner *et al*. (2008) and when mounted perpendicular to the bed, make non-intrusive Eulerian measurements of the vertical distance to the closest target (bed-level when the bed is dry and swash height when the bed is wet) based on the time of flight of a reflected signal. Offshore wave data was recorded by a waverider buoy in a water depth of 20m, while nearshore wave and water level data was measured by an ADV positioned 20 m offshore of the main scaffold rig. Additional measurements of current velocity, suspended sediment concentration, water depth and infiltration/exfiltration gradients were made to complement the bed-level measurements but are not discussed here. To put the high-frequency bed-level measurements into the context of the wider beach area, topographic surveys were completed on every low tide along 11 cross-shore transects, spaced 20 m apart and extending from the foredunes to the mean low tide line.

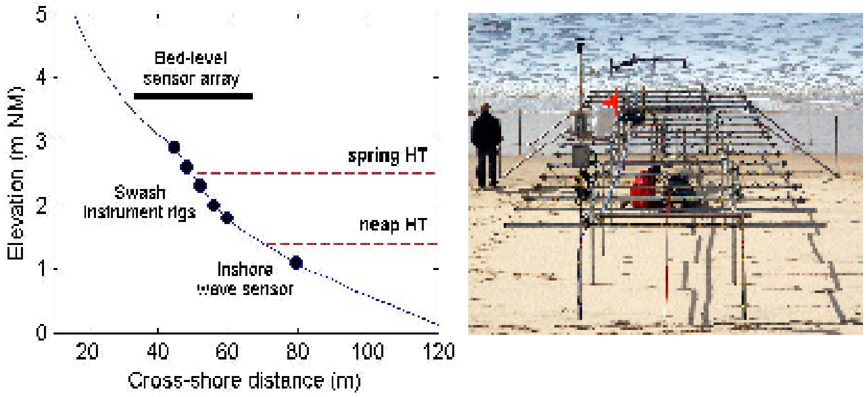


**Figure 2 – Beach profile at the start of the field experiment with instruments locations, and photograph showing the scaffolding structure used for mounting the instruments. The three cross-shore lines of bed-level sensors can be seen down each end, and down the middle, of the scaffold array.**

### Slapton Sands – Gravel Beach Field Programme

Additional data to complement that from Le Truc Vert was recorded during a 10 day field deployment at Slapton Sands, England between 31/4/08 and 9/5/08. Slapton Sands is a 4 km long gravel barrier beach in South Devon, South West England. The Barrier has a width of 100-140 m, a crest-elevation of 6-7m and is backed by a freshwater lagoon (Slapton Ley). The beach is composed of fine to medium gravel with a $D_{50}$ sediment size of 4-10 mm. Slapton faces East up the English Channel and is protected from Atlantic swells by a large headland (Figure 3). Consequently the wave climate at Slapton consists mostly of small, short period waves with a mean significant wave height of just 0.3 m. During the experiment, the significant wave height at the site varied in the range 0.3 m to 1.3 m.

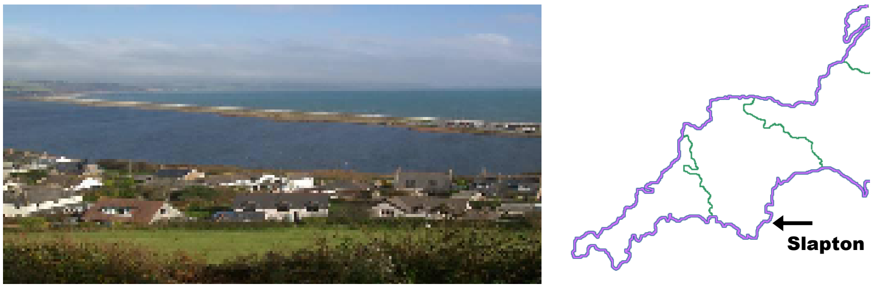


**Figure 3 – Photograph of Slapton Sands and Slapton Ley freshwater lagoon, and map showing the location of Slapton Sands in the South West of England.**

The experimental instrumentation was similar to that used at Le Truc Vert, but due to the challenging nature of working on a gravel beach, a few modifications were made. The beachface gradient at Slapton was approximately 1:5 and consequently the swash zone width (the distance from the rundown limit to the point of maximum uprush) was considerably smaller than that at Le Truc Vert. Consequently the 45 ultrasonic bed-level sensors were deployed at 0.5 m spacings along a single cross-shore transect on a modified scaffolding rig (Figure 4). The hydrodynamic measurements were the same as those at Le Truc Vert with the exception that due to the coarser nature of the sediment at Slapton, no suspended sediment concentration measurements were possible. As at Le Truc Vert, topographic surveys of the beach were undertaken at every low tide.

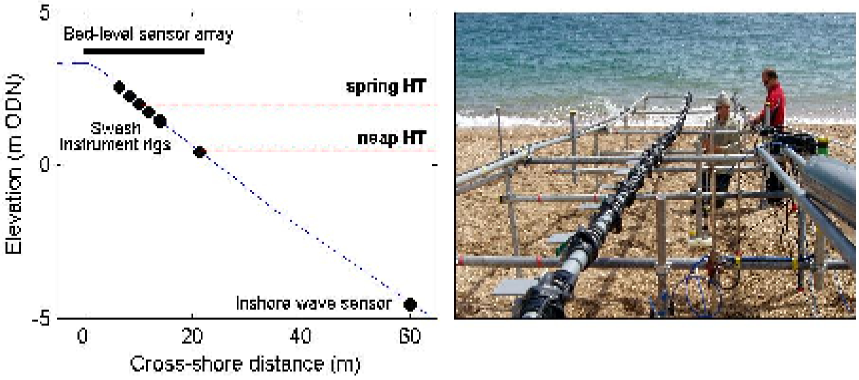


**Figure 4 – Beach profile at the start of the gravel beach field experiment with instruments locations and photograph showing the scaffolding structure used for mounting the instruments.**

## BED-LEVEL MEASUREMENTS

To demonstrate the nature of the data obtained from these experiments and highlight some very interesting preliminary findings, the following section presents some initial analysis of two short time-series from the sandy beach experiment. Comparable data is also available from the gravel beach experiment and future work will go on to examine the similarities and differences in swash zone processes for the two different beach types.

### Bed/Swash Elevation Data

Figure 5 shows a 30 minute segment of data obtained from a single bed-level sensor located in the upper swash ($x$ = 50.02 m) during the Truc Vert experiment. The values on the plot represent the elevation of the uppermost surface beneath the sensor (bed-level when the bed is dry and swash elevation when the bed is wet) and have been corrected for temperature effects. Examining this trace, the vertical spikes represent the raised water depth when a swash passes beneath the sensor and have a saw-tooth profile typical of swash (Hughes, 1992), while between these events 'flat' regions correspond to *in-situ* measurements of the bed and it is possible to estimate the bed-level change caused by a single swash event.

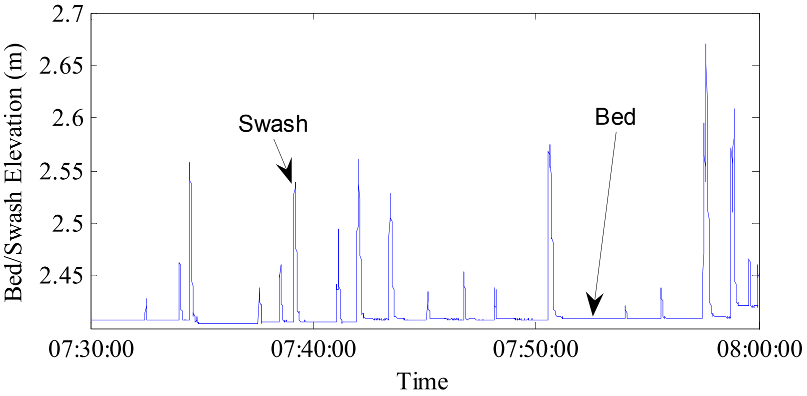


**Figure 5 - 30 minute time-series of data obtained from a single bed-level sensor located in the upper swash (*x*=50.02 m) during the Truc Vert experiment.**

Figure 6 presents the same 30 minute time period as the previous figure, but now pre-processed to separate the individual 'bed-level events' from swashes. For the example data included here, detection of the bed was defined by the following two criteria based on observations of the physical processes and some trial and error (after Turner *et al*, 2008):

$$|z(t+\delta t) - z(t)| \times f < 0.0005 \text{ ms}^{-1}$$
$$T_{bed} > 2 \text{ seconds}$$

where $z(t)$ and $z(t+\delta t)$ are the observed bed/swash elevations at two successive time-steps, $f$ (= $1/\delta t$) is the sampling frequency (4 Hz) and $T_{bed}$ is the duration of a suspected 'bed-level event'. Simply stated, the sensor was deemed to be detecting the bed when the elevation of the closest target (swash or bed) changed at a rate less than 0.5 mm per second and this condition persisted for a minimum of 2 seconds in duration. Applying these simple pre-processing criteria, Figure 6(a) depicts the individual bed inundation events, with the peak of each bore indicated. Note that a single inundation event may consist of one or more individual bores traversing the beach face. Figure 6(b) shows the intervening time periods when bed-level measurements were achieved. These particular bed-level data suggest a net accretion of 11 mm through the 30 minute sampling interval shown, much of which was achieved by a single swash event just before 0800 hrs.

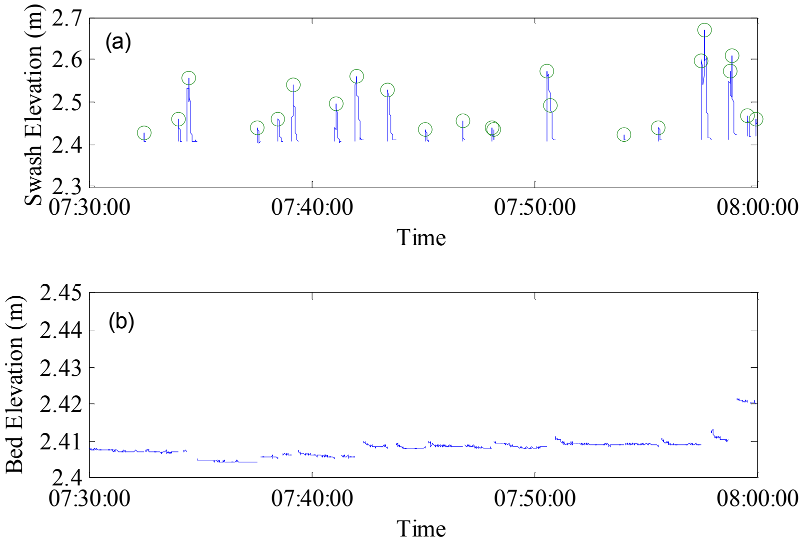


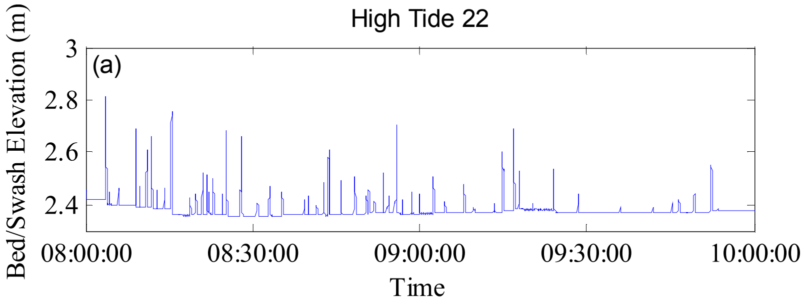
Figure 6 – (a) Time-series of extracted swash elevation data recorded during inundation events with the peak of each bore marked with a circle, and (b) a time-series of extracted bed-level data recorded between swash events.

## Bed-Level Measurements

The ability to measure wave-by-wave bed-levels continuously and repeatedly enables, for the first time, subtleties in beach face adjustment to be observed and quantified. To illustrate, Figure 7 presents two time-series of bed/swash elevation data obtained during two consecutive tides (Tide 22 and Tide 23) at Le Truc Vert. The time-series are taken from the same sensor, mounted in both cases in the mid high-tide swash zone ($x$=50.02 m) and during approximately the same part of the tidal curve. In both cases, the ebb tide was observed to fall through the location of the sensor and this can be seen in the gradual reduction of swash heights through the time-series. During Tide 22 the incident wave conditions, measured by a waverider buoy in 20 m water depth, were significant wave height, $H_s$ = 2.82 m and peak spectral period ($T_p$) = 12.5 s.

During Tide 23, the wave conditions were very similar to that during Tide 22, with an offshore significant wave height, $H_s = 3.12$ m and $T_p = 12.5$ s.

Comparison of these two datasets reveals a different bed-level response despite the similar physical conditions and the identical location of the sensor on the beachface. During Tide 22 an erosional trend was observed, with the beach face eroding by approximately 50 mm, the majority of which occurred during the first 15 minutes due to a small number of large swashes. In contrast, a slight net beach face accretion of 15 mm was observed during Tide 23. Closer inspection of the two time-series shows that relatively large bed-level changes (1 – 2 cm) were observed to occur intermittently in response to individual swashes. Indeed, further examination of the time-series suggests that the observed net erosion or accretion are not caused by the gradual accumulation of small erosive and accretionary changes for Tides 22 and 23 respectively, but in fact the morphological change is dominated by a small number of large events which have the same order of magnitude as the overall bed-level change during the full time-series. This idea is reinforced by the histograms of bed-level change events presented in Figure 8 which show that for both cases there are approximately equal numbers of small erosive and depositional bed-level change events. These small events approximately balance out and the majority of net change in both cases occurs due to the small number of bed-level changes greater than 10 mm. The high significance of a small number of events means that even the direction of net bed-level change at a single point on the beachface will be difficult to predict as it depends on a very fine balance between positive and negative changes.



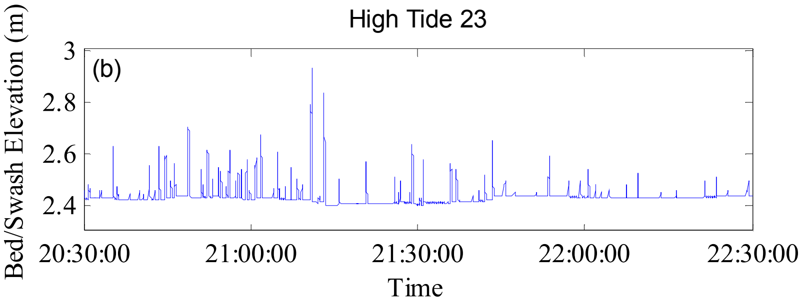


**Figure 7 – Two hour time-series of data during two consecutive ebb tides, (a) Tide 22 and (b) Tide 23, recorded at the same sensor position (x=xx) in the mid high-tide swash zone.**

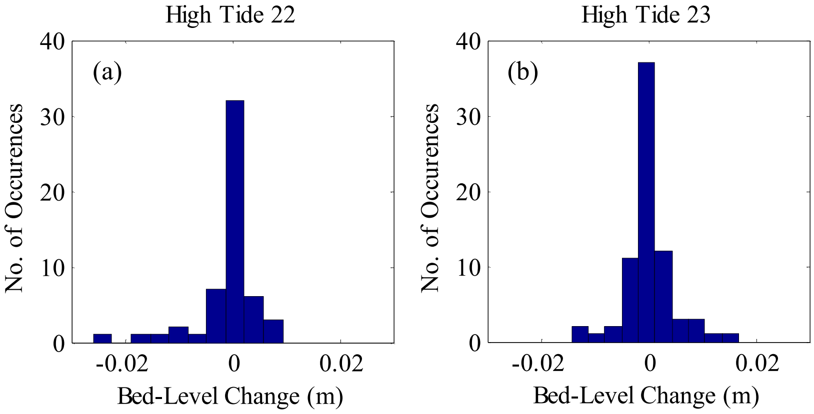


**Figure 8 – Histograms of the individual bed-level change events during the measurement periods shown in Figure 6 for (a) Tide 22 and (b) Tide 23.**

To synthesise and compare these observations, Table 1 presents a basic summary of the two bed-level time-series depicted. Note that the net bed-level change per swash event was defined by calculating the difference between each measured bed elevation immediately prior to an individual swash, to the measured bed elevation immediately prior to the next swash. Referring to Table 1, the mean bed-level change per uprush-backwash cycle was extremely small, at least two orders of magnitude smaller than the largest changes. This observation attests to the fact that in neither case the beach face was observed to dramatically erode or accrete (< 50 mm net change) during each of the two-hour measurement periods. However, the standard deviation of wave-by-wave bed-level changes was an order of magnitude greater, and the magnitudes of the largest bed-level accretion/erosion per wave were 18 mm and -24 mm respectively. To place this magnitude of single-wave bed-level change in context, at this rate and for a 10 second wave period, the beach face would erode-accrete by more than 9 m vertical elevation per hour! The fact that single-wave bed-level changes of the order of centimetres are measured (Figure 8), but that time-integrated bed-level changes of corresponding magnitude are generally not observed in nature suggests there is a form of dynamic equilibrium operating which limits rapid change at the beachface and the nature of this equilibrium is of great interest.

**Table 1: Summary of bed-level observations during Tides 22 and 23 (refer Figure 4).**

| Tide No. | Net Bed-Level Change (mm) | No. of Events | Mean Bed-Level Change Per Event (mm) | Standard Deviation (mm) |
|---|---|---|---|---|
| 22 | -50 | 54 | -0.078 | 0.56 |
| 23 | 15 | 73 | 0.015 | 0.45 |

## CONCLUSIONS

Recent reviews of the state of swash zone research have suggested that the swash zone is critical area for further research as it is currently poorly understood, yet of great importance to successful coastal modelling and management. To predict and model coastal erosion and accretion, the nearshore research community has identified it as a basic requirement that wave-by-wave sediment movement within this most active region of the beach be first quantified and elucidated (Puleo and Butt, 2006). The work presented here describes two large scale field experiments designed to obtain continuous field measurements of wave-by-wave beach face evolution in order to fill this knowledge gap.

The results from these experiments demonstrate that an array of ultrasonic bed-level sensors can be used to successfully obtain high quality measurements of bed and swash elevation at sufficient resolution to observe morphological change at the beachface at the timescale of individual waves. The data obtained from these field experiments provides us with a unique dataset which reveal rather complex fluctuations of the bed observed over time periods of minutes to hours. In particular, gross bed-level changes are shown to be many times greater than the observed rate of net morphodynamic change at the beachface.

The data obtained during the experiments described in this paper will enable bed-level adjustment at the beachface of sand and gravel beaches to be analysed in detail over short timescales in order to elucidate the processes that dominate morphodynamic response in the swash zone for two constrasting beach types.

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