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Reconstructing relative flooding intensities responsible for hurricane-induced deposits from Laguna Playa Grande, Vieques, Puerto Rico

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ABSTRACT

Extreme coastal flooding, primarily during hurricane strikes, has deposited sand-rich layers in Laguna Playa Grande, a back-barrier lagoon located on the island of Vieques, Puerto Rico. Siliciclastic grain-size distributions within these overwash deposits fine landward (away from the barrier and toward the mainland). A simple advective-settling model can explain this pattern of lateral sorting and is used to constrain the relative magnitude of past flooding events. A deposit associated with the A.D. 1928 San Felipe hurricane is used as a modern analogue to test the technique, which produces reasonable estimates for wave heights that exceed the barrier during the event. A 5000 yr reconstruction of local flooding intensity is developed that provides a measure of the competence for each overwash event to transport coarser-grained sediment a fixed distance into the lagoon. This reconstruction indicates that although the Laguna Playa Grande record exhibits large-scale changes in hurricane frequency on centennial to millennial time scales, the magnitude of these events has stayed relatively constant. Over the last 5000 yr, no evidence exists for an anomalously large hurricane or tsunami event with a competence for sediment transport greater than historical hurricane events.

Keywords: Caribbean, tropical cyclones, tsunamis, paleotempestology, sediment transport, grain-size distribution.

INTRODUCTION

Records of storm-induced overwash deposits serve as valuable resources for assessment of tropical cyclone frequency and intensity (Donnelly et al., 2001; Liu and Fearn, 1993; Nott, 2004). This previous work has focused on reconstructing the frequency of extreme flooding events without quantifying event magnitudes. Methods based on the physics of sediment transport can be applied to estimate the local flow conditions associated with past hurricanes. Recently, techniques for quantifying the magnitude of past inundation events have been tested for modern tsunami-induced overwash layers, sorted both vertically (Jaffe and Gelfenbaum, 2007) and laterally (Moore et al., 2007). These studies have focused on validating techniques with modern tsunami deposits of known intensity; however, an inverse modeling approach has yet to be applied to hurricane deposits. Here, we first validate an inverse hurricane modeling technique using the A.D. 1928 San Felipe hurricane deposit. The model is then used to reconstruct flooding conditions for 28 additional overwash layers deposited over the past 5000 yr at Laguna Playa Grande, a Caribbean lagoon located on the island of Vieques, Puerto Rico (Fig. 1).

Donnelly and Woodruff (2007) reconstructed a 5000 yr record of hurricane strikes using coarse-grained overwash deposits from Laguna Playa Grande. The location of the Laguna Playa Grande barrier appears to have remained relatively stable through this time, and lagoonal sedimentation rates are similar to the rates of sea-level rise measured for the region. The tidal range at the site is small (~0.2 m), and bathymetry in the lagoon is relatively flat and free of aquatic vegetation. Cores collected from Laguna Playa Grande contain several meters of organic-rich, cohesive clays and silts, interbedded with coarser-grained deposits. These coarser-grained layers are composed of material similar to that observed along the barrier beach, a mixture of rounded siliciclastic sand and calcium carbonate shells and shell fragments. Measured ages for the topmost coarser-grained layers correlate well with the timing of documented intense hurricane strikes. The Donnelly and Woodruff (2007) reconstruction for intense hurricanes was based on bulk grain-size measurements from a deposit of mixed and varying composition. As a result, the relative event magnitudes for individual deposits could not be assessed.

To quantify flooding intensities, we applied a simple advective-settling model to the isolated siliciclastic fraction of overwash deposits from cores along three shore-normal transects at the site (Fig. 1). To calibrate the model, we examined the spatial distribution of the 1928 San Felipe hurricane deposit, as well as a deposit that has particularly large bulk grain sizes dating to ca. A.D. 600 or 1350 yr B.P. Finally, a reconstruction of local flooding intensity was developed for the entire 5000 yr Laguna Playa Grande record by applying the inverse model to lagoon sediments collected at a suitable distance inland from the barrier.

METHODS FOR IDENTIFYING A.D. 1928 AND 1350 YR B.P. DEPOSITS

Based on the work of Donnelly and Woodruff (2007), the category 5 San Felipe hurricane of 1928 appears to have been one of the most intense hurricanes to leave a deposit at Laguna Playa Grande over the past 100 yr. This deposit is located ~15 cm below the lagoon-sediment interface. This burial depth is based on the mean sedimentation rate of 2 mm/yr obtained using both the A.D. 1963 peak in Cs-137, as well as evidence for abrupt clearing of vegetation from the island in A.D. 1840 (Fig. 2). The signal of land clearance is indicated by an increase in bulk sedimentary Ti at the burial depth of ~34 cm (Fig. 2; Appendix DR2 in the GSA Data Repository[1]). Ti has been found to be insensitive to redox processes and a relatively good sedimentary proxy for changes in terrestrial run-off (Haug et al., 2001). The abrupt ca. 1840 increase in Ti occurs at ~34 cm across the entire lagoon and suggests a similar sedimentation rate of ~2 mm/yr throughout the basin over approximately the past 160 yr.

In addition to the 1928 A.D. event layer, we also sampled a substantially larger deposit (both in thickness and bulk grain size) that was deposited ca. A.D. 600 or 1350 yr B.P. (Fig. 2). The deposit can be correlated throughout the cores based on a second abrupt basinwide increase in Ti that occurs just above the burial depth of this event deposit (Fig. 2; Appendix DR2). The sudden Ti increase at this layer is also accompanied by a distinct color change, a lightening from dark brown to light brown up-core, which provides an additional stratigraphic marker for identifying the 1350 yr B.P. deposit. A similar step-function increase in terrestrial-sourced material at roughly the same time was observed in a sediment core collected off the southern coast of Puerto Rico and has been interpreted to represent a rapid regional increase in precipitation (Nyberg et al., 2001).

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[1] GSA Data Repository item 2008095, Appendices DR1–DR6 (methods, archival data, wave runup estimates, flow approximations, suspended sediment flux estimates, and a discussion of deposit genesis), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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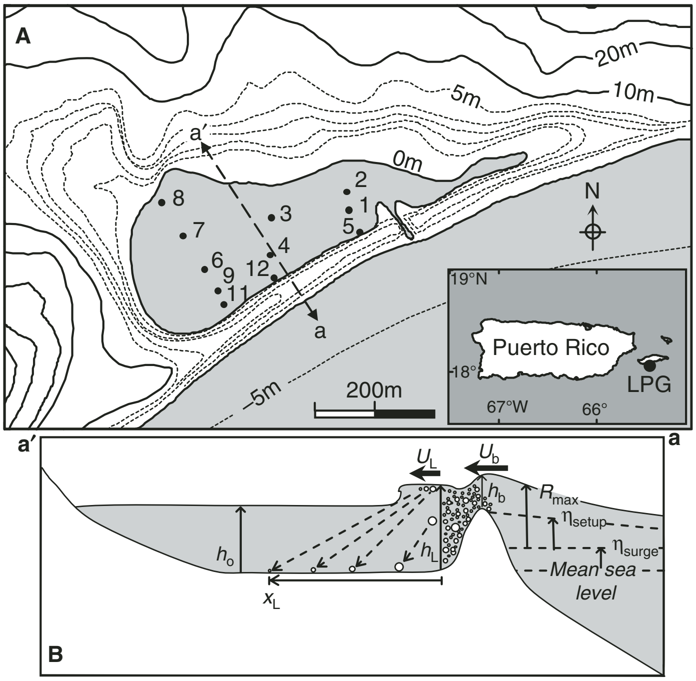

Figure 1. A: Site map of Laguna Playa Grande (LPG), Vieques, Puerto Rico (18.09°N, 65.52°W). Numbered dots indicate core positions, inset map shows regional location, and a-a′ dashed line identifies location of cross section shown in B. B: Shore-normal cross section illustrating overwash process described by advective-settling model, where η_{setup} and h_o represent time-averaged wave setup and lagoon's partially flooded water depth, respectively. All other variables are defined in text.

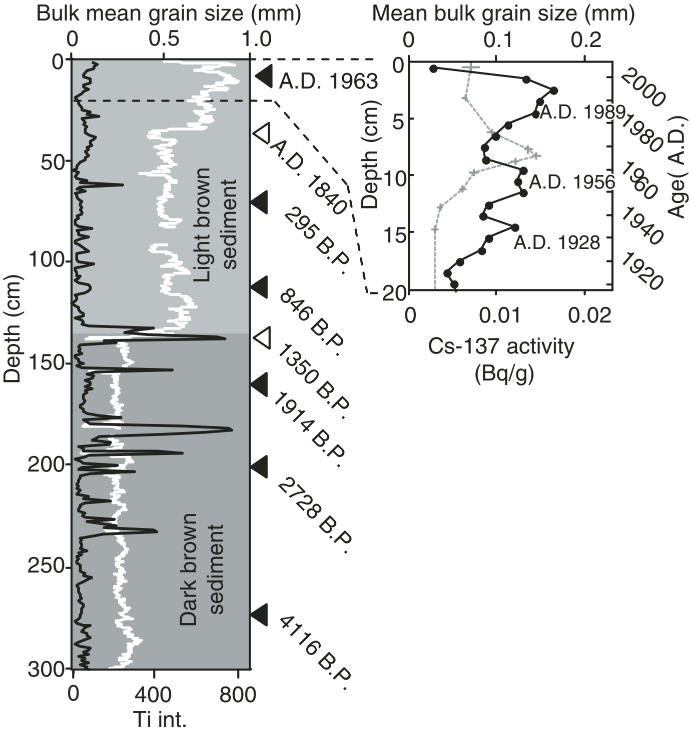

Figure 2. Ti peak area integral (white) and mean bulk grain sizes (black) for core 12 (left plot). Solid arrows represent approximate ages of radiocarbon-dated samples and A.D. 1963 Cs-137 peak obtained by Donnelly and Woodruff (2007). Depths of abrupt increases in Ti associated with land clearance ca. 1840 (110 yr B.P.) and ca. 1350 yr B.P. (A.D. 600) are noted with open triangles (ages based on a linear interpolation between Cs-137 and C-14 age controls). Change in shading indicates depth for observed change in sediment color and abrupt increase in Ti just above 1350 yr B.P. deposit. Right plot shows enlarged upper 20 cm of mean bulk grain size for core 12 (solid black line) and Cs-137 activities (dashed gray line). Age model is based on an accumulation rate of 2 mm/yr derived from A.D. 1963 Cs-137 peak at 8.5 cm and evidence of land clearance (ca. 1840) at 34 cm. Deposits attributable to documented hurricanes are noted. Methods for obtaining grain size, Cs-137, Ti, and radiocarbon measurements are provided in Appendix DR1 (see text footnote 1).

DEPOSIT COMPARISON AND SORTING PATTERNS

Siliciclastic particles were consistently smaller in the 1928 deposit compared to the 1350 yr B.P. deposit (Fig. 3), indicating that the 1350 yr B.P. event was capable of transporting coarser sediment farther into the lagoon. However, in the case of the 1350 yr B.P. deposit, siliciclastic particles were often significantly smaller than bulk sediments (Fig. 3B), primarily due to larger marine shells and shell fragments within the bulk material (carbonates composed 25% ± 6% of the samples by mass). In many cases, grain sizes for the bulk samples were observed to increase landward, probably due in part to the significantly smaller settling velocities associated with the porous and therefore less dense shell material (Appendix DR2). The grain-size discrepancies between bulk and siliciclastic measurements within the 1350 yr B.P. deposit demonstrate that the flooding intensity for the event was likely not as large as might be inferred using only the bulk sample. In contrast to the landward coarsening for bulk sediments, once shell and organic material were removed, the size of the remaining siliciclastic particles in the 1350 yr B.P. deposit systematically decreased away from the barrier and toward the mainland (Fig. 3). This same landward-fining trend was evident for the siliciclastic fraction of the 1928 deposit, and it provides additional evidence that both layers were deposited while being advected landward during marine flooding events. No clear vertical sorting trends could be discerned from the analyzed Laguna Playa Grande deposits (Appendix DR2).

ADVECTIVE-SETTLING MODEL

The landward-fining trends seen in the Laguna Playa Grande deposits indicate that all available particle sizes were not uniformly mixed throughout the basin during overwash activity but instead were spatially sorted during transport across the lagoon. The observed grain-size trends from deposits in each of the three shore-normal transects are also consistent with each other (Fig. 3), suggesting that sediment was carried into the lagoon by waves large enough to overtop the entire length of the barrier during large-scale inundation events. Field and experimental observations suggest that flow along the sloping backside of the barrier during these overwash conditions transitions to supercritical (Donnelly et al., 2006; Holland et al., 1991), where the top of the barrier acts as a hydraulic control (Baldock et al., 2005). Limited observations also suggest that sediment transport under extreme inundation is dominated by suspended load (Donnelly et al., 2006; Visser, 1998), and the temporal structure of velocities and concentrations under dissipative conditions occur on infragravity time scales, T= 20–250 s (Ruessink et al., 1998; Stockdon et al., 2006).

The observed patterns in lateral sorting can be reproduced using a relatively simple advective-settling model similar to that used by Moore et al. (2007). The model is relevant for sediment traveling primarily in suspension and assumes that the time it takes a particle to settle from the top of the flow to the bed is equal to the time associated with inundating currents transporting the suspended particle a horizontal distance into the lagoon, x_L, at an average flow velocity, U_L:

$$t = \frac{x_L}{U_L} = \frac{h_L}{w_s}, \qquad (1)$$

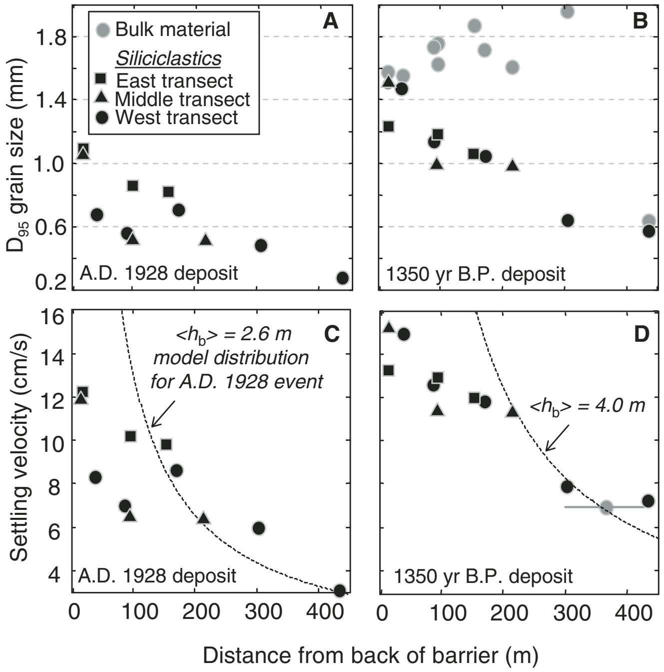

Figure 3. A–B: Shore-normal grain-size distributions measured for coarse fraction (>63 µm) of A.D. 1928 and 1350 yr B.P. deposits. C–D: Particle settling velocities estimated for grain sizes shown in A and B. Black dashed line indicates distribution predicted by advective-settling model using 2.6 m and 4 m flooding depths estimated for the 1928 and the 1350 yr B.P. events. Gray line in D indicates the average settling velocity and maximum range that shell material was transported into lagoon.

where h_L is the flow depth in the lagoon during flooding, and w_s is the particle settling velocity (Figure 1B). The product of flow depth and flow velocity can be obtained by Equation 1 but still requires an additional constraint to attain a unique solution. We build on this advective-settling approach by assuming that the inflow occurs as a bore propagating across the barrier and into the lagoon, where hydraulically critical flow occurs at the crest of the barrier, i.e., the Froude number, $\mathrm{Fr} = U_b/(gh_b)^{1/2} = 1$. Here, g is gravity, U_b is the flow speed over the barrier, and h_b is the flow depth over the barrier (Fig. 1B). In addition, based on mass continuity, we assume that the flow rate per unit width in the lagoon is equal to the flow rate of the bore. Because h_L exceeds h_b (Fig. 1B), the velocity in the lagoon is significantly less than the velocity at the barrier (Appendix DR4). We assume that the high velocities and wave-induced turbulence over the barrier cause intense resuspension, leading to a high concentration and relatively well-mixed vertical distribution of sediment at the barrier crest. As the sediment is advected into the lagoon, settling is assumed to be much more important than turbulent resuspension due to the large reduction of turbulent intensity between the barrier and the lagoon. Because the distance a particle is carried landward is inversely related to its settling velocity, smaller siliciclastic particles are advected further into the lagoon, which results in a landward-fining deposit similar to that observed within the event layers at Laguna Playa Grande.

Assuming the volumetric flow rate per unit width, q, at the barrier crest is critical and equal to the flow across the lagoon, the following relationship is obtained,

$$q = U_L h_L = U_b h_b = \sqrt{g h_b^{\,3}}. \qquad (2)$$

Equation 2 provides the additional constraint required by Equation 1 in order to obtain a unique solution for a quantity that scales with the flow depth over the barrier:

$$\langle h_b \rangle = \left(\frac{x_L^{\,2} w_s^{\,2}}{g} \right)^{1/3}. \qquad (3)$$

For this analysis, we used the settling velocity for the siliciclastic D_{95} size class (defined as the grain size for which 95% of sample has smaller grain sizes [by volume]) to represent the maximum grain size at each site (scatter in the data increased significantly for size fractions greater than D_{95} as a result of the limited number of grains in these larger size classes). Based on empirical results, w_s is related to the grain-size diameter for siliciclastic particles using the relationship developed by Ferguson and Church (2004). Predictions using this relationship produced similar settling velocities to those observed by settling-tube analyses of sieved samples from Laguna Playa Grande deposits (Appendix DR2).

MODEL ASSESSMENT AND RESULTS

To test the accuracy of the advective-settling model, we compared the <h_b> predictions using grain-size distributions from the 1928 deposit to storm-surge (η_{surge}) and maximum wave runup ($R_{\max}$) estimates at Laguna Playa Grande during this hurricane event (Fig. 1B). We assume that <h_b> is most likely related to the maximum instantaneous water level above the barrier during breaching, which is equal to the cumulative effects of storm surge and maximum wave runup ($\eta_{\mathrm{surge}} + R_{\max}$) minus the elevation of the barrier. Given that Vieques is a small island with steep offshore bathymetry, storm surge during hurricane activity is relatively small, and η_{surge} is estimated at 0.9 m (Mercado, 1994). Based on the meteorological conditions for the 1928 hurricane, we estimated a value of ~3.7 m for $R_{\max}$ (Appendix DR3). If this approximation for $R_{\max}$ is added to the estimate for η_{surge} by Mercado (1994), maximum water levels reached 4.6 m above mean sea level during the 1928 hurricane and exceeded the 2 m barrier by roughly 2.6 m.

Estimates for <h_b> using observations from the 1928 deposit are consistent with the 2.6 m flooding depths estimated for the event, but only at a suitable distance away from the barrier (>200 m, Fig. 3C). The observed settling velocities closer to the barrier are smaller than the values Equation 3 predict. This is most likely because the larger grain sizes required to predict wave heights close to the barrier do not mix to the top of the water column at sufficient concentrations. As an example, at 50 m from the barrier, Equation 3 predicts a particle settling velocity of 26 cm/s or a grain size of 3.9 mm for the 1928 event. These grain sizes are much larger than anything observed along the barrier ($D_{95} \approx 1.7$ mm for Laguna Playa Grande beach samples).

Estimates of <h_b> from the 1350 yr B.P. deposit are ~4 m, consistently greater than those predicted for the 1928 hurricane (Fig. 3D). These estimates are also consistent with approximations based on the distribution of shell material from the same deposit, the largest particles of which (D_{95} = 1–2 mm, $w_s \approx 7$ cm/s; Appendix DR2) appear to have settled out between core sites 7 and 8 (x = 300–430 m; Fig. 3B), producing an estimate for <h_b> of ~4 m.

Results from the A.D. 1928 and 1350 yr B.P. event layers suggest that <h_b> can be estimated for individual deposits within the Laguna Playa Grande record if the advective-settling model is applied to sediments collected at a sufficient distance (>200 m) from the barrier. As a result, we chose overwash deposits from core 3 (~214 m from barrier; Fig. 1) to develop a reconstruction of <h_b>. The resulting calculated values of <h_b> are similar throughout the record, ranging between 2 m and 4 m (Fig. 4).

Theoretical calculations suggest that model assumptions are valid for the range of wave heights estimated from core 3 (Appendixes DR4 and DR5). For instance, suspended sediment fluxes over the barrier are ~100–1000 times greater than the equilibrium fluxes that can be supported strictly by resuspension in the lagoon. This strongly suggests that for the conditions presented in Figure 4, settling dominates resuspension in the lagoon, a primary assumption made by the model. The preservation of historical hurricane deposits at Laguna Playa Grande, as well as markers

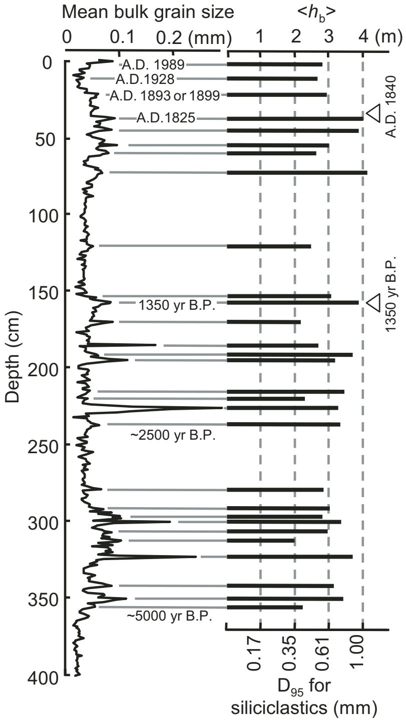

Figure 4. Mean bulk grain size data for core 3 along with estimates of <h_b> for isolated event layers. Equivalent D_{95} siliciclastic grain sizes used to calculate incremental values of <h_b> are noted. Depths of abrupt increases in Ti associated with land clearance ca. 1840 (110 yr B.P.) and ca. 1350 yr B.P. are noted with open triangles. Depths for approximate ages of 2500 and 5000 yr B.P. are based on the chronological constraints presented in Appendix DR2 (see text footnote 1). Years of the four most intense hurricanes passing within 75 km of the site since 1850 are noted, along with the less documented 1825 Santa Ana hurricane.

for other modern strata (A.D. 1840 land clearance and 1963 Cs-137 peak), also supports this conclusion by showing that erosion during inundation events has not been significant enough to disrupt past event layers. Finally, the suspended sediment flux from the barrier is 10–100 times greater than approximations for the bed-load flux in the basin based on calculations presented by Meyer-Peter and Müller (1948), which suggest that suspended loads from the barrier likely govern the distribution of overwash sediment in the lagoon.

Results from the reconstruction in Figure 4 show that the magnitude of <h_b> does not appear to have systematically varied over the past 5000 yr, and they indicate similar intensities of coast flooding for all 29 events analyzed. The reconstruction provides no evidence for anomalously large-scale tsunami or hurricane events when compared to historical deposits. For example, estimates of <h_b> for the 1350 yr B.P. event are relatively large when compared to the 1928 event but are similar to estimates for a deposit at 38 cm, which likely dates to the 1825 Santa Ana hurricane (Fig. 4). The Santa Ana hurricane was one of the most intense hurricanes to hit eastern Puerto Rico in the nineteenth century (Sola, 1995). Although direct observations of the event are limited, an analysis of damage caused by the event indicates that winds reached F3 intensity on the Fujita scale, exceeding 96 knots (Boose et al., 2004). Our analysis suggests that the sediment transport competence for this event was similar to that of the 1350 yr B.P. event.

CONCLUSIONS

Using inverse modeling techniques, a 5000 yr reconstruction of local flooding intensity from the northeast Caribbean is provided. Model results match observations for the 1928 San Felipe deposit and validate the technique for reconstructing hurricane-induced flooding at the site. Results show that although the Vieques overwash record indicates periods in which hurricane strikes have occurred more frequently, no event appears to have carried coarse-grained sediment any farther than storms occurring during the historic period. Thus, none of the 29 overwash deposits analyzed in this study appears to have been associated with an anomalously large hurricane or tsunami event, with a sediment transport competence significantly greater than intense historical hurricanes.

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