CHAPTER ONE HUNDRED SEVEN

BEACH RESPONSE TO LONG PERIOD LAKE-LEVEL VARIATION

by

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ABSTRACT

A 4-year set of beach and offshore profiles, measured at monthly intervals, is evaluated to determine the effect of wind-wave forcing and long period (1 year or greater) lake-level variation on beach profile change in the "tideless" Great Lakes. This evaluation indicates two distinct regions of change in the beach and nearshore area of these profiles. The beach-berm region responds directly to lake-level modulation of wind-wave forcing. This response occurs on two time scales (seasonal and long period), but always in direct relation to mean lake-level variation. The inner-bar actively changes under the influence of wind-waves, but appears to lack a well-defined seasonal pattern. Empirical eigenfunction analysis is applied to these data in order to statistically quantify the significance of these observed changes. This analysis provides confirmation of a hypothesized long-period (years) variation of the beach and berm in direct response to lake-level variation.

INTRODUCTION

Changes in beach profile are caused by variations in incident wave energy conditions and by changes in mean water level position. The seasonal onshore-offshore movement of beach sediment, caused by variations in incident wave conditions, has been discussed by numerous investigators [Shepard (9), Bascom (4), Sonu and Van Beek (10), and Aubrey et al. (1)]. Quantification of seasonal beach profile changes has been achieved by Winant et al. (13) and Aubrey (2)

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for oceanic coasts. Similar quantification of offshore and beach changes on a tideless coast has been carried out by Weishar and Wood (12).

Beach profile changes caused by variation in mean water level position occur on two time scales. Short-term changes (30 days or less) result from both tidal fluctuations and storm wave set-up. Long-term changes (1 year or greater) are related to eustatic or hydrologic changes along a coast. Bruun (5) developed a conceptual model which assumed that beach and offshore profile slope and position is maintained in direct response to a rise or fall in mean sea-level. This concept, known as equilibrium beach theory, is of special interest for the Great Lakes where annual and longer term variations in mean lake-level range from 50 to 200 cm. Hawley and Judge (8) and Hands (6 and 7) evaluated changes in offshore and beach profile in response to rising lake-level in Lake Michigan. Hands (7) discussed a "general sequence of response to increased water levels" which included shoreward migration of longshore bars and shore recession. Weishar and Wood (12) were able to quantify a relationship between offshore profile adjustment and lake-level rise and fall. Specifically, they showed that profile changes offshore from the inner bar (approximately 100 m offshore) were directly related to the mean annual variation in lake-level. However, Weishar and Wood (12) were not able to find a similar direct relationship between beach recession and advance and, respectively, rise and fall in lake-level. This result seems contrary to expectation from physical reasoning concerning the coastal process-response system.

The primary objective of this paper is to show how wind-wave forcing and long-term lake-level variations affect seasonal and long-term changes in beach profile of sandy "tideless" coasts of the Great Lakes. A 4-year set of precisely measured offshore and beach profiles has been collected at monthly intervals from the southern end of Lake Michigan (Figure 1). Empirical eigenfunction analysis is used to statistically quantify annual and long-term mean lake-level variation influences on beach profile adjustment. Short-term (30 days or less) variability is identified in this paper, but attention is focused primarily on long-term (1 year or greater) variability.

PHYSICAL SETTING

This study was conducted along the southeastern shore of Lake Michigan within the Indiana Dunes National Lakeshore, Indiana (Figure 1). This region is characterized by straight, medium-grained sand beaches, with coarse-sand and pebble-sized deposits intermittently present at the beach step and in the swash zone. The beach slopes gently offshore and is terminated onshore by glacial ridges or sand dunes ranging from 10 to 40 m in height. Figure 2 shows a generalized cross section of the beach and offshore region which is characterized by at least two well-defined submarine bars. The outer bar is located approximately 160 m offshore in 2.5 to 3.0 m of water. This bar is relatively stable but may be destroyed

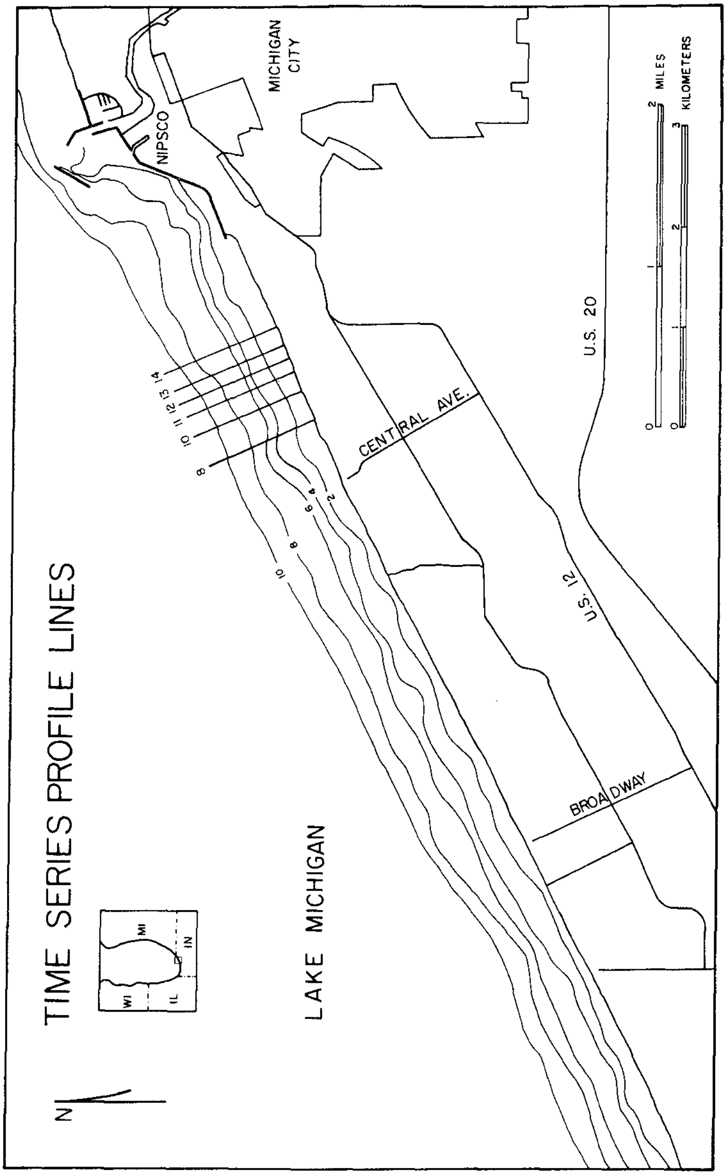

Figure 1. Study site location map.

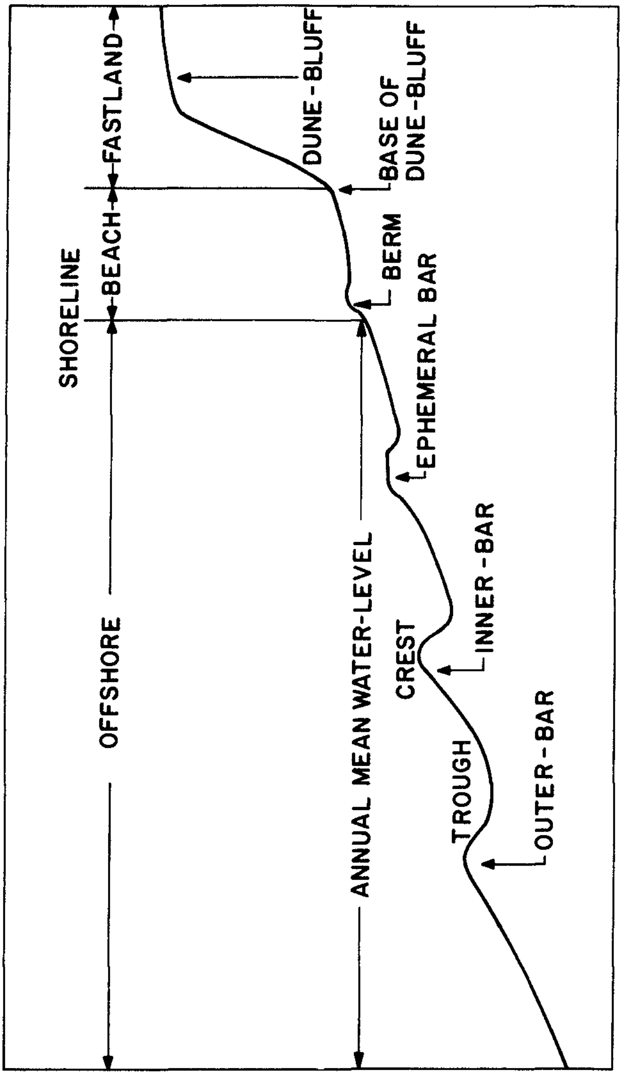

Figure 2. Beach profile showing characteristic features.

intermittently during passage of high-intensity storm events. The inner bar is located 60 to 90 m from shore in 1.0 to 1.5 m of water. This bar is more active than the outer bar because of frequent occurrence of waves breaking over its crest.

The study area lies within a closed littoral cell approximately 20 km in extent [Corps of Engineers (11)]. This cell is bounded by the Michigan City breakwater updrift (shown in Figure 1) and Burns Harbor breakwater downdrift. Sediment is supplied to this cell from the coastal ridge and dune system shoreward and to a much lesser extent from small streams located within the cell. Predominate wave activity is from the north, which causes a net longshore transport of sand towards the southwest. Net littoral-transport rates along this length of coastline are approximately 4.6×10^4 m^3/yr [Corps of Engineers, (11)].

The beach in this region responds to seasonal variation in incident wave climate. During summer, average wave heights are less than 1.0 m, which results in a gradual onshore buildup of the beach profile. Late fall and winter storm waves reach heights in excess of 3.0 m at the outer limits of the offshore zone. These storm waves overtop the entire back-beach profile, which results in direct erosion of beach ridge and dune slopes. From late December until early April the offshore and beach zones are either covered with ice and snow or protected from wave activity by nearshore ice ridges. Small amounts of fine sediment are deposited along the profile as this ice melts in early spring. Most of this fine sediment is redistributed across the foreshore by initial wave activity following ice melting. In spring, following ice melting, ephemeral bars are observed between the inner bar and beach. These bars migrate shoreward under the influence of waves and eventually attach to shore, forming ridge-and-runnel systems. This migration of sediment initiates change from the eroded winter profile to onshore buildup of the summer beach profile.

The coastlines of the Great Lakes are essentially tideless. Variation in mean still-water level does occur on an annual cycle with a range from 0.2 to 1.0 m. Long-period (4 to 22 years) lake-level variations with a maximum range of nearly 2.0 m are also present on all the Great Lakes.

FIELD EXPERIMENT

A series of topographic surveys was initiated in the spring of 1976 to monitor changes in offshore and beachface profiles. Survey data were collected at monthly intervals from May through November of 1976, 1977, 1978, and 1979 along six range lines in southeastern Lake Michigan (Figure 1).

Elevation measurements were taken from dune base to offshore depths in excess of 10.0 m. A conventional theodolite and rod survey was used to measure elevations across the beach at 3.0-m intervals. The shallow offshore region (0-3.0 m) was surveyed using a combination of rod soundings and fathometer soundings.

For those unfamiliar with the Great Lakes, it is important to note that early-morning lake-surface conditions can be "glassy" calm (no swell or local wind-waves present). Therefore, offshore surveys were conducted only during periods of essentially calm lake surface. Recognition of this condition helps to understand the reproducibility claimed in the following paragraphs.

A fathometer was used to profile the bottom from a depth of approximately 1.0 m to depths in excess of 10.0 m. These fathometer surveys overlapped the rod surveys by about 100 m in the shallow offshore region. All hydrographic surveys were conducted with a Raytheon Model DE-719-RTT precision survey fathometer. This instrument is capable of recording underwater topography in water depths between 0.5 and 125 m with an accuracy of ±0.5 percent (of measured depth).

Prior to each run, the unit was calibrated to adjust for temperature effect on the speed of sound in water. Still-water level was measured and recorded so that all bathymetric profiles could be reduced to Low Water Datum (LWD) and changes in water-level elevation would not be misinterpreted as topographic changes.

The method for determining boat position during the fathometer runs utilized base stations set up on the beach. A theodolite was placed directly over a base station and the range line was established by turning a predetermined horizontal angle from an adjacent base station. Three to five buoys were positioned at fixed intervals along each range line. The distance from each buoy to the base station was measured with a Hewlett-Packard Model 3805A Distance Meter. The HP 3805A has a range of 1600 m and is accurate to within .02 m at a distance of 1000 m. A rod sounding was taken at each buoy to provide additional calibration checks.

The hydrographic survey was recorded as a continuous profile while the boat maintained a "constant" speed over the range line. The boat was kept on line by a shore observer siting through the theodolite and communicating with the boat driver by walkie-talkies. Tick marks were placed on the fathometer chart paper as each buoy was passed. Using this procedure, the maximum boat deviation was less than 2.0 m off the range line and maximum offshore deviation was ±3.0 m.

OBSERVED SEASONAL PROFILE CHANGES

Four years of monthly beach and offshore bathymetric profile data were initially evaluated in order to identify dominant areas of profile change. This evaluation indicated three distinct areas of profile change: the beach-and-berm, the inner-bar, and the outer-bar regions. Each of these regions was observed to vary independently of the other two.

The beach-and-berm region, in early spring, is typically found in a highly eroded, winter-beach configuration. Ephemeral bars are usually present in shallow water immediately adjacent to the beach. Beach-and-berm buildup begins in late spring and early summer. Ephemeral bars migrate shoreward under the influence of locally generated wind-waves and attach themselves to the beach. The beach-and-berm region continues to accrete throughout the summer months. This accretion results in a widening of the beach and a lakeward movement of the berm crest. This observed sequence of profile change is similar to that described by Bajorunas and Duane (3) for their beach and shallow-water bar region in Lake Superior.

The beach-and-berm region begins to erode in late fall and early winter because of the increase in frequency and intensity of local storms. As this region erodes, the berm crest shifts toward the back-beach while the overall slope of the beach decreases. It is not possible to monitor the offshore region during the late winter months (January-March) because of extensive ice cover. However, the beach-and-berm region remains in an eroded state until the following spring.

The inner-bar region shows no well-defined pattern of seasonal migration. During the 4 years of monitoring, the inner bar was observed to shift onshore and offshore apparently in response to local storms. Although a sequential shoreward migration of the inner bar was observed in summer 1976 (Figure 3), most movement in this region was less well ordered (Figure 4). The monthly movement of the inner bar appears to be independent of movements in the beach-and-berm or outer-bar regions. It is possible that the monthly survey interval was too long to be able to properly characterize inner-bar movement. This possibility is evaluated more thoroughly in the statistical results section of this paper.

The outer-bar region of the bathymetric profile exhibits a consistent seasonal migration pattern. The outer bar migrates onshore from early spring to early winter (Figure 3 and 4). In the following early sring, after ice breakup, the outer bar is observed to be offshore from its early-winter position. Apparently, the outer bar must move offshore during the period from early ice formation to ice breakup. This regular pattern of onshore-offshore migration of the outer bar is observed in each of the four survey years.

STATISTICAL ANALYSIS

Empirical eigenfunction analysis results in a set of eigenvectors (empirical functions) and eigenvalues (mean square amplitudes) of a matrix of data thought to be composed of uncorrelated modes of variability. The primary reasons for using empirical eigenfunctions to evaluate beach and offshore profile data are: (1) they

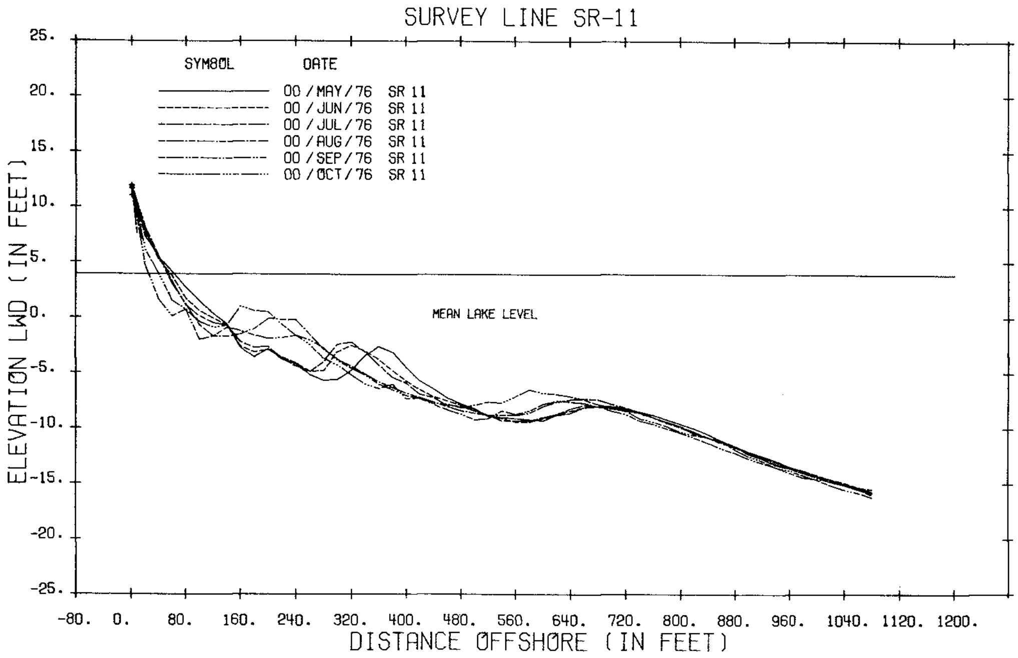

Figure 3. Sequential monthly profiles showing regular migration of the inner-bar.

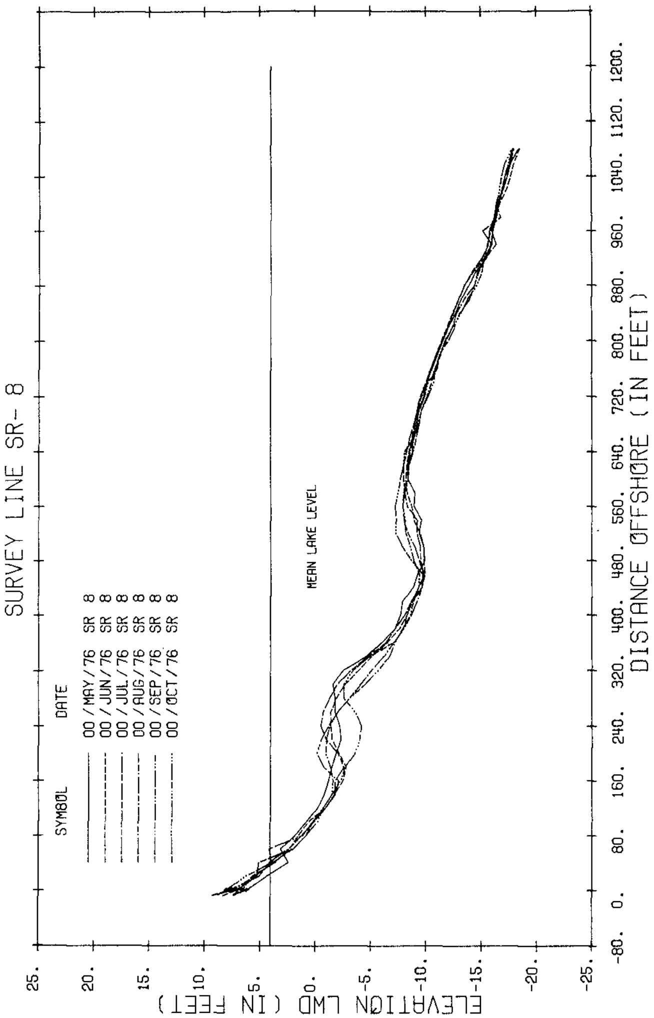

Figure 4. Sequential monthly profiles showing irregular movement of the inner-bar.

are assumed to be uncorrelated modes of variability of the data field, (2) they afford the most efficient method for compressing a data field, and (3) they simplify understanding procedures of minimum mean square error estimation. The details of this method can be found in many of the references mentioned earlier (see Winant et al. (13)).

In an earlier study Weishar and Wood (12) were successful in establishing a direct relationship between lake-level rise or fall and respectively an advance or retreat of the outer bar. However, they were unable to establish a similar direct relationship between beach recession and advance and respectively rise and fall in lake-level. This result is contradictory to Weishar and Wood's (12) model of beach and offshore profile rèsponse to long-term lake-level variation. The reason for this seeming contradiction is that sediment volume changes in the offshore bar system are large compared to beach volume changes. Beach response is, therefore, relatively insignificant in an empirical eigenfunction analysis of an entire cross-sectional profile of the beach and offshore zone. This analysis biasing should be rectified by simply truncating the cross-sectional profile data at a position shoreward of the outer bar trough.

A 4-year set of monthly beach and nearshore profiles, truncated on the offshore side of the inner bar (see Figure 2) was used to generate sets of empirical eigenfunctions. Each set of profile data began at the base of dune-bluff on the back beach and extended down the offshore side of the inner bar to a point where the same number of data points were included in each profile. Analysis of this data set should support the hypothesis that beach response on the "tideless" Great Lakes varies as a direct function of lake-level rise and fall.

RESULTS

Statistical analysis of the monthly data sets using empirical eigenfunctions resulted in three primary eigenfunctions whose eigenvalues accounted for over 91 percent of the total mean square variance contained within the data (Table 1). The eigenfunction with the largest eigenvalue accounted for approximately 72 percent of the mean square value. This eigenfunction essentially reflects the mean of the beach and nearshore profile and is referred to as the <u>mean-beach function</u>. The time dependence of the mean-beach function shows little variation over the 4-year data interval.

The eigenfunction with the second highest eigenvalue accounted for approximately 9 percent of the total mean square value or 28 percent of the residual variance from the mean-beach function. This function shows a broad undulating minimum extending across the berm and beach and is identified as the <u>beach-berm function</u>. The time dependence of this function shows an annual trend with maxima in spring and early fall and a minimum in July. This temporal trend corresponds directly with annual lake-level variation which reaches a maximum in July and a minimum in January-February.

The time dependence of the beach-berm function has a pronounced trend, across the zero amplitude line, which is continuous over the 4-year data interval 1976 to 1979. Such variation is characteristic of long period lake-level change. A comparison between the long period (annual) lake-level variation and the mean annual temporal variation of the beach-berm function tends to support the hypothesized relationship presented earlier in this paper. The cross-correlation coefficient between the mean temporal dependence of the beach-berm function and mean lake-level variation is 0.85 which is significant at a level of E = 0.01.

Table 1. Results of Composite 4-Year Empirical Eigenfunction Analysis

	SR-8	SR-10	SR-11	SR-13	SR-1
Eigen-value 1	74.6	68.5	72.9	64.3	70.5
Eigen-value 2	10.3(40.4)	12.4(39.3)	10.0(37.0)	16.4(45.9)	10.4(35.2)
Eigen-value 3	6.4(25.3)	9.6(29.0)	8.0(29.6)	9.7(27.3)	9.2(31.2)
Eigen-value 4	4.8(18.7)	5.8(18.5)	5.8(21.6)	6.0(16.9)	5.6(19.0)
Eigen-value 5	4.0(15.7)	3.7(11.9)	4.8(17.6)	3.5(9.8)	4.3(14.5)

NOTE: Number in parenthesis is percent of residual mean square variation after removing the first eigenfunction.

CONCLUSIONS

The preceding quantitative analysis has shown that long-term (1 year and greater) lake-level variation is a significant source of physical forcing on beach-berm topographic changes. It should be clarified that mean lake-level changes do not physically transport sediment in the beach erosion of the beach and offshore profile. Sediment transport in this region is related to long-term modulation of local wind-wave energy by mean lake-level change. The best correlation between the temporal response of the beach-berm function and lake-level response occurs on an annual time scale.

However, there also appears to be a weaker but significant correlation between monthly variation in lake-level and beach-berm function response. Conversely, temporal response of the inner-bar function has no coherent trend throughout the 4-year monthly data sets. This may be a result of aliasing of data in the inner-bar region. It is reasonable to assume that the inner-bar, located in relatively shallow water (1.0-2.0 m) would be influenced by relatively small wind-wave events. The time scale of meterologic system movement through the lower Great Lakes (3 to 7 days) is clearly less than the 30-day sampling interval.

As a direct result of this analysis the beach-berm portion of beach and offshore profiles on the "tideless" Great Lakes can be modelled using the same approach suggested by Weishar and Wood (12). However, their model should now have greater sensitivity of predicted response in the beach-berm region. Predictions of long-term coastal adjustment to lake-level and seasonal wave climate can now be extended to the entire beach and offshore profile of a Great Lakes coastline.

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