

# Detailed Measurement of NEHRP Site Classifications Throughout Las Vegas Valley, Nevada, for Building Code Enforcement by Clark County

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#### Abstract

Rapid growth of the Las Vegas, Nevada urban area over the past 50 years resulted in a population of over 2 million exposed to earthquake risks. Federal agencies did not allocate funds to protect this new population and economy. Local municipalities thus sponsored the measurement of an "Earthquake Parcel Map" in 2007. With implementation of the IBC and its NEHRP provisions, local property owners, builders, developers, and engineers agreed it would be most cost-effective for municipalities to provide consistent and efficient site measurements. Building departments of Clark County and the City of Henderson contracted with the Nevada System of Higher Ed. and Optim to make over 10,000 standardized Vs30 measurements using the SeisOpt<sup>®</sup> ReMi<sup>TM</sup> method across 1500 km<sup>2</sup> of urban area within 3 years. The municipalities funded the Parcel Map for less than \$20 per household. The Parcel Map shows boundaries between NEHRP soil classes are complex and impossible to predict without dense measurements. Urban planners, developers, and landowners use the Parcel Map to intelligently avoid over-strengthening buildings on stiffer sites, and properly assess the higher costs of developing softer sites.

With a spacing of 300 m or less, the Parcel Map classifies every parcel on the NEHRP scale. While Vs30 average values are unable to capture all the variability in the shallow surface that affect site conditions, the parcel mapping exposed details of localized harder and softer locations. Existing geological maps do not reveal the random patches of Class C that are scattered within the general region classified as Class D area, nor the isolated patches of Class D within wider areas classified as Class C, as directly measured by the Vs30 Parcel Mapping. Identification of such anomalies is only possible through direct measurements of shallow shear-wave velocities at the parcel scale. The detailed Vs30 mapping also delineated the location and boundaries of a previously unknown buried alluvial fan surface. The detailed Parcel Map shows that current parametric approaches applied to create site-condition maps cannot account for distinctions between closely related units, and fail where relationships between the parameters and velocity vary spatially. Additionally, the 1D velocity-depth profiles obtained towards the Parcel Mapping provide information on velocities, soil thicknesses, interface depths, and resonant frequencies towards further building-code development and seismic hazard mapping.

Keywords: Geotechnical shear velocity, Seismic microzonation, Community earthquake resilience, Building code, Site hazard class.



# 1. Introduction to the Clark County Earthquake Parcel Map

Rapid growth of the Las Vegas, Nevada urban area over the last 50 years resulted in a population of over 2 million newly exposed to earthquake risks. US Federal agencies did not allocate funds to protect this new population and economy. Local municipalities thus sponsored the measurement of an "Earthquake Parcel Map" in 2007. Clark County and the City of Henderson, Nevada completed the USA's first effort to map earthquake hazard class with systematic, direct measurements throughout an entire urban area. Urban development, disaster response planning, and especially building code implementation and enforcement motivated the map development.

The need for detailed direct Vs30 measurements for urban microzonation motivated Clark County and the City of Henderson towards production of this Parcel Map. Microzonation mapping of urban areas through direct measurement of shear-velocities allows engineers to satisfy building code requirements and safely design structures, without burdening the economy with the unnecessary costs of the unjustified over-strengthening required to meet specifications based on an over-conservative default Site Class D value. Under contract, the Nevada Seismological Laboratory and Optim SDS characterized approximately 1500 km<sup>2</sup> of Clark County and the City of Henderson over a three-year period, covering the urbanized areas as well as exurban areas of future development. The Parcel Map includes over 10,000 surface-wave array measurements. Refraction microtremor (ReMi, [1]) measurement and processing technology (Optim's SeisOpt<sup>®</sup> ReMi<sup>TM</sup>), adapted for large-scale data collection, acquired the 10,000 measurement sites. The resultant Parcel Map cost the municipalities less than \$20 per household. Property owners and engineers can accept Parcel Map Vs30 values, openly available from clarkcountyny.gov, in applying for building permits; or challenge map classifications with their own measurements. The Parcel Map benefits the entire community, including engineering companies, builders, owners, planners, emergency responders, and the public in addition to local authorities. Information from the Parcel Map is integrated with geological data and other hazard assessments to help formulate policy towards mitigating the risks from earthquakes.

A challenge for engineers and urban planners is to promote community resilience to earthquakes, while not making the cost of compliance impossibly high. Current earthquake hazard maps miss details of localized safer hard spots and dangerous unknown soft spots that sparse geological and geotechnical data cannot predict, and which only detailed, direct measurements can identify. Measurement of shear-wave velocity (Vs) in the shallow subsurface is essential for not only the estimation of building-code seismic hazard class for engineering applications, but also for seismic hazard assessment through the development of seismic-hazard maps and the calibration of recorded ground motion data. This paper explains the need for, and the benefits of, such detailed shear-velocity mapping. In addition, acknowledging the limitations of the single Vs30 parameter in representing site effects, we discuss additional classification parameters provided by the individual velocity-depth profiles determined through Parcel Mapping, towards comprehensive quantification of seismic site response.

The complete parcel class map for Las Vegas Valley is presented in Figure 1(a). A key result is that 80% of the 1500 km<sup>2</sup> area surveyed is stiffer than the default Site Class D specification. Regions classified as Class D in Figure 1(a) show a general correlation with the high-soil-hazard areas as identified by previous geotechnical soils maps. A concentration of fine-grained and dune sand deposits are observed from geological mapping of the central valley regions [2, 3, 4]. Parcel Mapping directly measured apparently random patches of Class C (green in Figure 1(a)) scattered within the region generally classified as Class D (blue in Figure 1(a)), as well as isolated patches of Class D within wider areas classified as Class C. These small areas of variation were not predicted by surface soil-hazard or geological maps. In several places, measurement density was increased to improve the characterization of the observed variation of Vs30, to better define site class boundaries and identify such localized areas of lower or higher velocities.

Such localized details are rarely included in the conservative site class maps and 3D velocity models produced by national agencies for regions such as the San Francisco Bay region, Puget Sound and Seattle areas, and the greater southern California region [e.g., 6, 7, 8, 9]. Such agency maps focus on research, and produce general mapping guided by interpolation and extrapolation of available data. In contrast, our direct, densely spaced measurements have allowed a more complete characterization of the seismic hazard, including its



intrinsic aleatory uncertainty. A portion of the complete Vs30 map showing un-classed individual Vs30 measurement values within Las Vegas Valley is displayed in Figure 1(b). Thiessen polygons were used to interpolate the point values, defined mathematically by the perpendicular bisectors of the lines between points. Presenting the data in this way, we can see the detail of randomly localized safer hard spots (warmer colors in Figure 1(b)) and dangerous soft spots (purple color in Figure 1(b)) that were otherwise unknown prior to Parcel Mapping. Only large numbers of direct measurements can identify such detailed localized variations.



Fig. 1 – (a) Map showing the NEHRP/IBC site classification results of the Earthquake Parcel Mapping projects undertaken by Clark County and the City of Henderson. Gray lines are municipal and state boundaries. The IBC "D" zone is medium blue; the IBC "C" zone is green; and the proposed "C+" zone is red. (b) Map of the Las Vegas Valley area of the Parcel Map. Individual Vs30 values for each array measurement site are displayed using Thiessen polygons. The Thiessen polygon map is mathematically generated from the point values, and defined by the perpendicular bisectors of the lines between the Vs30 measurement points. The boundaries of each polygon define the area that is closest to each measured point relative to all other points.

## 2. Site Classification Mapping for Seismic Hazard Application

Earthquake ground motions have long been identified to be a function of near-surface site conditions from observations of the New Madrid sequence [10], the 1891 Japan earthquake [11], and the 1906 San Francisco earthquake [12, 13]. Many studies have since recognized correlations between site amplification and geology [e.g., 14, 15], with formal documentation of this phenomenon given by Boore [16]. The lithology of geological units has been directly correlated to Vs30 values [e.g., 17], and likewise, correlations between ground motions and Vs30 have also been observed [e.g., 18, 19, 20]. Seismic shear-wave velocity of soils is a mechanical property, directly related to the stiffness and shear strength of the soil material [21]. Amplification is sensitive mainly to shear-wave velocity versus depth profile in the shallow subsurface is therefore essential for seismic hazard assessment. The time-averaged shear-wave velocity value for the top 100 feet or 30 meters (Vs100-foot or Vs30-meter), as per IBC 2006 Section 1613.5.5 representing the site class measurement, is integral to the seismic design of structures per the International Building Code and International Residential Code [22, 23] in the U.S.A.

As part of a simplified procedure used by practicing engineers to solve routine design problems (e.g., for non-critical structures), seismic site classification was initially developed as a way to meet the requirement for a

single parameter to characterize most of the dominant seismic response characteristics at typical building sites. Despite its simplicity, application of the average shear-wave velocity in the upper 30 meters to classify sites was subsequently found to significantly capture many first-order site effects [24] and has been deemed appropriate for use when developing ground motion prediction equations (GMPEs) and calculating seismic hazard analyses [25]. Parameterizations of site effects were required for engineering design, based on well-defined and generally available site attributes that are supported by both theory and observation [26]. Engineers have commonly used the average 30-m shear-wave velocity, Vs30, to meet this requirement to date.

Earthquake-hazard mapping has previously relied heavily upon extrapolation of statistical averages of measurements onto geological units as predictors of shallow shear-wave velocity [e.g., 14, 27, 28, 29, 30, 31]. Such efforts endeavor to map site conditions and Vs30 based on surface geology. However, geological formations and units are typically heterogeneous in composition, and vary in thickness, thus providing only a first order approximation for Vs30. To improve upon these extrapolation methods and help characterize the spatial variation of Vs30, parametric proxies such as geology [29], expanded and refined geology [30, 32], and slope or distance-from-hard-rock [31], have been used to extend measured Vs30 site characterizations for California and other regions of the world. Both the Wills and Clahan [30] and Wills and Guiterrez [31] studies represent efforts to improve the Wills et al. [29] geology-based Vs30 predictive map for California, which was initially reported by its developers to have a 25% error rate. Mapping of Vs30 site class by Holzer et al. [33] incorporated both measured shear-wave velocities and thicknesses of shallow geological units, observing that the thickness of surficial units significantly affects the predicted amplification. In an alternative approach, topographic slope has been introduced as a correlative to Vs30 [34, 32]. Recent work by Yong et al. [9] developed an automated terrain classification scheme based on multi-parameter taxonomic criteria (slope gradient, local convexity, and surface texture) that identified 16 different terrain types for California. Yong et al. [9] assert that the combination of multiple parameters "yields a more robust estimate than uniparametic models." More recently, hybrid approaches combining Vs30 approximations from topographic slope and surficial geology, are being developed that acknowledge site-specific direct spot measurements of Vs30 [e.g., 35, 36].

However, such approaches are unable to capture all the variability in the shallow surface that affect site conditions, and are likely to miss the details of localized harder and softer locations. Identification of such anomalies is possible only through direct measurements of shallow shear-wave velocities at the parcel scale, as observed in Figure 1. The need for direct, densely spaced measurements was clearly demonstrated through the characterization of shallow shear-wave velocity along three urban transects (16, 13, and 60 km long respectively) in Nevada and southern California [37, 38, 39]. Each transect consisted of a series of ReMi<sup>TM</sup> measurements, using arrays set approximately 300 m apart. Across all three transects, measurements correlate poorly against available soil and geologic maps, with no distinction between closely related units. Hazard maps when prepared from general geologic or soil maps often compared poorly against the transect measurements.

Such geology-based proxies rely on the false assumption that the shear-wave velocities of stratigraphic units are relatively constant. Geotechnical and geophysical investigations at the locality of a highway embankment showed that borehole data and in-situ tests at three sites within a mere 3 m radius exhibit large soil heterogeneity in the upper 15 m [40]. With the assumption of a homogeneous soil volume, Fenton [41] made 143 randomly placed cone penetration (CPT) soundings over an 18 km<sup>2</sup> area. Analysis of these measurements revealed that the vertical variation of tip resistance is fractal. The fractal self-similarity implies that variability increases indefinitely as the scale of measurement increases, at least until reaching a correlation distance. The spatial analysis of Thelen *et al.* [39] never reached any peak at a correlation distance, even though their 60-km profile completely crossed both the San Gabriel Valley and Los Angeles Basins. While, Hunter *et al.* [42] developed a Vs30 map for the city of Ottawa, utilizing over 21700 borehole logs, only 700 geophysical measurements were acquired over this large area. Both Clark County and the City of Henderson desired a more comprehensive mapping strategy, demanding dense measurements and increased sampling where variations necessitated. The results in Figures 1 and 2 show how the relationship with elevation, alluvial deposits, and site class determined by direct measurement is highly variable [43].



# 3. Parcel Map Velocities Versus Predictions Based on Topographic Slope

Figure 2(a) displays an enlargement of the complete Vs30 map of Figure 1(b), showing individual measurement values within Las Vegas Valley. Comparison between a subset of the 7614 Parcel-Map-measured site class values presented in Figure 2, and those predicted for each site location by the topographic criteria of Wald and Allen) [32] is shown in Figure 3. The direct measurements reveal that only 17% of Las Vegas Valley sites are classified as Site Class D, with 50% designated Class C. In comparison, the predictions of Wald and Allen [32] based on topographic slope for active tectonic regions, suggest 93% of the area should be classified as Class D and only 6% as Class C. Our direct measurements also established that 33% of the measurements, primarily located on alluvial slopes along the western side of the Valley, are site Class B (C+), while Wald and Allen [32] suggest only 6% of sites should be Class B. None of the direct measurements detected very low-velocity (<180 m/s) Class E soils, while the topographically planar valley floor suggested that six locations (<1%) could require special study as Class E.

Figure 2(c) displays a terrain-slope map of Las Vegas Valley, based on the categories defined by Wald and Allen [32] for tectonic regions. In this map the Class B/C (or C+/C) boundary, along the western side of the valley, shown in Figures 1(a) and 1(b), corresponds approximately to the area of higher topographic slope, except in the south. The southernmost fan was previously not depicted by sparse spot measurements [e.g., 44, 45, 46, 47]. The B/C boundary occurs at a different but relatively constant elevation along each of the three alluvial fans. The southernmost fan as depicted by the high velocities has no surface expression of slope along its toe. Comparisons between the measured Vs30, elevation, and the topographic-slope predictions [32], presented in Figure 4 along east-west profiles arranged from north to south (profile locations in Fig. 2(b)), confirm this observation. Each transect shows an abrupt increase in measured Vs30 values from Site Class D or C to Site Class C+(B). The predicted site class from the Wald and Allen [32] topographic model are also presented in Figure 4 as colors. In accordance with Figure 3, almost all sites are predicted by Wald and Allen [32] to be classified as Site Class D (cyan circles), even at locations where the elevation profiles indicate advancement onto the alluvial fan surface, highlighting the inadequacy of the topographic slope model in this region.

The highest measured Vs30 values in Figure 4 are noted along Profile 5, for which both the elevations and topographic slopes are lowest. Further, from north to south, the increase in Vs30 occurs where the elevation and topographic slope begins to rapidly increase in profiles 1 to 4. However, for both Profile 5 and 6, the increase in Vs30 is not as clearly associated with a change in elevation or topographic slope, and is not as abrupt. The increase in topographic slope along Profile 2 is signified by the prediction of site Class C values by Wald and Allen [32] at the western edge (yellow circles in Figure 4). This increase in elevation and slope is not manifested in an increase in measured Vs30, which decrease in value to the west even though slope is increasing. Interestingly, along profile 4, measured Vs30 values appear to decrease where the topographic slope is steepest, with the Wald and Allen [32] model predicting Site Class C (yellow) and B(C+, red) at the steepest point, just where measured Vs30 values are lowest along the alluvial fan surface. Figures 1 and 2, as well as the profiles presented in Figure 4, emphasize the inherent variability of shallow shear-wave velocity data and the variation observed in geologically complex regions. The use of a topographic slope approximation to define site class and earthquake site response [e.g., 32, 48], may be necessary for broad-scale applications such as the ShakeMap system [49, 50]. However, the disparity between the measured and terrain-predicted Vs30 values highlights the difficulty in applying and transferring parametric, proxy-based predictive methods to additional locatlities. These difficulties indicate the shortfalls of current techniques applied for mapping site conditions through extrapolation and interpolation [e.g., 34, 32, 29, 30, 9, 36].

### 4. Appropriateness of Volume-Averaging Vs30 Velocity Measurements

Volume averaging of shear-wave velocity is a result of all surface-wave measurement techniques. Averaging occurred over the 184-meter array length used for the measurements in the Clark County Parcel Map. We propose that this averaging results in shear-wave velocity measurements that are well suited to mapping earthquake hazard class, and for building code enforcement. In comparison, downhole measurements average over far smaller volumes of the subsurface, and may well be less appropriate for predicting earthquake shaking. The volume averaging of the velocity is on the scale of both building foundations and the wavelength of the



seismic waves that cause damage. These features of the technique make SeisOpt<sup>®</sup> ReMi<sup>TM</sup> a very effective method for site characterization of cities within the United States, and wherever the hazard classification is based on shear-wave velocity.



Fig. 2 – (a) Enlargement of the complete Vs30 map showing individual measurement values within Las Vegas Valley, detailing the localization of harder and softer spots. The dotted circle highlights a region where Vs30 measurements vary by as much as 1000 m/s over a 205 m distance. (b) Inset shows the location of the six velocity profiles shown in Figure 7. (c) Topographic slope map of Las Vegas Valley. The slope map was created using 30 m digital elevation models (DEM). The DEM was smoothed using the neighborhood mean over a 10-cell circle radius (radius =10). The eight topographic slope categories are representative of slope ranges for tectonic regions as defined by Wald and Allen [32].





Fig. 3 – Histogram showing the distribution of IBC/NEHRP Site Class classifications within Las Vegas Valley based on the direct measurements from the Parcel Map with those predicted by the topographic slope model of Allen and Wald [34].

The refraction microtremor array analyses are making use of the same 0.5-10 Hz frequencies that cause damaging earthquake ground shaking in earthquakes. For example, Cranswick *et al.* [51] observed the structural response of a 5-6 story building to motions from aftershocks of the 17 August 1999 I zmit earthquake to be concentrated at 2 to 3 Hz. This is the frequency interval over which the Parcel Map dispersion curves show the best constraint. For another of many examples, Shakal *et al.* [52] observed that during the 1994 Northridge earthquake the seven-story Van Nuys Building suffered structural damage and concrete spalling. This building's fundamental period lengthened from 1.5 to 2 sec during the earthquake. Similarly, 1-2 sec acceleration response correlated with building damage during the February 2011 Christchurch, New Zealand, earthquake [53]. Frankel *et al.* [54] observed a general increase of amplifications at spectral periods of 0.2 to 1.0 sec with decreasing Vs30 at strong motion sites that recorded the M=6.8 Nisqually, Washington, earthquake. Surprisingly, during the 2011 Tohoku Japan earthquake, unexpectedly long period 1-2 second motions caused significant damage to wooden-frame houses [55].

The speeds of waves measured using the ReMi<sup>TM</sup> technique occur at the same apertures, wavelengths, and frequencies as these somewhat long-period motions that have caused significant earthquake damage. In addition, the arguments presented above emphasize that downhole Vs data do not have spatially adequate sampling properties for determination of velocity variations at the parcel scale. The velocity volume averaging of ReMi<sup>TM</sup> measurements have a scale comparable to that of building foundations, and are therefore suitable for earthquake engineering and hazard use. Muria-Vila *et al.* [56] and Taborda and Bielak [57] observed and modeled shaking interactions between soils, foundations, and urban structures. They concluded that the nonlinear effects of soil-structure interaction typically peaked between 0.5 Hz and 3 Hz. For soft, dangerous soil having a shear-wave velocity of perhaps 200 m/s, the nonlinear wave effects are occurring over volumes at least 60 m in diameter, at these frequencies. Thus, some of the most troublesome nonlinear effects in earthquake risk evaluation are best evaluated with techniques that yield velocities averaged over similar-sized volumes. Such volumes are directly measured with ReMi<sup>TM</sup> and Parcel Mapping.

#### 5. Discussion

The shear-wave velocity of soils and rock is a measure of sediment stiffness, strength, and rigidity. In turn, seismic site response is a function of both soil stiffness and soil depth. Uniform stiffness of soils allowed clear demonstration of the relationship between variations in soil depth and structural damage during the 1967 Caracas earthquake [58]. Results of the Las Vegas Parcel Map provide additional information towards earthquake hazard assessment through the identification of soil properties at depth. Most of the 1D velocity-depth profiles measured during the Parcel Mapping obtained velocity structure down to 100 m depth. These velocity-depth profiles provide assessment of parameters required for more sophisticated site classifications than required by the IBC [22] to determine loading standards for building code compliance. One example is the NZS 1170.5:2004 site



subsoil classes from Standards New Zealand (2004) [59]. Under NZS 1170.5:2004, assessment of site subsoil classes involves the determination of near-surface shear-wave velocity values; depths to soil interfaces; natural period from velocities and interface depths; maximum depth limits for soils; and depths to bedrock. All of the preceding assessment parameters can be derived from the velocity-depth profiles resulting from ReMi<sup>TM</sup> array measurements. Incorporation of these supplementary parameters described by the Parcel Map velocity-depth profiles builds toward the development of more robust site classification and ground motion prediction.

Improved site effect classifications for modern design codes need to include recognition of the dependence of soil factors on dominant site frequency, as demonstrated by Schmidt et al. [60]. Classification schemes that use the predominant soil period in parallel to Vs30 better discriminate soil classes [61]. Towards development of new code classification schemes, Pitilakis et al. [62] developed site classifications using parameters defining the thickness of soil deposits, the average shear-wave velocity to the seismic bedrock and the fundamental period of the site. General geotechnical characterization of sites, that includes soil depth and stiffness, result in significant reduction in standard error when used for empirical ground motion estimation [63]. Studies like these highlight the need for Parcel Mapping efforts such as that presented here. Parcel Mapping provides an unprecedented wealth of velocity-depth information with which to rigorously test and develop more stringent soil and site classifications schemes, for both implementation of comprehensive building codes, and seismic site-response evaluation.

Despite the limitations of the single-value Vs30 parameter in defining the effects of soil structure on ground motion, applications utilizing Vs30 still clearly demonstrate its significance to describing the overall site effect on ground-motion estimation [e.g., 64]. The strong dependence of ground motion on the detailed near-surface Vs30 distribution and variability of the Clark County Parcel Map observed by Flinchum *et al.* [65] strengthens the case for the need for detailed microzonation measurements. Parcel Mapping is thus an essential component of seismic hazard evaluation in seismically active and highly populated metropolitan regions. Standardized large-scale shallow shear-wave velocity hazard mapping of earthquake-prone cities is long overdue. Maps generated using a consistent data acquisition and processing technique across an entire city avoid errors generated due to lack of expertise in interpreting geophysical data, and the bias individual practitioners may show toward the economic needs of their clients. The Parcel Map therefore results in a more reliable hazard evaluation with all the detail needed at the parcel, block, and building scale. Products and results of the earthquake Parcel Mapping project meet urgent assessment and compliance needs beyond building-code compliance in the U.S.A. The measured velocity-depth profiles used to determine Vs30 define many other parameters that satisfy worldwide building code requirements and improve the assessment of seismic site response.

### 5. Conclusions

- The ReMi<sup>™</sup> technique offers a fast and cost-effective method for Parcel Mapping and detailed earthquake hazard mapping, on an urban scale.
- The maps generated result in a more reliable hazard evaluation with all the detail needed at the parcel, block, and building scale.
- The detailed Parcel Map shows that current parametric approaches applied to create site-condition maps cannot account for distinctions between closely related units. Parametric estimates fail where relationships between the parameters and velocity vary spatially.
- The dense direct measurements of the Parcel Map demonstrate that physical measurements are essential for capturing the natural variability.
- The ReMi<sup>TM</sup> technique is more appropriate than downhole measurements as a means of site classification, since ReMi<sup>TM</sup> averages over volumes comparable to those of building foundations, employing the wavelengths of seismic waves that cause damage.
- The Parcel Map provides information towards building-code development as well as enforcement, through the multitude of measured velocity-depth profiles, providing information on subsurface velocities, soil thicknesses, interface depths, and resonant frequencies.



• Incorporation of these supplementary parameters measured by the Parcel Map velocity-depth profiles are needed for robust site classification.



Fig. 4 – Comparisons between Parcel-Map-measured Vs30 velocity (circles), and elevation ("+" symbols) along east-west profiles, across the alluvial fans along the western margin of Las Vegas Valley. The locations of the six profiles, from north to south, are shown in Figure 2(b). The plotted measured Vs30 values are color-coded according to the predicted site class from the Wald and Allen [32] topographic model: Class D = cyan; Class C = yellow; Class B (C+) = red.

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