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A simple method for simulating microseism H/V spectral ratio in 3D structure

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ABSTRACT: The understanding of detailed 3D basin structure is very important for seismic hazard analysis because ground shaking can be both amplified and prolonged due to basin effects and causing significant damage. Background seismic noise is ubiquitous and continuous and these characteristics make ambient seismic noise useful to study velocity structure because neither infrequent earthquakes nor expensive explosions are needed. The horizontal to vertical (H/V) spectral ratio method is a common technique to study the structure of the basin using background seismic noise. Many observations of the H/V ratio recorded at seismic stations over basins display systematic decreases in the frequency of the dominant H/V peak with increasing basin thickness. However, some observations cannot be fully explained by theoretical simulations of the H/V ratio based on 1D velocity profiles beneath the stations. In order to study the precise relationship between the H/V ratio and the basin structure, wavefield simulation of background noise for 3D velocity structure can be quite useful. However, this simulation is still far from being routine because our knowledge of the noise source is quite poor. In this paper, we propose a simple technique to directly simulate the H/V ratio instead of the wavefield of background noise. To evaluate the method, we performed numerical experiments for the Santa Clara Valley and the results show that the synthetics can predict the observations well. We also performed several sensitivity tests for the source and the velocity structure of the basin and found that Rayleigh type wave propagation and a minimum velocity contrast between the basin and background media are required to make the H/V ratio sensitive to the basin structure. Although we also found that the H/V ratio technique has a limitation in determining small scale basin structure at deeper depth, this technique can still be used to evaluate pre-existing velocity models and give some constraints on the development of new velocity models for the basins.

Key words: microseisms, H/V spectral ratio, basin structure

1. INTRODUCTION

The understanding of 3D basin structure is very important for the estimation of strong ground motions. Recently several techniques have been developed to construct basin velocity structure using background seismic noise. The technique of H/V ratio from background noise, such as microseisms for periods greater than 2 s and microtremors for shorter periods, was first used to estimate site amplification by Nakamura (1989). Since then many observational studies have shown that the thickness of the deep basins can be determined from the frequency of the dominant peak (hereafter referred to as FDP) in the H/V ratio of background noise in the northwestern part of the Kanto Plain in Japan (Yamanaka et al., 1994), the Coachella Valley in California (Field, 1996), the western Lower Rhine Embayment in Germany (Ibs-von Seht and Wohlenberg, 1999), the Mississippi embayment in Missouri (Bodin and Horton, 1999), the Bajo Segura basin in Spain (Delgado et al., 2000), and the Santa Clara Valley of California (Dolenc and Dreger, 2005). Along with observations, theoretical studies have shown that the H/V ratio from background noise can be well explained by wave propagation in relevant 1D velocity models (Field and Jacob, 1993; Lermo and Chávez-García, 1994; Bodin and Horton, 1999). In addition, Tanimoto and Alvizuri (2006) reported that it is possible to invert the H/V ratio of microseisms for the shallow velocity structure by introducing 1D sensitivity kernels. However, a couple of studies have shown that 1D wave propagation cannot fully explain the H/V ratio for the deep basins where 2D or 3D wave propagation effects are significant (Dolenc and Dreger, 2005; Guéguen et al., 2007). It indicates that more studies on the relation between the H/V ratio and 3D (or 2D) velocity structure are necessary to determine reliable basin structure from the observed H/V ratio. In this study, we propose a simple method to simulate the H/V ratio for 3D media and verify our method by using the well-developed 3D velocity model (Brocher 2005; Brocher et al., 1997) of the Santa Clara Valley (SCV).

2. METHODS

Microseisms are the dominant seismic noise in the frequency range from 0.1 to 5 Hz (Webb, 1998) and they are excited by pressure changes on the ocean bottom (Longuet-Higgins, 1950; Kedar et al., 2008). Since our understanding of pressure variations on the ocean bottom and the coupling mechanism between the ocean and sea floor is not perfect, the reliable simulation of the microseism wavefield is still far from being established. However, we are interested in the H/V spectral ratio from microseisms rather than their wavefields. Dolenc and Dreger (2005) observed that FDP does not depend on the level of the excitation of microseisms. This observation indicates that taking the H/V ratio inher-

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ently cancels the source effects and the propagation effects due to the basin structure become dominant. In other words, understanding the detailed source process of microseisms is not required to simulate the H/V ratio. This observation encouraged us to develop a simple method to estimate FDP of microseisms for the 3D basin by computing a series of basin responses to continuous monochromatic sine waves with various frequencies. SCV is a good site for testing our method because a couple of well-developed 3D velocity models are available as discussed below, and high quality microseism data was collected during the Santa Clara Valley Seismic Experiment (SCVSE) (Lindh et al., 1999; Fletcher et al., 2003). We computed Green's functions for 41 SCVSE stations (Fig. 1) using the USGS Bay Area Velocity Model 05.1.0, which was constructed by the joint effort of the USGS Earthquake Hazards Program and the USGS National

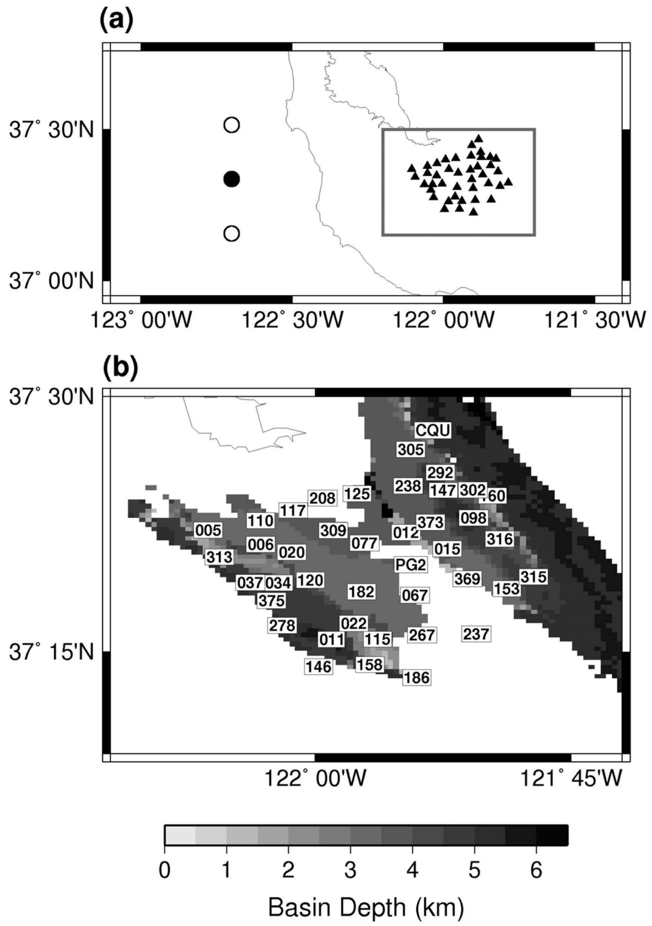

Fig. 1. (a) The dimension of the 3D finite-difference model used for synthetic computation in map view. Small triangles represent the stations deployed during SCVSE. Solid circle indicates the location of the point source of the microseism source. Two open circles are also the microseism locations used for the sensitivity test for source location. The box indicates the region in (b). (b) The background shading represents the depth of the Santa Clara basin obtained from the 3D USGS velocity model. The station names are indicated inside the box.

Cooperative Geologic Mapping Program (Brocher, 2005; Brocher et al., 1997). The 3D finite-difference code (E3D) of Larsen and Schulz (1995) was used for synthetic computation and a shallow (500 m) vertical point compensated linear vector dipole (CLVD, Knopoff and Randall, 1970) source was assumed as a source of microseisms at the continental margin (Fig. 1). A CLVD was used because it results in isotropic Rayleigh wave radiation. In practice, we reconstructed a 3D velocity model whose size is 150 (km) × 90 (km) × 40 (km) in E-W, N-S and depth directions with uniform grid spacing of 250 m from the USGS 3D model (Fig. 1a) and computed synthetic waveforms with the duration of 600 s and time interval of 0.015 s. For computational efficiency, the minimum shear wave velocity is set to 1 km/s. The detailed process to compute the H/V ratio from synthetic waveforms is as follows; First, a simple Gaussian source time function inherently convolved to compute 3D synthetic seismograms with E3D is removed by deconvolution. Second, in order to reduce grid-dispersion effects (Levander, 1988), a low pass filter with a corner frequency of 0.8 Hz is applied to the synthetics, where this maximum frequency corresponds to a 5 grid point spatial sampling of the wavefield. Third, continuous monochromatic sine waves with discrete frequencies for a range from 0.025 to 0.8 Hz with an interval of 0.025 Hz are convolved with low-pass filtered synthetic waveforms for each station. Fourth, the maximum amplitudes for vertical, radial and tangential components of convolved waveforms for each frequency are taken in the time window after the waveforms becoming stable (past the startup transient). Finally, the horizontal amplitudes are computed by taking the geometric mean of the maximum tangential and radial amplitudes. This is essentially a zero damping spectral response method. In this paper, the definition of the H/V ratio is the ratio of maximum vertical and horizontal amplitudes as a function of frequency. Since synthetic vertical and horizontal amplitudes are not stable with frequency, sometimes abnormally small vertical amplitudes cause unrealistically large peaks in the H/V ratio. To reduce this artificial effect, we take the moving average over 5 adjacent data points in the horizontal and vertical amplitudes before taking the H/V ratio (Fig. 2). Finally, FDP can be measured from the dominant peak of the H/V ratio for all SCVSE stations.

3. A COMPARISON BETWEEN OBSERVATIONS AND SYNTHETICS

The synthetic H/V ratios for the SCVSE stations are compared with the observed H/V ratios from Dolenc and Dreger (2005). Figure 3 shows the variations in FDP at all stations plotted as a function of the basin thickness. For the method used to determine the basin thickness from the model, see Dolenc et al. (2005). The variations in synthetic and observed FDP show very similar trends. FDP decreases with increas-

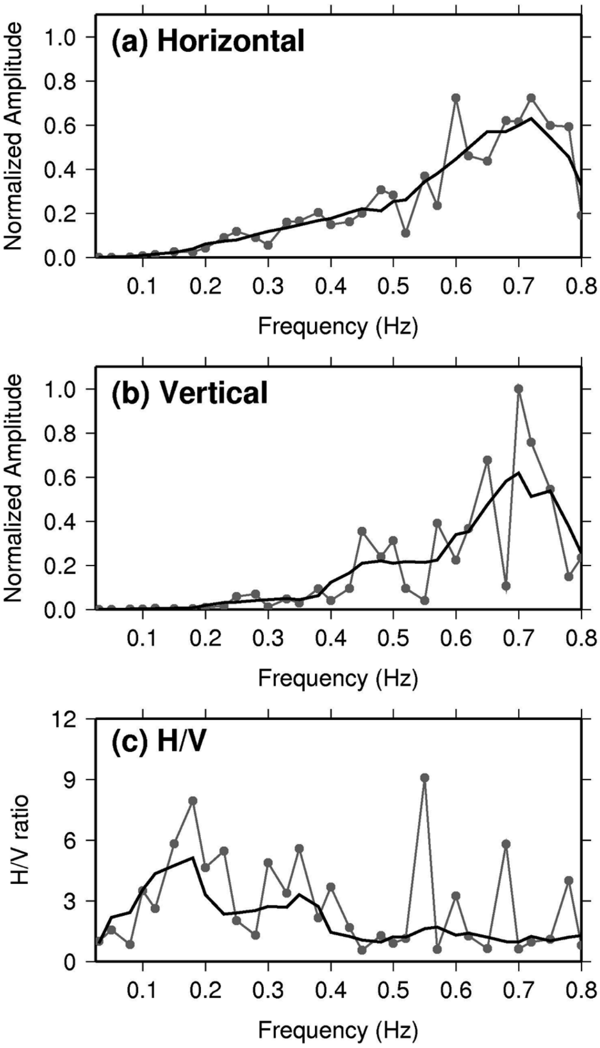

Fig. 2. (a) Horizontal amplitudes from synthetic waveforms convolved with various frequency sine waves at station 147 (gray line with solid circle). Black line shows a 5 points moving average. (b) Same as (a) for vertical component. For presentation purpose, curves in (a) and (b) are normalized by maximum amplitude. (c) The H/V spectral ratio obtained from (a) and (b). It is clear that moving average can effectively reduce the abnormal peak around 0.55 Hz.

ing basin thickness up to a thickness of 2 or 3 km. For deeper basin depths, the values of FDP become stable without much scatter. We also computed the variation in FDP for the UC Berkeley (UCB) 3D model for the same region (Stidham, 1999; Stidham et al., 1999). The result shows that FDP roughly correlates with basin thickness up to 2 km, but correlation is much weaker and individual FDPs are more scattered than the USGS model. The shift of the trend at around 2 to 3 km depth observed in the USGS simulation is not found in this case, because the maximum basin thickness of the UCB model is only 2 km (Fig. 3). Here the determination of the basin thickness for the UCB model is straightforward because the UCB model has a definite

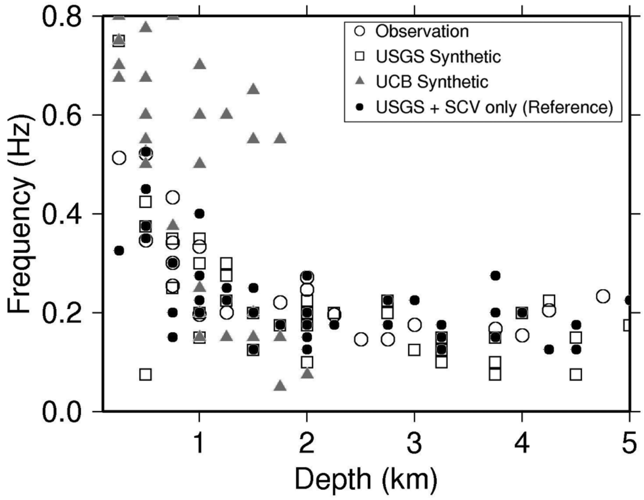

Fig. 3. The frequencies of the dominant H/V spectral peaks (FDP) for observed and synthetic SCVSE data sets. Open circles show observed FDPs. Open square and gray triangles represent the simulated FDPs for USGS and UCB 3D velocity models, respectively. Solid circles are the same as open squares but 1D velocity models is assumed for the region outside of the basin.

boundary between the basin and background media. Although these simulation results show that synthetic FDP is sensitive to the basin model, it is interesting to confirm that the variation in FDP is solely depending on the basin structure rather than 3D wave propagation effects due to complex velocity structure outside of the basin. We tested a modified 3D model by assuming a simple standard 1D velocity structure outside of the basin. A standard velocity profile was taken under the bedrock site in the western part of the San Andreas Fault from the USGS 3D model, which represents an average velocity profile outside of the basin. The variation in FDP for this simplified model is also very close to the observed and synthetic FDP for the original model (Fig. 3). This result indicates that the USGS model represents the Santa Clara Valley basin structure well and our simple convolution method is applicable to simulate the variation in FDP. For the following numerical experiments, we assumed this simplified model as our reference model.

4. SENSITIVITY TEST FOR SOURCE TYPES

For numerical experiments in the previous section a vertical CLVD was assumed as a point source located at the continental margin since this source has isotropic Rayleigh wave radiation. As we mentioned before, the detailed source process may not be important for the H/V ratio. However, it is still interesting to test the effects due to different source types and locations. First, we test a horizontal single force instead of a vertical CLVD. For the single force direction, we take the direction optimized to generate Love waves at the recording stations. The variation in synthetic FDP for

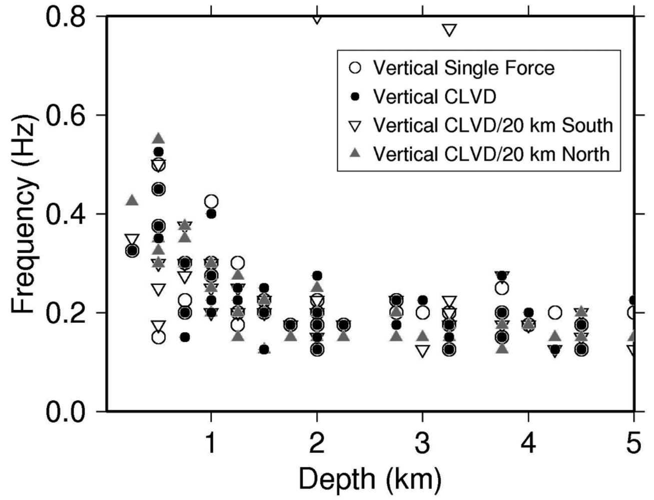

Fig. 4. The variations of FDP with depths of the basin for different sources. Open circles are simulated FDPs for vertical single force source located at a continental margin (Solid circle in Fig. 1a). Solid circles are the same as open circles but vertical CLVD source is assumed. Open and gray triangles are FDPs for vertical CLVD source but their location is shifted by 20 km to the south and north, respectively (Open circles in Fig. 1a). The 3D velocity model having 3D basin velocity structure and 1D background profile for outside of the basin is used for the synthetics. Although we take the moving average over 5 adjacent data points, there are a couple of outliers, which indicates that individual FDP is not reliable in some cases. However, the overall trend of FDP is still meaningful.

the horizontal single force is completely different from that of the vertical CLVD. We cannot find any correlation between FDP and the basin thickness for the horizontal single force. It indicates that the H/V ratio is not controlled by Love type energy propagation. Second, we test the vertical single force and the variation in FDP is similar to that with the vertical CLVD because both sources will mostly generate Rayleigh type seismic energy, which is dominant in the real microseism wavefield (Haubrich and McCamy, 1969). Third, we test the strike slip mechanism in which the fault geometry has a Love wave lobe and Rayleigh wave node for the direction to the center of the basin. This numerical experiment presents a similar trend obtained for the vertical CLVD and the vertical single force cases (not shown in the figure). It indicates that even weak Rayleigh type energy compared to Love is enough to make FDP sensitive to the basin structure. Finally we test whether the variation in FDP is sensitive to the locations of the source. We consider two cases in which sources are relocated to the north and south by 20 km from the original location and performed the same analysis. The variations in FDP for these two cases do not differ much, which indicates that source location is not an important factor controlling the variation in FDP (Fig. 4). In other words, the very precise location of the microseism source is not required to use this method to simulate the H/V ratio.

5. SENSITIVITY TEST FOR VELOCITY CONTRASTS BETWEEN THE BASIN AND BACKGROUND

In the previous section, we showed that the synthetic FDP correlates with the basin thickness especially for shallow depths. Since two parameters, such as thickness and velocity, can define the basin structure, it is worthwhile to perform sensitivity tests for different velocity contrasts between the basin and background media. For this simulation, we perturb the velocities inside the SCV basin from the reference model defined in the previous section. We compute the velocity contrast between the basin and the standard profile and then add 20 and 50% or subtract 20% of the velocity contrast at each depth in the basin. Figure 5 shows velocity profiles for three perturbed models under station 120 and the corresponding variations in FDP. The simulations show that velocity change by up to 20% results in very similar trends of FDP to that for the reference model. However, the model with the highest basin velocity (smallest velocity contrast) provides a significantly different trend of FDP

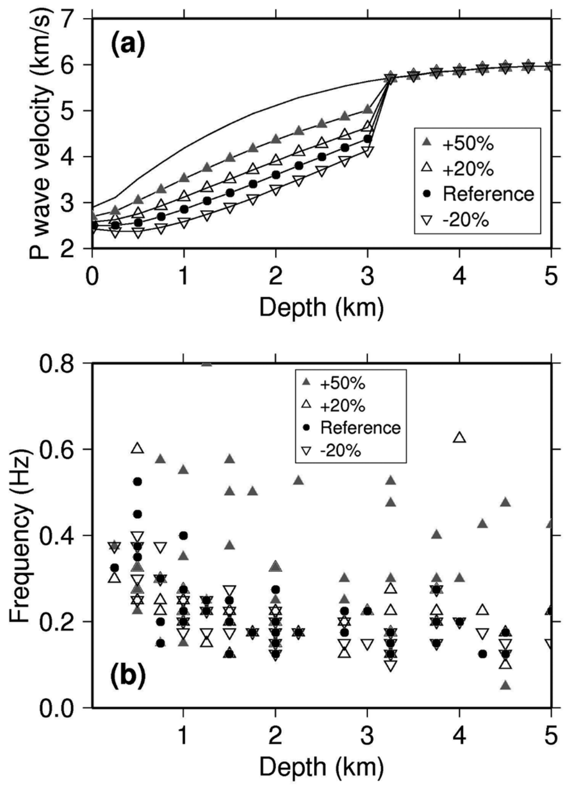

Fig. 5. (a) Thin black curve shows the background velocity model used for outside and beneath the basin. Four other curves with different symbols indicate various velocity structures inside the basin. The velocities inside the basin are modified by reducing and increasing velocity contrast between the basin and the background velocities. For example, positive 50 percent means that velocities inside the basin are increased by 50 percent of the original velocity contrast at each depth. (b) The corresponding FDPs for four models defined in (a).

compared to the reference model. This indicates that there is a minimum velocity contrast between the basin and surrounding media that is required to make FDP sensitive to the thickness of the basin. However, the variation in FDP is not completely sensitive to the small change in velocity structure inside the basin once velocity contrast is larger than a minimum contrast.

6. DISCUSSION AND CONCLUSIONS

We developed a simple technique to simulate the H/V ratio in a 3D basin model due to continuous background noise, especially microseisms. This method is analogous to an undamped spectral response treatment or analysis of simulated 3-component wavefields. The synthetic tests for two published 3D models for the SCV show that the proposed method can predict the observed variation in FDP quite well, indicating that our technique has the potential to be used for evaluating pre-existing 3D basin models. Some sensitivity tests indicate that Rayleigh wave propagation through the basin and minimum velocity contrast between the basin and surrounding media are required to use the H/V ratio approach for studying the structure of the basin. The variation in FDP is sensitive to the basin thickness but it becomes stable when the basin thickness reaches a certain depth. There are two possible explanations for this. First, the velocity contrast between the basin and surrounding media is negligible at deeper depth. Therefore, deeper depth basin structure is effectively transparent to the seismic wavefield. Simulation of the P-wave time delays from teleseismic events for the USGS 3D velocity model at SCV stations shows a similar trend as the one for the observed FDP (Dolenc et al., 2005). In other words, the time delay increases with increasing basin thickness up to a certain depth and then stabilized. Since the P-wave time delay depends only on the mean velocity and thickness of the basin, this result indicates that the velocity contrast between the basin and the background media is small at deeper depth. It suggests that the seismic thickness of SCV may be much shallower than estimates based on gravity data (Jachens et al., 1997; Catchings et al., 2006). Second, the lateral demension of the basin decreases with increasing depth, and long period seismic waves appear insensitive to the small scale deeper structure. To confirm which factor really controls the variation in FDP, we perform a numerical experiment using basin models with simple geometry and constant velocity contrast. Figure 6 shows the variations of FDP for two simple basins. The first basin model has a cone shape basin structure with maximum thickness of 6 km and the second one has a truncated cone shape with maximum thickness of 3 km. Two basins are identical for shallower depths up to 3 km. The numerical experiment result shows that the trends are very similar to one for the USGS model with negligible velocity contrast at deeper depths. The change in trend occurs at between 2 and 3 km depth for both basin models. This result indicates that the existence of the change in trend is not due to the negligible velocity contrast at depth, but is in fact due to the tapering of the basin to small dimension. Although the similar trends for two simple basins may infer that FDP is not sensitive to the relatively small basin size at deeper depth, we still need more experiments for many basin models with various shapes to study which factor really controls the overall trend of FDP.

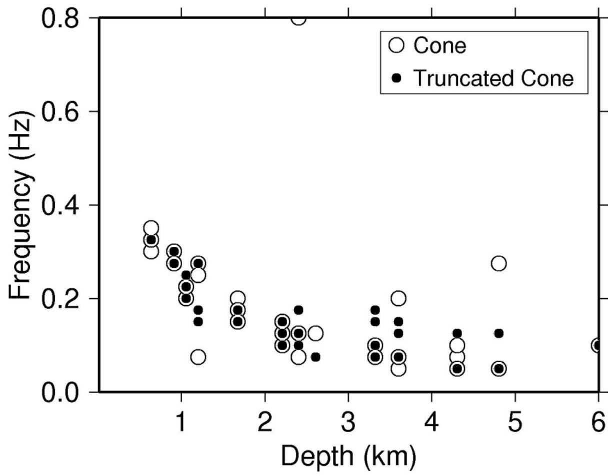

Fig. 6. FDPs for two simple basin models. Open and solid circles indicate FDPs for the cone and truncated cone shape basin models. Depth is taken from cone shape model.

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