Seismic tomography of a Maya pyramid ruin, Chan Chich, Belize

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ABSTRACT

In March 2001, a series of seismic surveys were conducted over a Maya ruin complex at Chan Chich, Belize, Central America. As part of these studies, a seismic tomography survey, using three-component (3-C) geophones and a hammer source, was undertaken around Structure A-15 (an 18 m high pyramid ruin). We used 27 source locations with 20 3-C geophones, all with a 2.5 m spacing on a contour around the pyramid. In this paper, we analyze the three-component datasets and their spectra (0-250 Hz), pick first-break arrivals from 540 vertical component seismic traces, and perform a traveltime inversion to estimate the velocities inside the pyramid. We find a P-wave velocity structure of about 400 m/s for the detrital layer on the pyramid with interior values of 500 m/s to 700 m/s. These velocity results are in reasonable agreement with those found in a similar, preliminary experiment in 2000 at Chan Chich (Xu and Stewart, 2000). There is evidence of a low-velocity anomaly among the higher velocity areas.

INTRODUCTION

The Maya civilization of Central America designed and built many magnificent structures. The remnants of these edifying efforts are seen in the hundreds of ruins from Honduras to the Yucatan. Archaeologists are active in attempting to understand the Maya people through many avenues, including the physical excavation of numerous sites. Excavation, however, is an expensive, time-consuming, and invasive process. Thus, it needs to be targeted accurately. Geophysical methods can be appropriately enlisted to create non-invasive images of archaeological sites and structures, thereby helping to define proper places for assessment or excavation. Indeed, if the geophysical images were to become good enough, some excavations might not be necessary at all – the required information being interpretable from the images.

To pursue the development of seismic imaging to assist in archaeological studies, we conducted a series of preliminary seismic surveys in Belize, Central America in the summer of 2000. The data from these surveys were used to develop analysis techniques for seismic tomographic imaging around pyramid ruins and high-resolution reflection imaging over plazas and platforms (Henley, 2000; Xu and Stewart, 2000). The encouraging results from these surveys motivated us to return to conduct augmented surveys in the spring of 2001. We re-surveyed the large A-15 structure at Chan Chich, Belize. This time, we used 20 geophones instead of 10 and struck the hammer about 3 times per shot point instead of the previous 20. There were 27 shots, each located between the receivers, around a contour on the pyramid. The receiver interval was 2.5 m. The geometry is shown in Figure 1.

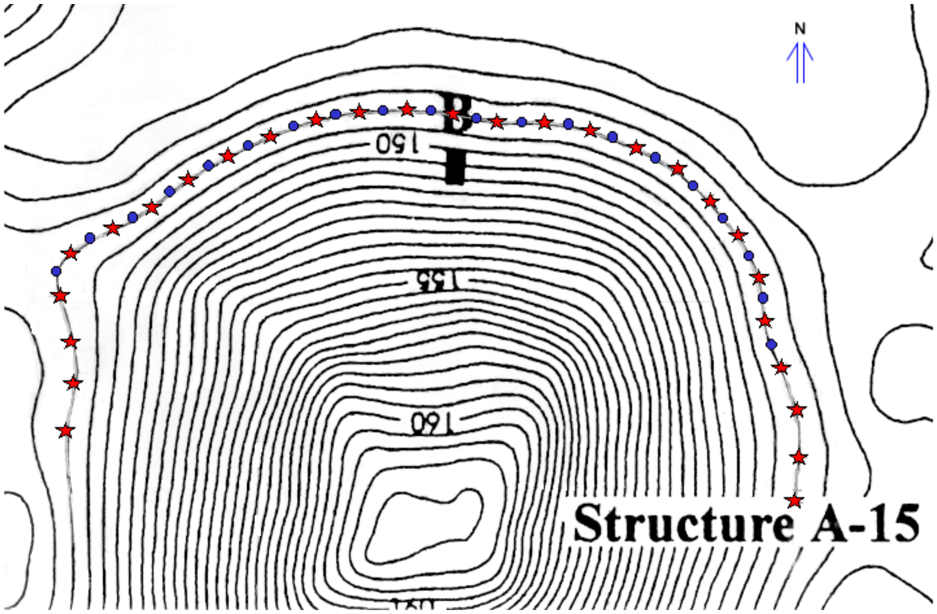

FIG. 1. Topographic contour map of the pyramid. The pyramid is about 30 m by 30 m at its base. Elevation annotations are in metres. The survey geometry is overlain with blue dots indicating receivers and red stars denoting shot locations.

There are 27×20=540 traces in total. We use these data and a linearized traveltime inversion method to estimate the velocity structure inside the pyramid.

DATA ANALYSIS

In viewing the raw three-component seismic data, we find that the vertical component provides the best quality, with clear events and consistent first breaks. Figure 2 shows three component data with a 200 ms window AGC operator, from top to bottom V, H1 (inline) and H2 (xline). The left three panels are shots 1 to 6, and right panels are shots 18 to 23. We picked first breaks (shown in red) on vertical component data and display them (in green) on the H1 and H2 data. We observe that the vertical component always detects the earliest wave, even when the shot is between two geophones.

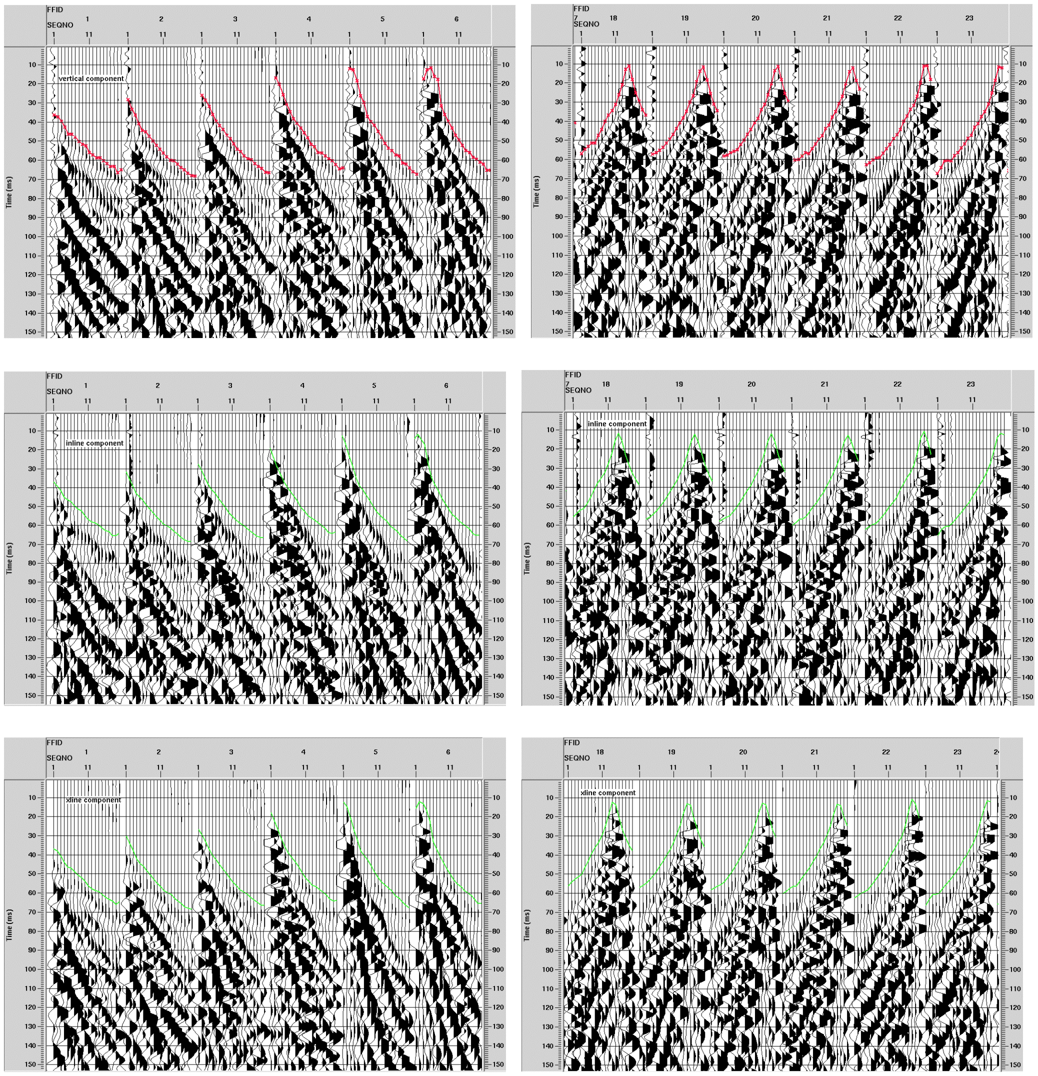

FIG. 2. Display of Vertical (V), horizontal-inline (H1) and horizontal-xline (H2) component shot gathers from top to bottom with a 200ms AGC applied. The three panels on the left are from shots 1-6 and on the left shots 18-23.

The hammer-seismic source produces a fairly broadband signal up to about 250 Hz (40 dB down). Figure 3 displays the amplitude spectrum of shot #19. The other shots show similar spectra.

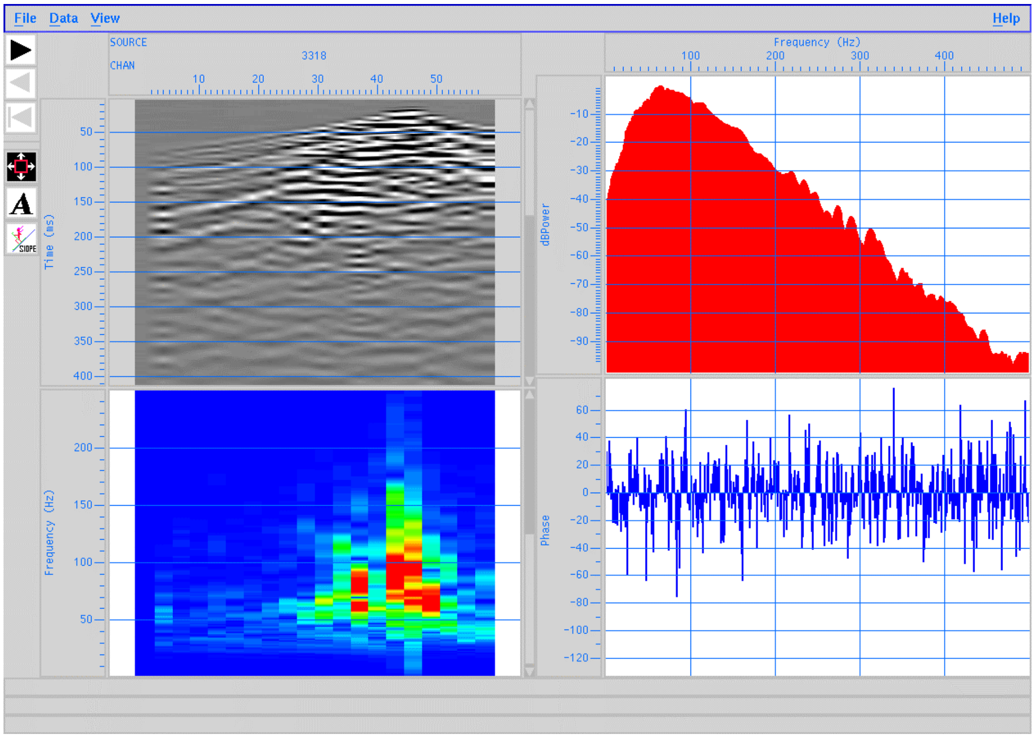

FIG. 3. Display of the vertical component seismograms and frequency spectrum for shot #19.

INVERSION

From last year's result, we found velocities in the 100 m/s – 800 m/s range. Given a velocity of about 500 m/s with a 150 Hz signal, we expect wavelengths of approximately 3 ~ 4 metres. We have found that gridding the area of interest at 4 m x 4 m provides the best (least oscillatory) solution. For this analysis, we assume straight raypaths. While this is an approximation, it should be reasonably accurate over the distances considered, with Fermat's principle stating that traveltimes will be insensitive to small changes in travelpath. We omitted the last four shots because of ambiguities in their geometry and so use 23 shots giving 460 observations.

Using the methods of Xu and Stewart (2000), we inverted the new traveltime data for their underlying velocities. Again, the problem is cast as a tomographic traveltime inversion as a system of 460 linear equations:

$$t_i = \sum_j D_{ij} \cdot s_j \tag{1}$$

where t_i is total traveltime of i^{th} shot-receiver pair, s_j is slowness of j^{th} grid, and D_{ij} is the distance of i^{th} ray traveling in j^{th} grid. Each shot-receiver pair builds one equation.

Expressed in matrix form:

$$\mathbf{t} = \mathbf{D} \cdot \mathbf{s} \qquad (2)$$

We start from 4 m × 4 m grid. As outlined in Figure 2, we label the N-S direction as **z**, and the E-W direction as **x**. The z-values range from 0 m to 24 m while x goes from 0 m to 40 m. There are 6 rows (z) and 10 columns (x) for a total of 60 pixels.

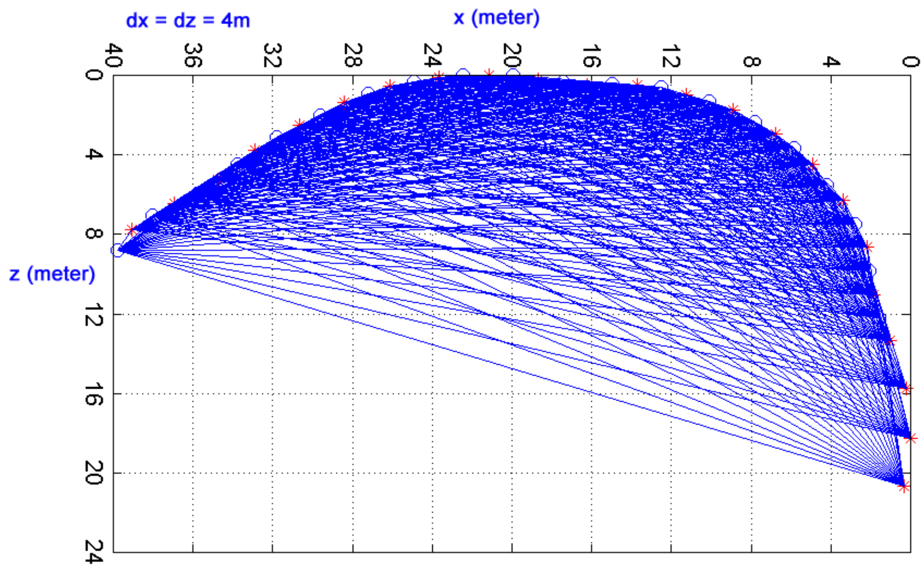

FIG. 4. Grid with z range from 0 to 24 m, x values from 0 to 40 m, and pixel size dx=dz=4m. Red (*) symbols represent shot points while blue (o) symbols denote receiver points. Straight rays between sources and receivers are shown in blue.

Given the coordinates of the shots and receivers, **D** is calculated. In this case, dx = dz = 4, the size of **D** is 460×60. The matrix **D** is defined as soon as the grid is defined.

The method of singular value decomposition (SVD) is used to solve for the model parameters $\mathbf{s}_{inv}$ (slowness vector). In SVD, we use a stabilization factor of 1.0e-6.

Figure 5 shows picked first-breaks (blue circles), the calculated traveltimes (red stars) from the inverted slownesses, and the difference between them $\Delta t = t_{inv} - t_{FB}$ (green line). We see that most of the traveltime residuals (errors) are within ±5 ms.

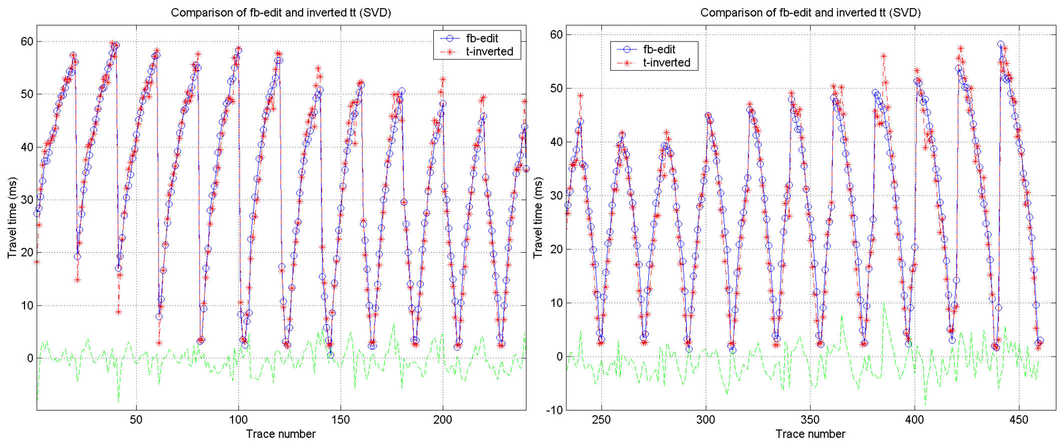

FIG. 5. Comparison of the observed first-break times and calculated times from inversion-estimated slowness model.

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v_tomoC23 = (m/s)
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0	474.75	338.89	431.22	406.42	0
387.48	511.72	609.55	697.20	539.34	0
497.65	705.04	664.97	853.85	508.15	0
520.34	829.53	860.82	597.02	113.70	0
488.00	721.45	748.27	731.00	0	0
485.22	559.35	449.78	0	0	0
551.72	849.68	0	1313.4	0	0
516.72	0	0	500.00	0	0
268.30	255.35	310.01	0	0	0
0	819.50	414.86	0	0	0

Table 1. Velocity values calculated from the inversion.

We do find several negative slowness values - that are clearly unphysical. These are generally in regions of lower fold and perhaps less reliable. For display purposes, the velocity values of those negative slowness grids are set to 0. The final velocity bar map and contour map are shown in Figure 6 and 7.

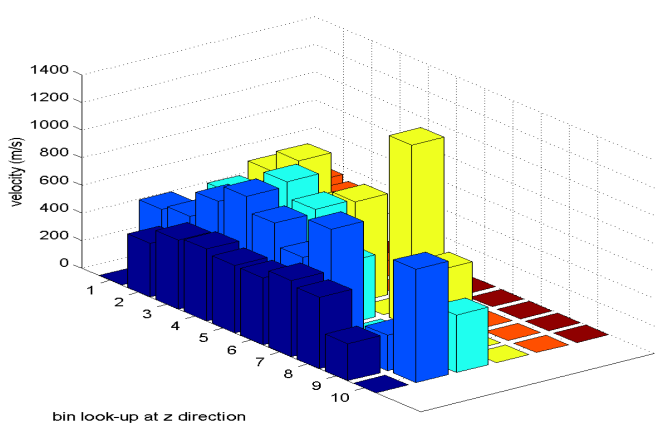

FIG. 6. Three-dimensional bar map of slownesses (the reciprocal of velocity).

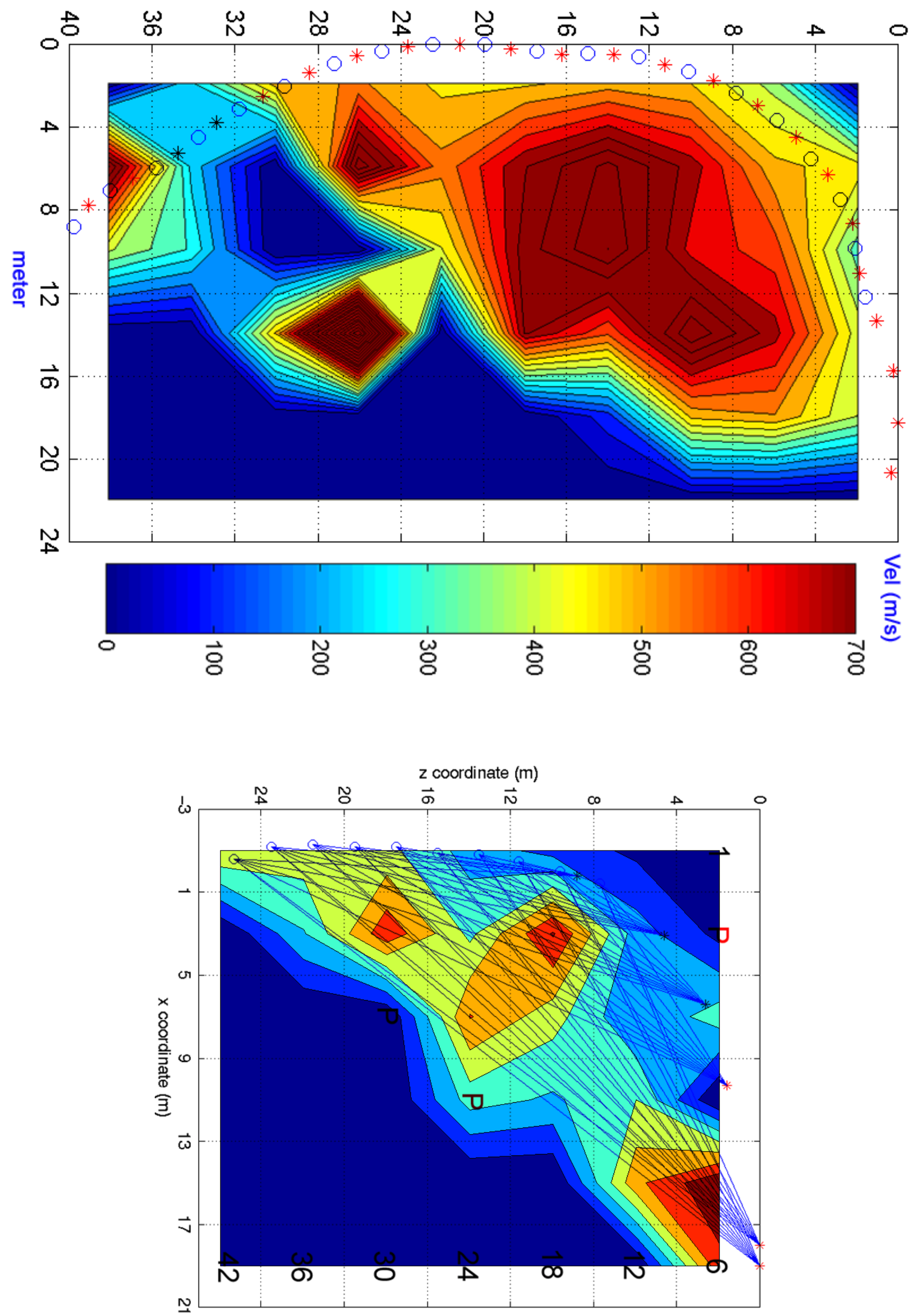

FIG. 7. Comparison of the final velocity (m/s) maps between year 2001 and year 2000. The recent (2001) map is shown above the 2000 map.

Figure 7 shows the comparison of the estimated velocity structure between year 2000 and year 2001. This year's result demonstrates shows a broader coverage, but similar set of velocities.

CONCLUSIONS

We acquired seismic tomographic data around a pyramid ruin structure at Chan Chich, Belize. The data displayed consistent first-break arrivals. We were able to calculate an internal velocity structure for the pyramid using a linearized inversion technique. The velocity tomogram shows velocities at the pyramid surface of about 300 m/s with internal velocities in the 600~700 m/s range.

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