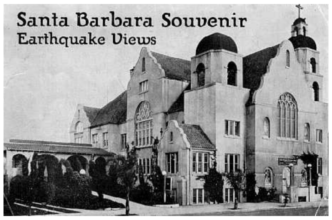

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SHALLOW STRUCTURE OF TAIPEI BASIN USING HIGH-FREQUENCY RECEIVER FUNCTION TECHNIQUE

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ABSTRACT

Receiver function is a conventional technique for studying the structure of crust and upper mantle beneath the seismometer. The amplitude and timing of the composite P-to-S converted waves can be modeling to figure out the main feature of the velocity structure. In this study, we tried to apply the receiver function technique on the high-frequency acceleration seismograms recorded by TSMIP stations of CWB to estimate the shallow S-wave velocity structure in the Taipei Basin. And our results have showed the feasibility of the high-frequency receiver function technique for shallow structures.

The Taipei basin is a triangular alluvium basin with the complex Tertiary basement and the weak Quaternary alluvium. The site effects of the basin amplifying and extending the seismic waves result in the major seismic disasters in Taipei. From the variations of receiver function waveforms with respect to azimuth, the complex structure beneath the stations can be concluded, such as a dipping plane or large lateral velocity heterogeneity. The averaged receiver function of each station in the basin we calculated exhibit some converted phases reflected the major shallow interfaces beneath the basin. The waveforms and arrival times varied with the locations of stations. After the forward modeling of the Genetic Algorithms (GA) searching, we estimated the depths and shape of the Tertiary basement and other interfaces under the Taipei basin.

INTRODUCTION

Taipei Basin, including the Taipei City, the capital of Taiwan, and the New Taipei City, located in the northern Taiwan is the metropolitan areas with the highest population density. The basin was filled with thick and soft Quaternary deposits which amplified the incident seismic waveforms (Wen and Peng, 1998). The site effects of the basin structure have caused several seismic disasters in the Taipei Basin. The building collapses caused by the 1999 Chi-Chi earthquake (M_L 7.3) and 2002 331 east coast earthquake (M_L 6.8) were the significant examples recently. According to widely distributed 30 drilling wells and 300 shallow reflection seismic lines, the Tertiary basement and the Quaternary strata above the basement were described (Teng et al., 2001; Wang et al., 2004). However, the structures of some major interfaces affecting the propagation of seismic wave in the basin are still unclear. For reducing the earthquake hazards in the future, the complete and detailed S-wave velocity structure under the Taipei Basin is essential to conduct site-effect estimations, theoretical simulations of strong motion, and seismic hazard assessments.

Teleseismic receiver function method has been developed to provide local information on S-wave velocity discontinuities beneath the recording station (Langston, 1979; Owen et al., 1984; Ammon et al., 1990; Ammon, 1991). The method is excellent at clearly showing the Ps converted phases used to estimate the depth of the discontinuities even if seismograms are contaminated by noise and scattering waves. The receiver functions of stations distributing over a region are efficient to estimate their three dimensional structures. Because the largest S-wave velocity discontinuity generally coincides with the Moho, the method was popularly used to study the structures from the lower crust to the upper mantle. However, if the site is filled by sediments, the sediment-bedrock interface becomes a major velocity discontinuity. The waveforms from these receiver functions are dominantly controlled by the sedimentary structures within the first few seconds after the direct P arrival. Information from the deeper structure may be masked by multiples from this large near-surface discontinuity (Zelt and Ellis, 1998). As a result, the sensitivity of the receiver functions to variations in both the velocity and thickness of the surface layer becomes dramatically increased. Julià et al. (2004) inverted the seismic velocities and densities for the sedimentary cover in the New Madrid Seismic Zone. The whole thicknesses of the Cenozoic and Cretaceous sediments within the depth of one kilometer are respectively estimated by performing an inversion of receiver functions computed at individual broadband station. Zheng et al. (2005) applied the receiver function method to image the sedimentary structure of the Bohai Bay Basin in Eastern China. The sedimentary cover with the depth about 2-12 km in the basin were well estimated. The aim of this study is to apply the receiver function technique on the high-frequency acceleration seismograms recorded by Taiwan Strong Motion Instrumention Program (TSMIP) stations of Central Weather Bureau (CWB) to estimate the shallow S-wave velocity structure in Taipei Basin.

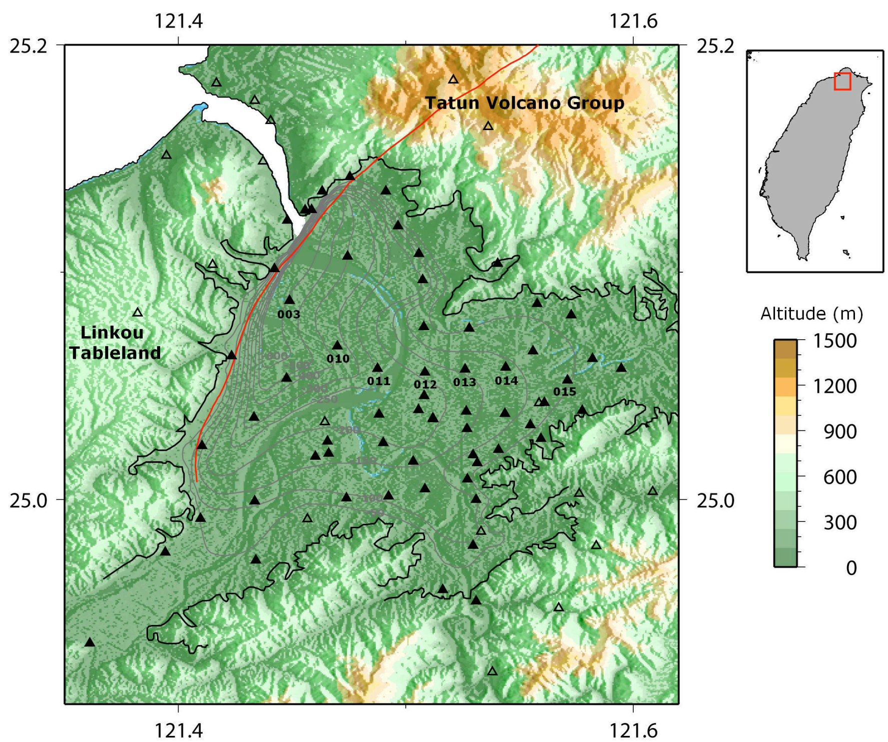

Fig. 1. Topography of the Taipei Basin. The thick black lines are the boundaries of the Taipei Basin. The depth contours of the Tertiary basement in the basin are shown by the gray lines (Wang et al., 2004). The thick red line is the Sanchiao Fault indicated as an active fault. The TSMIP stations are shown as triangles in which the filled ones are the stations we used in the study. The stations we mentioned in the article are marked with a number which is the station name without the heading "TAP" below the station.

GEOLOGIC BACKGROUND

Taipei Basin is a triangular basin with about 20 km length of the side (Fig. 1). The basin is bounded by the Pleistocene Tatun Volcano groups in the north, Western foothills in the southeast, and Linko tableland in the west. The elevation of topography around the basin varies between sea level and about 1100 m. Four young formations are found sitting flat above the basement which is at most 700 m deep (Teng et al. 2001). During the Pliocene and the Pleistocene age, gravels and conglomerates were widely deposited in the Linkou area which was a delta fan produced by reverse faulting activities. About 400 thousand years ago, the area became a tensile environment and resulted in that the Hsinchuang fault altered its sense of movement and became a normal fault, now rename as Sanchiao fault. The normal faulting activities of the Sanchiao fault caused the sinking of the Taipei basin and took shape the basin. Thus, the deepest part of the basin is along the NW border, where the Sanchiao fault is located.

Four newly deposited unconsolidated strata were overlying the basement because of the geohistory of the Taipei Basin. The top near-surface layer, called the Sungshan Formation, dominates the site effects because of its loose sand and silt content (Wen et al. 1995). The Chingmei Formation beneath the Sungshan Formation is mainly composed of gravels and overlies the sand-and-silt Wuku Formation. The fourth Quaternary stratum is the gravel-rich Banchiao Formation overlied on the Tertiary Basement. Based on the data of drilling wells and shallow reflection seismic lines, the two major discontinuities in the basin, the bottom of the Songshan Formation (Fig. 2) and the basement (Fig. 1), were respectively figured. The Songshan Formation is relatively thin (about 50 m) with very low S-wave-velocity. The deepest of the Tertiary Basement is about 700–1000 m along the western border of the Taipei Basin. Table 1 shows the P- and S-wave velocities and depths of the strata in the Taipei Basin (Wang et al., 2004).

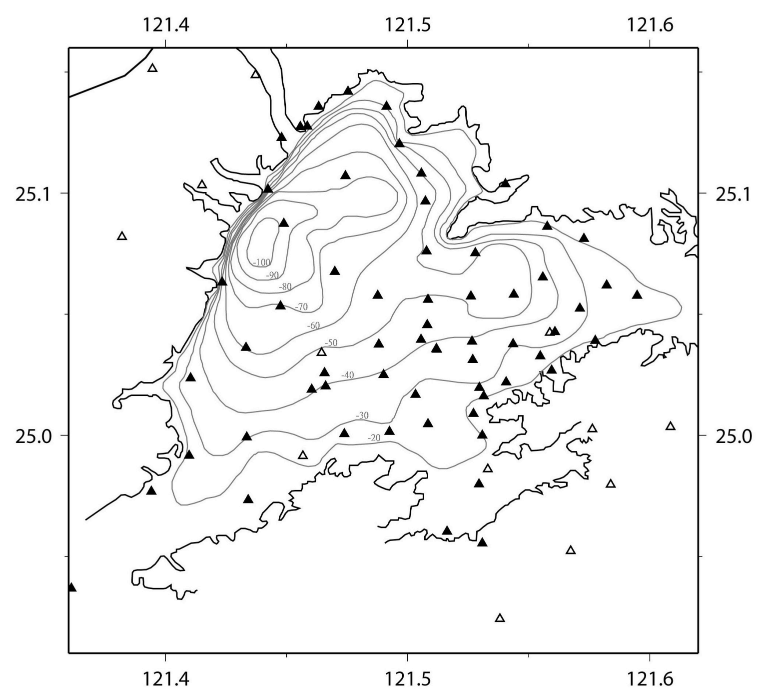

Fig. 2. Depth contours of the Sungshan Formation which is the topmost strata of the Taipei Basin (Wang et al., 2004). The TSMIP stations are shown as triangles in which the filled ones are the stations we used in the study.

ANALYSIS OF RECEIVER FUNCTION

In the Taipei Basin, the dense TSMIP stations provide a large number of excellent seismic data for our study. The instruments installed at the stations are all triaxial accelerometer (Liu et al., 1999). Sixty-four TSMIP stations located in the Taipei Basin were chosen (Fig. 1). The period of the database is from 1992 to 2009. The earthquakes we used are all local ones occurred within or around the Taiwan Island. Each waveform was visually inspected to eliminate recordings with low signal-to-noise ratios, anomalous glitches, and calibration issues. The pickings of the P- and S-wave arrivals were also reviewed. We commutated the receiver functions of the seismograms in acceleration rather than velocity used for teleseismic receiver function. In the commutation of receiver functions, the width a = 50 of the Gaussian low-pass filter and the water level c = 0.05 were applied. Figure 3a shows all receiver functions of the TAP010 in order of back-azimuth. Because most earthquakes located in the seismic zone of eastern Taiwan and Western Foothills, the back-azimuth just cover the range from 110° to 220°. Most receiver functions of TAP010 exhibits two apparent converted phases at 0.6 and 1.0 second. In the receiver functions, the systematic variation of converted phase waveforms versus ray back azimuth and the appearance of seismic energy on both the radial and transverse components both reflect the existence of the dipping velocity discontinuity.

After the selection the receiver functions with similar and reasonable waveform, the average receiver functions for each station were calculated. The average of seventeen receiver functions for TAP010 (Fig. 3) enhances the converted phases and reduce the inharmonic arrivals. The average receiver functions of seven TSMIP stations (marked in Fig. 1) located on an E-W direction line in the Taipei Basin are drawn in Fig. 4. The difference of receiver functions between stations is obvious, but the similar converted phase can be observed at most stations with different arrival times. The stations located on the western side where the basin is deeper show later arrival times, and the stations located on the eastern side where the basin is shallower show earlier arrival times. The converted phases with the arrival times less then 1.5 second should produced by the shallow velocity discontinuity within the basin. The variation of arrival times versus location proves the shape of basin affect the high-frequency receiver function. The receiver function technique is effective to analyze the strong motion data observed in the Taipei Basin.

In the study, Genetic Algorithms (GA) was applied to search for the S-wave velocity model with the best fitness between observed and synthetic receiver function. GA searching is a powerful global optimization method. The algorithm consists of selection, crossover, and mutation of individuals in a population; it can search both globally and locally for an optimal solution (Goldberg, 1989). According to the Table 1 (Wang et al., 2004), we assumed a model with six layers covering a half space for the GA searching. The P- and S- velocities of the layers were fixed to avoid the trade-off between the velocity and thickness of layers. We estimated the thickness of each stratum based on the assumption that all the strata in the basin are homogeneous. The searching range of S-wave velocity model was shown by the blue dash lines in Fig. 5a. The full GA process included conducting fifty GA searches. Each GA search was terminated at the 500th generation. The population size of each generation was fifty. Therefore, the total number of repetitions for forward modeling was 1,250,000.

Figure 5a shows the results of the GA searching for the station TAP010. The results of GA searching display the effective convergence of the wide searching ranges for thickness. The synthetic receiver function corresponding to the best model fit the observed one well (Fig. 5b). The phases converted at the four major interfaces under the Taipei Basin were identified. The inverted S-wave velocity model of TAP010 slightly overestimates the depth of the Tertiary Basement in previously study (Fig. 1). The high contrast of the basement produces the converted phase observed at 1 second. The biggest phase observed at 0.6 second converts at the bottom of the Wuku Formation with the depth of about 200 m. The bottom of the Sungshan and Chingmei Formation produced the small converted phases respectively at 0.3 and 0.4 second.

Table 1. P- and S-wave velocities and depths of the strata in the Taipei Basin (Wang et al., 2004).

Stratum	Depth (m)		P-wave (km/sec)	S-wave (km/sec)
	NW	SE		
Sungshan Formation	0-20	0-15	450	170
	20-50	15-35	1500	230
	50-100	35-50	1600	340
Chingmei Formation	100-160	50-100	1800	450
Wuku Formation	160-320	100-200	2000	600?
Banchiao Formation	320-700?	200-300	2200	880?
Tertiary Basement	-	-	3000	1500?

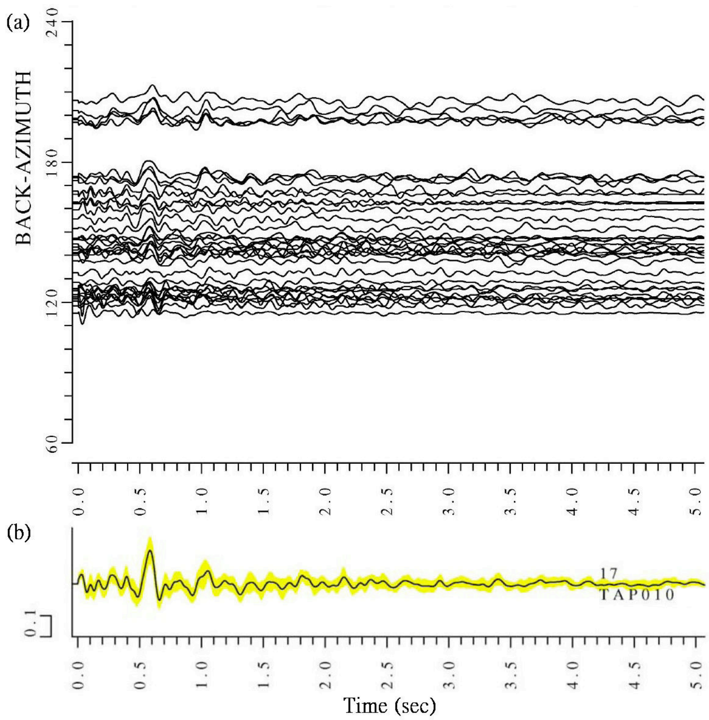

Fig. 3. Receiver functions of TAP010. (a) shows the all receiver functions of earthquakes we used in order of back-azimuth. (b) is the average of the seventeen selected receiver function for TAP010. The yellow shadow shows the standard deviation.

STRUCTURES OF TAIPEI BASIN

The above-mentioned analysis process of receiver function was applied to the sixty-four TSMIP stations in the Taipei Basin. The average receiver functions were calculated and modeled to estimate the 1D S-wave velocity models for the stations. Because the velocities of layers were fixed, the depths of the major interfaces were easily identified. We combined the 1D models of all the stations widely distributed in the basin to delineate the 3D structures of the strata. Figure 6 are the depth contour maps of the four major interfaces under the Taipei Basin delineated based on the synthetics of the receiver functions. The thickness of the topmost Sungshan Formation is between 80 m in southeast and 120 m in northwest. The distribution of the strata we estimated agrees with the result of the drilling and seismic surveys (Fig. 2), but there are two noticeable differences between Fig. 6a and Fig. 2. The deepest range we estimated in the northwest is larger than that of Fig. 2 (Wang et al., 2004). The bottom of the Sungshan Formation in Sungshan area in Fig. 2 is the deepest part of the eastern half with a shape of extended platform in the depth of about 50 m. Our result controlled by the receiver function of TAP014 in the same area exhibits much deeper depth. The deep-hole shape under TAP014 is abnormal and may result from the multiple and close phases (Fig. 4).

Although the stations are ant dense enough to figure out the deep shape of the Tertiary Basement along the northwestern border in the basin, several stations located in the area, including TAP003, TAP016 and TAP094, exhibit the depth of more than 600 m for the basement. The Tertiary Basement we delineated (Fig. 6d) shows similar trend with the Fig. 2 (Wang et al., 2004). The basement gradually dips from southeast to northwest. The deepest part along the northwest border form a sharp graben because the normal faulting activities. We also delineated the bottom of the Chingmei Formation and Wuku Formation. The distributions for the two layers both agree with the estimation of Wang et al. (2004) (Table 1). According to the shapes of the four major interfaces, the gradual change of the sedimentary environment can be presumed.

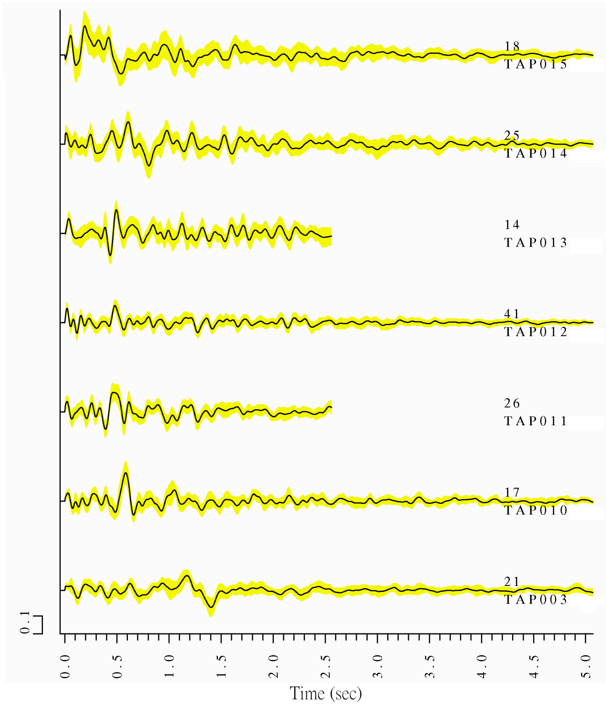

Fig. 4. Average receiver functions of seven TSMIP stations located on an E-W direction line in the Taipei Basin and marked in Fig. 1. The yellow shadows show the standard deviations. The numbers of receiver functions we used to average for the stations are shown above the station names

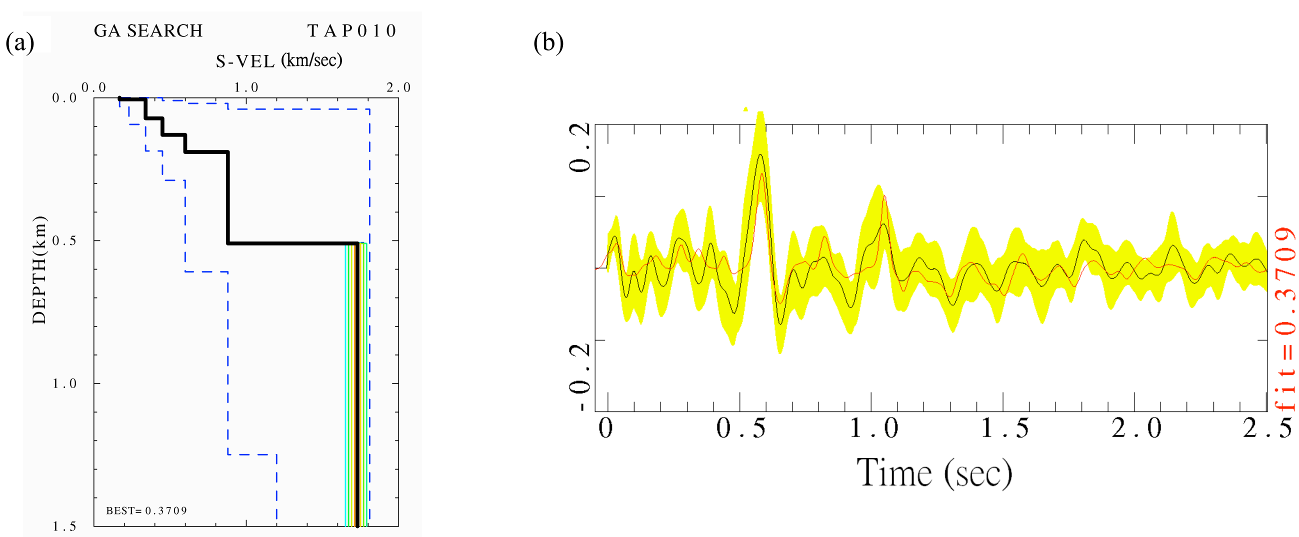

Fig. 5. Best result of TAP010 searched by Genetic Algorithm. (a) is the S-wave velocity model of GA searching. The blue dash lines show the searching range of the S-wave velocity in the GA searching. The black bold line is the S-wave velocity model with the best fitness of the GA searching. The lines with various colors are the best twenty models. (b) is the comparison between the observed average receiver function (black line) and the synthetic one (red line) with the best fitness based on the GA searching.

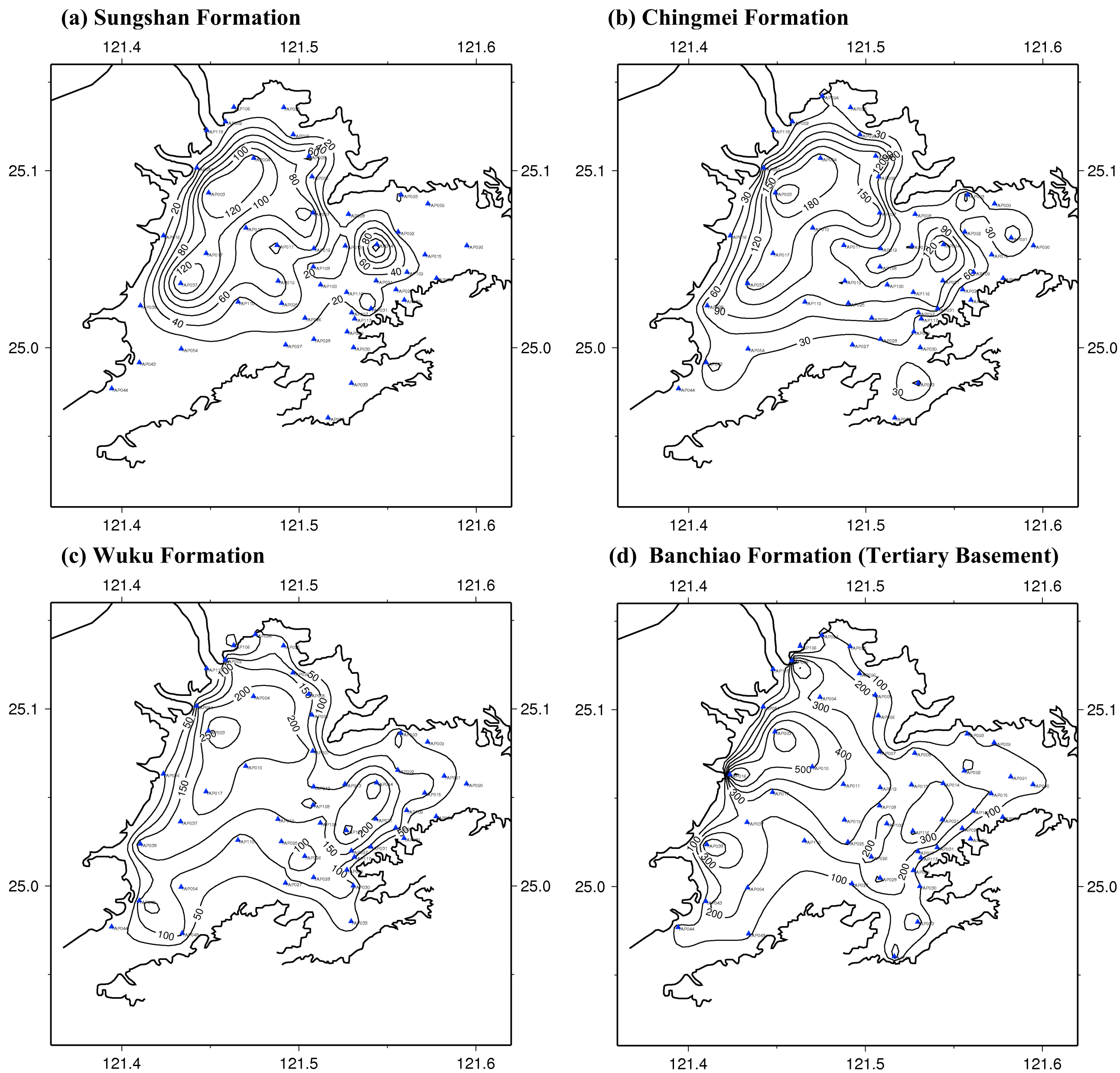

Fig. 6. Depth contour (meter) maps of the four major interfaces under the Taipei Basin estimated based on the synthetics of the receiver functions for the TSMIP stations shown respectively by the triangles. (a) is the bottom of the Sungshan Formation. (b) is the bottom of the Chingmei Formation. (c) is the bottom of the Wuku Formation. (d) is the bottom of the Banchiao Formation which is the top of the Tertiary Basement under the Taipei Basin .

CONCLUTIONS

The receiver function technique has applied on the high-frequency acceleration seismograms recorded by TSMIP stations of CWB to estimate the shallow S-wave velocity structure in the Taipei Basin. The averaged receiver function of each station exhibit apparent converted phases reflected the major shallow interfaces under the basin. After the forward modeling of GA searching, we delineated the brief 3D structures of the four Quaternary strata under the Taipei basin. The thicknesses and shapes of the interfaces we estimated are all comparable with that of the previous drilling and seismic survey. The results proved that the high-frequency receiver function is feasible to figure out the shallow discontinuity with high velocity contrast. The technique will provide another tool to study the shallow sedimentary structures which is essential to conduct site-effect estimations, theoretical simulations of strong motion, and seismic hazard assessments.

Because the shallow structures are usually more complex, the high-frequency receiver function is easy to be contaminated by not only the artificial noise but also the non-horizontal and inhomogeneous layers. Besides, the receiver function analysis theoretically requires near-vertical incidence plane waves to elucidate the structure directly beneath a seismic station. We suggest that the high-frequency receiver function should apply on the seismic station with a lot of data. The original seismic waveforms and receiver functions should be carefully inspected and selected for the waveform with real converted phases of velocity discontinuities. The sufficient data will help conclude the systemic receiver functions to estimate the structures we are interesting in.

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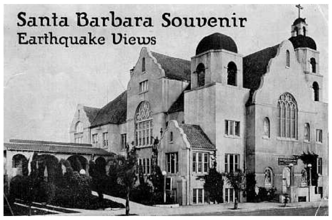

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