TAO, Vol. 9, No. 3, 301-316, September 1998

Onshore/Offshore Wide-Angle Deep Seismic Profiling in Taiwan

Y. H. Yeh[1], R. C. Shih[2], C. H. Lin[1], C. C. Liu[1], H. Y. Yen[3], B. S. Huang[1], C. S. Liu[4], P. Z. Chen[2], C. S. Huang[2], C. J. Wu[2], and F. T. Wu[5]

(Manuscript received 16 January 1998, in final form 10 September 1998)

ABSTRACT

In summer 1995, in collaboration with the deep multi-channel seismic profiling project around the island of Taiwan, an onshore-offshore wide-angle deep seismic profiling experiment was conducted in Taiwan. The results are expected to provide the first complete seismic images of the deep crustal structure for a better understanding of the Taiwan orogeny and subduction-collision system. The experiment consists of three profiles, one along each of the central and southern cross-island highways and another on the south-link highway of the island. For the first two lines, 35 three-component portable seismographs were deployed along each of the 116 and 135 km-long profiles onshore, with airgun shots being fired at distances eastward form the east coast of up to 133 km and 170 km , respectively. On the third line, 6 stations were deployed along the 20 km-long profile. For this line, the R/V Ewing provided shots from the Philippine Sea westward to the eastern coast of the Hengchun Peninsula and then from the western coast of the Hengchun Peninsula westward away from Taiwan. The total length of the third line was about 310 km. The average station intervals were about 4 km. The preliminary results along the three profiles show a very thick crust beneath Taiwan. In addition, the velocity structures show that lateral variation of velocity in the upper crust is generally larger than that in the lower crust and uppermost mantle. Large thickness variations in the crust were also obtained. The crustal thickness beneath Taiwan diminishes gradually toward the west, but dramatically toward the east. The topographic high is not well associated with the crustal thickness. The thickest crust is to the east of the central mountain range, which may indicate that Taiwan has not yet reached its isostatic equilibrium. In this paper, the preliminary results along the southern cross-island profile are given as an

[1]Inst. of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC
[2]Inst. of Seismology, National Chung Cheng Univ., Chiayi, Taiwan, ROC
[3]Inst. of Geophysics, National Central University, Chungli, Taiwan, ROC
[4]Inst. of Oceanography, National Taiwan Univ., Taipei, Taiwan, ROC
[5]Dept. of Geological Sciences, SUNY Binghamton, NY, USA

example. Detailed results of the three profiles will be given elsewhere.

(Key words: Onshore/Offshore, Wide-Angle, Deep crustal structure)

1. INTRODUCTION

The island of Taiwan is located along a segment of the convergent boundary between the Eurasian Plate and the Philippine Sea Plate. The strong orogeny in Taiwan has often been explained either by the thin-skin tectonic model (Suppe *et al.*, 1981), in which the mountains are built in a wedge-shaped trough on top of a decollement, or by the lithospheric deformation model (Wu *et al.*, 1997). Many scientists have been using seismic or gravity data to study the crustal structure beneath Taiwan. They have also established depth models of the continental Moho beneath Taiwan (Yeh and Tsai, 1981; Rocker *et al.*, 1987; Lin *et al.*, 1989; Rau and Wu, 1994; Yen *et al.*, 1995; Lin, 1996; Ma *et al.*, 1996). However, more reliable data to provide an understanding of the detailed crust structures beneath Taiwan are still needed.

Wide-angle deep seismic profiling has proven to be a successful method to study deep crustal structures (Braun and Smith, 1989; Beaudoin *et al.*, 1992; Gohl and Smithson, 1993; Thomas *et al.*, 1994; O'Reilly *et al.*, 1994; Zelt and Forsyth, 1994; Davey *et al.*, 1995; Knapp *et al.*, 1995; Mechie *et al.*, 1995; O'Leary *et al.*, 1995; Operto *et al.*, 1995; Zelt and White, 1995; and Davey *et al.*, 1996). Because of its superior resolution, the use of wide-angle deep seismic profiling in deep crustal structure study is becoming more popular.

In summer 1995, the R/V Ewing was scheduled to conduct deep multi-channel deep seismic reflection profiling experiments around the island of Taiwan. It was hoped that this experiment would provide a clear image of the deep crustal structures around the island. To examine the existence of the decollement as well as the shape of the Moho under Taiwan, an onshore/offshore wide-angle deep seismic profiling experiment was conducted at the same time. The results provide the first complete seismic images of the deep crustal structure beneath Taiwan, and lead to a better understanding of the Taiwan orogeny and subduction-collision system.

In addition, the deep structure images derived from the wide-angle deep seismic profiles can be used to further refine the above cited depth models. By completing the published Bouguer anomaly map of Taiwan, we will be able to show the more detailed crustal structures of Taiwan. The results of the wide-angle deep seismic profiles can provide us with better constraints for deeper structure study as well. For instance, for teleseismic data for core phases, we have found that the approaching waves essentially have a planar wavefront within dimensions of 3 by 3 degrees of Taiwan and at a nearly vertical incidence (Huang, 1996). Using the travel-time delays of the core phase, we will be able to interpret the regional tectonics of Taiwan. These wide-angle seismic data will also provide information on the lateral variation of the upper mantle beneath Taiwan.

This paper aims to give an overall description of the experiments. More detailed processing of recorded data and the geodynamic significance of the observed seismic reflectivity will be discussed elsewhere. A preliminary result of this study will be given by using the profile along the southern cross-island highway as an example. The more detailed results of the three profiles will be shown in other individual papers.

2. FIELD WORK AND INSTRUMENTATIONS

The onshore/offshore wide-angle seismic experiment was conducted in August and September of 1995. The experiment consisted of 3 deployments onshore, which crossed the principal tectonic structures of Taiwan (Figure 1), basically along the central and southern cross-island highways and the south-link highway of the island. Powerful energy released from the R/V Maurice Ewing airgun array was used to generate source signals. The marine data acquisition system of the R/V Maurice Ewing consists of a 20-airgun array of 8365 cubic inches, which allows energy to propagate to a great depth and distance.

For the first two lines, we deployed 35 three-component portable seismographs along each line. The first profile (Line 1) had 116 km of its length onshore and 133 km offshore. The shooting of airguns began at the eastern coast and moved eastward. The second profile (Line 2) had 135 km of its the length onshore and 170 km offshore. Shooting of the airguns was as for the first profile. On the third line (Line 3), because other instruments were prepared for the operation along the southern cross-island highway profile, only 6 portable seismographs were deployed along the 20 km-long profile. Along Line 3, reversed shooting seismic profiles were recorded, with the R/V Ewing beginning to fire shots in the Philippine Sea cruising westward to the east coast of the Hengchun Peninsula, and then from the west coast of the peninsula moving westward away from Taiwan. The total length of the third line was about 310 km. The average station intervals for each line were about 4 km.

The seismic recorders used in this experiment included 19 Reftek recorders, 4 provided by the Institute of Earth Sciences (IES), Academia Sinica and 15 borrowed from IRIS/PASSCAL by the State University of New York at Binghamton, and 16 Kinematrics K2 recorders from IES. Reftek and K2 recorders are both 24-bit instruments equipped with a large hard disk for long-term continuous recording. Geophones used in this experiment were L-28 4.5 Hz 3-component velocity-type sensors. In the field, the data was recorded continuously for all three profiles with a sampling rate of 10 ms. The Reftek recorders had been used in Taiwan before the experiment, but this was the first time the 16 Kinematrics K2 recorders had ever been used in Taiwan. To maintain proper functioning of the experiment, the K2 and Reftek recorders were deployed alternately, station by station, from east to west. Along the third profile, Reftek recorders were used six for all stations. For each recorder, one GPS receiver was attached to control the timing, and the error was controlled within 500ns.

Since three-fifths of Taiwan is mountainous, it was very difficult to deploy a linear profile across cross the island. To achieve the most linear condition, we chose the first two lines basically along the central and southern cross-island highways and the third line along the south-link highway of the island. The total onshore length of Line 1 was 116 km, which basically follows the central cross-island highway from the east to Gukan, and then goes into the Dahsuihsan mountain range, cuts through the Western Coast Plain area and finally stops at the Taichung harbor. Detailed information on each station has been described in Wu (1996). The station spacing was about 3.5 km. Elevation along this profile varied over about 2.5 km (Fig-

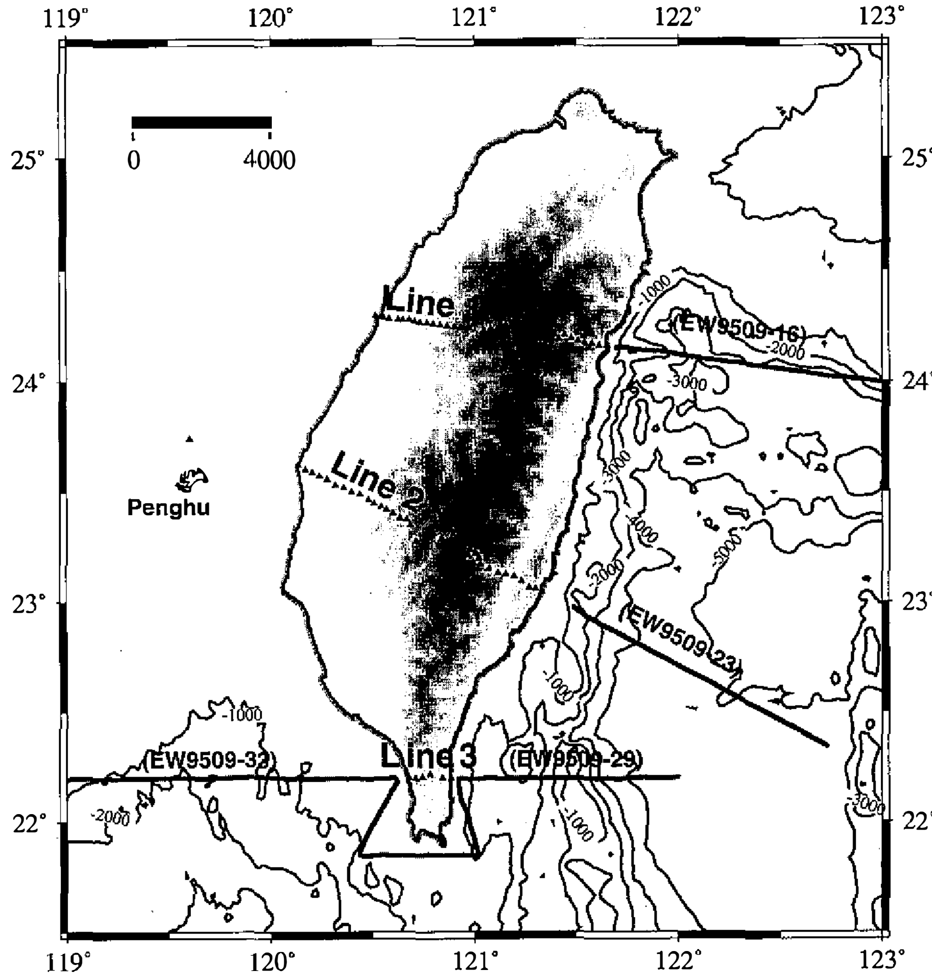

Fig. 1. Deployment of 3 profiles in onshore/offshore wide-angle deep seismic profiling experiment in Taiwan. Solid triangles onshore represent deployed stations. Solid lines offshore are cruise track of the R/V Maurice Ewing. Basically, first two lines follow the central southern cross-island highways and third line follows south-link highway of island. Line numbers corresponding to EW9509 Cruise are EW9509-16, EW9509-23, EW9509-29, and EW9509-33.

ure 2). Offshore, the R/V Maurice Ewing sailed eastward from the east coast of Taiwan, firing a total of 1256 shots at intervals of 40 seconds, which gave an average shot spacing of about 106 m over a total length of 133 km. The line number for the cruise was EW9509-16.

Line 2 basically follows the southern cross-island highway from the east to Meishan in the Central Mountain Range, and then passes through the Alishan mountain range and the

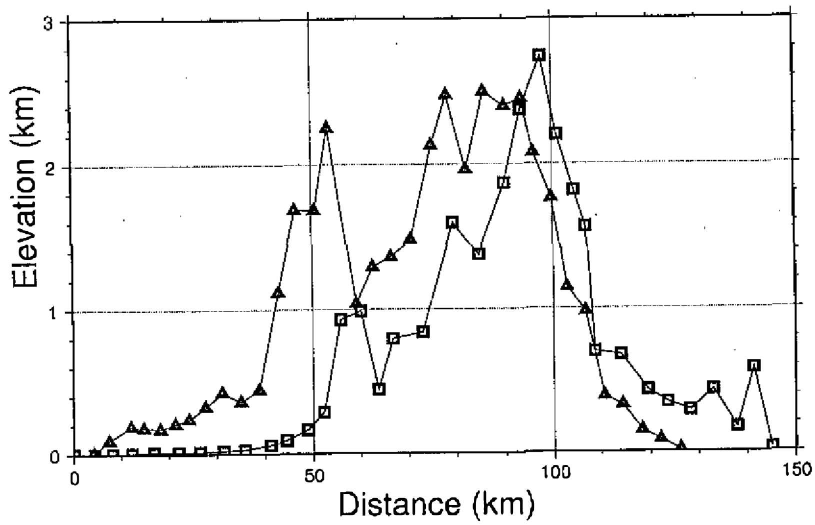

Fig. 2. Elevation of deployed stations along first 2 profiles. Triangles represent Line 1 (116 km long; spacing interval about of 3.5 km). Squares represent Line 2 (135 km long; spacing interval of about 4 km).

western plain area, and ends at Putzliao harbor. The location and site condition of the stations have been described in Chen (1996). Along the 135 km onshore profile, the 35 portable 3-component seismographs were deployed at an average station spacing of 4 km. The elevation along this profile varied over about 2.7 km from west to east onshore (see Figure 2). Offshore, the airgun array was fired every 40 seconds by the R/V Ewing from the eastern Taiwan eastward for about 170 km (line EW9509-23). The average shot interval was about 93 m, and there were a total of 1543 shots.

The third profile (Line 3) was the shortest distance onshore, but the longest offshore. Six Reftek recorders were deployed along the 20 km of the south link highway (Yu, 1997). The stations were at intervals of about 4 km, and the elevation relief between stations was moderate. Offshore, the airgun array was fired every 20 second from the R/V Ewing which sailed from east of Taiwan westward to Taiwan, line EW9509-29, and then went around the southern tip of the island to sail westward away from Taiwan along line EW9509-33. The total length offshore was about 310 km. On line EW9509-29 and EW9509-33, 2309 and 3050 shots were recorded, respectively. The shot interval was about 50 m. For these six stations, not only an in-line reversed shooting profile but also a fan shooting geometry were recorded, consisting of lines EW950930, EW9509-31 and EW9509-32, which went around the southern tip of Taiwan.

3. DATA CONDITIONING

The fieldwork for the onshore/offshore seismic profiling was successfully accomplished, and a lot of high quality 3-component seismic data were collected during the experiment. Most of the vertical-component data and some of the horizontal-component data to have been processed present their best quality. The preprocessing procedure started with cutting the continuously recorded raw data into traces of 40 or 20 seconds, according to the airgun shot time. After that, all the traces were converted into SEGY format, sorted into receiver gathers and processed with a number of processing strategies, including despiking, filtering, energy compensation, trace balancing, and deconvolution. The data processing software, SIOSEIS, was developed by the University of California, San Diego. We removed the spiky anomalies from the receiver gatherings and applied a band-pass filter of 4 - 10 Hz to all traces. After that, spherical divergent correction was applied to compensate for the seismic energy, and to balance the energy between traces. Then the adjacent traces were mixed in pairs and spiking deconvolution was applied to improve the signal to noise ratio in every receiver gathering. The processed data were finally displayed with automatic gain control (AGC) to enhance the coherent phases, including the direct phases (Pg), the reflected phases (PcP) and the refracted phases (Pc) within the crust, the refracted phases (Pn) within the mantle, and the reflected phases from the uppermost mantle (PmP). Here we show three receiver gatherings from each line to illustrate the characteristics of the recorded signals along the different profiles.

Figure 3 shows the receiver gatherings at station 33 on the central cross-island highway profile. The station was about 7 km away from the eastern coast and was installed with a K2 recorder. The spacing between traces was about 116 m. In this figure, we may see clear events of Pg, Pc, and Pn. The most unambiguous are the direct phases (Pg) which usually appear in larger amplitude at the shortest offset between shot and station. The Pg phase is defined as a refracted wave, or turning wave, that travels through the uppermost part of the crust. The slope of the Pg arrivals, representing the apparent velocity, directly provides the velocity at where the ray goes to the deepest part of the crust. The refracted phases within the crust (Pc) and within the mantle (Pn) were observed at a larger offset with smaller amplitude in the section. The above phenomenon was simply caused by energy decay in the space. The Pg phase with a steep slope directly reveals the lower velocity in the shallow crust, while the gentle slopes of the Pc and Pn phases are associated with the larger velocity in the lower crust and upper mantle. Using the ray-tracing forward modeling algorithm provided by Zelt and Smith (1992), the phases for the seismic events were also identified. In Figure 3, we may see clear events traveling up to 140 km and the duration of the airgun signals from previous shots as well. The velocity structure of this profile is shown in Shih (1998; this issue).

Figure 4 shows the receiver gatherings at station 22 in the southern cross-island highway profile. The station was located in the Central Mountain Range and installed with a Reftek recorder. The data displayed in Figure 4 were from the 9^{th} to the 29^{th} second of the total of 40 seconds. The trace spacing in this section is about 93 m. In this figure, we may see clear events of Pg, PcP, PmP, and Pc. The reflected phases PcP and PmP are commonly defined as reflected waves within the crust and from the Moho, respectively. The PcP phase is also observed at a smaller offset, but it is a little bit farther than that of the Pg phase. In general, the travel-time of the PcP phase is usually larger than that of Pg phase, because the PcP phase travels deeper than the Pg phases. The slope of PcP and PmP arrivals largely depends on the geometry of the reflecting interface. For example, a larger slope was expected for phases reflected from an up-dipping interface while a smaller slope was obtained for phases reflected

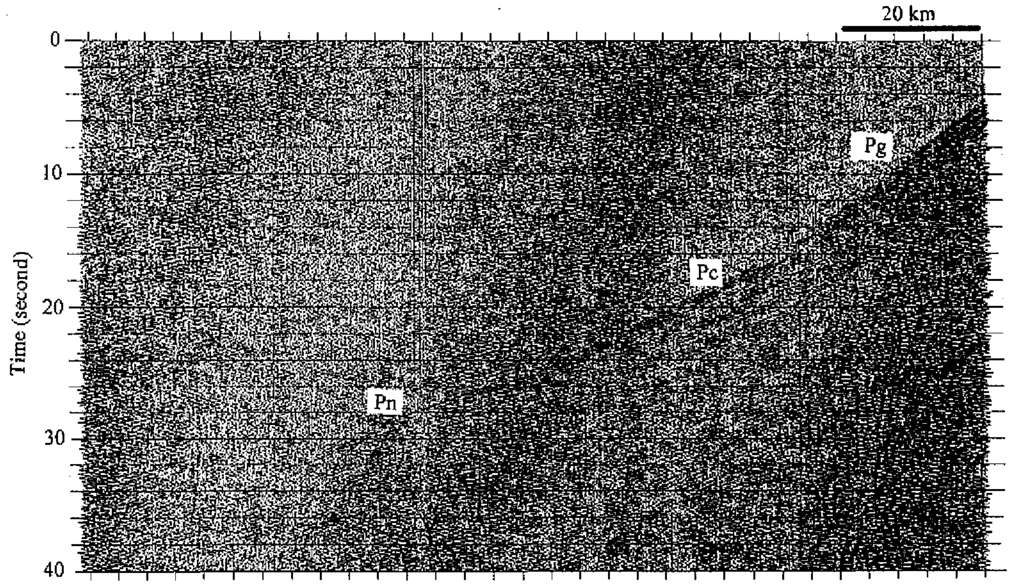

Fig. 3. Receiver gathering from station 33 on central cross-island highway on eastern coast by K2 recorder. Total recording time for each trace was 40 seconds with 10 ms sampling interval. Spacing between traces was about 116 m. In this figure, clear events of Pg, Pc, and Pn may be seen. Also present are clear events traveling up to 140 km and duration of airgun signals from previous shots.

from a down-dipping interface. In Figure 4, we may also see clear events traveling up to 210 km.

Figure 5 shows the receiver gatherings at station 28 of the south-link highway. The station is located in the middle of the profile and was installed with a Reftek recorder. In the profile, the R/V Ewing began firing shots in the Pacific and moved westward to Taiwan, corresponding to line EW9509-29. The trace spacing in this section is about 50m. In this figure, we may see clear events of Pg, PcP, PmP, Pc, and Pn. Along the profile of the line EW9509-29, the apparent velocities of Pg, Pc, and Pn were between 3.2 and 3.8 km/sec, between 4.0 and 5.1 km/sec, and 7.1 km/sec, respectively (Yu, 1997).

Not every receiver gathering shows good quality after processing. Probably because of the strong energy attenuation, along Lines 1 and 2, we could not retrieve any seismic signal from the stations on the Western Coast Plain. On the Western Coast Plain a total of 11 and 13 stations on Lines 1 and 2, respectively, were abandoned.

Strong coherent phases were recorded at a number of onshore stations. Most of these phases could be identified directly according to their characteristics including both amplitude and apparent velocity. The reflected phases from the uppermost mantle were stacked to image the deep crustal structures, and the travel times of the prominent arrivals were used to model the velocity structures beneath Taiwan.

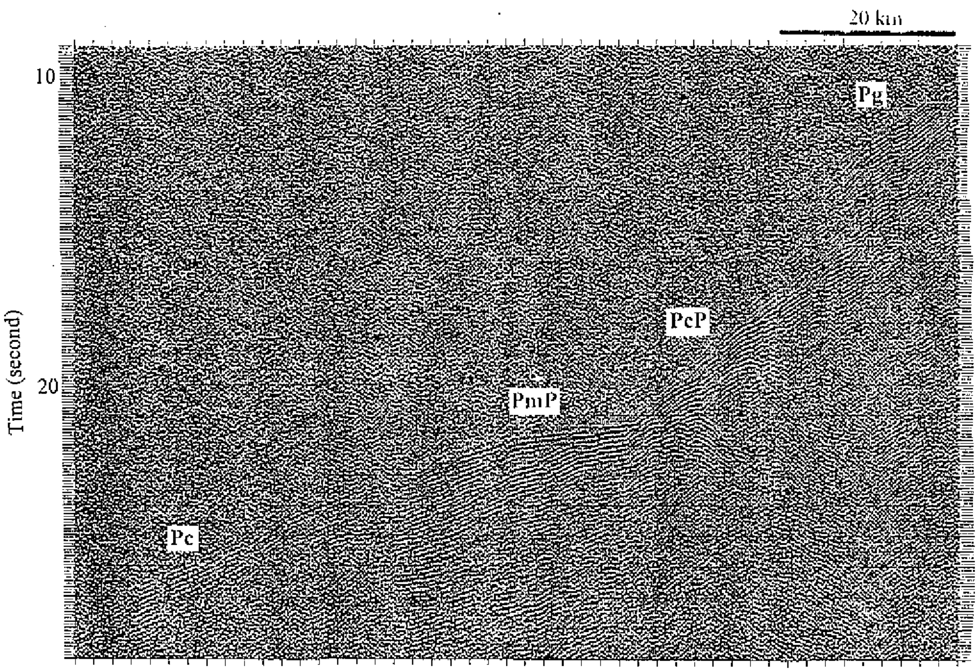

Fig. 4. Receiver gathering of station 22 along southern cross-island highway in Central Mountain Range by Reftek recorder. Total recording time for each trace was 40 seconds with 10 ms sampling interval. Here, data from 9^{th} second to 29^{th} second are shown. Trace spacing is about 93m. In this figure, clear events of Pg, PcP, PmP, and Pc may be seen, and clear events up to 210 km.

4. DEEP CRUSTAL STRUCTURE BENEATH THE SOUTHERN CROSS-ISLAND HIGHWAY LINE

4.1 The Stacked Image

For wide-angle seismic reflection data, since the offset between shot and receiver is too large and the phases are distorted, we cannot simply apply the conventional common-mid-point (CMP) stacking method to form the image of a structure. In this study, an algorithm that was modified from the CMP stacking method was used to obtain the deep crustal structure. The algorithm started by dividing the survey line into segments 100 m wide. By using each node as a central point, two adjacent segments were formed to become a bin, each of 200 m. Also the mid-point positions for all the traces in a receiver gathering were calculated. Then we moved the 200-m wide bin along the profile at every 100-m, and searched for those traces whose mid-point positions were inside that bin, after their travel times were dynamically corrected to the zero-offset position, the traces inside the same bin were stacked to form the image. The size of the bin, 200 m, was chosen to give enough traces for stacking, without loss of resolution.

Although it would be better if all the signals in the same bin for the data from every receiver gathering could be stacked, this was not possible because along Lines 1 and 2 there exist very severe static problems. In addition, it was impossible to conduct large dynamite shots along the two profiles onshore. We were unable to obtain the shallow velocity structure for doing the static correction and to stack the reflection image by using data from all the receiver gatherings. The stacked image obtained by using the method described in the last paragraph was from a single receiver gathering only. If the velocity used for the dynamic correction were appropriate, the stacked images viewed from all the receiver gatherings would be in the same pattern. Otherwise, the image after stacking would be smeared. This algorithm has been applied to our data for Lines 1 and 2 (Chen, 1996; and Wu, 1996). In this paper, a preliminary result of the stacked image for the profile along the southern cross-island high way is shown. Detailed interpretations of the subsurface structures for all three profiles and the inferred tectonic significance from the wide-angle seismic reflection data will be discussed in separate papers elsewhere.

It was very difficult to control the stacking velocity in this type of surveying geometry, because the offset was too large. In an attempt to form the best subsurface images, different stacking velocities for each record were tried. Applying different velocities to stack the data

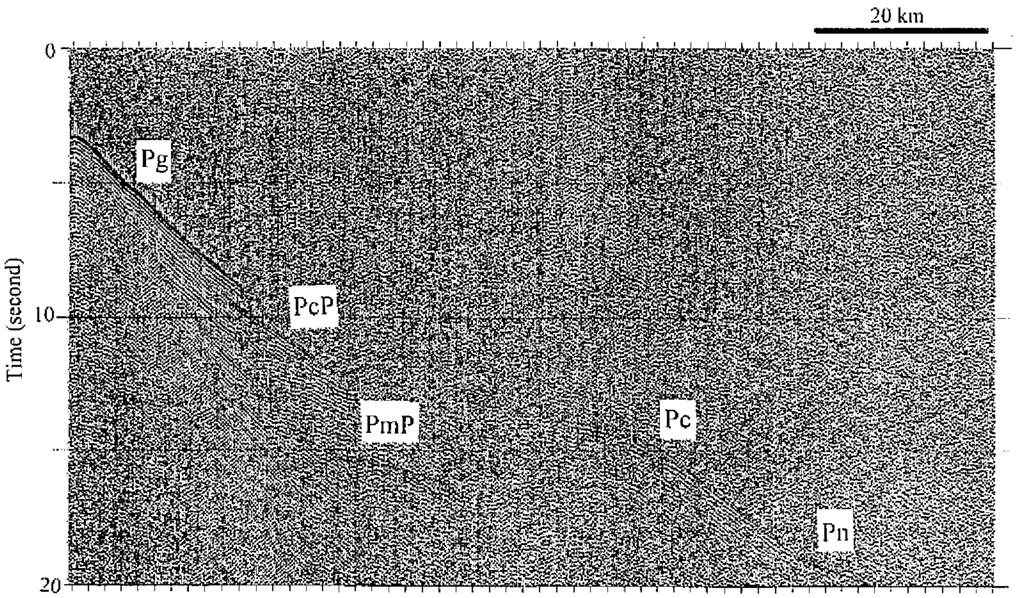

Fig. 5. Receiver gathering at station 28 in middle of the south-link highway by Reftek recorder. In profile, R/V Maurice Ewing was firing shots from Pacific and cruising westward to Taiwan. Total recording time for each trace was 20 seconds with 10 ms sampling interval. Trace spacing is about 50 m. In this figure, clear events of Pg, PcP, PmP, Pc, and Pn may be seen.

forces the events to dip in different directions. Only if the velocity is correct, can all the stacked images be made to lie in consistence direction (Chen, 1996). Figure 6 shows one stacked image from station 23 on the southern cross-island highway profile. The final stacking velocity chosen for the southern profile is a constant velocity of 6000 m/sec. Figure 6a shows the original stacked data and 6b shows the interpreted images, where only the reflected signals were used. The final image (in Figure 7) of the deep crustal structure was interpreted by the stacked data from the stations 15, 17, 23, 29, and 33 (Chen, 1996). As can be seen from the results, the Moho dips westward and down to a depth of 50 km. In this figure, we may see a westward dipping Moho discontinuity, although it doesn't directly imply the subduction zone.

4.2 Result From the Ray-Tracing Forward Modeling

In this paper, the program for 2-D ray-tracing forward modeling provided by Zelt and Smith (1992) was used to model the crustal structure. The parameterization presented here is a layered, variable-block-size representation of two-dimensional isotropic velocity structure. Each layer boundary is specified by an arbitrary number and spacing of boundary nodes, connected by linear interpolation. The number and position of nodes may differ for each boundary. A single node may be used to represent a horizontal boundary, whereas multiple nodes may specify detailed topography. Within each layer, an arbitrary number and spacing of upper and lower layer velocity points species the P-wave velocity field. The number and position of the upper layer velocity points may be different from the lower layer velocity points and that in other layers. The complete velocity field within each layer is defined such that the velocity varies linearly with position along the upper and lower layer boundaries between the specified points. This criterion is also applied between the upper and lower boundaries in the vertical direction. A single velocity point specifies a constant velocity along an upper or lower layer boundary across the full length of the model. A constant-velocity layer is specified by a single velocity value for the layer.

For ray tracing, each layer is divided laterally into trapezoidal blocks, which were separated by vertical boundaries that were automatically included wherever there was an upper or lower layer boundary node at a velocity point. Although velocity discontinuities may exist across layer boundaries, the velocity is laterally continuous within layers across the vertical boundaries. A layer boundary can represent an interface without an associated velocity discontinuity by applying the velocity at the base of the upper layer or at the top of the lower layer.

At this stage, we have only picked the best quality prominent arrivals for the ray-tracing forward modeling. By combining the 3D model derived by Rau and Wu (1995), and Lin *et al.* (1996), the parameters of the initial model were first set up and only velocities were assigned to the grid and boundary points (see Shih *et al.*, this issue, for a detailed description of the model parameterization).

All the selected events were first tested for their grouping to make sure their phases was correct. The model was first applied to one single receiver gathering, and then tested for another receiver gatherings. If the model was satisfactory, then we added another receiver gathering for further testing. Otherwise, the model was revised and tested from the first receiver

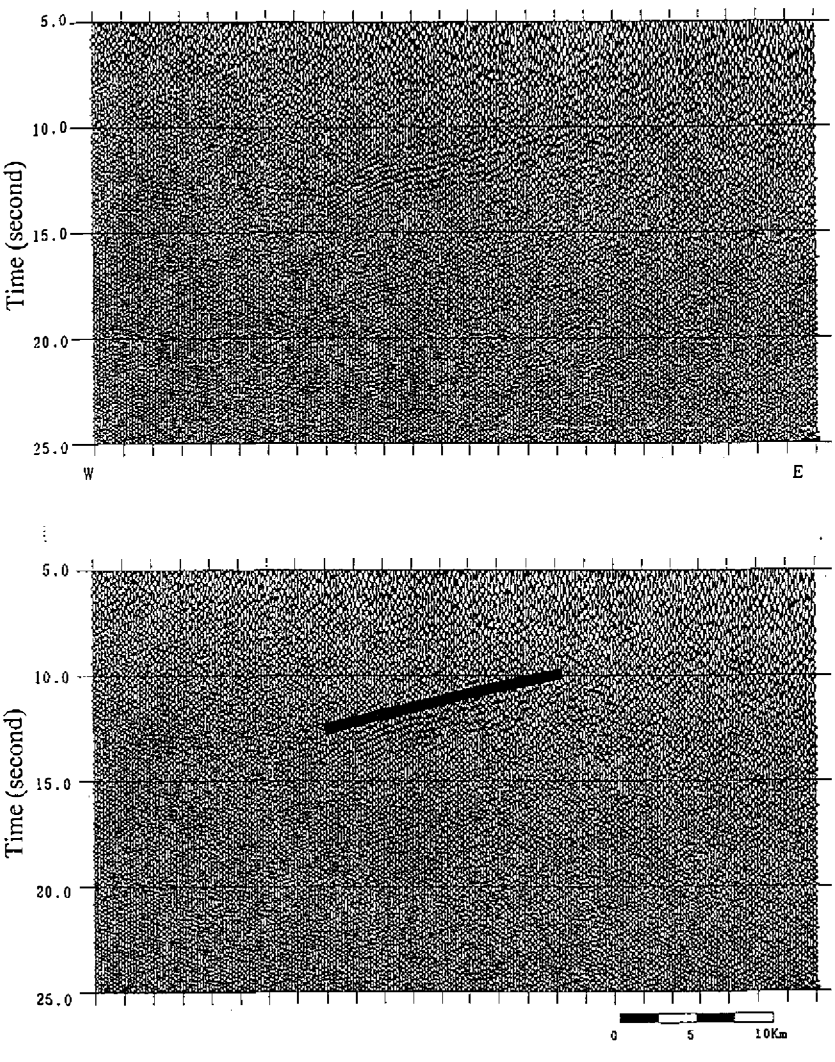

Fig. 6. Stacked image of station 23 in southern cross-island highway profile. Velocity used for profile was 6000 m/sec. Figure 6a shows original stacked data and 6b shows interpreted images, where only reflected signals were used.

gathering again. The previous procedure was repeated until the model was suitable for all the stations used. In this study, quality Pg, PcP, PmP and Pc data were obtained from the records. The PmP was used for the stacking method described in the previous section. Figure 8 shows a preliminary modeling result for the profile along the southern cross-island highway. The three dashed lines represent, from top to the bottom, the surface, the boundary between upper and lower crust, and the Moho discontinuity, respectively. Figure 8 also shows the ray densities for model constraint.

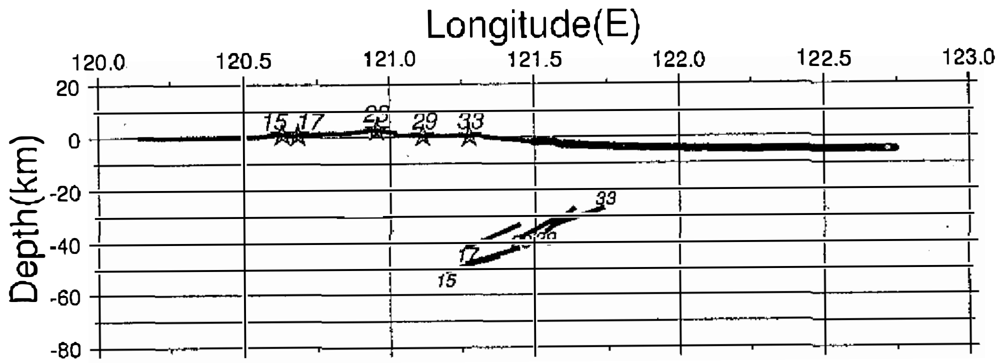

Fig. 7. Final interpreted image of deep crustal structure along southern cross-island highway profile. Image was interpreted using stacked data from stations 15, 17, 23, 29, and 33.

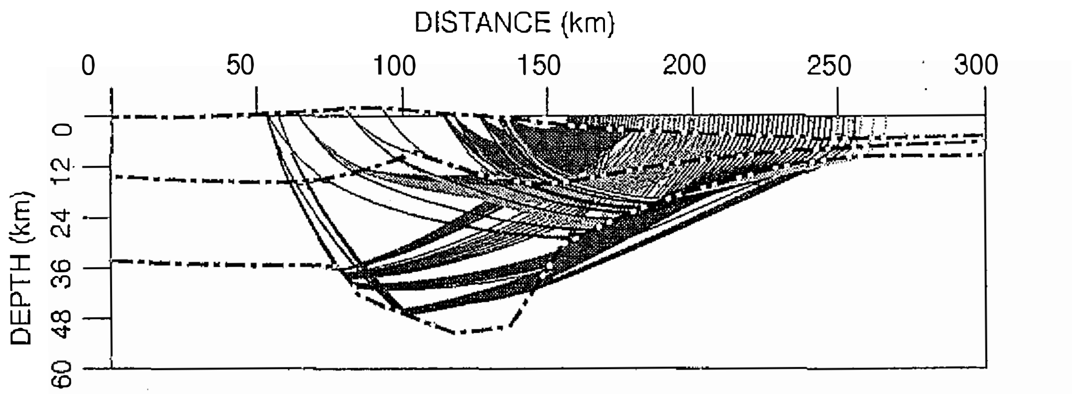

Fig. 8. Preliminary modeling result of profile along southern cross-island highway. Three dashed lines from top to bottom represent surface, boundary between upper and lower crust, and Moho discontinuity, respectively. Ray density for model constraints are also shown in this figure.

In Figure 8 a distinct difference between oceanic and continental crusts may be seen. The thickness of 5 km was modeled for the Philippine Sea crust under the Pacific. The crust thickens toward the west until it reaches a maximum thickness of 50 km under the Central Mountain Range. The great depth is consistent with the result from the stacking method presented in the previous section. West of the Central Mountain Range, the thickness of the crust reduces to around 36 km. Strong lateral velocity variation was also seen in this figure. A very thick lower crust may also be seen in the Figure. The topographic high is not well associated with the crustal thickness. The thickest crust is to the east of the Central Mountain Range, which may indicate that Taiwan has not yet reached its isostatic equilibrium.

5. DISCUSSION AND CONCLUSIONS

Taiwan is located between the Eurasian Plate and the Philippine Sea Plate, where strong orogeny is well known; however, quality data were limited to details of the deep crust structures under the island. In this experiment we have acquired a large amount of high quality data. Currently, we have processed most of our vertical component data and obtained the 2-D crustal structures by employing ray-tracing forward modeling and a modified stacking method. In this paper, a preliminary result of the crustal structure along the southern cross-island highway is shown. The deep crustal structure derived along Line 1 is shown in Shih (1998), this issue. Crustal structure beneath the profile along the south-link highway will also be shown soon. From the derived subsurface images, clear images of the deep crustal structure beneath the three profiles were seen. The result shall improve our understanding of the Taiwan orogeny. These results will be further combined with a detailed gravity map to infer the lateral heterogeneity and to evaluate the results of several recent tomographic studies in Taiwan.

During the experiment, extreme care was taken in the deployment of the geophones to ensure the site conditions were satisfied. As may be seen, high quality data were observed during the experiment for many stations; however, at some stations good data could still not be recorded. Generally, data were recorded with fair to good quality from the Central Mountain Range eastward, but data in the Western Plain area was of poor quality. This situation shortened the length of the coverage of the study area. In other words, we could not image the deep crustal structure on the western side of Taiwan.

A reversed shooting was planned for the second line that was along the southern cross-island profile. However, due to poor weather condition, it was not carried out. Fortunately, the R/V Maurice Ewing was still able to shoot in the Taiwan Strait for other profiles. Data were recorded on Penghu Island and at some other stationary stations of the Central Weather Bureau (CWB) in western Taiwan during that period. The instrument used for the CWB stationary stations were S13 with a 1 Hz sensor. During that period, very high quality data were collected at the CWB stationary stations at Penghu, JeaBay, Wanda, and Alishan, but at no other stations in the Western Coast Plain area. There are many possible reasons for the bad data problem. For instance, the airgun energy may have been either too small or highly attenuated. High attenuation in the Western Coast Plain area may be the major reason since we have seen that the great airgun signals traveled long distances.

Wide-angle seismic reflection and refraction data are very useful for studying deep crustal structures. Currently, the two most commonly used data processing strategies are travel time inversion and stacking methods. The stacking method generally suffered from problems such as sparse points, static correction and complexity of wavefield at wide-angles. Therefore, the resolutions of stacked images are sometimes far beyond required. The absence of shooting also led to a lack of the very important information on shallow velocity. The travel time inversion method produces a more accurate subsurface image than the modified stacking method; however, only limited distinguished events are picked for processing and many more events are withdrawn. Since more and more wide-angle seismic reflection experiments are being conducted worldwide, the need to develop a more robust data processing technique is becoming apparent.

Due to the limits of the surveying geometry, except for the third profile, the subsurface structure in the western part of Taiwan could not be imaged. In order to obtain the more detailed structure beneath Taiwan, the later phases still need to be recovered from the records.

Acknowledgments The authors would like to thank many colleagues and students at the Institute of Earth Sciences, Academia Sinica, National Chung Cheng University, National Taiwan University and National Central University for their extensive support in fieldwork. This experiment could not have succeeded without their hard work. We also thank IRIS for lending us the Reftek instruments. The programs of 2-D ray-tracing provided by prof. C. A. Zelt are also appreciated. The great assistance provided by the R/V Ewing is most appreciated. The National Science Council of the Republic of China generously supported this work, under grant number NSC85-2111-M-001-011Y.

REFERENCES

Beaudoin, B. C., G. S. Fuis, W. D. Mooney, and N. J. Nokleberg, 1992: Thin, low velocity crust beneath the south Yukon-Tauaua terrain, East Central Alaska: result from Trans-Alaska Crustal Transect Refraction/Wide-angle reflection data. *J. Geophys. Res.*, **97**, 1921-1942.

Braun, D. R., and R. B. Smith, 1989: Two-dimensional inversion for crustal structure using refraction/wide-angle reflection data from the 1986 PASSCAL basin-range experiment. *EOS*, **70**, 1206.

Chen, P. Z., 1996: Data analysis of the sea-land deep seismic profiling experiment - profile along the southern cross-island highway, Master's thesis, National ChungCheng University. (In Chinese)

Davey, F. J., A. Melhuish, D. Woodward, D. Okaya, T. Henrey, M. Roberts, T. Stern, and S. Kleffmann, 1995: Crustal reflections associated with the Alpine fault, South island, New Zealand. *EOS*, **76**, 550.

Davey, F. J., A. Melhuish, D. Woodward, D. Okaya, T. Henrey, M. Roberts, T. Stern, and S. Kleffmann, 1996: Preliminary results from a geophysical study across a modern, continent-continent collisional plate boundary - the southern Alps, NZ, *submitted to Tectonophysics.*

Gohl, K., and S. B. Smithson, 1993: Structure of Archean crust and passive margin of southwest Greenland from seismic wide-angle data. *J. Geophys. Res.*, **98**, 6623-6638.

Huang B. S., 1996: Investigation of the inner-outer core boundary structure from seismograms of a deep earthquake recorded by a regional seismic array. *Geophys. Res. Lett.*, **23**, 209-212

Huang, C. S., 1997: Travel-time inversion of the onshore/offshore seismic data - the southern cross-island highway profile, Master's thesis, National ChungCheng University. (In Chinese)

Knapp, J. H., D. N., Steer, L. D., Brown, and D. Alsdorf, 1995: URSEIS'95: Explosive-source deep seismic reflection profiling of the southern Urals, Central Russia. *EOS*, **76**, 550.

Lai, H. L., 1997: Travel-time inversion of the onshore/offshore seismic data - the central cross-island highway profile, Master's thesis, National ChungCheng University. (In Chinese)

Lin, C. H., Y. H. Yeh, and S. W. Rocker, 1989: Seismic velocity structures in the Sanyi-Fengyuan area, central Taiwan. *Proc. Geol. Soc. China*, **32**, 1, 101-120.

Lin, C. H., 1996: Crustal structures estimated from arrival differences of the first P-waves in Taiwan. *J. Geol. Soc. China*, **39**, 1-12.

Ma, K. F., J. H. Wang, and D. Zhao, 1996: Three-dimensional seismic velocity structure of the crust and uppermost mantle beneath Taiwan. *J. Phys. Earth*, **44**, 85-105.

Mechie, J., F. Wenzel, and R. Meissner, 1995: A deep crustal seismic section beneath the Indus-Yarlung structure, Tibet from Wide-angle seismic data. *EOS*, **76**, 550.

O'Leary, D. M., R. M. Ellis, R. A. Stephenson, L. S., Lane and C. A. Zelt, 1995: Crustal structure of the northern Yukon and Macenzie. northwestern Canada. *J. Geophys. Res.*, **100**, 9905-9920.

Operto, S., C. Caloeron, P. Stoffa, F. Akbar, K. Macintosh, T. Shipley, 1995: Preliminary 3-D velocity structure offshore Costa Rica: Travel-time inversion from 2-D intersection in-line seismic profiles. *EOS*, **76**, 550.

O'Relly, B. M., F. Hauser, A. W. B. Jacob, P. M. Shannon, J. Makris, and U. Vogt, 1995: The transition between the Erris and the Rockall basins: new evidence from wide-angle seismic data, *Tectonophysics*, **241**, 143-163.

Rau, R. J., and F. T. Wu, 1995: Tomographic imaging of lithospheric structures under Taiwan. *Earth and Planet. Sci. Lett.*, **133**, 517-532.

Rocker, S. W., Y. H. Yeh, and Y. B. Tsai, 1987: Three dimension P and S wave velocity structures beneath Taiwan: Deep structure of an arc-continent collision. *J. Geophys. Res.*, **92**, 10547-10570.

Shih, R. C., C. H. Lin, H. L. Lai, Y. H. Yeh, B. S. Huang, and H. Y. Yen, 1998: Crustal structures across central Taiwan from modeling of the onshore-offshore wide-angle seismic data, *TAO*, **9**, 317-328.

Suppe, J., 1981: Mechanics of mountain building and metamorphism in Taiwan. *Mem Geol. Soc. China*, **4**, 67-89.

Thomas, M. B., S. F. Gray, A. F. Michael, P. George, and J. M. Michael, 1994: Mapping the megathrust beneath the north Gulf of Alaska using wide-angle seismic data. *J. Geophys. Res.*, **99**, 11663-11685.

Wu, C. J., 1996: Data analysis of the sea-land deep seismic profiling experiment - profile along the central cross-island highway, Master's thesis, National ChungCheng University. (In Chinese)

Wu, F. T., D. Salzburg, and R. J. Rau, 1997: Taiwan orogeny: thin skin or lithospheric collision?. *Tectonophysics*, **274**, 191-220.

Yeh, Y. H., and Y. B. Tsai, 1981: Crustal structures of central Taiwan from inversion of P-wave arrival times. *Bull. Inst. Earth Sci.*, Academia Sinica, **1**, 83-102.

Yen, H. Y., Y. H. Yeh, C. H. Lin, K. J. Chen, and Y. B. Tsai, 1995: Gravity survey of Taiwan. *J. Physical Earth*, *43*, 683-696.

Yu, S. S., 1997: Travel-time inversion of the onshore/offshore seismic data - the south-link highway profile, Master's thesis, National ChungCheng University. (In Chinese)

Zelt, C. A., and R. B. Smith, 1992: Seismic travel time inversion for 2-D crustal velocity. *Geophys. J. Int.*, **108**, 16-34.

Zelt, C. A., and D. A. Forsyth, 1994: Modeling wide-angle seismic data for crustal structure: southeastern Grenville Province. *J. Geophys. Res.*, **89**, 11687-11704.

Zelt, C. A., and D. J. White, 1995: Crustal structure and tectonics of the southern Canadian Cordilla. *J. Geophys. Res.*, **100**, 24255-24273.