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A High-Resolution Seismic Array Experiment in the Hualien Area,Taiwan

Yih-Hsiung Yeh[1], Horng-Yuan Yen[2], Kou-Cheng Chen[1], Jer-Ming Chiu[3]
Cheng-Horng Lin[1], Wen-Tzong Liang[1], Bor-Shouh Huang[1]
Ching-Ren Lin[1] and Tsai-Yuan Hou[1]

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ABSTRACT

A high-resolution seismic array experiment using a 30-station second-generation of Portable Array for Numerical Data Acquisition (PANDA II) array was deployed in the Hualien area, Taiwan from late July 1993 to September 1995. This array covered an area of roughly 60 km x 30 km extending from an oceanic crust (the Coastal Range) across a suture zone (the Longitudinal Valley) into a continental crust (the Central Range) with 5- to 10-km interstation spacing. Each station was equipped with a 2-Hz three-component seismometer and had four channels with three data channels and one gain channel. This experiment making use of the PANDA II system was the first of its kind in the world. The PANDA II is a second generation of PANDA with major improvements in its dynamic range and telemetry scheme. It has a maximum of 132 dB dynamic range by using a five-step gain ranging system (18 dB each). Seismic signals and gain information were telemetered by radio to a recording center where two PC-486 computers were used for on-line digital data acquisition and off-line data analysis. More than 1,600 local and regional earthquakes with magnitudes up to 6.2 were recorded on-scale in the first five months. This experiment shows that both the monitoring capability and the locating reliability of earthquakes by the PANDA II array are better than those by the regional seismic network. This indicates that the PANDA II system is a better seismographic system for studying seismicity and related tectonics in great detail. The experiment also reveals that seismicity in the Hualien area is characterized by an abundance of shallow crustal earthquakes.

(Key words : PANDA II, Portable array, Seismicity)

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[1] Institute of Earth Sciences, Academia Sinica, Nankang, Taipei, Taiwan, R.O.C.
[2] Institute of Geophysics, National Central Univ., Chung-Li, Taiwan, R.O.C.
[3] Center for Earthquake Research and Information, The University of Memphis, TN 38152, USA

1. INTRODUCTION

The island of Taiwan is located along a segment of the convergent boundary between the Eurasian and the Philippine Sea plates, where collision as well as subduction are taking place. Many tectonic features in and around the Taiwan region have started to emerge from the analyses of the available data base of the two telemetered regional seismic networks, the Taiwan Telemetered Seismographic Network (TTSN) and the Central Weather Bureau Seismographic Network (CWBSN). These two networks have been merged and operated by the Central Weather Bureau since 1991. The major collision zone is located in eastern Taiwan, where the Longitudinal Valley is considered the suture zone. To the northeast of Taiwan, the Philippine Sea plate subducts beneath the Eurasian plate to the north. In contrast, in the south of Taiwan, the Eurasian plate underthrusts the Philippine Sea plate to the east along the Manila trench. Details of these tectonic features can't, however, be resolved by an analysis of the existing data base simply because of the inherent limitations of the regional seismic networks. These limitations include low dynamic range (<60dB) and large interstation spacings (30-50 km). Further advances in the understanding of the tectonic evolution and structures in and around Taiwan will have to depend on yet further observations from the employment of better instruments.

The Portable Array for Numerical Data Acquisition (PANDA) system has been developed by the Center for Earthquake Research and Information (CERI) of the University of Memphis, and in several studies, it has successfully demonstrated the importance of sensitive and high dynamic-range instruments in the improvement of data quality and their subsequent interpretations (*e.g.*, Chiu *et al.*, 1991a; Cahill *et al.*, 1992; Regnier *et al.*, 1994; Chen *et al.*, 1994, 1996). After many meetings during the past few years among the authors, a project known as "the High-Resolution Seismic Array Experiment in the Taiwan Area" has been discussed. The ultimate goal of this project is to overcome the inherent limitations in today's seismic observations in the Taiwan region. Considering both the spatial resolution and spatial coverage associated with various scientific targets and the limitations in radio telemetry due to the high mountain ranges over two thirds of the island, an optimum seismic array study of the very complicated Taiwan area requires at least three deployments, each covering one third of the island. However, it was agreed upon that before proceeding of the large-scale experiment a prototype experiment with a small aperature seismic array in the Hualien area would provide an excellent opportunity to gain unprecedented experience in designing an optimum seismic array with seismic array operation, data processing, and interpretation of high-resolution results. Not only would this be unique to the area but also it would be critical for a future large-scale seismic array experiment covering the entire area. The reason the Hualien area was selected for this prototype experiment is that this area is located in a region with high seismic activity because the Philippine Sea plate starts to subduct toward the north beneath the Eurasian plate in the vicinity. The instrument used in this experiment was the PANDA II system, a second generation of PANDA with major improvements in its dynamic range and telemetry scheme. This was the first time this system was used in the world.

2. INSTRUMENT—THE PANDA II SYSTEM

The PANDA II system is the outgrowth of efforts for the continued developments in the areas of seismic telemetry and automated digital seismic recording system by the CERI of the University of Memphis (Chiu *et al.*, 1991a, 1991b). Based on both field experience and technological developments, this system was incorporated improvements since the design of the original PANDA. The major improvements have been in dynamic range, telemetry topology and network geometry, along with the increased mobility of the network and central recording facilities. The design goals of the PANDA II which have been accomplished include: (1) three-component digital recording; (2) high dynamic range; (3) low power consumption and solar power for field stations; (4) a flexible telemetry system with the ability to repeat signals to overcome topographic limitations that would otherwise constrain the seismic network geometry; (5) synchronized digital recording of either triggered or continuous data at a central site; (6) ease of installation and maintenance; (7) common time base at a recording station; and (8) the capacity of digital data archiving and analysis at the central receiving site.

2.1 Field Station: Front-end Gain Ranging System

The analog gain ranging system uses a "floating point" representation to send data with a total range greater than 126 dB over conventional analog FM channels that have, on the average, a dynamic range of 54 dB. The analog front end consists of a preamplifier with +/-12 dB of gain in 6 dB steps. The preamplifier drives a bank of five amplifiers with fixed gains, each separated by 18 dB, giving a total range of gains from 0 dB to 72 dB. Each station produces four channels, three for seismic signals and one for gain information. By examining the amplifier bank outputs of the three seismic channels, a common gain is selected for the three channels. Negative gain changes (*i.e.* switching to a lower gain) occur just before any one of the three amplifiers at the present gain setting saturate. If the amplitude of the input signal grows sufficiently fast, several gain reduction steps may occur in rapid succession (the maximum of four negative gain steps can occur in less than 0.001 sec). After switching to a lower gain setting, operation continues at that gain as long as at least one of the three amplifiers at the next highest gain level remains in saturation. Once all the amplifiers at the gain level above the selected gain setting have remained unsaturated for a predetermined time, the gain is changed to the next higher setting. An output multiplexer controlled by the gain range circuitry connects the desired amplifier to the voltage control oscillation (VCO). The gain range information is carried on a fourth channel using frequency shift keying (FSK). The three seismic channels from each station are converted to FM by highly linear VCOs and are multiplexed together with the FSK gain channel for transmission to the central receiving site.

2.2 Data Transmission

The audio bandwidth of the standard FM radios is wide enough for 12 VCO channels, meaning that one radio link can carry data for three stations. This allows the seismic stations to double as repeaters with the addition of a receiver (the multiplexer is already included for the processing of the single station data). This enables the telemetry network topology to incorporate single and double repeats, a feature which enables PANDA II to overcome most topographic challenges to the network layout. A detailed description of the PANDA II telemetry system including the hardware design has been provided by Steiner (1992).

2.3 Central Recording Site

The analog discriminators are of modified conventional design. In addition to the normal frequency to voltage conversion, provision has been made to speed the setting time of the discriminator's low-pass output filter to improve the transient response during gain ranging. In order to reconstruct the original seismic data around a gain change, both the field electronics and the discriminators are required to settle less than one sample period at the input to the A/D. At the same time and incompatible with this requirement for instantaneous gain changes, the analog signal at the A/D must be band limited to less than the 50 Hz Nyquist frequency to prevent aliasing.

2.4 Digital Data Acquisition System

In addition to the new field stations and discriminator hardware, PANDA II also uses a new data collection system, which is a modification of the latest version of International Association of Seismology and Physics of the Earth's Interior (IASPEI) PC-based seismic system, the XRTP (Lee, 1993). This system includes two networked 486 PCs. One PC forms the on-line system capable of recording up to 128 channels of data. The other PC is an off-line system for archiving and analyzing data in the field. The data aquisition system is characterized by 1) 128 analog input channels; 2) 12-bit (60 dB) A/D; 3) a sampling rate of at least 100 samples per second per channel; 4) a digital oscilloscope capable of displaying any preselected 32 channels, or a sequential set of 16 channels, in real time; 5) the ability to record data either continuously or by event triggering; 6) a 2 mega-baud local area network to link the data acquisition and processing/archiving systems; 7) a processing/archiving system capable of performing interactive seismic analysis in real time with access to all data without affecting data acquisition; and 8) an effective archiving sub-system to store the digital waveform and associated data.

The construction of this newly developed system was completed in June 1993, and it was deployed in the Hualien area from late-July 1993 to September 1995 for the first time used in the world.

3. EXPERIMENT IN THE HUALIEN AREA

The 30 PANDA II stations were deployed in the Hualien area (Figure 1) from late July 1993 to September 1995. Although it may take longer to install PANDA II stations than portable recorders, unlike the portable recorders, the telemetered stations do not require regular visitation for the retrieval of data. Additionally, they allow for sophisticated trigger algorithms to ensure the completeness of the data base. This means that PANDA II stations can be deployed in remote areas, such as high mountains. The Hualien array covered an area roughly 60 x 30 km with 5- to 10-km interstation spacing, extending from an oceanic crust (the Coastal Range) across a suture zone (the Longitudinal Valley) into a continental crust (the Central Range). Seismic signals from each seismometer were directly connected to the PANDA II field box for amplification, gain ranging and multiplexing. They were then transmitted continuously via FM radios in 216 to 220 MHz frequency bands to the central recording center. It is important that the radio frequency for each channel be assigned carefully to avoid unwanted interference from other radios or between adjacent channels. The PANDA II system has been equipped with a very flexible telemetry scheme. In this experiment, the transmission of seismic signals and gain information of all 30 stations were grouped into 10 radio links with each consisting of three stations: an outer, a middle and an inner station. Basically, the seismic signals and gain information from an outer station were transmitted to a middle station where additional four channels were added and re-transmitted to an inner station. A total of 12 channels were multiplexed at the inner station and then transmitted to the recording center where a 128-channel multiplexer and a PC-486 computer were used for on-line digital data acquisition. In order to avoid any topographic or radio interference in the study area, however, the data and gain channels from both the outer and middle stations for 4 links in this array were directly transmitted to their corresponding inner stations and then to the recording center. The transmission of radio links for all stations to the recording center is also shown in Figure 1. The central recording center (solid square symbol shown in Fig. 1) was set up at the Hualien Observatory of the Central Weather Bureau.

Any seismometer or force balance acceleration (FBA) can be used as a sensor in the PANDA II system. In this study, the Mark Product L-4A, 2-Hz three-component seismometer was selected. The amplitude and phase responses of the PANDA II system together with the L-4A seismometer are shown in Figure 2. The amplitude response curve is almost flat in the frequency range of 2 to 25 Hz. Using a five-step gain ranging system which automatically adjusts gains in 18-dB steps to all signal channels on the basis of the preset parameters of saturation threshold and a minimum time period after each gain change, the PANDA II system deployed in this region had a maximum dynamic range of 132 dB. Once gain change was necessary; the information of gain change was recorded on a gain channel, and the three-component seismic signals at that gain step were recorded on the data channels. In addition to the gain information, the station identification code, battery voltage, temperature and humidity were also recorded on the gain channel when the system was at the base gain level. Either a solar panel or alternatively AC power can be used for power supply at each station. In this array, a PC-486 with a 12-bit A/D converter was used to record the real-time digital data at the recording center. The latest version of IASPEI PC-based software, the XRTP (Lee, 1993), was applied for real-time data acquisition. The XRTP employs a simple STA/LTA trigger algorithm to find trigger on a multi-channel time window criterion for event and end of event detection. With a very dense array in the Hualien area, more than 10 triggers were required for an event to be declared valid. In this experiment, the PANDA II system was operated at 100 samples/sec in a trigger mode to record earthquakes. In addition, another PC-486 with networking directly to the on-line PC, a laser printer and an optical disk driver were used for off-line data processing and archiving. All digital seismic data were archived in erasable optical disks.

Seismic data collected by the PANDA II stations were stored in the PC-SUDS format (Banfill, 1993a). The IASPEI Software Library Supplement #1 (Banfill, 1993b) was used for routine processing. Before the data could be used, a gain channel decode procedure through the decoder software developed by Chen *et al.* (1993) has to be followed in order to recover the true seismic data. A very efficient software for picking phases from the three-component waveform files in the PC-SUDS format developed by Chen *et al.*(1993) was also used.

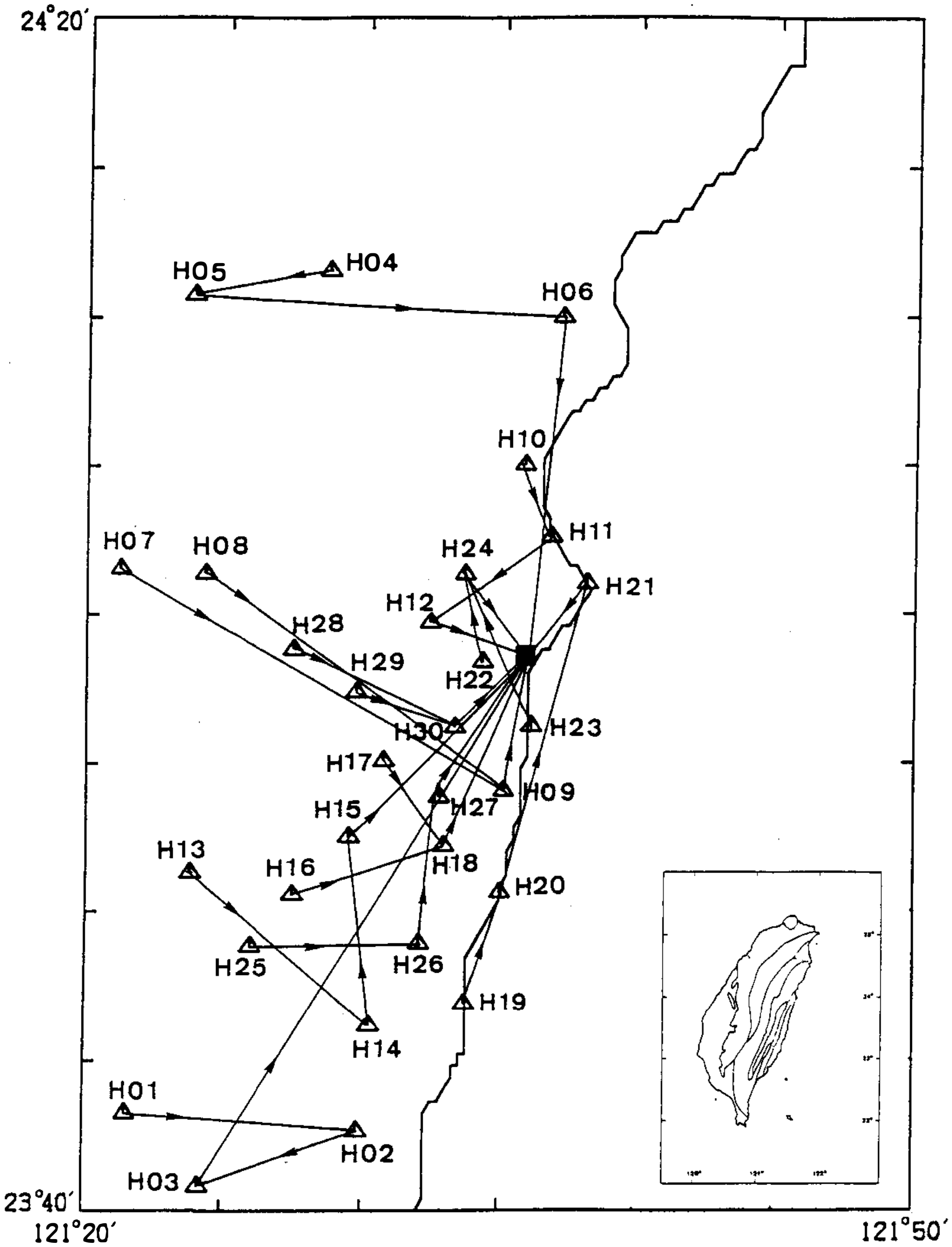


Fig. 1. Thirty PANDA II stations in the Hualien area and their radio links of data transmissions to the central recording center (solid square). Open triangles denote the stations. Arrows represent the transmitting directions of seismic signals. The inset map on the right shows the geologic provinces of Taiwan (after Ho, 1986).

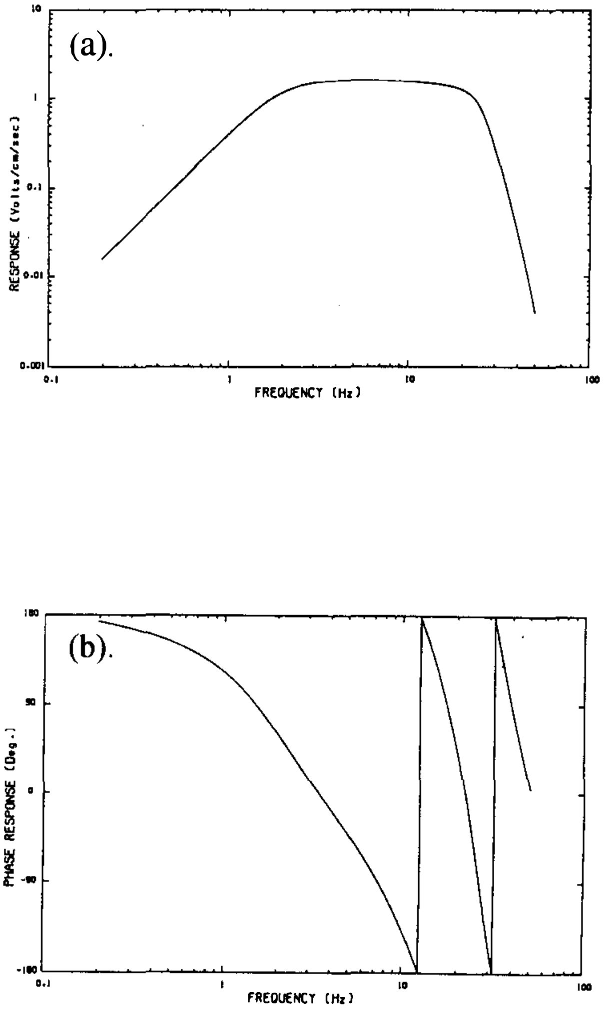
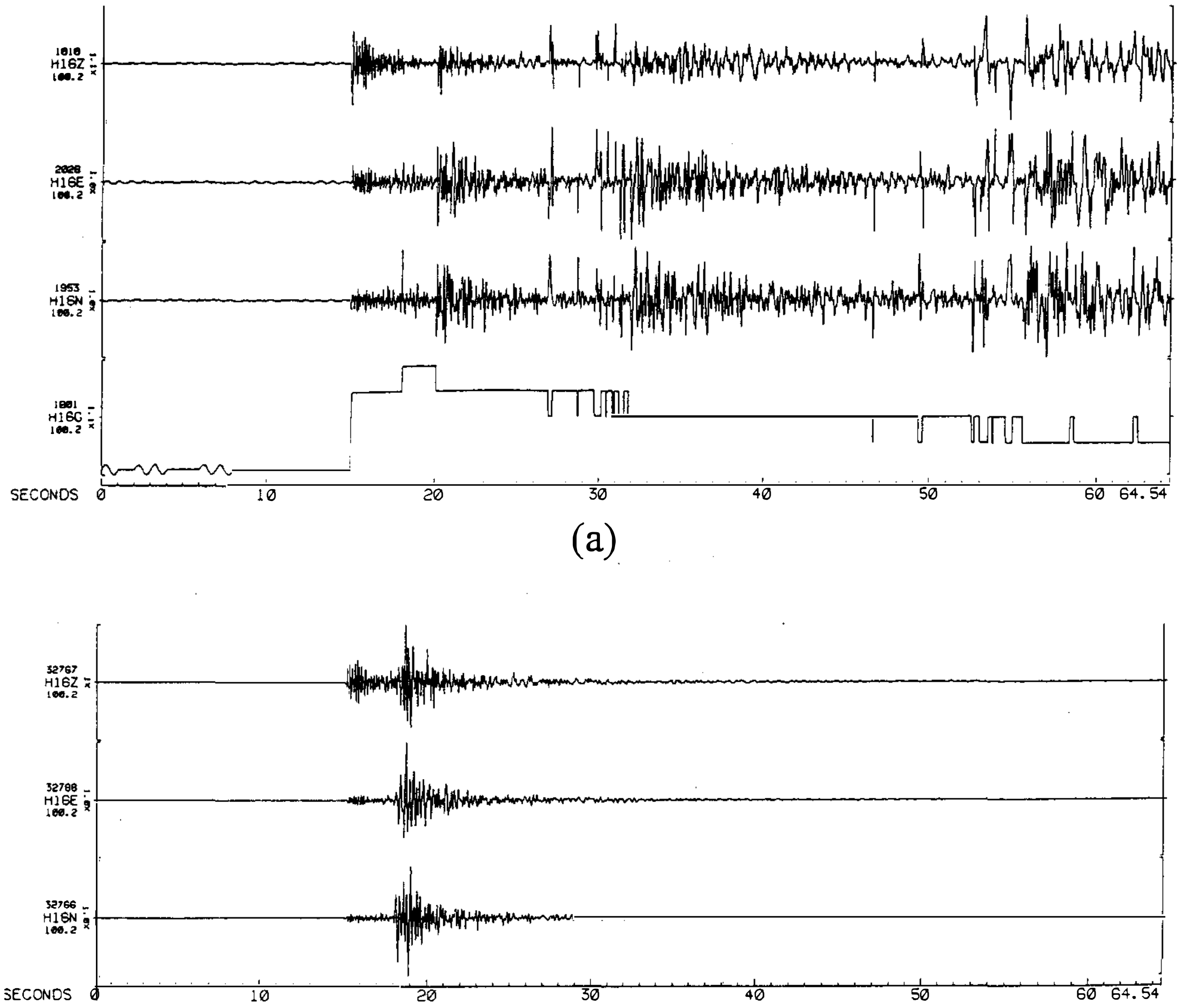


Fig. 2. (a) Amplitude and (b) phase response of the PANDA II telemetry system together with the L-4A seismometer.

More than 1,600 local and regional earthquakes with magnitudes up to 6.2 were recorded on-scale in the first five months of this experiment. Some teleseismic events were also on-scale recorded, including the Guam earthquake (M8.2) in early August 1993. Figure 3a shows an example of the raw seismograms of a local earthquake recorded by one station. For each station, there are three data channels, including vertical (Z) and two horizontal (EW and NS) components as well as one gain channel, including gain and other information. As shown in Figure 3b, the gain channel was jumped to the fourth step since ground shaking was strong due to the larger magnitude and shorter hypocentral distance. From the raw seismograms, it is impossible to visualize the real waveforms and identify the phase arrivals. After the gain channel was decoded and the gain factor was removed from the raw seismograms, however, the corresponding high-quality three-component seismograms can be totally recovered (Figure 3b). The waveforms and the impulse onsets of the P-wave and S-wave are clearly shown on the seismograms. The details of PANDA II seismic data routine processing was documented by Chen *et al.* (1993).

4. COMPARISON WITH THE REGIONAL SEISMIC NETWORK



(a)

(b)

Fig. 3. (a) Raw seismograms recorded by the PANDA II stations in the Hualien area. (b) High-resolution three-component seismograms after the removal of gain factors from the raw seismograms shown in Figure 3a.

Figure 4 presents the distribution of epicenters and focal depth profiles along the NS and EW directions in and around Taiwan (120°-122°E and 21.8°-25.25°N) located by the PANDA II array from late July to December, 1993. The total number of events is 1529. The epicenters in the Hualien area (121.2°-121.8°E and 23.7°-24.3° N) in the same period located by the PANDA II array and by the regional seismic network, CWBSN, are presented in Figures 5a and 5b, respectively. Their focal depth profiles along the NS direction are also plotted in the corresponding figures. The crustal seismic velocity structure used for locating earthquakes by the PANDA II array is the same as that used routinely by the regional seismic network. The velocity structure was determined by Yeh and Tsai (1981). From these figures, it is clearly seen that seismicity in this area is characterized by an abundance of crustal earthquakes. The total number of events located by the PANDA II is about 2.6 times that by the regional seismic network. This indicates that the monitoring capability of the PANDA II array is better than that of the regional seismic network.

In order to compare the reliability of the earthquake locations by the PANDA II array and by the regional seismic network, the root mean square (RMS) values of the travel time residuals of earthquake locations by the two systems for corresponding earthquakes are plotted in Figure 6. The RMS values for the PANDA II array are apparently smaller and narrower in range than those for the regional seismic network. In addition, both the location errors of the epicenters and focal depths for the PANDA II array are smaller than those for the regional seismic network, especially in focal depths, as revealed in Figure 7. These features imply that the accuracy of locating an earthquake is enhanced substantially by the PANDA II array. Such

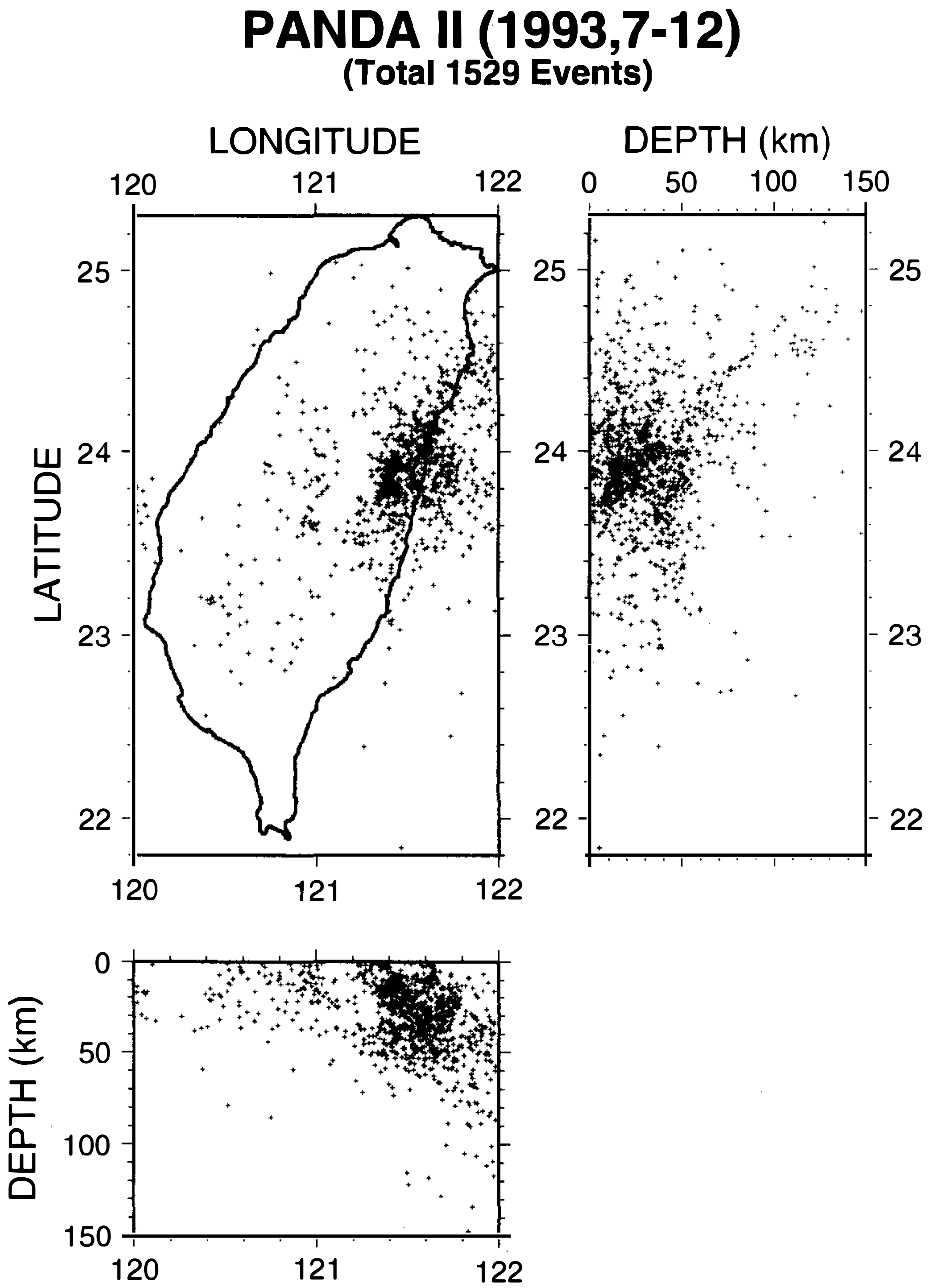
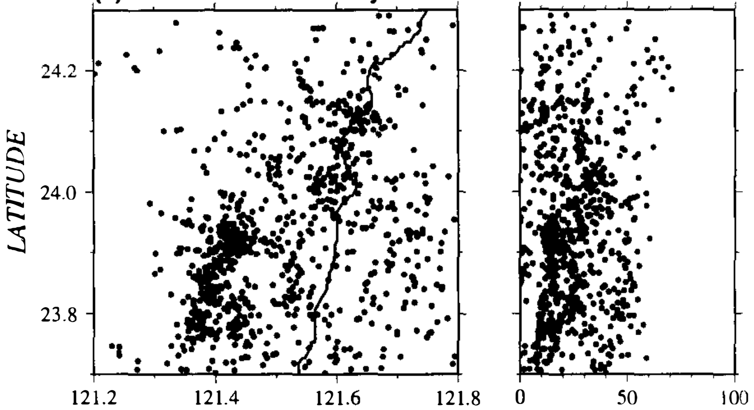


Fig. 4. Distribution of the epicenters and focal depth profiles along the NS and EW directions in and around Taiwan (120°-122°E and 21.8°-25.25°N) located by the PANDA II array from late July to December, 1993. The total number of events was 1,529.

(a). 913 events located by PANDA II



(b). 358 events located by the CWBSN

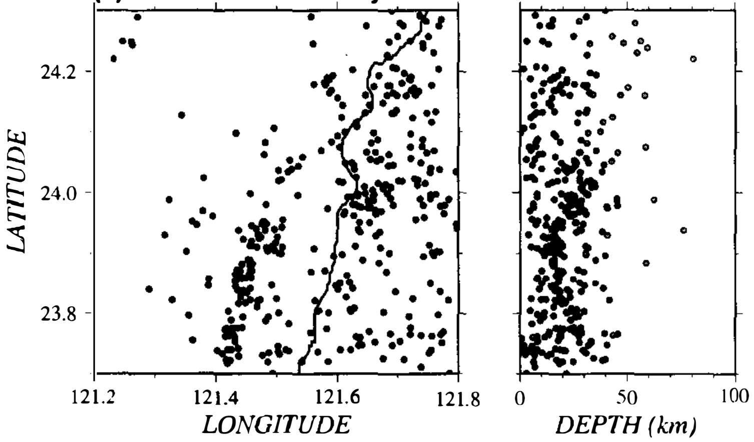


Fig. 5. Distribution of epicenters and focal depth profile along the NS direction in the Hualien area (121.2°-121.8° E and 23.7°-24.3° N) in the same period as that of Fig. 4 located by (a) the PANDA II array and (b) the CWBSN, respectively.

results are expected since the PANDA II array has a higher resolution than does the regional seismic network because the array has a higher dynamic range and smaller interstation spacings. Figure 8 shows a plot of the comparisons of the epicenters and focal depths as determined by the two systems. In this figure, the open circles are for earthquake locations from the regional seismic network, while the solid circles are from the PANDA II array. Significant discrepancies in the epicenters and focal depths for the corresponding earthquakes between the two systems are revealed. Their statistical differences are shown in Figure 9. The majority of the epicenters located by the PANDA II shift to the west and to the north with respect to those located by the regional seismic network. Most of the shifting magnitudes are in the range of 0 to 10 km, but some are up to 20 km or more to the west. Therefore, many events inside the PANDA II array were mislocated by as much as 10 to 20 km to the east by the regional seismic network. This means an on-land event can easily be misidentified as an off-shore event due to a few of the stations in the study area. As for the focal depths, the depth variations, the differences between depths determined by the PANDA II array and by the regional seismic network, are mainly from -5 km to +10 km. Thus, details concerning seismicity and tectonics using the data of the regional seismic network must be interpreted with great care.

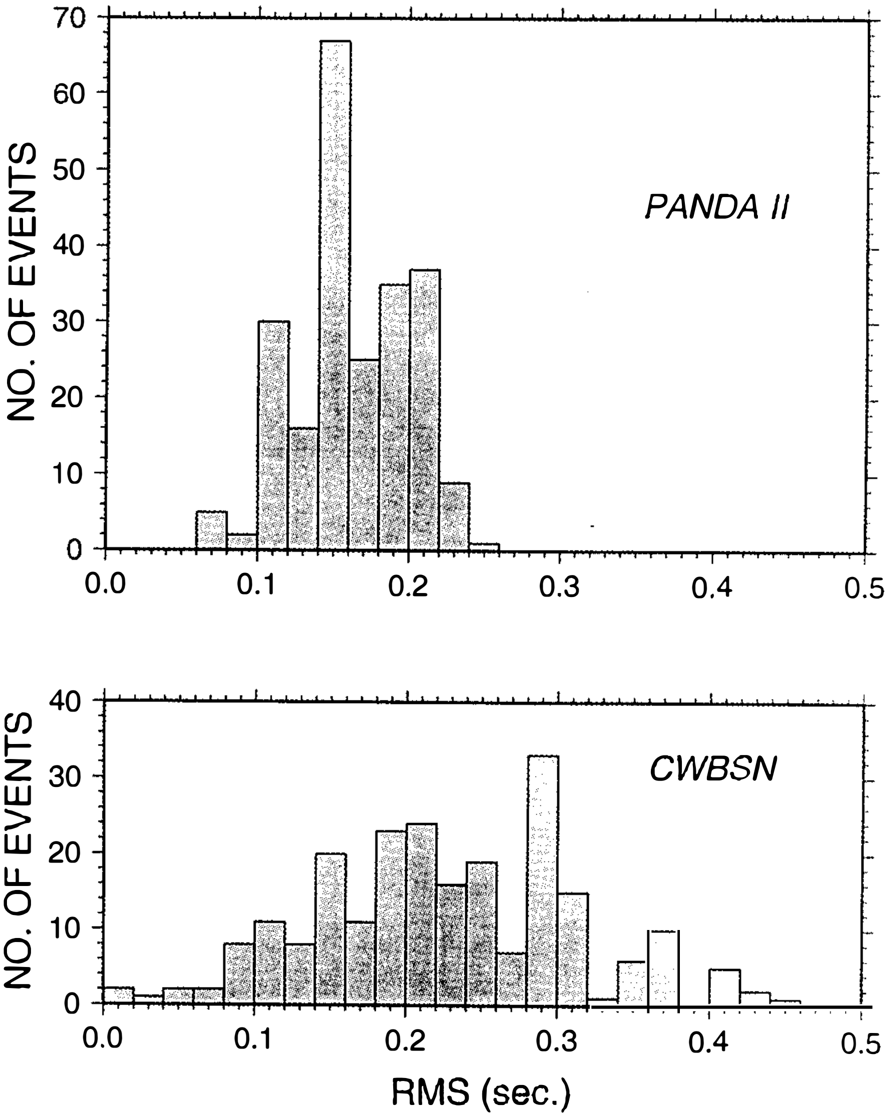


Fig. 6. Histograms of root mean square (RMS) values of the travel time residuals of earthquake locations by the PANDA II array and by the regional seismic network for corresponding earthquakes.

Based on the above comparisons, it is obvious that the PANDA II array with higher dynamic range and smaller interstation spacings is much more capable and reliable than the regional seismic network. In other words, for studying seismicity and related tectonics in detail, the PANDA II system is far superior to the regional seismic network.

5. DISCUSSION AND CONCLUSIONS

This study was the first time that the PANDA II system had ever been used in the world. The system was deployed in the Hualien area, Taiwan from late July 1993 to September 1995 right after it had been constructed. This array covered an area roughly 60 x 30 km with 5- to 10-km interstation spacing, extending from an oceanic crust (the Coastal Range) across a suture zone (the Longitudinal Valley) into continental crust (the Central Range). The PANDA II system, a second generation of PANDA with major improvements in its dynamic range and

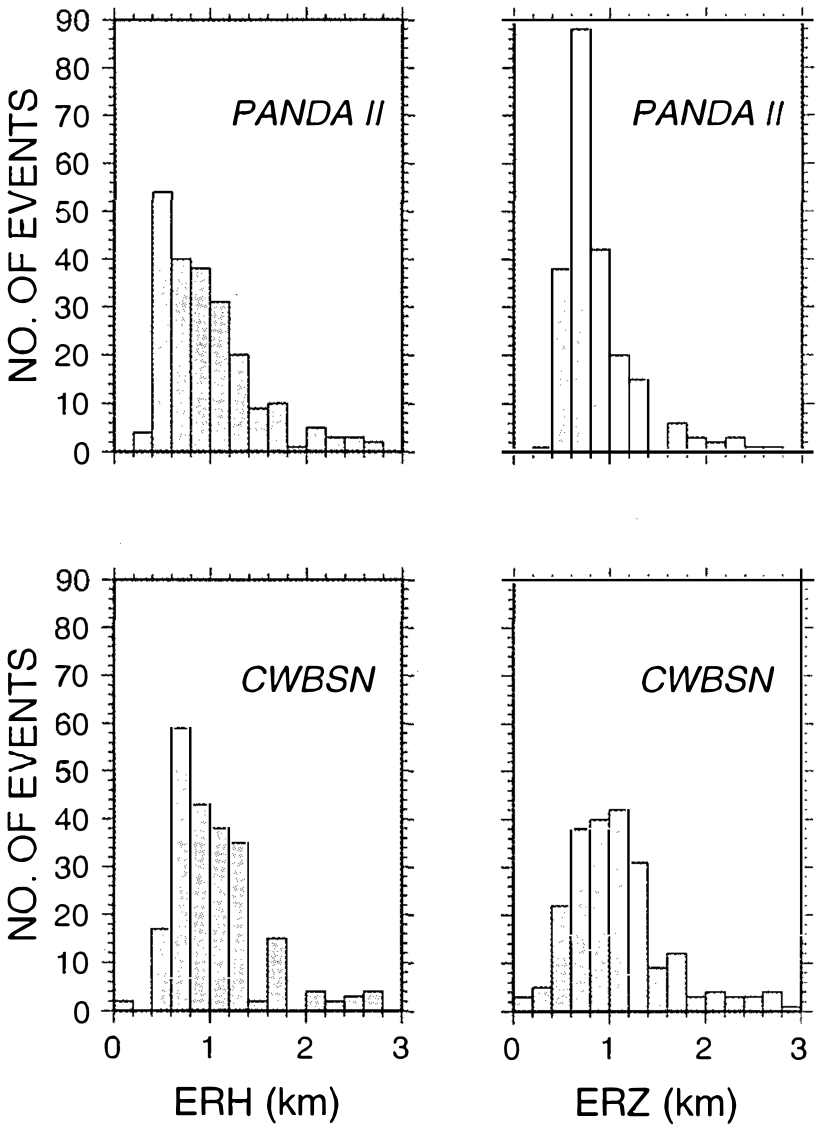


Fig. 7. Histograms of the location errors of epicenters and focal depths by the PANDA II array and by the regional seismic network for corresponding earthquakes.

telemetry scheme, deployed there had a maximum dynamic range of 132 dB by using a five-step gain ranging system which automatically adjusts gain in 18-dB steps to all signal channels on the basis of the preset parameters of saturation threshold and a minimum time period after each gain change. In the PANDA system, its dynamic range is about 96 dB by using the high-gain/low-gain technique (Chiu *et al.*, 1991a). In the PANDA II array, the Mark Product L-4A, 2-Hz three-component was used as a sensor at each station. The transmissions of signals from stations to the central recording center were grouped into 10 radio links. At the recording center, two PC-486 computers were used for on-line digital data acquisition and off-line data analysis. All seismic data were recorded in a trigger mode.

More than 1,600 local and regional earthquakes with magnitudes up to 6.2 were on-scale recorded in the first five months. This study shows that seismicity in the Hualien area was characterized by an abundance of shallow crustal earthquakes. Based on the comparisons of the data recorded by the PANDA II array and the regional seismic network in the period of

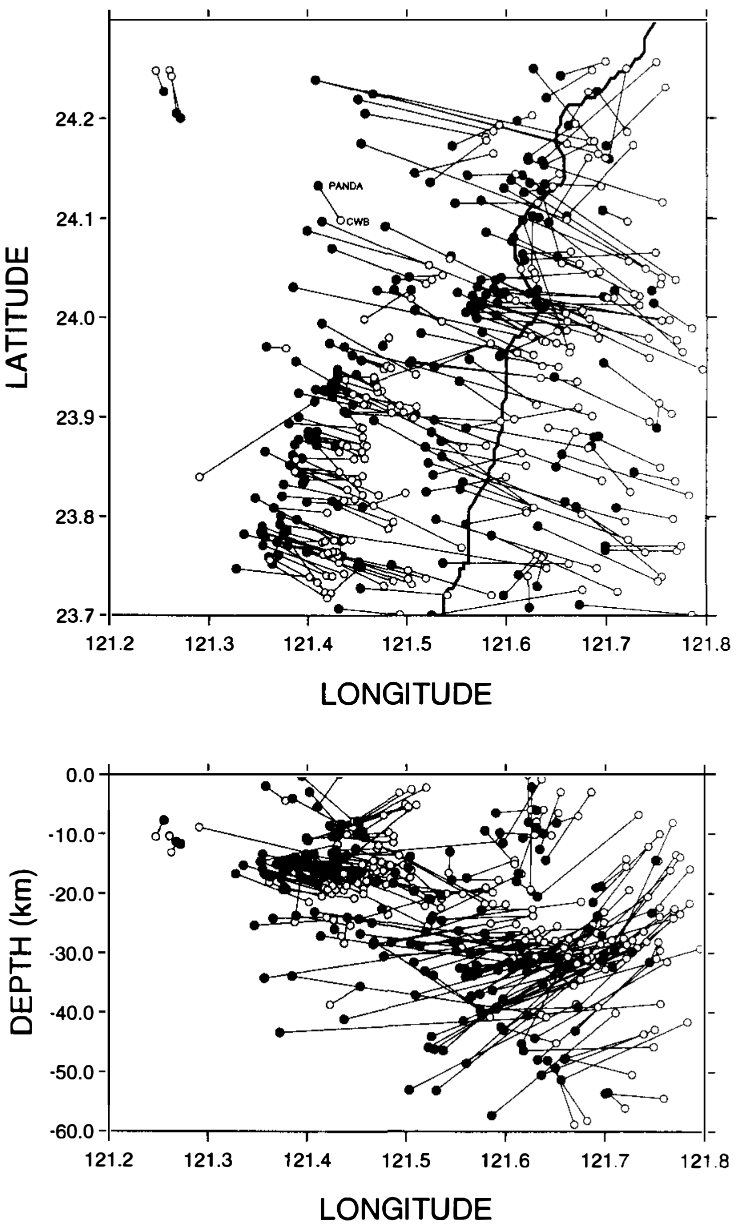


Fig. 8. Epicenters and focal depth profiles determined by the two seismic systems. Open circle symbols are for the regional seismic network, while the solid circle symbols are for the PANDA II array.

July-December 1993, the monitoring capability and locating reliability of earthquakes by the PANDA II are better than that which is recorded by the regional seismic network. In other words, this experiment demonstrates the impact of modern seismic instruments on the improvement of data resolution. Thus, it is concluded that the PANDA II is a better sesimographic system for studying seismicity and related tectonics in detail.

The earthquake data recorded by the PANDA II array are currently being used in the three-dimensional tomographic inversion to image P and S velocity structures, joint hypocentral determination (JHD) analysis to quantify the lateral crustal velocity variations, relocation of earthquakes by the three-dimensional model to finalize the seismicity pattern and focal mechanism for a comprehensive tectonic interpretation of the Hualien area. These studies will

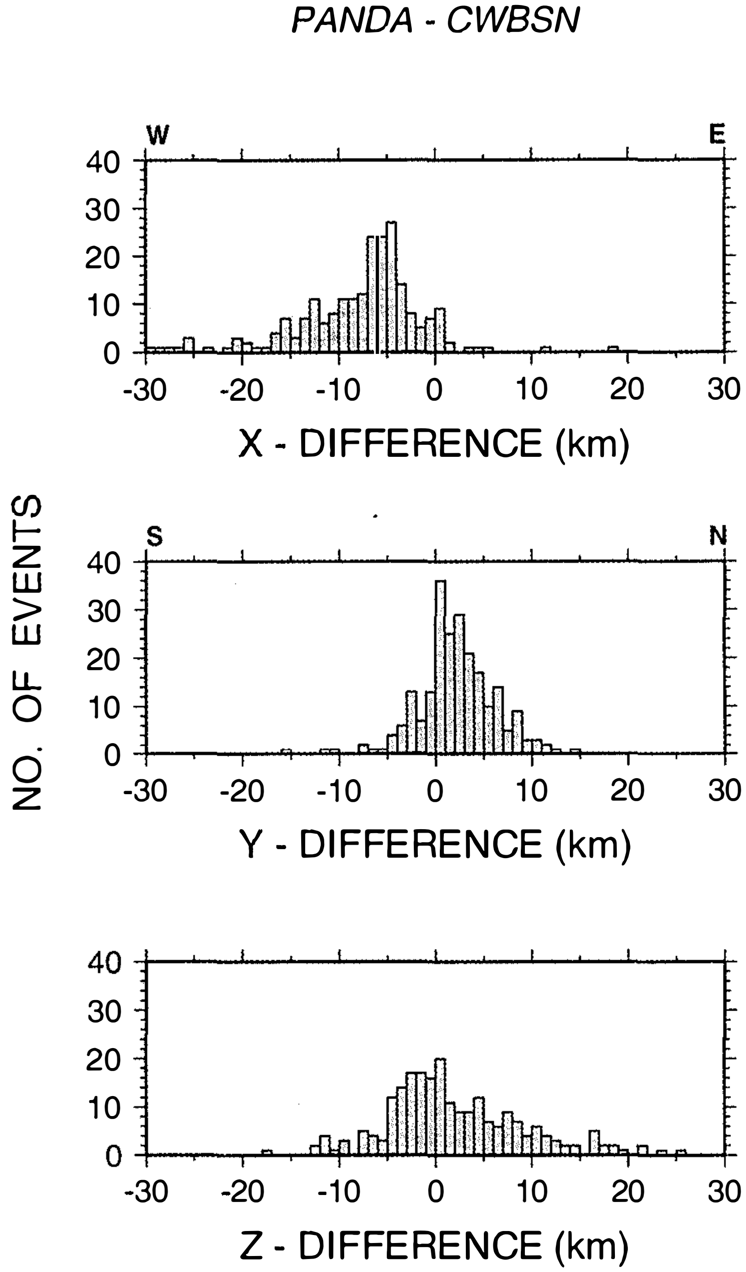


Fig. 9. Histograms of the differences of the epicenters in EW and Ns directions and focal depths (PANDA II-CWBSN).

be completed in the near future. From the seismograms, significant differences in waveforms have been seen among stations located on the oceanic crust and on the continental crust, and several secondary arrivals have also been clearly identified between the direct P- and S- arrivals. Their analyses are also currently being undertaken.

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