A portable broadband seismic network in Vietnam for investigating tectonic deformation, the Earth's Interior and experimentation for earthquake and tsunami early warning

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Abstract

In coordination and collaboration with researchers at the Vietnamese Academy of Science and Technology, Hanoi, Vietnam, National Taiwan University and Academia Sinica, both in Taipei, Taiwan, a 25-station broadband seismic array was installed in northern Vietnam and is now underway to acquire a high density, wide dynamic range seismic data. Those stations are designed to image and interpret crust and mantle structures beneath the surface of northern Vietnam, including the geodynamic evolution of the Red River Shear Zone. During this period, significant local, regional and teleseismic events were well recorded. The excellent distance and azimuth coverage from available events help answer questions about deep seismic structures beneath array and its regional tectonic evolution. Utilizing an unusual opportunity, this array recorded near antipodal seismic waves from significant seismic events which occurred in South America and may thus provide valuable seismic data for the study of the Earth deep interior. Similar instruments are planned for distribution in southern Vietnam in near future to study the deep structure of the South China Sea. Finally, those stations are scheduled for planned upgrades as real time transmission stations for earthquake monitoring and tsunami warning for the South China Sea.

Introduction

Insight on the processes of continental collision and resultant effects has been obtained by studying the Himalayan mountain belt and surrounding regions (Tapponnier et al., 1986; Molnar et al., 1993). The crustal thickening in and around the Tibetan Plateau and Tibetan uplift are direct results of the collision between the Indian and Asian continents. Large scale strike-slip movement along the Red River Shear Zone (RRSZ) has been recognized as a direct relation to this collision process and is widely viewed as a key process in shaping present-day Southeast Asia and its responsibility for the opening of the South China Sea (Lee and Lawver, 1995; Chung et al., 1997). Knowledge of fault structure and deformation mechanisms in the deep earth is central to our understanding of how the lithosphere behaves during a continent to continent collision. Mantle dynamics and plate interactions of this region have been repeatedly examined using geological and geochemical observations (Chung et al., 1998). However, owing to fewer related Geophysical survey and seismic observations, the present tectonic stress and deep crust and upper mantle structures which provide a unique constraint for geodynamic evolution in Southeast Asia is still unclear. Regional seismic arrays may provide a powerful means of mapping the details of deep-Earth structure and seismology and remains to be the best tool available as of this issue to examine them. However, spatial aliasing due to the less-than-optimal distribution of global seismometers and sparseness of permanent regional seismic networks in this area have long made it difficult to determine regional tectonic stresses and deep-Earth structure based upon observations accumulated from studying regional earthquakes and teleseismic waves. The temporary deployment of portable broadband seismometers can help by providing high-resolution windows into deep mantle.

More than 50 portable broadband seismic instruments are currently operated by the Institute of Earth Sciences, Academia Sinica (IESAS) as a part of the Broadband Array in Taiwan for Seismology (BATS; Kao et al., 1998) and designed to be deployed within Taiwan and its surrounding islands to study the earth deep interior and seismic hazards. The National Science Council, Taipei, Taiwan (NSC) and IESAS have encouraged the distribution abroad for international cooperation and extension of the study topics. In coordination and collaboration with researchers at the Vietnamese Academy of Science and Technology (VAST), National Taiwan University (NTU) and Academia Sinica, a 25-station broadband seismic array was installed in northern Vietnam in 2006. Those stations uniformly cover northern Vietnam and provide a high density, wide and dynamic range seismic data to study the tectonic evolution of the RRSZ. We hope to provide additional constraints on the style of crustal deformation and mantle evolution by quantifying these observations and to improve our understanding of the geological processes at work. Furthermore, the array provides useful information to determine crust and mantle structures for regional earthquake monitoring and seismic hazard reduction in this region as well as investigating the Earth deep interior using recorded near antipodal seismograms.

Active Faults and Seismicity in Vietnam

The RRSZ has been recognized as a large-scale left-lateral movement to support the hypothesis of continental extrusion resulting from the collision of India with Asia (Tapponnier et al., 1986). It has often been regarded as a suture separating South China from the Indochina blocks and as a lithosphere-scale strike-slip fault (Lee and Lawver, 1995; Leloup et al., 1995). Allowing for eastward extrusion of South China, the continued deformation of Asia eventually resulted in reactivation of the RRSZ in a right-lateral sense, and the opening of the South China Sea is regarded as pull-apart deformation of the southeastern termination of the RRSZ.

According to the contact relationship between the old pre-Cenozoic block in Indochina Peninsula and the South China block, the Red River Fault Zone was divided into two parts extending from land to ocean, the north and south segments. The activities of the north and the south segments were different. Earthquake activity in north segment is higher than that in south segment. The south segment of the RRSZ crosses northern Vietnam and dominates its tectonic evolution. Like the RRSZ, most of the main faults in Vietnam are strike-slip faults. The NW-SE deep strike-slip fault system in the North is more active than the longitudinal NE-SW fault system. According to the earthquake catalog compiled by the Institute of Geophysics (VAST), 90% of the earthquakes have taken place in northwestern Vietnam (Figure 1). Aside from this region, there were no reports of earthquakes of a magnitude larger than 5.5. Vietnam has been classified as a low seimicity region. However, this country is still tectonically active as evidenced by some moderate earthquakes in Vietnam and adjacent areas reportedly induce remarkable damages, the same as historical earthquake damage reports. Strong damage events were reported to occur in the Northwest of Vietnam near Dien Bien in November 1935, and on February 19, 2001, and near Tuan Giao on June 24, 1983 (Nguyen, 2007). They caused the destruction of buildings and structures in the area of thousands square kilometers. Furthermore, some earthquakes related to volcanic activity are moderate and occur off shore in the center part of Vietnam. Thus, as a result of economic advances, more and more high-rise buildings and large public facilities are constructed in major cities of Vietnam, seismic hazard analysis and reduction will gain in importance in the near future for design and risk evaluation.

Deployment and Data Processing

In December 2005, we began our portable array deployment. We installed 15-set broadband seismic instruments using seismic stations of the Vietnam seismic network located in northwestern Vietnam (Figure 2). Four of them employed Streckeisen STS-2 sensors and others employed Nanometrics Trillium 40 broadband sensors. Those seismometers measure ground motion over a wide frequency range with flat response to velocity from at least 0.025 to 50 Hz (Trillium 40). STS-2 seismometers have an extended lower limit to 0.008 Hz. The output from the seismometers is recorded on a

Quanterra/Kinemetrics Q330 recorder with 24-bit analogue-to-digital conversion. The ground motion signal is recorded continuously and digitized at a rate of 100 samples per second which allows us to record nearly half year of continuous data on a 20-Gbyte high-capacity recording system (the Quanterra PB14F Packet Baler). Time keeping is provided by a built in Global Positioning System (GPS) clock which resets the internal clock each hour to keep timing errors below 1 mini second. Power is supplied by a 12-V automotive battery that is recharged through AC power or solar panels. This network was extended to 25 stations in 2006 and included several new stations located at northeastern side of the Red River and one station located the nearby of the Ho Chi Minh city in south Vietnam. Each new station was equipped with a Quanterra Q330 digitizer, Kinemetrics Baler-14 and Nanometrics Trillium broadband seismometer. This array has a uniform distribution in northern Vietnam which covered the RRSZ and the high seismic activity region of northwestern Vietnam with an inter-station spacing of about 100 km (Figure 2).

Array data are routinely retrieved by VAST and IESAS staff. Once the seismic data are collected from field stations, they are copied to backup devices and then data segments are extracted for events satisfying a simple magnitude-distance criterion. Not only local earthquakes occur within this network but also significant regional and teleseismic events can be well recorded. During this operation period, the level of seismic activity in the surrounding region was high, and a large number of earthquakes were recorded. The extracted waveform data are converted to the SAC format and archived as an event database for future analysis. Local events are selected using the earthquake catalog compiled by the Vietnam seismic network operated by the Institute of Geophysics, VAST. Events are also selected using the preliminary Determination of Epicenters (PDE) published by the US Geological Survey. The available regional and teleseismic events from this network are shown in Figure 3. Symbols indicate the locations of all events for which data have been extracted from the continuous data streams up to December 2007. The events are shown in two hemisphere presentations, thus, out to 90° in a linear polar projection centered on this portable array, and from 90° to 180° in a comparable projection about the antipole. It shows wide azimuth and distance cover ranges of significant seismic events. With the continuous data sampling available at 100 Hz we can extract the entire seismic wavefield extending from the near earthquake high-frequency body waves to the long-period surface waves to study the earthquake source process and Earth seismic structure. Furthermore, this network provides an unusual opportunity to record near antipodal seismic waves from significant seismic events which occurred in southern America (Figure 3b) to study the Earth's deep interior.

Based upon continuously collected seismic data, the noise level at stations installed at 2005 has been analyzed to evaluate the quality of stations for periods ranging from 0.1 to 100 sec. We selected a large number of one hour waveform segments within an available period for this noise analysis. For each segment of continuous data, a procedure to estimate the power spectral density (PSD) developed by McNamara and Buland (2004) was employed, and the PSD at each seismic station is estimated. Using this approach, we may calculate and document ambient seismic background noise for direct comparison to standard low and high noise models (new low noise model [NLNM] and new high noise model [NHNM]; Peterson, 1993). Table 1 shows a summary report for analyzed results of the BHZ channels of this network where it was found that the observed ambient noise is strongly dependent on site conditions. Stations located at rock sites in general have lower noise levels than alluvium sites. Many stations of the Vietnam seismic network are located in villages and manual operation, high frequency artificial noise (SP) in general has a higher noise level than a typical broadband station (SSLB) of BATS, however, natural original middle and long period (MP and LP) noise of most Vietnam network stations has lower levels than the Taiwan station SSLB. Noise monitoring for this network is ongoing and extending to newly installed stations.

Illustration of Issues for Recorded Array Waveforms

Within the observation period, many seismograms from events at different ranges were recorded with good S/N ratios. In this paper, we present several examples to show various kinds of seismic phases recoded by this array and a brief discussion for its possible applications.

1. Teleseismic travel time residuals for deep seismic structures beneath this array

The distance from the network in northern Vietnam to zones of large earthquakes is very effective for studying the deep structure beneath this array. A record section of P-wave and its later reflection for an M_b 6.2 Event in the Aleutian Islands at depth of 117 km is illustrated in Figure 4a. Those array seismograms can be used to determine the relative travel residuals with respect to expected arrival times from, for example, the IASP91 model of Kennett and Engdahl (1991) as indicated in Figure 4b. The residual pattern shows the lateral variation of seismic travel times across this array. A major part of the analysis of data from this array is directed toward delineating the three-dimensional variations in the crust and upper mantle beneath the RRSZ using body-wave tomography and teleseismic receiver functions. The results of such studies can be used to image the deep structures of the RRSZ and to deduce its geodynamic evolution.

2. Major regional shallow events for regional crustal structures analysis

In 2007, two major shallow events occurred at regional distances relative to this array and are well recorded (Figure 5a). One located in Laos on May 16 registered a magnitude of Mw 6.3 and the other in Yunnan, China on June 2 posted a magnitude of Mw 6.2. Both events are located by the global seismic network with significant uncertainties due to the ill distribution of global seismometers for this area. Observations from this array provide more information to constrain source behaviors and event locations of both events and its aftershocks. Figure 5b shows clear crust phases of recorded array seismograms from the Laos' event. Those observations may provide useful information to identify the crust structure of this area and its lateral variations. The determined regional structures should be helpful in improving earthquake-monitoring and detection by a network of seismic stations in this region.

3. Core phases for Earth deep interior studies

Vietnam is located at the antipode of South America's deep seismic zone and one of rare places where the antipodal waveforms can be observed frequently. In principle, P-waves travel a large area of earth core and focus again at its antipole before being detected on a seismograph. The antipodal seismic data from an earthquake enhance weak phases by a focusing effect. An antipodal earthquake and its nearby events are very effective for studying waves traveled through center of the earth's core. A record section of the core phases for an Mw 8.0 event occurred in Peru on August 15, 2007 is illustrated in Figure 6, along with a schematic diagram of ray paths from source to receiver. Poupinet et al. (1993) demonstrated that the details of the near antipodal P-wave trains can be used to provide constraints on the structure of inner-outer core boundary. Observation from array seismograms to track multiple arrivals across a group of stations provides significantly more information than can be found from a single record. By comparing information from a number of nearby antipodal sources, we hope to contribute new information about the Earth's inner core.

Upgrade for Real Time Earthquake Monitoring and Early Warning

The Taiwan broadband seismic array deployed in northern Vietnam was originally designed as field-based observation project. Instruments are planned to continue about 2 year observation. After then, those instruments will be searching for distribution in the whole Vietnam region to observe seismic waves to study the deep structure of the South China Sea. Site surveys and station construction in middle and southern Vietnam are ongoing. After both deployments, some high quality stations may be left as permanent stations and add to continuous GPS observations. The instruments will be maintained and operated by the Institute of Geophysics, VAST under international cooperation and each station will be equipped with a Quanterra Q330 digitizer and PB14F Packet Baler which provide the ability to detect triggering in local and a network capability to transmitted signals within stations. We are interested in cooperating with VAST to test and develop this array to include a real time function to monitor earthquakes activity in the near future. Furthermore, to consider the ability to observe seismic activity from micro earthquakes to damaged events, a low gain acceleration sensor is necessary for each station. The project can be considered as a prototype system to construct a regional broadband seismic network. However, the implementation of a modern seismic network involves many different types of research and technological aspects considered in relation to the development of sophisticated data management and processing, especially as the configuration of the proposed network has large array size greater than 1600 km in its long axis. Fortunately, the collective experience of IESAS operating BATS for more than a decade may help to solve part of this difficulty.

To consider the tsunami potential of the surrounding area of the South China Sea (SCS), IESAS is planning to add several stations in the Philippine islands. The installation plan is currently being discussed with the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The configuration of the planned network is shown in Figure 7 and includes two BATS stations on small islands within the SCS. Recently, BATS has been founded to construct satellite real-time data transmission system for data collection and help to develop a real-time seismic network to monitor earthquake and tsunami early warning of SCS.

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Figure Caption

Figure 1. Map of active faults and earthquake epicenters distribution in Vietnam from 1067 to 2002 (after Nguyen, 2007).

Figure 2. The portable broadband seismic array in northern Vietnam. Blue symbols indicate stations installed at the end of 2005. Symbols in red indicate stations installed in mid 2006. All stations are currently operating.

Figure 3. Events for which data has been extracted from the continuous data acquired this array. (a) Epicentral distances from 0 to 90°. (b) Epicentral distances from 90 to 180°. Large red circles denote event epicenters with a magnitude Mw greater than 6, blue circles indicate events with a magnitude Mw within 5.5 to 6, and small green circles for events with a magnitude Mw within 5.0 to 5.5.

Figure 4. (a) Original vertical-component seismograms show initial arrivals from an earthquake with a magnitude M_b 6.2 occurred in the Aleutian Islands at a depth of 117 km on April 29, 2007. The letters on the right denote the seismic stations. (b) Distribution of relative travel time at each station as recorded for this event. Blue and red circles denote negative and positive residuals, respectively. The scale for the residuals (in second) is shown at the bottom.

Figure 5. (a) Map of two significant regional events which occurred in 2007 and well recoded by the northern Vietnam portable seismic array. (b) Array record section of an Mw 6.3 event occurred in Laos on May 16, 2007. This section is plotted following a reduced velocity 8.1 km/sec in distance axis. Solid lines represent theoretical travel time curves predicted using the Earth model IAS91. For the shallow focal depth of this event, phases Pb and Sb represent P and S wave bottoming in the lower crust, respectively. Phases Pn and Sn represent P and S wave bottoming in the uppermost mantle, respectively.

Figure 6. (a) Ray paths of PKP and PP waves observed at antipodal distance (After Rial and Cormier, 1980). (b) Array record section of the core phases for an Mw 8.0 event occurred in Peru on August 15, 2007 at near antipodal distances. Several seismic phases which penetrate different portions of the Earth are also shown. Solid lines represent theoretical travel time curves predicted using the Earth model IAS91.

Figure 7. The planned broadband seismic network surrounding the South China Sea. Square symbols with red color represent two existed BATS stations. Blue square symbols represent the planned stations which will be deployed in the near future.

Table 1. BHZ Channel Noise at Vietnam Broadband Seismic Network

Station	Sensor	SP	MP	LP
BGVB	Trillium	D	B	C
DBVB	STS-2	E	B	D
DHVB	Trillium	D+	B	C
DSVB	Trillium	D+	B	C+
HBVB	Trillium	E	A	B-
LAVB	Trillium	E	B	C
LCVB	Trillium	C	A	B-
MCVB	Trillium	D+	A	B-
PLVB	STS-2	D-	C	C
SLVB	Trillium	C	A	B-
SPVB	STS-2	E	B	A
TGVB	Trillium	C	A	B-
THVB	Trillium	D	C	B-
TTVB	Trillium	C	A	B-
VIVB	STS-2	E	C	D
SSLB/BATS	STS-2	C	C	B

SP defines noise with period shorter than 1 second, MP defines noise period within one and ten second and LP defines noise period longer than ten seconds.
A: 10 db > Value –NLNM; B: 20 db > Value –NLNM > 10DB;
C: 30 db > Value –NLNM > 20dB; D: 40 db >Value –NLNM > 30dB;
E: Value –NLNM > 40dB

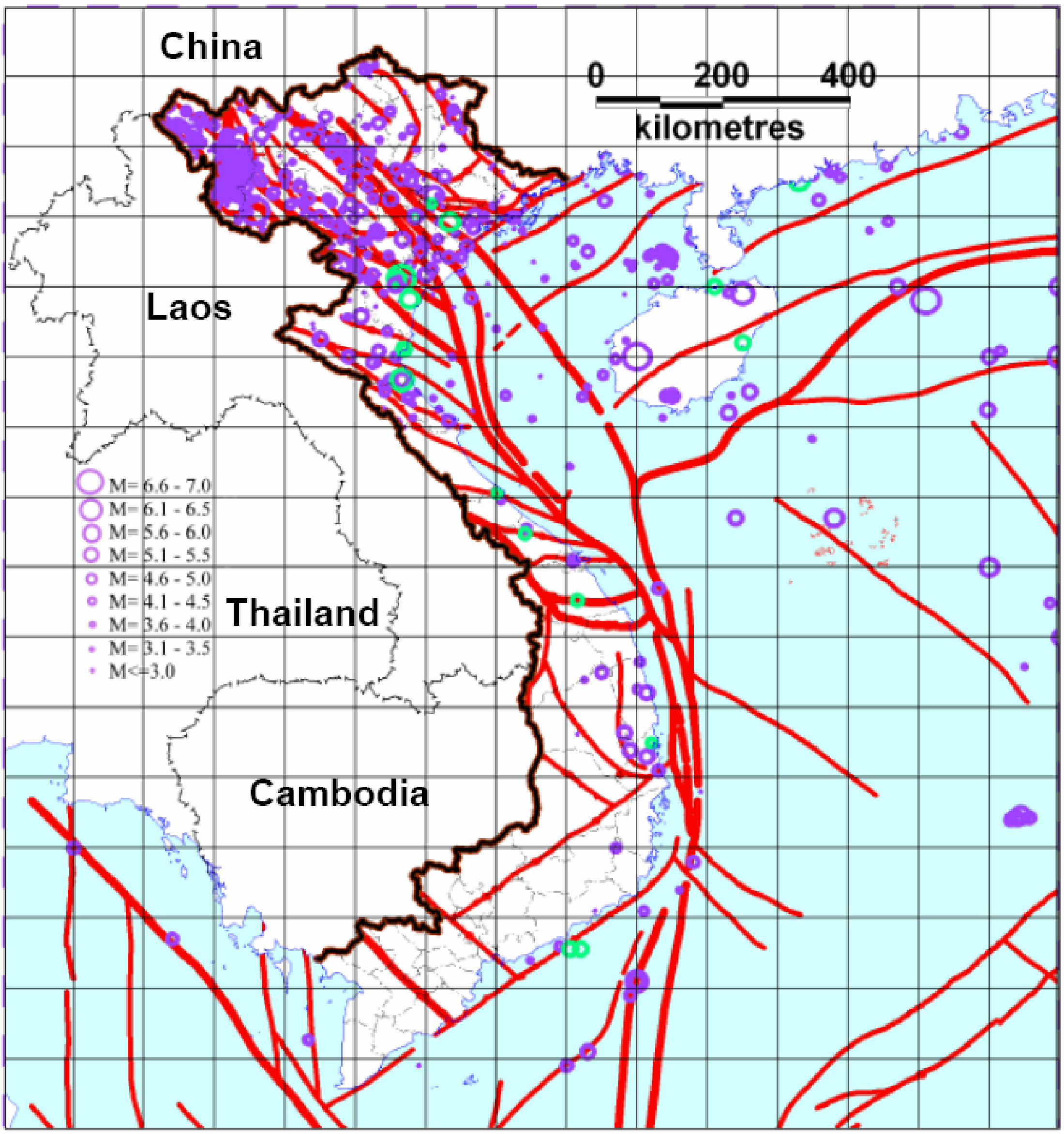

China
Laos
Thailand
Cambodia
0 200 400
kilometres
M= 6.6 - 7.0
M= 6.1 - 6.5
M= 5.6 - 6.0
M= 5.1 - 5.5
M= 4.6 - 5.0
M= 4.1 - 4.5
M= 3.6 - 4.0
M= 3.1 - 3.5
M<=3.0

Figure 1

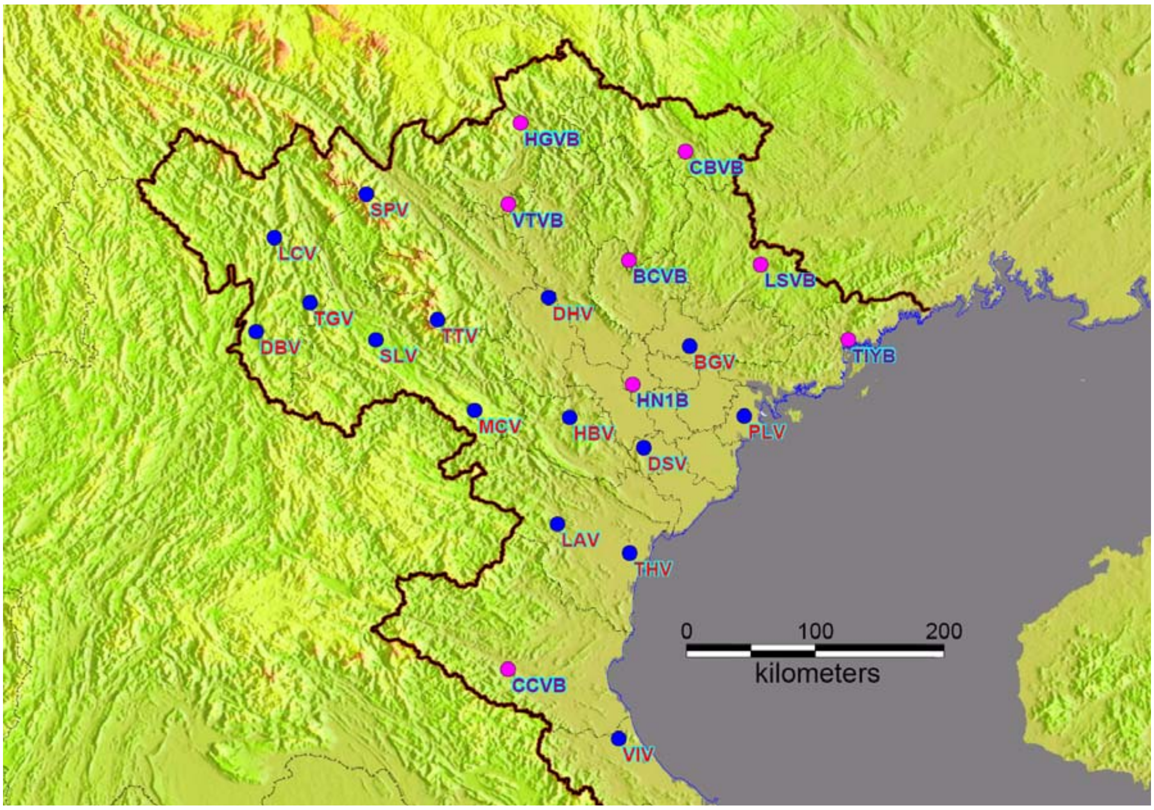

HGVB
CBVB
SPV
VTVB
LCV
BCVB
LSVB
DHV
TGV
TTV
DBV
SLV
TIYB
BGV
HN1B
MCV
HBV
PLV
DSV
LAV
THV
0
100
200
kilometers
CCVB
VIV

Figure 2

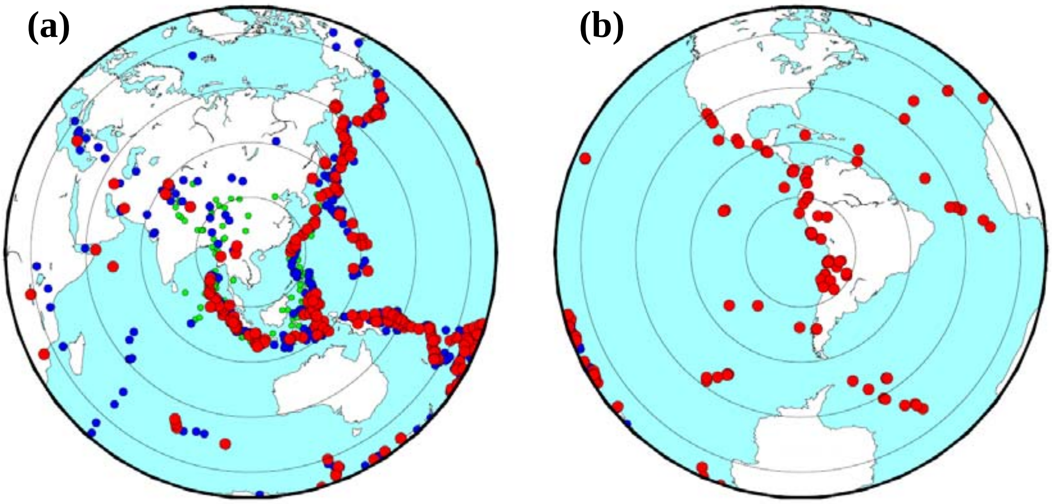
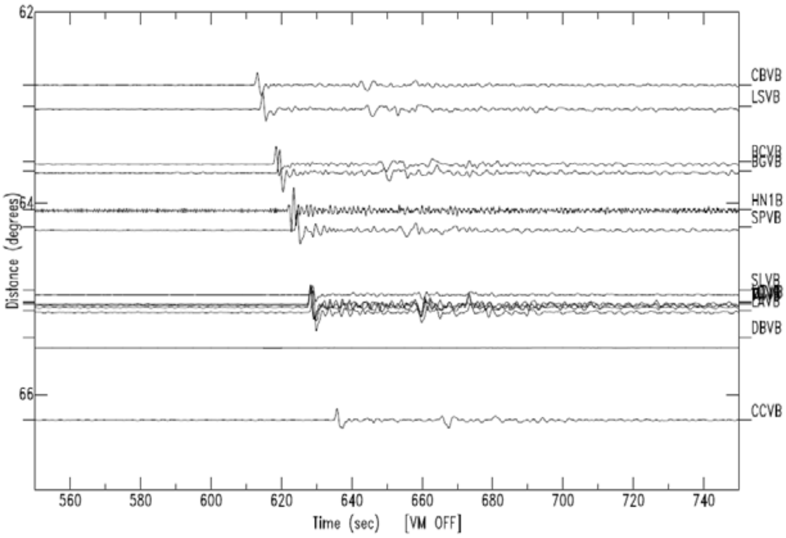
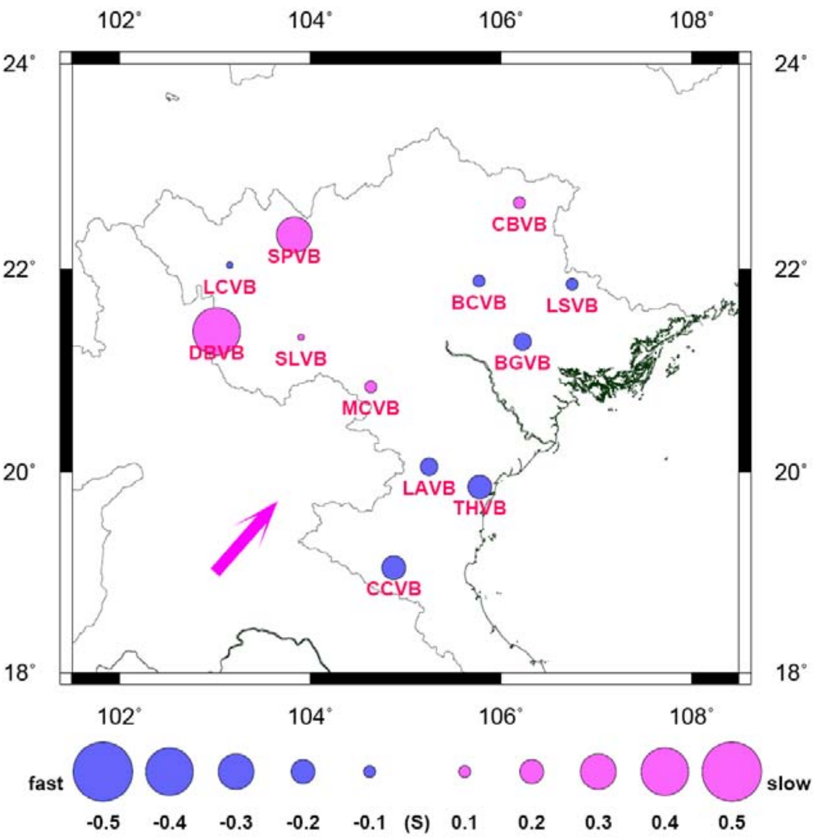


Figure 3

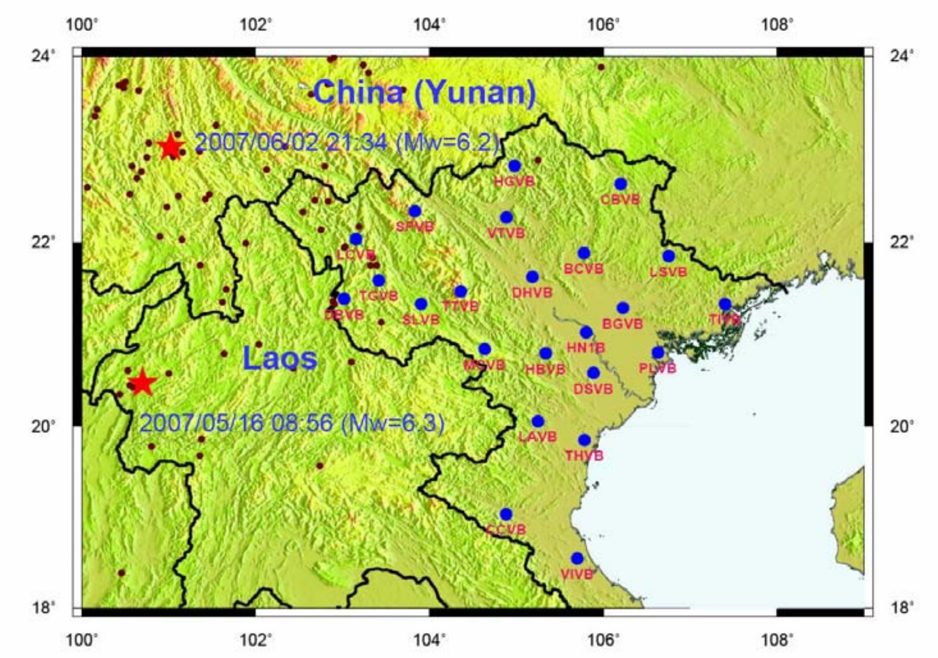

62
64
66
Distance (degrees)
CBVB
LSVB
BCVB
BGVB
HN1B
SPVB
SLVB
DBVB
CCVB
560
580
600
620
640
660
680
700
720
740
Time (sec) [VM OFF]

(a)

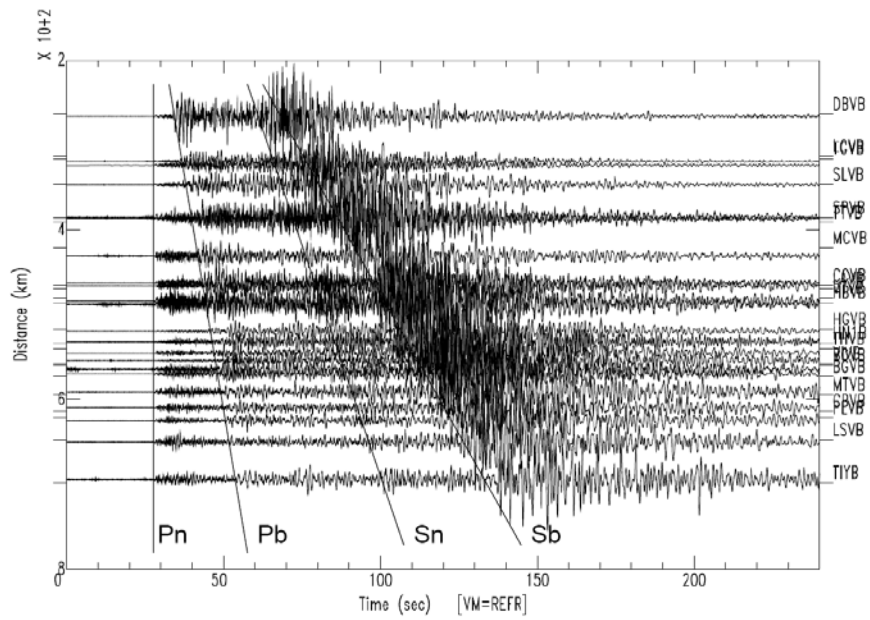

102°
104°
106°
108°
24°
22°
20°
18°
CBVB
SPVB
LCVB
BCVB
LSVB
DBVB
SLVB
BGVB
MCVB
LAVB
THVB
CCVB
fast
slow
-0.5
-0.4
-0.3
-0.2
-0.1
(S)
0.1
0.2
0.3
0.4
0.5

(b)

Figure 4

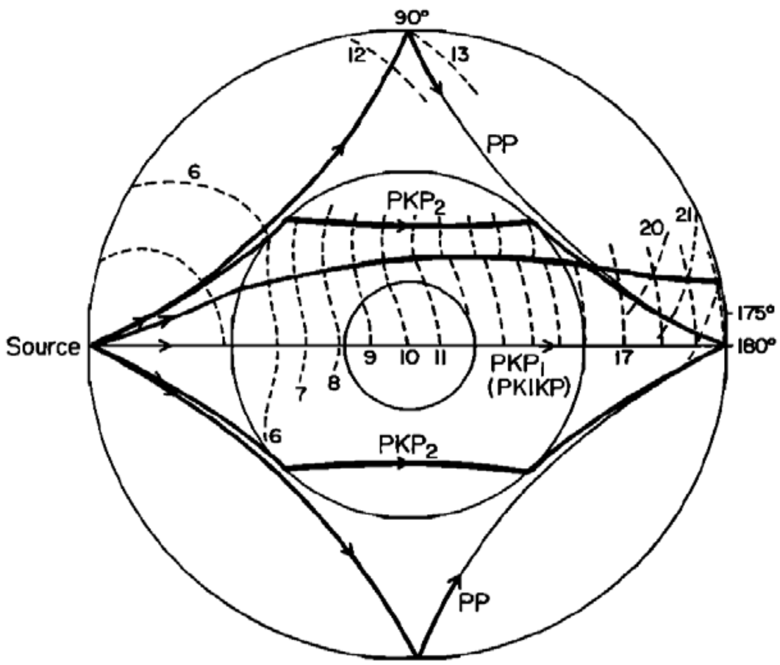

China (Yunan)
2007/06/02 21:34 (Mw=6.2)
Laos
2007/05/16 08:56 (Mw=6.3)
HGVB
CBVB
SPVB
VTVB
LCVB
BCVB
LSVB
TGVB
DHVB
DBVB
SLVB
TTVB
BGVB
TIYB
HN1B
MCVB
HBVB
PLVB
DSVB
LAVB
THVB
CCVB
VIVB

(a)

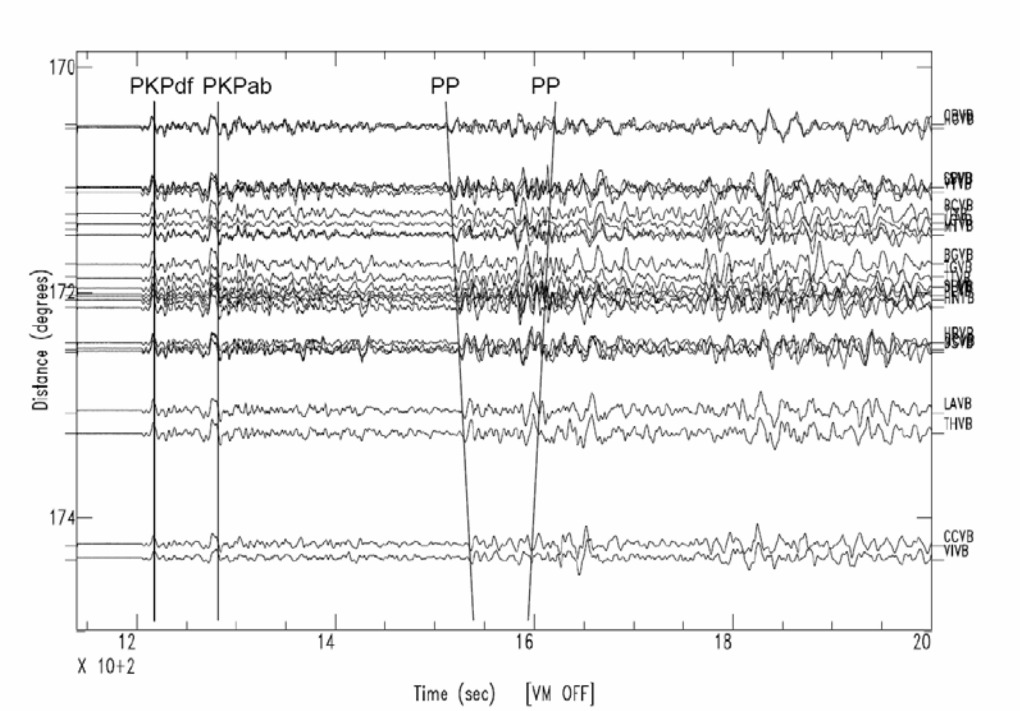

X 10+2
Distance (km)
Time (sec) [VM=REFR]
Pn
Pb
Sn
Sb
DBVB
SLVB
MCVB
HGVB
BGVB
MTVB
LSVB
TIYB

(b)

Figure 5


90°
12
13
PP
6
PKP2
20
21
175°
Source
9
10
11
PKP1
(PKIKP)
17
180°
7
8
6
PKP2
PP

(a)


PKPdf
PKPab
PP
PP
170
172
174
Distance (degrees)
LAVB
THVB
CCVB
VIVB
12
14
16
18
20
X 10+2
Time (sec)
[VM OFF]

(b)

Figure 6

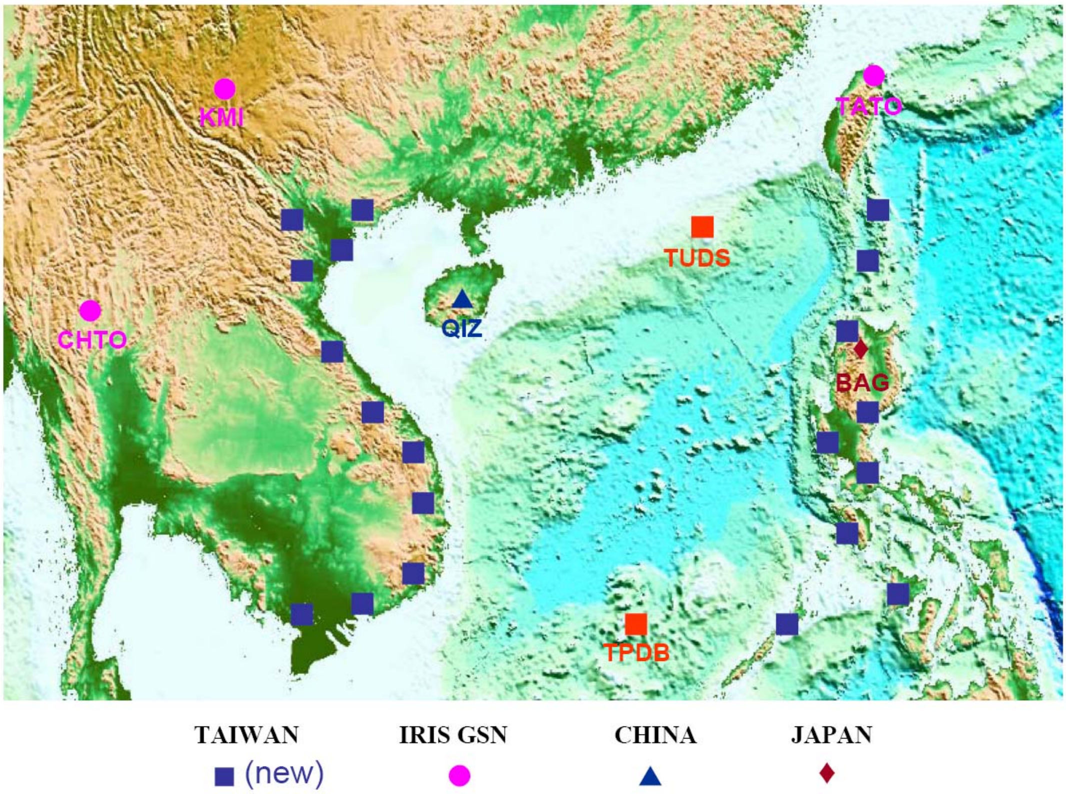

KMI
TATO
TUDS
CHTO
QIZ
BAG
TPDB
TAIWAN
(new)
IRIS GSN
CHINA
JAPAN

Figure 7