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Contributed Paper

Characterization of Khlong Marui Fault Zone Using Seismic Reflection and Shear-wave Velocity Profiles: Case Study in Khiriratnikhom District, Surat Thani Province, Southern Thailand

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ABSTRACT

Detailed fault mapping and characterization are important for seismic hazard assessment. The Khlong Marui Fault Zone (KMFZ) is a major active strike-slip fault system in southern Thailand. It extends in a southwest-northeast direction from Phuket towards Surat Thani province. Although the general fault system can be identified from surface observations, investigation of the fault zone in Surat Thani province is challenging because the surface expression is not obvious and thick sediments cover the area. Therefore, shallow seismic reflection profiles were acquired in the Khiriratnikhom district, Surat Thani province. The aims of this study were to characterize the subsurface geological structures in the vicinity of the fault zone. For the seismic data analysis, conventional data processing such as data editing, static correction and frequency filtering are effective in enhancing signal to noise ratio of stacked section. However, detailed geological information at shallow levels in the subsurface are not well imaged due to the effects of data acquisition and processing. To address this limitation, seismic reflection and shear wave velocity (Vs) profiles were obtained from multichannel analysis of surface waves (MASW) and are jointly interpreted. The results show a sequence of subsurface boundaries extending from the surface to a depth of about 250 m. The variations in seismic velocities and vertical offset of the main horizon are the fault signature observed on seismic sections and in the shear wave velocity fields. The results coincide well with the fault strike obtained from a previous geophysical interpretation. This finding suggests the possibility of ongoing activity of the KMFZ.

Keywords: seismic reflection, shear wave velocity, MASW, Khlong Marui fault zone, Surat Thani

1. INTRODUCTION

During the past decade, increasing damage and loss of lives associated with earthquakes has been recorded, especially in and around urban areas and in vicinity of weak zones within major fault systems [1, 2]. Even if the earthquake epicenter is far away from the area, the geological characteristics beneath the fault zone can play an important role in seismic wave amplification [3]. Therefore, availability of subsurface geologic information is critical for long-term seismic hazard assessments and for future development plans in the region. Generally, geophysical investigations using seismic reflection survey have been applied to image subsurface geological structures, especially to detect and characterize the hidden faults under the fault zone [4, 5, 6].

Tectonically, Thailand is considered to be a low seismicity region since it is far away from plate boundaries. However, historical and instrumental studies have recorded a number of moderate earthquake events since 1950 and most have occurred along known fault zones [7, 8, 9, 10]. About 14 fault zones in Thailand have been identified as active faults and two of these fault zones are situated in southern Thailand: the Ranong Fault Zone (RFZ) and the Khlong Marui Fault Zone (KMFZ) [11]. The KMFZ was the main target for the integrated geophysical study of this fault zone project, which was initiated in 2011. Evidence, previously gathered from geological and geophysical data at a pilot study performed in the Vibhavadee district, Surat Thani province [12], suggests that there are a number of buried faults existing along the proposed fault segments. However, no clear evidence of the major fault zone were observed in the pilot study. As a part of the project, the regional trend of fault strike identified from remote sensing, seismic reflection, airborne radiometric and geomagnetic data [13] revealed that the KMFZ may pass through Surat Thani province from Phanom, Bantakun, Khiriratnikhom, Punpin and Thachang district to the Gulf of Thailand (Figure 1). Although there is evidence of tectonic activity associated with the KMFZ, the geological structure and characteristics of the fault zone are still unclear. Therefore, an extensive study of fault characterizations beneath the variable thickness Quaternary sediment is incorporated into the recent study. Six seismic reflection profiles, of about 2-3 km each, were surveyed roughly perpendicular to the fault strike in the Khiriratnikhom district, Surat Thani province. Among them, 3 lines were used to confirm the existence of a fault segment that has been outlined by the Department of Mineral Resources (DMR) and the other 3 lines were used to detect and characterize sections of the fault zone that have been identified by previous geophysical data [13]. Although seismic reflection methods provide an image of subsurface geological structures, their shallow information is often inadequate due to the effect of acquisition geometry and data processing. Thus, shear wave velocity (Vs) profiles derived from the MASW methods were partly combined for gaining near surface information. The advantages of the MASW methods are that they provide superior resolution to P-wave methods in soft soil and take into account any velocity inversion [14, 15]. In this study, after briefly describing the geology at the study sites, we explain how data were acquired and processed. Results and interpretation of the seismic sections and Vs profiles at all survey lines will be illustrated.

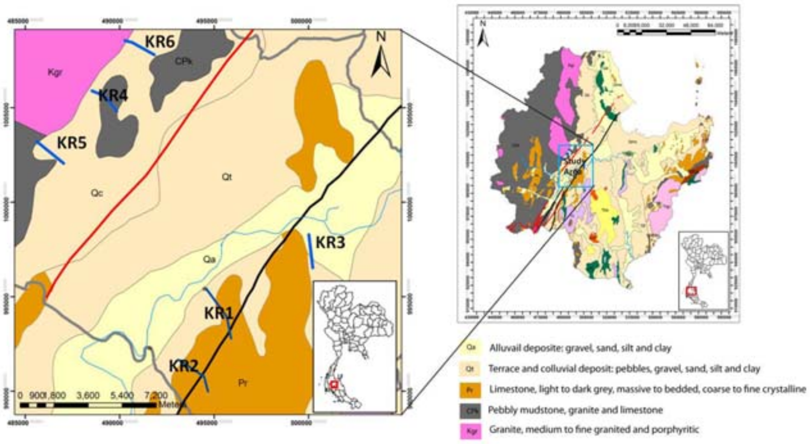

Figure 1. Geological map showing KMFZ distributions and the study area. Zooming panel shows 6 survey lines (KR1-KR6). Red line marked the KMFZ proposed by DMR and black line marked the KMFZ proposed by previous geophysical data.

2. GEOLOGICAL SETTING

Since the end of Mesozoic era, tectonic movements in conjunction with collisions of Indo-Australian, Eurasian and West Pacific plates formed the structurally complex areas, such as Gulf of Thailand and Andaman Sea [16, 17]. After the completion of clockwise rotations of crustal blocks, the KMFZ was developed [18]. The KMFZ is considered to be an active strike-slip fault that cuts across Peninsula Thailand from Phuket Island in the southwest towards Surat Thani Province in the northeast (Figure 1). The strike of the fault zone can be traced for a distance exceeding 150 km and 10 km width, and comprised of about 10 segments [19, 20].

Khiriratnikhom district lies in the central part of Surat Thani province where the Tapee River runs in a NE-SW direction and is surrounded by N-S trending mountainous ranges (Figure 1). The basement is represented by rocks of Carboniferous-Permian period found in western mountain areas, composed of limestone, mudstone, shale, sandstone and siltstone. Permian limestone occurs in the middle part and contain Permian fossils. The siltstones are yellow-brown in color, thinly bedded and contain carbonaceous layers. Triassic-Jurassic sedimentary rocks and Triassic-Cretaceous sedimentary rocks are distributed in the southern region. Both sedimentary rock units are composed of sandstone, siltstone, limestone lenses, and conglomerate. In the northern part, Triassic-Jurassic granitic rocks are dominated by batholiths and plutons. A Quaternary sedimentary basin formed in the vicinity of the main river. This sedimentary fill is represented by fluvial (Qa) and terrace (Qt) deposit [21]. The terrace deposits (Qt) consists mainly of gravel, clay, and coarse grain and poorly sorted of sand layers. The fluvial deposit (Qa) are composed of an alternating sequence of silty clay and sand layers.

3. MATERIALS AND METHODS

3.1 Theoretical Background

Reflection seismology can determine possible changes in subsurface elastic properties by measuring the two-way travel time of seismic waves propagated from a surface seismic source into the subsurface and reflected back to the surface. At the interface between layers with contrasting acoustic impedance, the reflection signal is governed by Zoeppritz equation [22] and at normal incident it is simply described by the reflection coefficient (R).

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} \quad (1)$$

Where ρ_1 and ρ_2 are the density of medium 1 and medium 2, while V_1 and V_2 are the wave velocity of medium 1 and medium 2, respectively.

Multichannel Analysis of Surface Waves (MASW) is a non-intrusive, fast and cost-effective geophysical method recently developed for Vs determination and increasingly used in earthquake and geotechnical engineering studies [23]. The MASW method utilizes dispersion characteristic of Rayleigh waves (ground roll) as the crucial property to estimate the shear wave velocities. Ground roll are often observed in the conventional seismic reflection/refraction data, especially when low natural-frequency geophones are used. Consequently, the same dataset can be analysed for seismic reflection and MASW methods. The propagation velocity of shear wave in an elastic medium is given by equation 2 [22]:

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

Where μ is shear modulus and ρ is density of the medium. Dynamic elastic properties of soil including shear modulus derived from seismic velocities and density are importance for site investigation and construction purposes.

3.2 Data Acquisitions

Six seismic reflection survey lines namely KR1 to KR6 were acquired in a northwest to southeast direction and roughly perpendicular to the two proposed fault segments associated with the KMFZ (Figure 1). The total lengths of the survey lines range from approximately 2-3 km. As mentioned earlier, survey lines KR1, KR2 and KR3 were used to detect the fault zone proposed by previous geophysical studies, whereas KR4, KR5 and KR6 were used to verify the fault location proposed by DMR. The field surveys were difficult because of limited access to some areas, such as in the vicinity of the Tapee River and the urban area. In particular, we were not able to acquire data across the proposed fault by DMR and the south-eastern part of the survey lines was skipped. Therefore, survey lines were selected along the agricultural roads and relatively flat topography to avoid the extremely noisy conditions from traffic and the urbanized region. Off-end source/receiver geometry was used in conjunction with 24 geophones at 5 m spacing (Figure 2a and 2c). The natural frequency of the vertical geophones used is 14 Hz. A walkaway noise test performed in the area reveals that a 30 m minimum offset appear to be optimum recording window. For the seismic source, 10-15 hits of 5 kg sledgehammer on steel plate provided sufficient signal-to-noise ratio of seismic energy. Source spacing was set at 5 m intervals, providing 12 folds coverage every 2.5 m CMP in the subsurface using roll along movement. The data were recorded by a 24-channel Geometric SmartSeis seismograph using a record length and sampling interval of 1024 ms and 0.5 ms, respectively. Recording such a long seismic trace allows us to extract the Vs profile by analysis of the surface waves (Figure 2b). Recording parameters of the seismic profile are shown in Table 1.

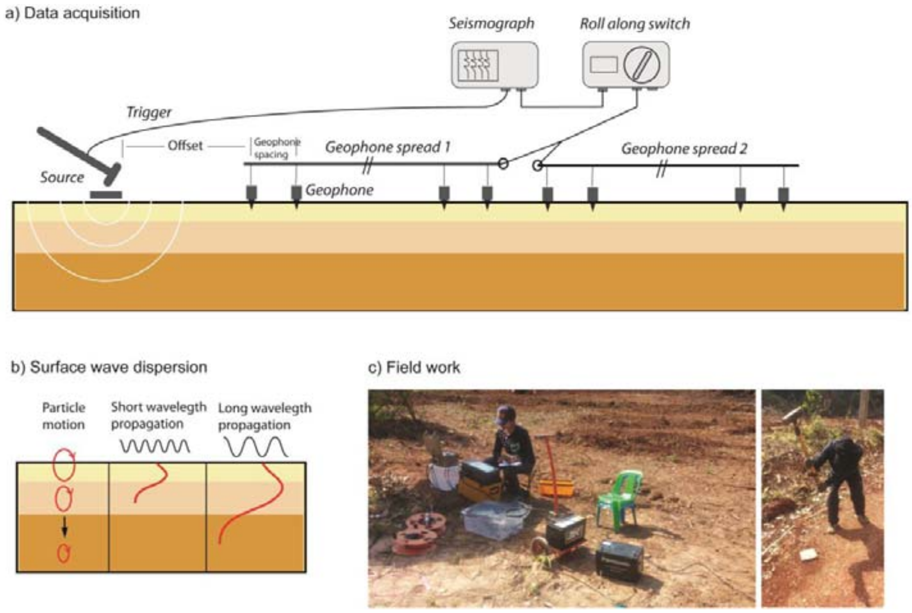

Figure 2. a) Details of data acquisition geometry and parameters. b) Surface wave characteristics and dispersion. c) Field surveys.

Table 1. Data recording information.

Recording parameters	Details
Recording system	Geometric SmartSeis
Source	5 kg Sledgehammer
Geophones	Vertical, 14 Hz
Short interval	5 m
Receiver interval	5 m
Offset	30 m
Channels	24, off-end
Sampling interval	0.5 ms
Record length	1.024 s

3.3 Data Processing

Seismic reflection data processing was performed using the Globe Claritas Version 5.5 software [24]. The processing flow applied to the seismic data is summarized in Table 2. Converting raw data from SEG2 to SEGY format is done as pre-processing step. An example of raw shot gathers is shown in Figure 3. Clear reflector events can be seen in the upper part while a low signal-to-noise ratio due to the contamination of ground roll is observed in the lower part. The field geometry files were edited and assigned into the raw data followed by routine editing of the dead and noisy traces. Refraction static corrections were applied to the data to compensate the effect of near-surface low velocity layer [25]. Automatic gain control (AGC) with 150 ms sliding time window was applied to balance the trace. By inspection of the power spectra (Figure 3), the low frequency band from 15 to 40 Hz represents the low frequency and strong amplitudes of ground roll, while background noise dominates at frequencies higher than 150 Hz. Therefore, band-pass filter of 30-150 Hz appears to enhance the useful signal frequencies as shown in Figure 2b. After CDP sorting, stacking velocities functions in the range from 1000-3000 m/s were picked based on an integrated analysis of constant velocity stack and semblance plots. The velocities were updated twice and used for normal moveout (NMO) correction.

The 70% NMO stretch mute was used to eliminate refraction energy and preserve shallow reflections. The stack sections were produced after stacking is performed for all CDP traces. Finally, the time sections were converted to depth sections using the interval velocity field.

Table 2. Processing steps for seismic reflection data.

Step	Descriptions and Parameters
1. Data import	SEG2 to SEGY conversion
2. Setup of filed geometry	Assign input shot locations and receiver locations into headers
3. Editing	Kill bad traces and fix polarity reversals
4. Elevation statics and Refraction statics (Field statics)	Calculate static corrections based on near surface models and elevations
5. Band-pass filtering	Minimum phase Butterworth filtering f = 15, 30, 150, 240 Hz, Design amplitude = 0,1,1,0
6. Automatic gain control (AGC)	Adjust amplitude using 150ms sliding window
7. CMP sorting	Sort data by common midpoint number
8. Velocity analysis	Integrate analysis of constant stacked velocity panels and semblance plots
9. Normal moveout (NMO)	Apply stacking velocity function including 70% stretch mute
10. Stack	
11. Time to depth conversion	Convert to depth section using interval velocity

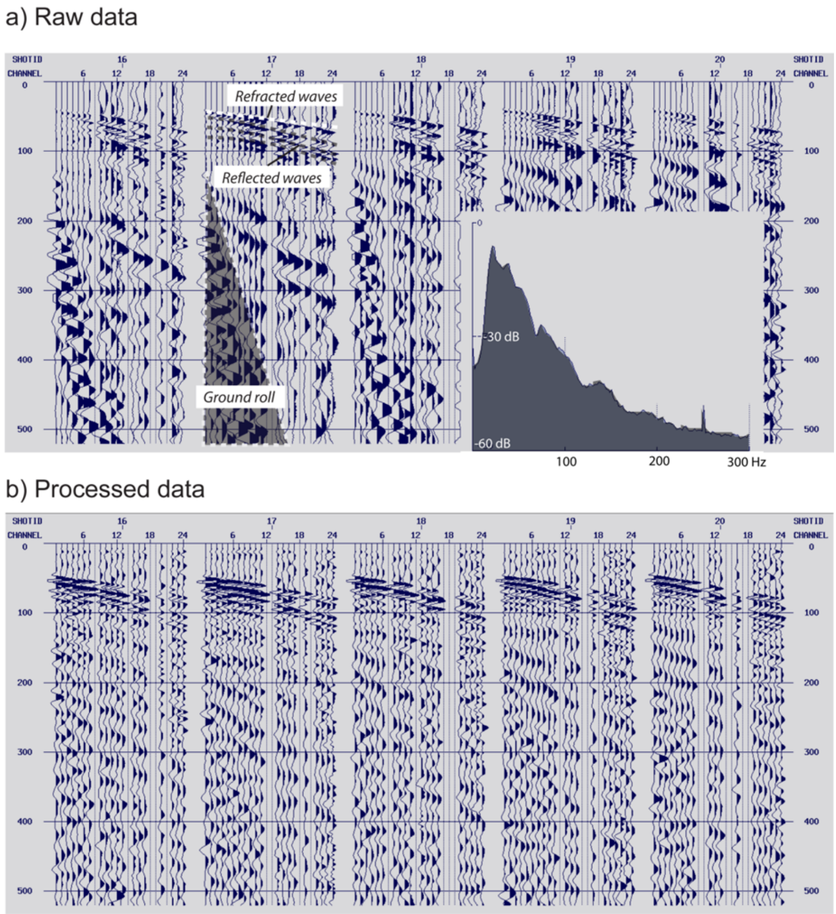

Figure 3. Example of shot gather showing (a) raw data and their power spectra, (b) the results after some processing steps were applied, including editing, static corrections, filtering and AGC.

For the MASW method, data were processed using the SurfSeis version 3 software developed by the Kansas Geological Survey, USA. The processing utilized an iterative inversion method to convert the picked dispersion curve into a 1D S-wave velocity model. First, the SEG2 format, raw data were converted to the software input format. Then, noisy traces were removed and high cut filtering was applied to remove high frequency reflection energy and ambient noise. A shot gather in time-space (t-x) domain was transformed into the phase velocity-frequency (f-v) domain using a 2D transformation (Figure 4). Dispersion curves were extracted by picking the phase velocity at different frequency values. By setting up an initial model based on a dispersion curve and adjusting the model parameter (Vs) with the objective of minimizing the error between the calculated and picked dispersion curve, a 1D velocity model placed at the center of the geophone spread is archived (Figure 4). To account for the non-uniqueness of the solution found in the inversion process, the optimum models were selected based on tracking RMS error and considering geological information. Finally, 1D Vs profiles were interpolated along the survey line to generate a 2D Vs section.

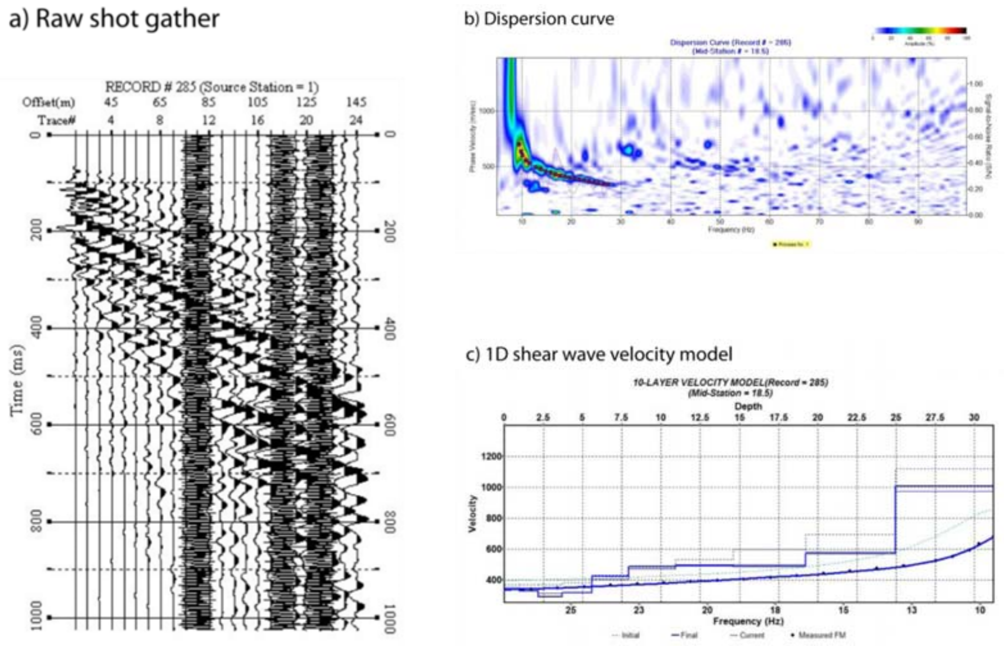

Figure 4. Example of raw shot gather (a), picked dispersion curve (b) and 1D Vs model from MASW analysis (c).

4. Results and Discussions

The results are interpreted based on integration of the seismic sections, 2D Vs sections, geology and lithology information from available shallow boreholes near the area. The lack of deep boreholes and the low resolution of previous geophysical studies have made structural interpretation difficult. In this study, the estimated vertical resolution for the seismic section is about 8 m based on the one-quarter wavelength criteria and using the 60 Hz dominant frequency and average velocity of 2000 m/s. Faulting is indicated based on the coherency loss of some strong continuous reflections, the abrupt change in dip angle of reflections, and presence of diffraction events [22].

Interpreted time sections and depth sections and 2D Vs sections for KR1-KR3 survey lines are illustrated in Figure 5 and 6. The first coherent horizon in the seismic sections is observed at approximately 30-100 m depth, and it appears to be down-dipping from northwest toward southeast (marked as yellow solid line in Figure 5). This is probably the base of Quaternary sediments or transition zone between Quaternary and Permian unit. The structural setting of this horizon appears to be karst topography. Below this horizon a seismic pattern of discontinuous and variously dipping reflectors is visible to about 250 m depth, corresponding to the highly fractured rocks at the fault zone in the sequences of Permian limestone unit (Figure 5 and 6). Clear evidence of limestone can be seen in the borehole, mountain and outcrop near the survey lines (Figure 7). The fault plane appears on the seismic section as a normal fault in certain area that dips to the east and west with steep angle of about 70-90 degrees. Relatively small vertical offset observed in some part of the main horizon may characterize the strike-slip faults deform with small amounts of transtension, whereas 30-50 m vertical offset is interpreted to represent the fault throw of major fault system. In addition, one of the main criteria used in identifying strike-slip faults in seismic sections are complex flower structures [26]. This feature is characterized by fan-like, rather steep faults converge at depth into a single and sub-vertical fault. Although the seismic energy was limited and the deeper faults were not imaged in the sections, evidences of partly flower structures in line KR1-KR3 (Figure 5) may indicate the strike-slip movement. This observation confirmed the fault strike derived from previous geomagnetic interpretation [12] and indicates that tectonic activity along the fault zone may be complicated. The location of the fault plane is also coincident with the abrupt change in the shallow Vs field (Figure 6). This suggests that faults possibly affect the shallow subsurface in this area. By visual inspection of the Vs fields, the internal structures of Quaternary unit itself can be divided into 2 layers, where the cover layer is characterized by low velocity of about 200-500 m/s with 10-20 m thickness.

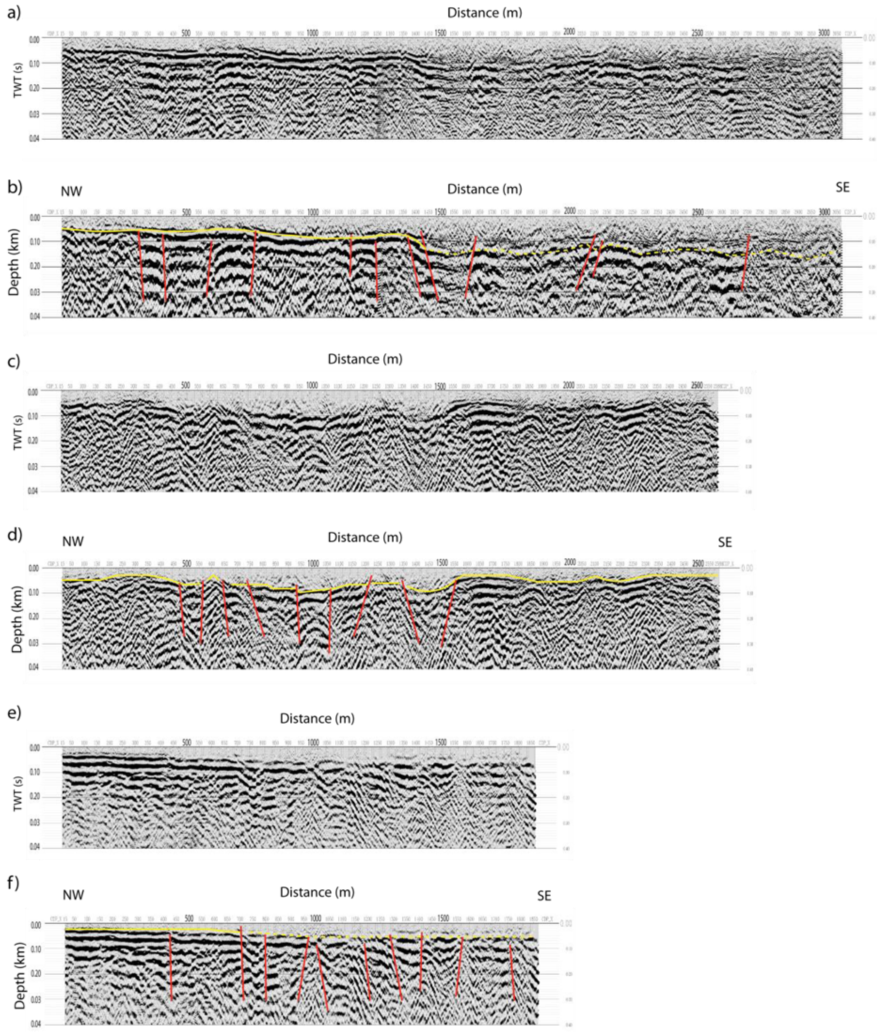

Figure 5. Time sections and depth sections with interpretation of survey line KR1 (a and b), KR2 (c and d), and KR3 (e and f), respectively. Main horizon is marked as yellow line, while possible fault is marked as red line.

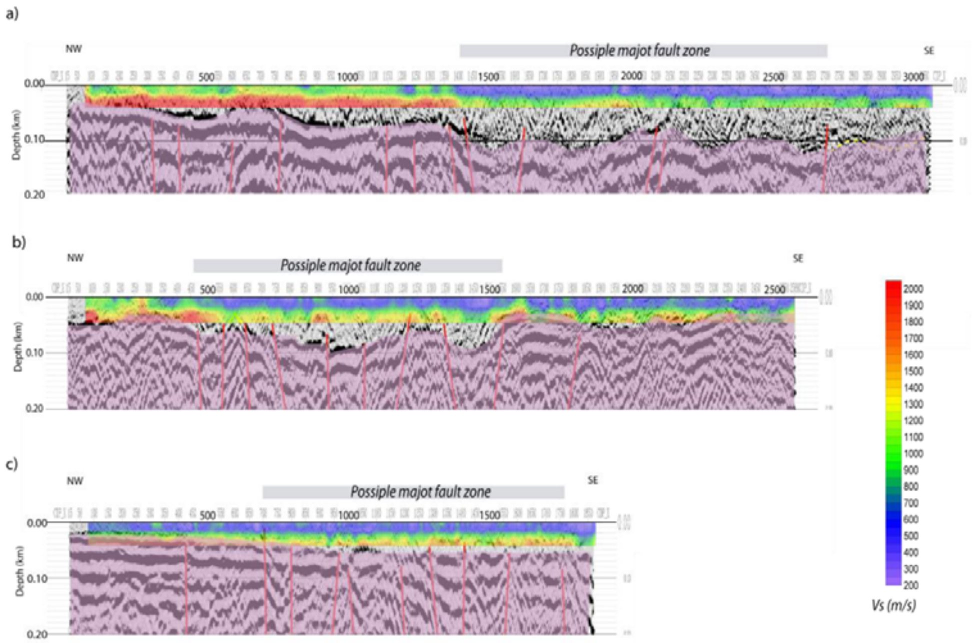

Figure 6. Zooming panel for the depth sections of survey line KR1 (a), KR2 (b) and KR3 (c), overlain by their Vs sections. Note that the depth sections are displayed with vertical exaggeration of 2.

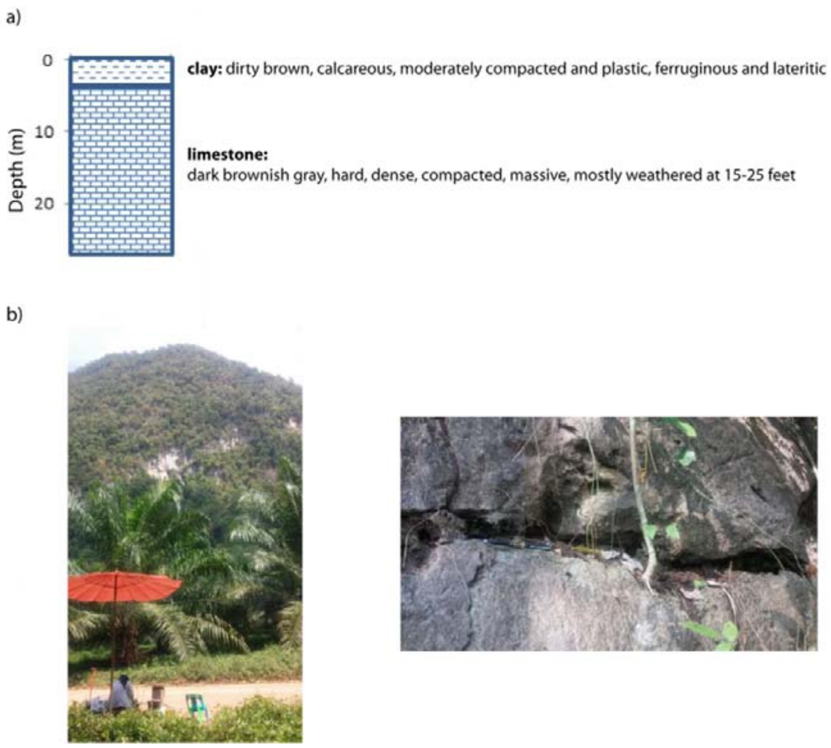

Figure 7. (a) An available borehole information near the survey lines. (b) Limestone mountain and fractured outcrop near the survey lines.

In the northern Khiriratnikhom district, there is a clear flat horizon that follows most of the KR4-KR6 survey lines at about 20-30 m depth which could be consistent with the top of Carboniferous-Permian units. One of the main uncertainties in the structural interpretation is that there is no clear evidence of buried fault associated with major fault zone observed beneath these survey lines (Figure 8). However, it is interesting to note that a prominent undulation in the main horizon is clearly seen in the middle of KR6 survey line. Based on geology and available boreholes, this event could potentially be a granite intrusion in the area.

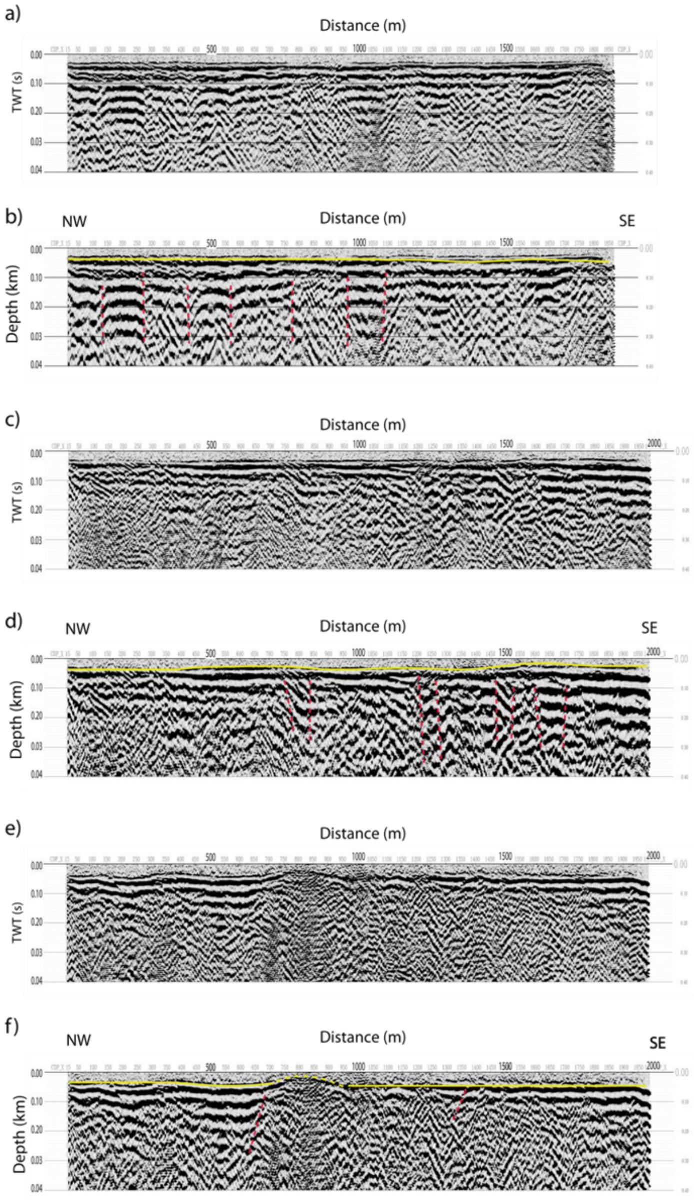

Figure 8. Time sections and depth sections with interpretation of survey line KR4 (a and b), KR5 (c and d), and KR6 (e and f), respectively. Main horizon is marked as yellow line, while possible fault is marked as red line.

5. Conclusions

A total of six seismic reflection profiles were acquired in Khiriratnikhom district, Surat Thani province with the aim of charactering the subsurface associated with the KMFZ. The main finding can be drawn based on integrated analyses of the seismic reflection and Vs sections obtained from the MASW methods. A small discrete offset of the main horizon, weak and terminated reflection as well as abrupt changes in Vs in the shallow subsurface are evidence for the buried faults beneath the three seismic profiles. This agrees with the fault strike that has been proposed by previous geophysical data. However, no clear evidence of the fault is visible in the other three seismic reflection profiles located in the northern part of the study area. Apart from fault zone, granitic rock may extrude to the near surface in this region. This study together with the information from trenching, earthquake and tectonic information will allow better understanding the seismic hazard assessment of the area.

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