

# GEOMETRY, FAULTING AND NEAR-SURFACE STRUCTURES AT THE MARGINS OF HAT YAI BASIN, SOUTHERN THAILAND: CONSTRAINTS FROM SEISMIC DATA

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## Abstract

Hat Yai district and vicinity is located in Hat Yai basin, one of the thick Quaternary basin fills in southern peninsular, Thailand. Infrastructures development, urban planning, groundwater management and seismic hazard are the main concerns in this region. Therefore, two seismic reflection survey lines ranging from 2-3 km were acquired nearby the boundary of Hat Yai basin to characterize the subsurface and determine the basin geometry and the fault zones. Shear wave velocity ( $V_s$ ) distribution and average  $V_s$  at the upper 30 m of the shallow subsurface ( $V_{s30}$ ) were also extracted from the dataset based on multichannel analysis of surface wave (MASW) analysis. The results confirmed that the strata geometry of Hat Yai basin is a rift type basin with sediments fills that are fault-bounded. The shallow fault segments observed in the sections are characterized by high angle, indicating extension in nature. Three Quaternary sedimentary units were distinguished in the upper 200 m depth of the basin. However, the contact between bedrock and sedimentary sequences within the basin was not clearly imaged on the seismic sections due to the source power and resolution limitation. Knowledge of fault zone structure and  $V_s$  distribution in the shallow subsurface is important for understanding seismic hazard and risk in the basin.

**Keywords:** Seismic reflection, shear wave velocity, MASW, Hat Yai basin, fault

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## Introduction

Hat Yai basin is a sub-basin of the Songkhla Lake basin, located in peninsular southern of Thailand. The basin is bounded by Songkhla Lake and the Gulf of Thailand to the north and Thai-Malaysian border to the south. Hat Yai district occupies large area of the basin and it is recognized as the heart of economic, educational and cultural region in southern Thailand. Therefore, understanding the basin geometry and the fault zones is important for infrastructures development, general land use, urban planning, groundwater management as well as implications for seismic hazard in the region. There is little published information on the study area with regard to seismic stratigraphy, basin geometry and faulting (Jongjit *et al.*, 2010). Available boreholes drilled for groundwater supply allow for the construction of hydrogeological model of the basin (Lukjan *et al.*, 2016). However, boundary condition inferred from boreholes provides limited constraints on faulting and basement depth. Geophysical study based on gravity measurement revealed the regional geometry that Hat Yai basin is 1 km deep at its deepest, 60 km long and 20 km wide (Lohawijarn, 2005). The basin geometry obtained from gravity model is somewhat limited by low spatial resolution due to the large spacing between gravity measuring points of about 1-2 km. Although, historical earthquakes records and peak ground acceleration (PGA) analysis revealed that the study area and vicinity are characterized as low level of seismic hazard (Ornthammarath *et al.*, 2010), it is interesting to concern about site amplification because the distance earthquakes in Andaman and Sumatra region could induce the ground shakings that have been felt in the basin (Sutiwanich *et al.*, 2012). Yordkayhun *et al.* (2015) have characterized the site respond to ground vibration in Hat Yai district using shear wave velocity at the uppermost 30 m depth (Vs30). It was found that the majority parts of the area are characterized by stiff soil (site class D) to very dense soil and soft rock (site class C) based on National Earthquake Hazards Reduction Program (NEHRP) site classification. In

geotechnical earthquake engineering perspective, these site classes have potential to pose the medium amplification rate of ground shaking as observed in the basin elsewhere (Thitimakorn and Raenak, 2016). In this study, seismic reflection method and multichannel analysis of surface wave (MASW) were combined with the aims to fulfill the information regarding the basin boundaries and the faulting in the basin.

The seismic reflection method has been successfully applied to delineate basin geometry and active faulting in variable areas (Pratt *et al.*, 1998; Demanet *et al.*, 2001; Lundberg and Juhlin, 2011; Saetang *et al.*, 2014). At shallow depths, high-resolution seismic reflection method has been applied to map shallow subsurface structures, depth of water tables, and identification of engineering related problems with degree of success (McBride and Nelson, 2001; Giustiniani *et al.*, 2008; Yordkayhun *et al.*, 2009). The MASW method is the seismic method that effectively used to evaluate the stiffness of the ground. It deals with dispersion analysis of surface waves and uses to estimate shear wave velocity (Vs) at the shallower depth range of investigation (Anbazhagan and Sitharam, 2008). In addition, a weighted-average shear wave velocity in the topmost 30 m of sediments (Vs30) is a key indicator for classifying the degree of ground-motion amplification in response to earthquakes, as provided by the National Earthquake Hazards Reduction Program (NEHRP) and the International Building Code (IBC) (BSSC, 2003, Maheswari *et al.*, 2010). We believe that the integration of geophysical information allow us to better image and understand the subsurface of Hat Yai basin.

## Materials and Methods

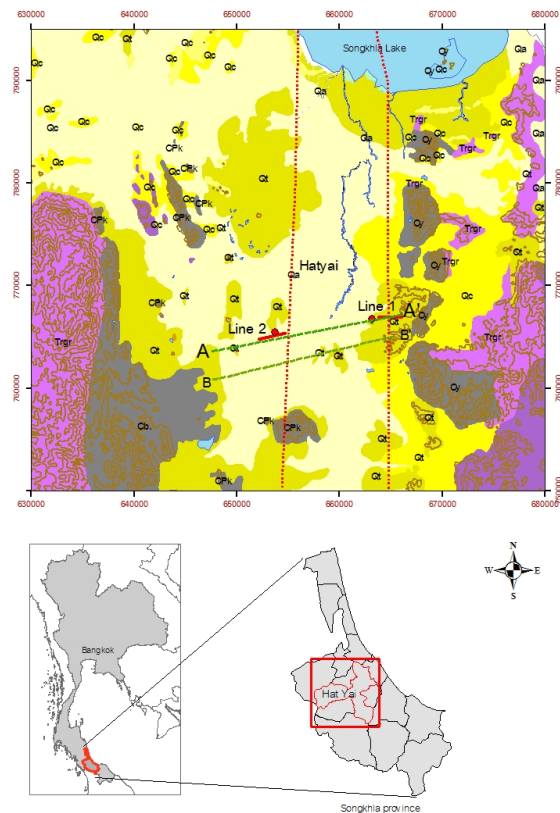
### Geological Setting

Structural pattern of Hat Yai basin is mainly controlled by block faulting in the Gulf of Thailand (GoT). Normal fault system oriented in the north-south direction formed

Hat Yai basin as a graben whereas the western hill ranges and the small basins east of the area formed as part of a horst (Sawata *et al.*, 1983). The area is considered to be low seismicity region since it is not affected by the two active faults, Khlong Marui fault and Ranong fault zone in southern Thailand. However, there were reports of the ground shakings that have been felt in the basin due to site amplification from the distance earthquakes in Andaman and Sumatra region (Sutiwanich *et al.*, 2012).

The topography of Hat Yai basin is relatively flat area with an elevation range from 0 to 20 m above mean sea level. Local

geology of the area is characterized by basin fill stratigraphy of Quaternary unconsolidated sediments eroded from the surrounding mountains (Figure 1). Unconsolidated terrace (Qt) and colluvial deposits (Qc) consist of coarse sands, gravels, silts and clay that are partly weathered from host rock and mostly found near the hills and outcrop boundaries (Saardsud and Srisangjun, 2002). Unconsolidated alluvial deposits (Qa) of fine sands, gravels, silts and clay are extensively distributed in vicinity of the main streams (Klong Toey and Klong U-tapoa) that running south to north through the basin. Unconsolidated beach



**Figure 1.** Geologic map of the study area. Descriptions for the main geological units are as following: Qa = Alluvial deposits: Quaternary, Qb = Beach deposits: Quaternary, Qc = Colluvial deposits: Quaternary, Qt = Terrace deposits: Quaternary, Cy = Shale, chert and conglomerate: Carboniferous, and Trgr = Granite: Triassic. Red solid lines marked the seismic survey lines. Red dot lines outlined the basin boundaries obtained from gravity model (Lohawijarn, 2005). Green dashed lines highlight the interpreted profile in this study (AA') and an available gravity model (BB')

deposits (Qb), consisting of beach sands, silts and clay are covered near the lake in the northern part of the area. Logs from sparse drill holes indicate that the distinction between coarse-grained, permeable, and fine-grained formed the aquifer system in the basin. Three aquifer units comprise the Hat Yai aquifer at depth 20-40 m, Khu-Tao aquifer at depth 45-80 m and Khohong aquifer at deeper than 100 m depth, respectively (Lukjan *et al.*, 2016). Granitic rocks intruding into Carboniferous to Triassic age of sedimentary and metamorphic rocks act as the underlying basement of the basin. Examples of basement complex rocks can be found in the outcrop and mountain ranges which protrude above the basin fill in the western and eastern flanks.

### Seismic Reflection and MASW Methods

Seismic reflection method utilizes seismic waves propagated from a surface seismic source into the subsurface and the recorded two-way traveltime of reflected energy at the interface between layers with acoustic impedance (the product of density and seismic velocity) contrast to delineate the subsurface structures. The waveform of reflection signal at any incident rays is governed by Zoeppritz equation (Sheriff *et al.*, 1991). In case of normal incident ray path, 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  $\rho_1$  and  $\rho_2$  are the density of the 1<sup>st</sup> layer and 2<sup>nd</sup> layer, while  $V_1$  and  $V_2$  are the wave velocity of the 1<sup>st</sup> layer and 2<sup>nd</sup> layer, respectively.

MASW method utilizes the dispersion characteristics of surface wave, e.g., Rayleigh wave in heterogeneous media to estimate shear wave velocity ( $V_s$ ) of the subsurface. As dispersive characteristic is deal with different frequencies travel with the different phase velocities, dispersion analysis of surface wave and inversion are the main procedures to estimate the  $V_s$  versus depth (Park *et al.*, 1999). In general, Rayleigh wave velocity ( $V_R$ )

in an elastic half space ranges from 0.87 $V_s$  to 0.96 $V_s$  depending on the range of Poisson's ratio (Richart *et al.*, 1970).  $V_s$  is directly linked to a material's stiffness of the ground as expressed by Equation 2.

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

where  $\mu$  is shear modulus and  $\rho$  is density of the medium. Shear modulus derived from seismic velocities is one of dynamic elastic properties of soil which is importance for earthquake and geotechnical engineering issues. Moreover, the seismic site classification as per National Earthquake Hazards Reduction Program (NERHP) standard used  $V_{s30}$  values as a key factor for earthquake site response analyses (Kanli *et al.*, 2006; Karastathis *et al.*, 2010). The  $V_{s30}$  can be calculated by Equation 3.

$$V_{s(30)} = \frac{30}{\sum_{i=1}^n \frac{d_i}{V_{si}}} \quad (3)$$

Where  $d_i$  and  $V_{si}$  denote the thickness (in meter) and  $V_s$  of the  $i^{th}$  layer, in a total of  $n$  layers existing upper 30 m depth.

### Data Acquisitions

Two seismic reflection survey lines were carried out at the eastern (Line 1) and western (Line 2) suspected margin of the basin (Figure 1). The line direction was roughly transverse to the proposed basin boarder as outlined by gravity model (Lohawijarn, 2005). The total length of Line 1 is about 2.3 km and Line 2 (west profile) is about 3.0 km, respectively. Although survey lines were designed to cover the boundaries of the basin, we were not able to acquire data across the proposed western boundary of the basin due to the limited access to the urban area. Data were recorded with Geometric SmartSeis seismograph using sampling interval and record length of 0.5 ms and 1,024 ms, respectively. Twenty-four vertical geophones with 5 m interval were firmly placed



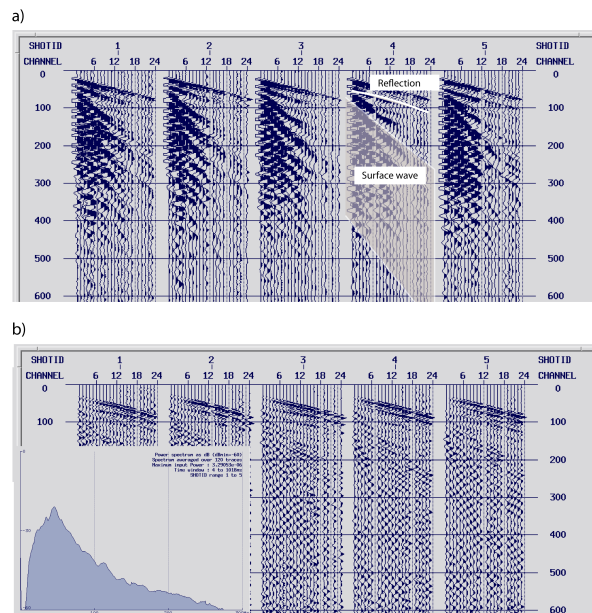
into the ground. Off-end source/receiver geometry with 30 m offset were laid out along the profiles using roll along system. By using 5 kg sledgehammer with 5 m interval as a seismic source, 12 common depth point (CDP) fold of coverage were obtained. 5-10 hammer blows were hit at each shot point to enhance the signal to noise ratio of the data. To preserve the surface wave energy in the raw data, any frequency filters were not applied during the data acquisition. This allows us to perform MASW analysis by using the same dataset (Yordkayhun *et al.*, 2016). Acquisition parameters of the seismic surveys are listed in Table 1.

**Table 1. A list of seismic acquisition parameters**

| Parameters         | Details                 |
|--------------------|-------------------------|
| Energy sources     | 5 kg sledgehammer       |
| Geophone           | 14 Hz vertical geophone |
| Geophone spacing   | 5 m                     |
| Shot spacing       | 5 m                     |
| Offset             | 30 m                    |
| Recording system   | Geometric SmartSeis     |
| Number of channels | 24 channels             |
| Record length      | 1,000 ms                |
| Sampling interval  | 0.5 ms                  |

### Data Processing

As examples of raw shot gathers shown in Figure 2, the data were not of high quality due to the location of surveys lies in the heavily populated area. Therefore, cultural noise from traffics, and other sources generated noise in the shot recorded. Clear reflection events are observed at the shallow part, whereas ground-roll and other coherent noises are dominated at the deeper part of records. The seismic data were processed using GLOBE CLARITAS software developed by the Geological & Nuclear (GNS Science), New Zealand. The processing flows for the seismic reflection data are illustrated in Table 2. The basic processing sequence was automatic gain control (AGC), refraction static corrections, band-pass filtering, muting, Normal move-out (NMO) velocity analyses and common mid-point stacking (CMP) (Yilmaz, 2001). Refraction static corrections are designed to compensate for the delay of seismic waves propagation in relatively thin heterogeneous weathering layers. We used a tomography model derived from the picked first-arrival times to determine refraction static corrections. To define frequency



**Figure 2. Example of shot gathers showing raw data (a) and filtered data (b)**

characteristics of the data, frequency spectra of some shot records were analyzed. It is observed that dominant frequency of the data is about 30-80 Hz, whereas the source-generated noises appeared to have higher frequency. Band-pass filtered testing through a range of frequencies, demonstrated that band-pass filtering the raw shot gathers from 40-120 Hz yield the best signal-to-noise ratio for this study (Figure 2(b)). Even though the band-pass filtering effectively eliminated much of the low-frequency surface-wave noise, the ground-roll it is still present in the data. Bottom mute were used to remove the ground-roll and other coherent noises from the shot records. To obtain the CMP-stacked section, NMO velocity analysis was done based on an integrated analysis of constant velocity stack and hyperbolic curve fitting of the reflections. The stacking velocities of the primary reflections appeared on the sections as 800-3,000 m/s. Migration tests did not improve the final image owing to low signal-to-noise ratio. Finally, interval velocity was used for time to depth conversion. Typical vertical resolution of the final stacked section

varied from 10 m at 100 m depth to 20 m at 200 m depth, with a dominant frequency of 30-40 Hz through this range. Resolution below 200 m is poor due to a high ambient noise level.

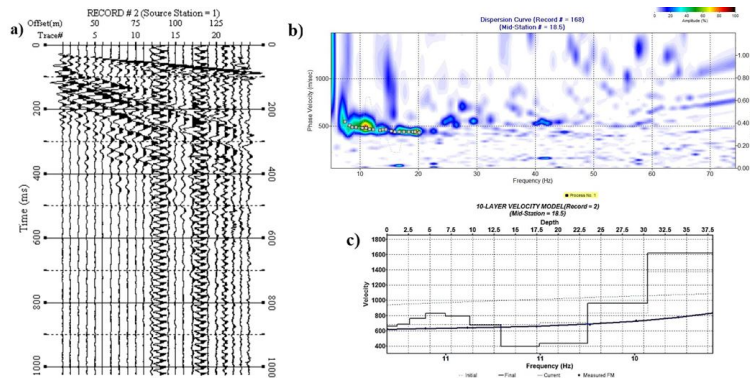
For MASW analysis as briefly described in Table 3, data were processed using SurfSeis software version 4 developed by Kansas Geological Survey (KGS). The step began with transformation of each shot record from time-space (t-x) domain to the phase velocity-frequency (f-v) domain using 2D Fourier Transform technique (Park *et al.*, 1999). Then specific dispersion curves were extracted from the data by picking the peaks of dispersion energy over a range of frequencies. Iterative nonlinear inversion method performed on the dispersion curves resulted in 1-D shear-wave velocity (Vs) profiles (Xia *et al.*, 1999). The inversion method used a starting model, consisting of Vs, Vp, density and thickness as a key model parameters before beginning to search for the solution in an iterative manner with the objective of minimizing the error between the calculated and picked dispersion

**Table 2. Seismic reflection data processing steps**

| Processing Step                             | Description and parameters                                                                        |
|---------------------------------------------|---------------------------------------------------------------------------------------------------|
| 1. Setup of field geometry                  | Assign input shot location and receiver locations into headers                                    |
| 2. Editing bad traces                       | Remove bad traces                                                                                 |
| 3. Elevation statics and refraction statics | Calculate static correction based on near surface models and elevations                           |
| 4. Band-pass filtering                      | Minimum phase Butterworth filtering<br>$f_c = 20, 40, 120, 200$ Hz, Design Amplitude = 0, 1, 1, 0 |
| 5. Automatic gain control (AGC)             | Adjust reflection amplitude using 250 ms window                                                   |
| 6. Bottom mute                              | Zero data in the ground roll rang                                                                 |
| 7. CMP sorting                              | Sort data by common midpoint number                                                               |
| 8. Velocity analysis                        | Find velocity value that fit layers                                                               |
| 9. NMO correction                           | Apply stacking velocity function including 70% stretch mute                                       |
| 10. Stack                                   |                                                                                                   |
| 11. Time to depth conversion                | Using interval velocity field                                                                     |

**Table 3. Processing steps of MASW analysis**

| Processing step        | Detail                                                                                 |
|------------------------|----------------------------------------------------------------------------------------|
| 1. Data import         | Convert SEG2 format into KGS format                                                    |
| 2. Assign geometry     | Assign shot location and receiver location                                             |
| 3. Editing             | Kill dead traces                                                                       |
| 4. High cut filtering  | Remove high frequency noises                                                           |
| 5. Dispersion analysis | Transformed the time-space (t-x) domain into the frequency-phase velocity (f-v) domain |
| 6. Inversion           | Create 1D shear wave velocity profile                                                  |



**Figure 3. MASW data processing steps. a) Raw shot record in time domain, b) dispersion curve picked in f-v domain, and c) 1D shear wave velocity profile**

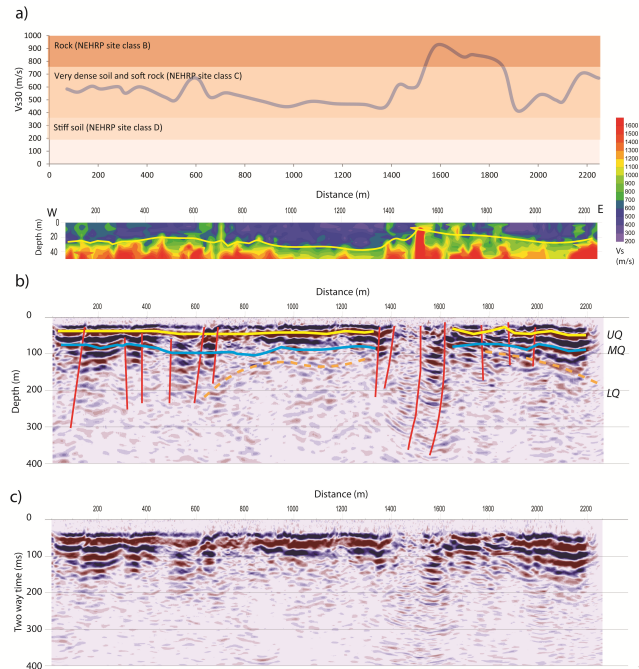
curve. To create a 2D Vs section, a series of 1D Vs profiles were interpolated along the survey line. Figure 3 illustrates a shot gather with its dispersion energy picked and Vs model as representative of geological units.

## Results and Discussion

### Lithologies and Shallow Structural Relationships

For structural interpretation, the interval velocity, amplitude and continuity of the seismic horizons are used to classify the sediments and bedrock of the basin. Available water wells near the seismic profile help constrain the interpretation of the sedimentary deposits in the upper 100 m depth. Vs sections and Vs30 profiles of the east and west seismic lines along with stacked time sections and depth sections with structural interpretation are illustrated in Figures 4 and 5, respectively. The seismic sections reveal 2 coherent subhorizontal reflection packages overlying generally dipping features. The upper horizon (UQ) found at depth of 30-40 m is interpreted to be base of younger Quaternary sediments based on their widespread occurrence over the study area. By tracking locally continuous horizon in the stacked section, the general trend of this unit is found to be in good agreement with those observed in the Vs section. Low seismic velocities ( $V_p$  is about 900-1,200 m/s,  $V_s$  is about 200-600 m/s) are indicative of dry to

unconsolidated gravels, sands, clay and silts of alluvium, colluvium and terrace deposits. Site characteristics across Hat Yai basin obtained from this study are in consistent with finding of Yordkayhun *et al.* (2015) in that the majority parts of the district are characterized by stiff soil to very dense soil and soft rock, belonging to site class D and C, respectively. Low Vs30 of site class D is occupied within the flood plain area. The higher Vs30 of site class C are characteristic for the terrace and colluvium deposits nearby the western and eastern boundaries. Although this layer represent the Hat Yai unconfined aquifer, information from water well indicates that fill deposit may be presented as thin layers that cannot be resolved by the resolution of the seismic data. The lower horizon represents the mid-Quaternary sediments (MQ) at about 80-100 m depth are the likely origin of the gently dipping, to undulating reflection unit. Their comparatively higher P-wave velocities ( $V_p$  is about 1,500-1,700 m/s,  $V_s$  is about higher than 600 m/s) probably represent compact and water-saturated gravels, sands, and silts of Khu-Tao confined aquifer. MQ unit are markedly more complex than those of the overlying UQ unit owing to it partly have internal faulting, folding and some are abruptly truncated and offset. The west profile, from 0 to 1.2 km appears to have a relatively uniform distribution of sediments of the same origin but bounding fault strongly affect the geometry of these sedimentary units, tilting it towards the fault plane. The lower



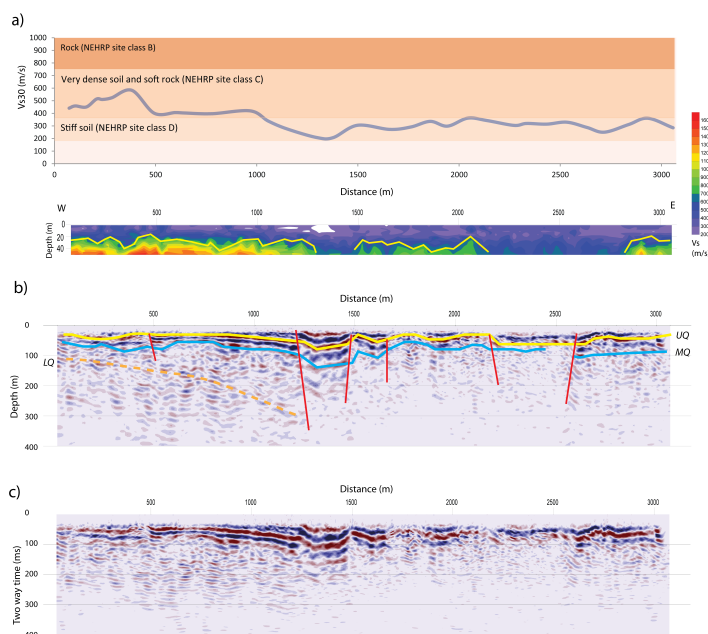
**Figure 4. a) Vs sections and Vs30 profiles of Line 1. b) Depth sections with structural interpretation of Line 1. c) Stacked time section of Line 1**

Quaternary sedimentary (LQ) below the MQ unit produce the chaotic to gently dipping reflections. This is likely debris from gravitational mass movements from the ridge or the large input from the terrace deposits. We marked this horizon as the top of Carboniferous basement. However, this unit is not well imaged in the seismic data because the lack of energy from the seismic source, and/or structural complexity makes interpretation quite ambiguous. In addition, poor resolution is also evident in the interval velocity field, where velocities below even 200 m are not well constrained by reflection velocity analysis.

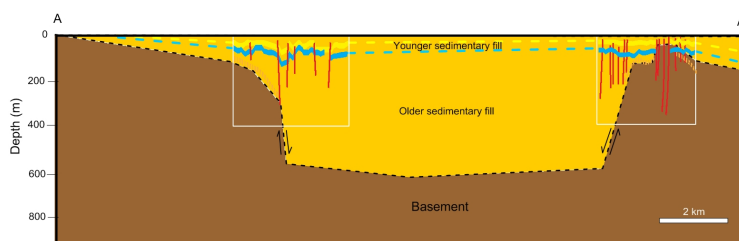
### Faulting

Faulting and folding in the seismic sections were identified by discontinuity across the seismic horizons and reflection packages with markedly different dips and curved reflections. A number of minor faults observed on the seismic sections can be correlated with extensional forces as visible

via tilted block faulting along the west and east seismic profiles (Figures 4 and 5). Some of these faults extend to the upper sedimentary units. In the west seismic profile (Line 2), the horst and graben are distinguished by observing 20-30 m vertical displacement (throw) of the main horizons. This fault has a steep angle dipping towards the eastern side and it is considered to be a major bounding fault zone as characterized by a contact zone of variable reflection continuity and reflection-free areas. In the east profile (Line 1), the reflection-free area and the high Vs values observed at 1,400-1,800 m on seismic section suggest that faulting and folding are accommodated as part of horst. We suspected that complex fault patterns in Hat Yai basin are linked with faulting in vicinity of the Gulf of Thailand (GoT). As the deformation history in the GoT outlined by Morley (2001), the fault patterns, and fault displacement patterns can be complex due to the rotation of the extension direction during the Miocene.



**Figure 5. a) Vs sections and Vs30 profiles of Line 2. b) Depth sections with structural interpretation of Line 2. c) Stacked time section of Line 2**



**Figure 6. Geometry of Hat Yai basin along profile AA' as constrained by gravity and seismic data**

### Basin Geometry

Due to the gravity model along the seismic lines (profile AA' in Figure 1) was not available, the basin geometry was constrained by the adjacent gravity model along the profile BB' (Lohawijarn, 2005). It was determined that the strata geometry of Hat Yai basin along the profile AA' is a rift type basin with sediments that are fault-bounded (Figure 6). A series of normal faults, which form segments of the graben bounding fault, are developed on the western and eastern basin margins. They limited on the western side and eastern side by

eastward and westward steeply dipping fault system, respectively. On the western margin of the basin, thicker sedimentary accumulations are present, where the eastern part of the basin has a substantially thinner sedimentary cover due to the uplifting of the basement. However, delineation of the basement based on seismic results is not straightforward owing to the limitation of investigation depth. Note that the degree of uncertainty associated with basin geometry is still considerable challenge of geophysical studies. In particular, there are open questions regarding the basin bound fault

detection and resolution limits of seismic and gravity modeling.

## Conclusions

The main purposes of this study were to determine the subsurface structures and delineating possible basin geometry and faulting in vicinity of the basin margin. From the seismic reflection and Vs profiles obtained by MASW analysis of the two seismic profiles, three Quaternary sedimentary units can be distinguished in the upper 200 m depth of the Hat Yai basin. Results have been confirmed that there exists a graben structure and sedimentation in the basin was controlled by the marginal bounding fault. The other shallow faults observed in the section are characterized by high angle, trending in the same manner as the major bounding fault. However, the contact between basement rocks and sedimentary sequences within the basin was not clearly distinguishable on the seismic lines. Hence, it is recommended that more acquired seismic data and integration with other geophysical prospecting should be performed to get higher confidence on a clear picture of the subsurface and basin geometry.

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