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Application of Enhanced Ground Geophysical Data to Active Fault Analysis in the Southern Sri Sawat Fault Segment, South of Srinakarin Dam, Western Thailand

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ABSTRACT: The study area (approximately 5,000 m^2) in Sri Sawat, Kanchanaburi province, is occupied by the Quaternary deposits and Triassic sedimentary rocks. This area is about 3 km to the south of the Srinakarin Dam located in the southern part of the Sri sawat fault. Main structural features in the area are northwest-trending normal faults as clearly recognized from aerial photographs and satellite imageries. The fault segments, common at the foothill, are dominated by Triassic sedimentary strata. The prime objective of this study is to recognize Quaternary fault zones using ground geophysical methods including magnetic, very low frequency electromagnetic (VLF-EM) and resistivity. Five survey lines of ground geophysical survey (100 m long) with traverse line of 10 m and 5 m of sample spacing interval are assigned in the northeast trending perpendicular to the inferred main geological structure. About 100 stations were selected for measurement, and all data were enhanced using the GEOSOFT and VLF PAK programs. The result indicates that, the fault zone shows higher resistivity values and lower magnetic and VLF-EM responses than those of the mudstone country rocks. The ground geophysical results reveal two systems of faults; both are shallow (at about 0-5 m below surface) and orient in the northwest-southeast trend with opposite dip directions. The fault almost at the northern end is very close to the foothill and is considered to be the major fault. This fault strikes in the northwest-southeast direction, dips to the southwest apparently less than 45° and crosscuts Triassic rocks. This major fault, however, is regarded as "less potentially active" fault. The other faultis regarded as the minor and antithetic fault, and located in the Quaternary deposit at southern end. It strikes northwest-southeast and dips to the northeast at the same angle. This fault is recorded as a minor fault possibly crosscutting the Quaternary colluvial sediments, and is considered to be the active fault.

KEYWORDS: Sri Sawat Fault, Kanchanaburi, Resistivity method, Magnetic method, VLF-EM method.

INTRODUCTION

Earthquake becomes a common natural disaster that has an extreme and vigorous destruction. One of the causes generating earthquakes is the earth movement along an active fault. In some parts of Thailand, particularly those of the northern and the western regions, earthquake activities were recorded not only by historical/archaeological means but also by instrumental approaches. Two major faults in Kanchanaburi, western Thailand - the Sri Sawat and the Three Pagoda Faults- are documented to be associated with earthquake activities[1, 2]. Earlier maps, e.g. those generated by Bunopas[3] and Shretha[4], show that these two fault zones cut across many kinds of rocks ranging in ages from Precambrian to Quaternary.

The Sri Sawat Fault extends from the southeastern part of Myanmar through the western part of Thailand, with about 380 km in length. Its major trend is northwest-southeast. With the applications of several geologic and seismotectonic parameters, it has been assigned to be potentially active[4, 5]. Additionally, based on these parameters, Nuttee[6] subdivided the Sri Sawat Fault into 3 main segments–northern, central, and southern.

At present, there are several methods applied to detect faults associated with earthquakes. McCalpin[7] noted that the most common geological approaches include geomorphic, geodetic, geochronological, and geophysical methods. The geophysical means, both from ground and airborne investigations, are proved to help interpret paleoseismic assessment successfully in several earthquakes–dominated regions[8,9]. Among the geophysical methods applied, ground magnetic and resistivity have been used widely in detecting concealed and subsurface active faults[10, 11]. Recently the VLF-EM method has been used to detect such active faults in Japan[12], Canada[13], USA[14], and Kerhuelen Island (France)[15]. Most of the geophysical studies in Thailand have focused on occurrence of mineral deposits and subsurface mineral exploration.

The objectives of this study are to determine fault orientation in the southern Sri Sawat fault segment using ground magnetic, resistivity and VLF-EM surveys and to apply these results to locate the most appropriate site for paleoseismic trenching. This study seems to be the first study in Thailand that ground geophysical methods were first applied to paleoseismic analysis. Since the fault being investigated is near the dam site and the Kanchanaburi city, it is necessary to understand if the fault is "active" or not. In this study, we define the active fault following the well-accepted definitions proposed by ICOLD[16] and USGS[17] as the fault reasonably identified, located, and known to have produced historical earthquakes or showing geological evidence of Holocene (11,000 years) displacement and which, because of its present tectonic setting, can undergo movement during the anticipated life of man-made structures.

Location of the Study Area

The study area is about 3 km in the southern part of the Srinakarin Dam at Ban Kaeng Kab, Sri Sawat district, Kanchanaburi province, Thailand (Fig 1). The area covering about 5,000 m^2, is located at longitude 99°11′24″E and latitude 14°20′3″N (or UTM Grid $^{5}19^{500m}$ E – $^{5}19^{700m}$ E and $^{15}86^{200m}$ N – $^{15}86^{300m}$ N). The study area is a part of 1:50,000 topographic map of Ban Kaeng Riang, sheet no. 4837IV, series L7017. Geomorphologically, the area where active fault is interpreted to pass through[18] is dominated by mountain and undulating area. Mountains have moderate to steep slopes and trend in the northeast-southwest direction with their elevations ranging from 100 m to 500 m above the present mean sea level. Geologically, rocks around the survey area comprise 4 lithologies. Among these rocks, Triassic clastic rocks (unit B in Fig. 2b) are mostly related to study area. Several parts of them are covered with colluvial deposits. Other rocks include Permian limestone, Cambrian quartzite, and Quaternary deposits (units D, E, and A in Fig. 2b)

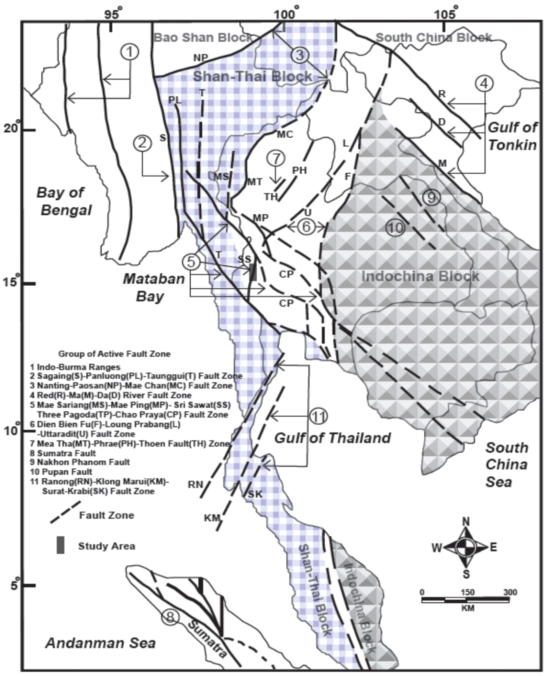
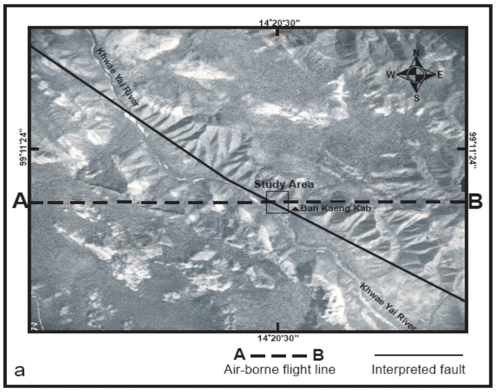


Fig 1. Present-day tectonic map showing major active fault zones in the mainland Southeast Asia (after Charusiri et al. 2002). The location of the study area is on the Sri Sawat fault zone (shaded box).

Previous Works

There have not been many studies about earthquakes done in Thailand. Mostly, those studies concerned regional areas[1, 2]. Siribhakdi[1] reported present-day seismicity in Thailand and her surrounding countries, and studied epicenteral distribution in Thailand back to the past 1,500 years. Many of these earthquakes are recorded to have close relation with four major faults, including the Three Pagoda, the Sri



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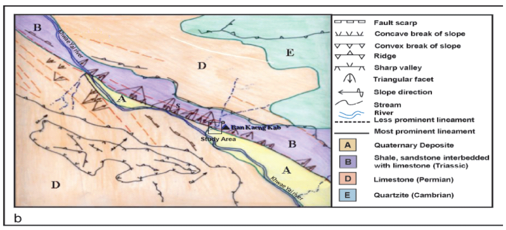

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Fig 2. **a** Aerial photograph showing the location of the a lineaments which is interpret as a fault.
b Morphotectonic map covering the study area showing triangular facets:
A = Unconsolidated deposits (Quaternary), B = Shale, sandstone interceded with Limestone (Triassic), D = Limestone (Permian), E = Quartzite (Cambrian).

Sawat, the Moei-Uthai Thani and the Mae Hong Son-Mae Sarieng Faults.

Klaipongpan et al.[19] investigated geological and seismicity evaluation in April 1983 earthquake at the Srinakarin Dam. The results, obtained from the evaluation of overall characteristic seismicity and revision of world wide data on seismic and geologic characteristics of reservoir triggered seismicity (RTS), are ensured to accept the high possibility of reservoir induced seismicity phenomena.

Hinthong[20] investigated the role of tectonic settings in earthquake events in Thailand. He reported that the seismic source zone in Tenasserim range (or Zone F of Nutalaya et al.[21]) was responsible for the principal present-day northwest-southeast right-lateral strike slip Fault Zones, i.e., the Moei Uthai Thani Fault, the Three Pagoda Fault, and the associated Sri Sawat Fault. Those faults and fault zones are believed to be responsible for the earthquake activities in the western Thailand.

Sarapirome and Khundee[22] presented a preliminary study on neotectonics in the Mae Hong Son-Khun Yuam valley, northwestern Thailand. They used the statistic parameters including orientation and length of lineaments, data on earthquake epicenters, and hot springs. In their studies, the Quaternary faults were gathered and analyzed in order to seek how these data could be used to imply the neotectonics of their study.

Charusiri et al.[23] applied several remote sensing techniques in studying geological structures related to earthquakes in Thailand and neighboring countries. The result was useful for determining the seismic-source zones to indicate the earthquake-prone areas. A new seismo-tectonic (or seismic-source zone) map was also proposed.

Paleoseismic studies in the Srinakarin Dam study area are rare. Very recently Nuttee[6] and Songmuang[16] applied results of aerial photographic and landsat TM5 interpretation to the study of active faults.

Materials and Methods

Methodology

The method of this study involved 5 consecutive steps.

The first step was to compile previous works and pertinent data related to earthquakes and active faults in the western Thailand. The second step was to define the study area based on remote sensing results[18] (Fig. 2a & 2b) and airborne geophysical data (Fig.3) for detailed ground geophysical survey. The third step was to perform field operation and to collect geophysical data, which include a) magnetic method[24], b) VLF-EM method[25], and c) resistivity method[26]. The forth step was to process/analyze data, which involved conversion of primary data to digital data and to construct anomaly maps and sections with the assistance of software program. The last step was to delineate locations and orientation of active faults from those maps and profiles and to propose locations of trenching for more-detailed paleoearthquake exploration.

Survey Design

Field investigation indicated that the Triassic sedimentary strata display as a relatively flat plain at the steeper angle foot slopes of the Cambrian quartzite. In general this plain is mostly covered by colluvial deposits. Result from remote-sensing interpretation (Fig.2b) revealed that the main structural lineament is in the northwest-southeast direction in the study area. Similar

Table 1. Detail of survey lines used in the study area.

Line	Azimuth (°)	Distance (m)	Starting point	Terminal point
L00	40 ° - 220 °	100	L00-00	L00-100
L10	40 ° - 220 °	100	L10-00	L10-100
L20	40 ° - 220 °	100	L20-00	L20-100
L30	40 ° - 220 °	100	L30-00	L30-100
L50	55° - 235 °	100	L50-00	L50-100

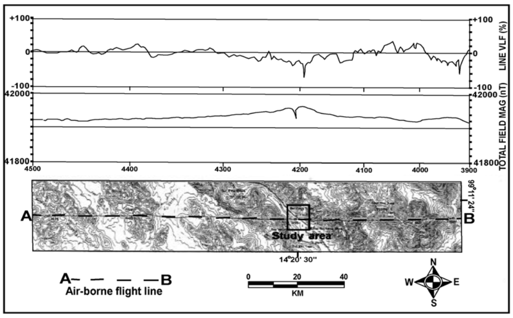


Fig 3. Magnetic and VLF-EM air-borne data showing low-value anomalies inferred herein as a fault in the study area.

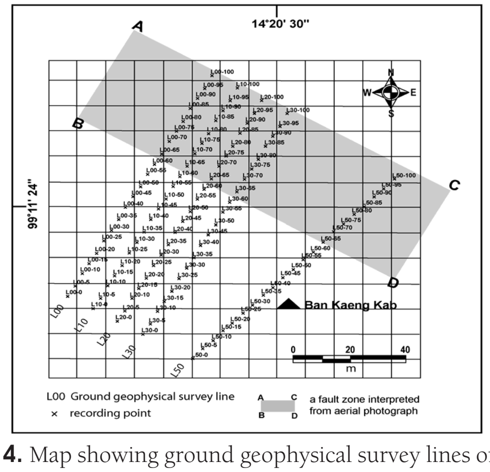


Fig 4. Map showing ground geophysical survey lines orientated in the NE –SW direction roughly perpendicular to the main lineament structure interpreted from aerial photograph, in the NW trend.

result was made for the interpretation from both magnetic and VLF-EM airborne data that there exists a fault situated at the same location (Fig. 3). Ground survey lines were therefore designed to be perpendicular to the main trend of the structural lineaments. Five survey lines were conducted in the northwest-southeast direction, with 10-m line spacing, and each almost perpendicular to the main structural feature. A total of 21 sample points from individual survey lines were collected in this study. The details of the entire survey lines are shown in Table 1 and Fig 4.

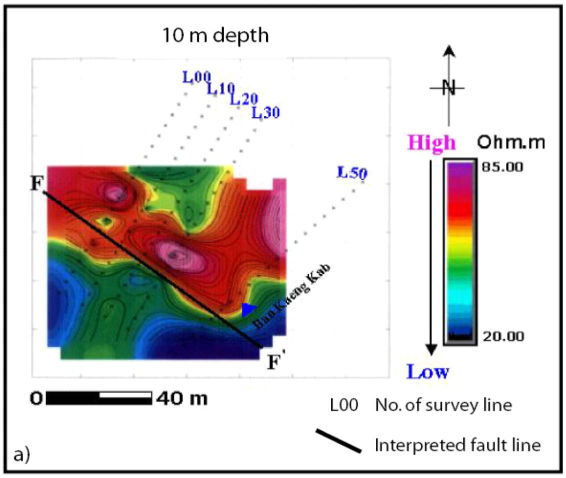
For the magnetic and VLF-EM surveys, we assigned record spacing of 5 m for collecting data and detecting signals/anomalies based on method described by Briener[24]. For the resistivity survey, we applied the time-domain method to measure resistivity values at the depths of 10, 15, 20, 25, 30, and 35 m based on dipole-dipole configuration array.

Results

Resistivity Method

We constructed resistivity contour maps and resistivity profiles (both cross and long sections) from digital database using GEOSOFT program (Figs. 5a and 5b). The color bar scale illustrates resistivity values. Contoured data are displayed in two-dimension and yield high accuracy in order to mark the position of the fault.

In this study, the resistivity values vary from 23.05 to 83.68 ohm.m. Such value ranges are similar to those of the normal resistivity values for common



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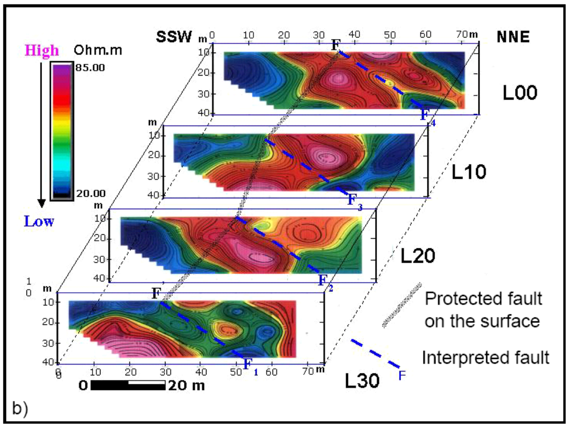

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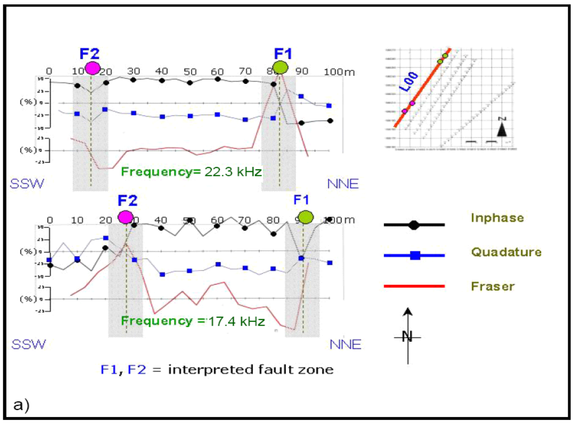
Fig 5. **a** Resistivity contour map at 10 m depth, the Kaeng Kab area, Kanchanaburi.
FF' indicates the structural lineament (or fault).
b Four in-line resistivity sections in the study area. Dashed lines in the section represent the interpreted faults. Connection of individual sections indicates the approximate fault plane orientation in the study area.



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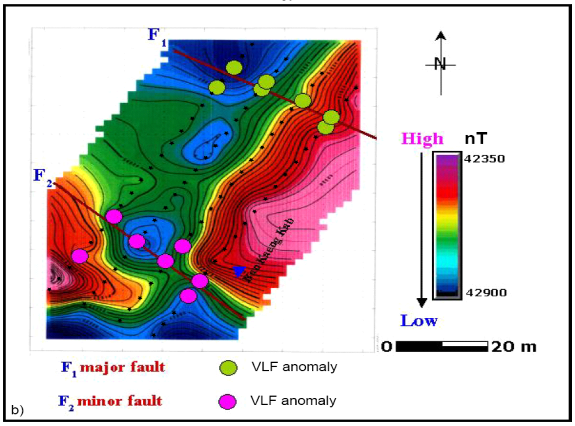

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Fig 6. **a** The VLF-EM's anomaly at L00 (a). VLF-EM response showing inphase, quadature, and fraser values along the survey line L00 at 22.3 kHz and 17.4 kHz frequencies. Two outstanding values F2 and F1 are marked close to both ends of the survey line.
b An overlay of VLF-EM anomalies onto the magnetic contour map showing the major structural lineament with inferred significant anomalies orientating in the NW direction.

sedimentary rocks[27] (e.g. sandstone and shale). Therefore, based on the resistivity result and the field survey, we interpret that rocks beneath the study area would be sedimentary. However, there are some point data that have lower values than the normal sedimentary rocks. There is a sharp boundary between relatively high and low resistivity values in the middle part of the study area, as shown by a color relief map determined when the secondary electromagnetic fields show different phase from the primary electromagnetic fields. Generally, inphase values are positive component while quadrature values are negative component of the secondary electromagnetic field from the target[15]. The Fraser filter values are also inphase values, which are filtered in order to emphasize the positions of anomalies. In another word, the input of Fraser filter is the way to enhance the visualization of the anomaly positions, as shown in Fig.6a. Two points (F_1 and F_2) are quite obvious along each survey line (line L00 and L10) at both frequencies applied. At F_1 and F_2 points, all the EM values are either much lower or higher than normal background values.

Interpretation

From the result of resistivity contour maps at 10-m depths (Fig. 5a), the anomaly line is characterized by the low resistivity continuity in the northwest-southeast direction. This can be interpreted as a fault cutting through Triassic sedimentary rock unit. Thus, the fault can be detected obviously at the depth of approximately 10 m (Fig 5a).

Besides, four resistivity survey lines also indicate a low resistivity anomaly zone. This can be easily seen when these sections were shown together (Fig 5b). These anomalies are at the same positions as those observed in resistivity contour maps. Their trends in the northwest direction and the moderate–angle with apparent dip not exceeding 45 degrees are observed. In the current investigation, the long section of the survey line L50, however, does not include in the interpretation because the section is too far from the others.

From the magnetic contour map and magnetic profiles (Figs. 7a to 7c), we interpreted that there is a sharp contact between two contrasting magnetic values located in the central part and in the northeast-southwest direction. The anomaly in the magnetic cross profiles is regarded as the boundary contact (or structural lineament zone) between two contrasting rock units of different properties, which yield the magnetic susceptibility values different from the others. Similar situation is also encountered in the magnetic long profiles (Fig. 7b), such as at the survey line L20, located in the southern part of the map, where the discontinuity is observed.

From the result shown as long profile and cross profiles (see Figs 7a and 7b), we consider that two fault

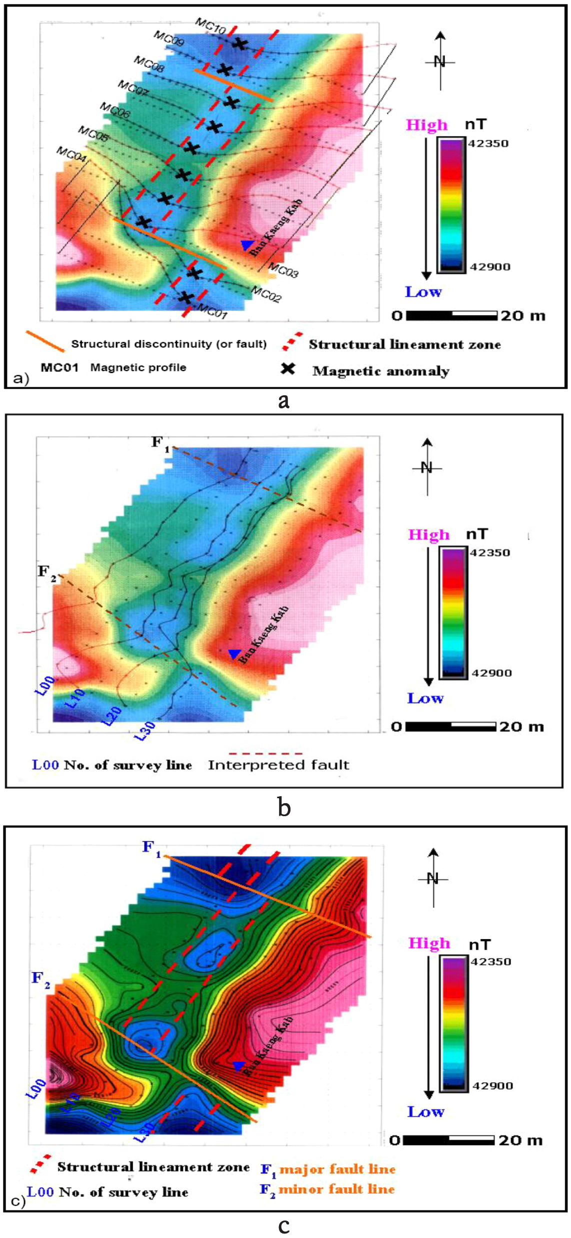

Fig 7. **a** Magnetic map of the Kaeng Kab area, with the overlay of cross profiles showing the continuous structural lineament (dashed line, interpreted as contact plane of two contrasting rock units). A solid line represents the shift of the structure lineament.
b Magnetic map of the Kaeng Kab area, with the overlay of in-line profiles showing two dashed lines connecting low magnetic values. These dashed lines (F1 and F2) are interpreted structural lineament in the NW trend.
c Two fault zones (solid line) and a structural contact interpreted from the magnetic contour map of the Kaeng Kab area, Kanchanaburi.

traces are present at recording point No. 20-30 (F_2 in the southern end) and the other at No. 90 (F_1 in the northern end) of each survey line. These faults orientate in the northwest-southeast direction. F_2 is more distinct than F_1 due to the appearance of discontinuity in F_2.

From both results of inphase-quadrature and fraser filters, the positions of anomalies can be located. Each position is situated almost at the southern and northern ends of the study area. Interestingly, the anomalies are observed along the similar trend of the magnetic anomalies (Fig. 6b).

Discussion

Based upon results of the ground geophysical investigations, the existence of Quaternary fault is discussed below

Results from the resistivity survey can assist to delineate the orientation and dip of fault planes both from enhanced resistivity contour maps and from long sections. The result indicates the low continuous values aligned in the northwest-southeast direction, particularly at the depth of 10 m. The moderate angle of fault planes can be determined from strike line sections.

Results from the magnetic survey indicate the fault plane at the depth of 5 m or less based upon magnetic cross profile. Two fault planes of the northwest trending are recognized in the northern and southern parts of the study area. The fault in the northern part of the study corresponds very well with the major lineament interpreted from LANSAT images. In conclusion, based upon the magnetic contour map, the overall picture of the surveyed area is defined in the sense that sharp discontinuity (or fault) of the contact (zone) is delineated.

VLF-EM survey, which is the most sensitive instrument, can detect the fault easily and always with its microstructures and noise. Interpretation along with magnetic results can assist to delineate the fault. Detection of anomalies is lower than 5 m deep fault. The EM results based on analyses of inphase, quadrature and Fraser filter graphs can detect clearly major and minor faults as well as micro structures.

In this study, the most effective ground geophysical method for detecting active faults is the magnetic method. The magnetic anomaly can be detected most easily. The second best is the VLF-EM method, which can also be applied successfully. However, noise and sensitivity of the VLF-EM methods can give rise to geologically meaningless anomaly. The resistivity method cannot yield the best result for the fault orientation but it can detect the dip of fault. Integration of more than one method in order to get the most accurate results is necessary in this study case.

The result of ground geophysical survey enables us to delineate a concealed fault, especially the major fault, which can be detected by aerial photograph. This fault strikes in the northwest-southeast, dips to the southwest direction, and cross cuts Triassic rocks very close to the foothill. Moreover, ground geophysical results can be applied to locate minor fault or concealed faults striking in the northwest-southeast, dipping to the northeast direction, which are located in the Quaternary colluvial deposits.

Comparing ground geophysical methods with remote-sensing data, the remote sensing data alone can be applied successfully in the more regional investigation for detecting the Quaternary faults on the surface, while the ground geophysical method can

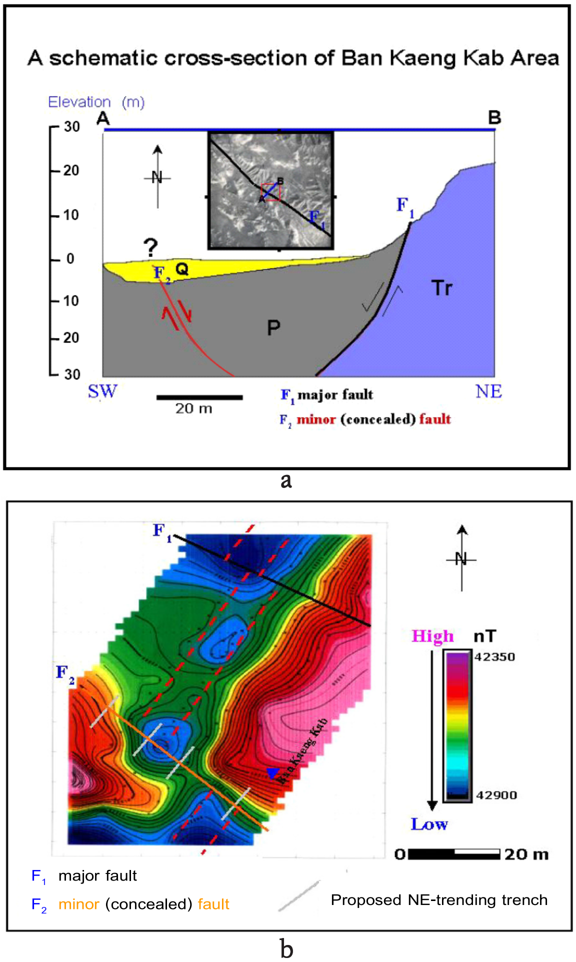

Fig 8. a Schematic geologic cross section of the study area at Ban Kaeng Kab based on geophysical and geological interpretation showing the fault orientation of the major fault (F1) and the minor fault (F2).
b Magnetic map showing locations of faults (F1 and F2). The gray lines where 20m long exploratory trenches are located. The trenches being designed are about 20m long and must be perpendicular to the NW - trending fault.

assist to delineate concealed faults in the larger scale and give more detail of subsurface data than remote sensing data.

Based upon interpretation of the Quaternary Fault by Songmuang[18] together with the current interpretation of the enhanced ground geophysical data mentioned previously, the geologic cross section in the north northeast - south southwest direction through the study area could be constructed. The study area in Kaeng Kab village is mainly occupied by the Quaternary deposit in the middle part, Cambrian and Triassic clastic sedimentary rocks in the northern and Permian carbonates in the southern part. One major fault is observed to cross cut the Permian and the Triassic sedimentary strata. The fault orientates in the northwest trend and dips southwestward at moderate angles. We regarded that this fault shows vertical slip displacement and is located clearly at the foothill. The other which is a minor fault, is located about 60 m to the south of the major fault. This minor fault cannot be detected from using aerial photographic analysis. It is elevated about 5 m from the ground surface covered by the Quaternary sediments (Fig 8). The fault cuts into the Triassic sedimentary rocks and aligned in the northwest direction. However, its moderate angle to the northeast is in the opposite sense to the major fault. Structurally, this minor fault is likely to be the "antithetic fault[29]". It is probable that the movement along the major fault caused the movement of the antithetic and minor fault in the past, since the antithetic fault cuttings through Quaternary sediments can be constrained more for younger movement than the much older sediments. Based on this poorly supported result, we therefore believe that the minor fault is more active at present than the major one. The major fault may have moved before, but now it becomes less important than the minor fault.

It is, therefore, reasonable to note that results on remote sensing interpretation alone can be applied particularly in the more regional scale for detecting Quaternary faults on the surface[18, 30]. However, the ground geophysical survey, particularly the magnetic method, can be employed to locate a concealed fault in a local scale.

Finally, results from the enhanced ground geophysical data can define an appropriate area for paleoseismic trenching from the interesting specific anomaly in order to cut down expenses and time. As a result, gray solid lines in Fig. 9 (about 10 m long) perpendicular to the F2 fault in the south are proposed for the trenching.

Conclusion and Recommendation

Results from magnetic, VLF-EM, and resistivity survey show that in this study the most effective ground geophysical method for detecting the geometry of the concealed faults is the magnetic method. However the VLF-EM method is successful and can be applied to detect faults at shallower depth (5 m) than the magnetic survey. This kind of EM method can be best applied for detecting faults in Quaternary deposits. Enhanced ground geophysical methods seem to be more effective than the remote sensing methods in terms of their accuracy in locating faults.

This study indicates that the southern part of the Sri Sawat fault is "active" because the fault detected cuts across colluvial sediments of the Quaternary. However, more detailed study such as paleoseismic trenching and dating, can be carried out after interpretation of combined geological results has been performed. It is also recommended that survey lines should be designed in smaller record spacing such as 1 m instead of 5 m in order to detect fault planes at shallower depth.

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