

Article

Identification and Verification of the Movement of the Hidden Active Fault Using Electrical Resistivity Tomography and Excavation

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Abstract: Identifying the movement of the branches of the hidden Thakhek fault in Thailand is challenging due to the absence of evident landforms indicating an active fault. In this study, we analyzed a digital elevation model (DEM) to identify potential landforms. A 2D Electrical Resistivity Tomography (ERT) survey was conducted to locate the hidden Thakhek fault. The results reveal vivid images of resistivity contrast, interpreted as two reverse faults, with mudstone exhibiting low resistivity in the middle, flanked by thick sediment layers with higher resistivity. Three trenches were excavated perpendicular to the two interpreted reverse faults. The displacement of reverse faulting appears to have shifted mudstone over Quaternary sediments, with vertical offsets revealed in trenches NWY-1, NWY-2, and NWY-3. This movement could be identified as a positive flower structure. Additionally, lakes are identified as a negative flower structure along the traces. These features result from strike-slip strains under a locally appropriate compressional and extensional environment in a shearing strike-slip fault.

Keywords: active fault; Thakhek fault; 2D electrical resistivity tomogram; trenching



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1. Introduction

The active fault zone along the eastern edge of the Khorat Plateau demonstrates strike-slip movement. This zone reportedly comprises three significant faults oriented NW–SE, showing evidence of neotectonic displacements [1,2]. The fault zone is clearly characterized by a linear or curvilinear principal lateral displacement zone in satellite image investigations [3]. Landforms of strike-slip faults can be identified in satellite images due to significant lateral displacement, such as wrench-fault troughs, pull-apart basins, or a combination of both [4,5]. Wrench-fault troughs can form relatively long and narrow basins [6]. Moreover, they can create a depressed area, such as a sag pond, a rhomb graben, or a pull-apart basin, identified on a larger scale [7].

The Thakhek-Sepon-Danang active fault zone runs predominantly NW–SE [8–10] and extends from Laos into Vietnam, spanning over 550 km. This fault zone comprises three major faults, as illustrated in Figure 1 [9,11,12]. During the neotectonic stage, the fault zone experienced two main phases: the early phase (Late Miocene—early Pliocene) with left-lateral slip, and the late phase (Late Pliocene–Quaternary) with right-lateral slip [9]. The fault zone partly runs along the Mekong River at the Thailand–Laos border, characterized by left-lateral slip, and is mapped as a steeply dipping NW-striking fault [13,14]. Fault

motion formed the plateau edge on the Lao side, caused by compressional forces resulting in older rocks moving upwards [14]. Many prominent active fault morphologies are visible in satellite images of Laos [1].

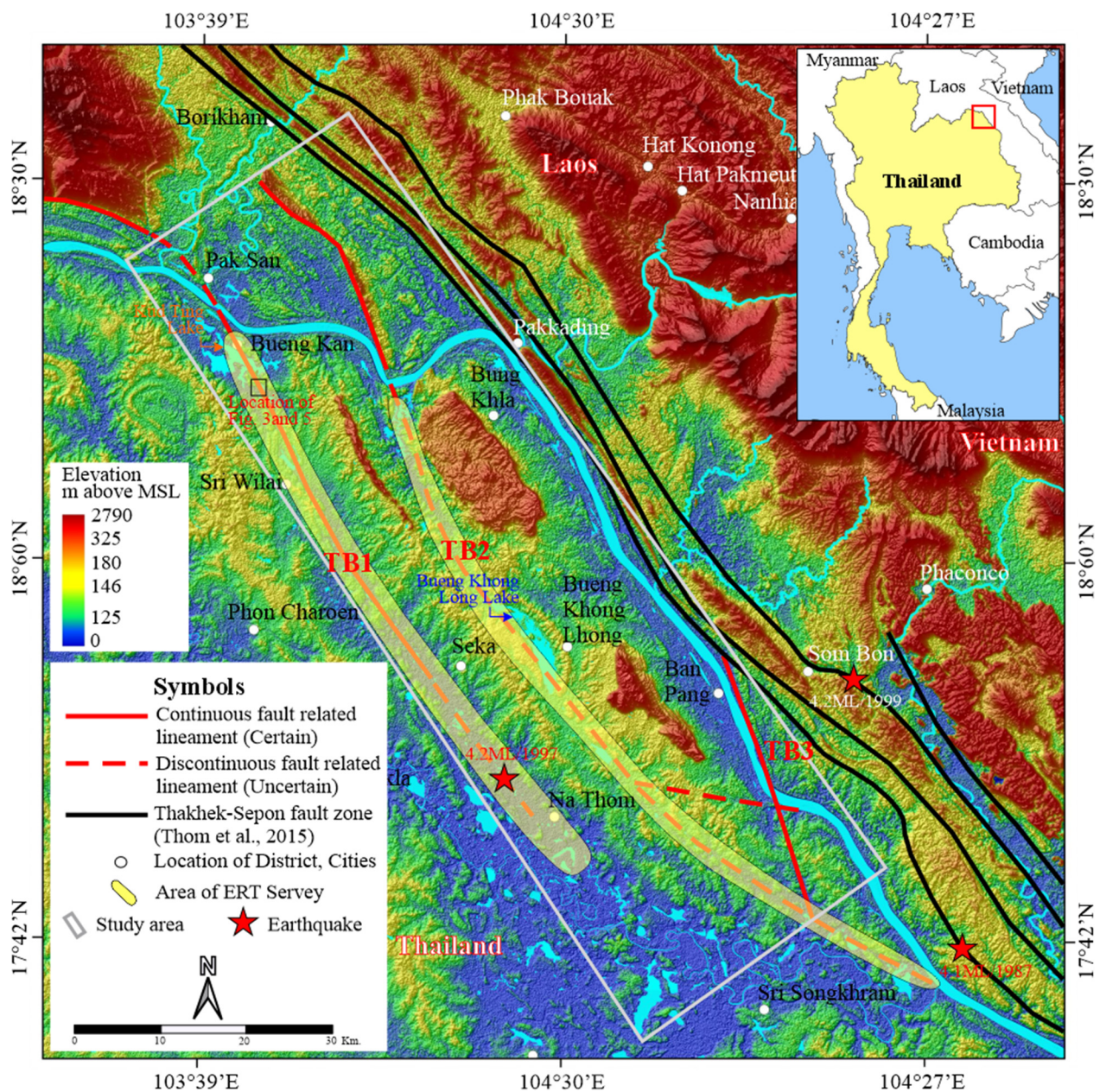


Figure 1. Interpretation of the Thakhek fault using DEM, showing major faults extending from Laos into Thailand. The TB1 and TB2 traces are inferred to branch from the main strike-slip fault, extending into Northeast Thailand with a general NW–SE orientation. The locations of Figures 3 and 5 are indicated on TB1 trace [9].

Flower structure is one of the important features that can be used to identify strike-slip faults and shear zones [5,15]. The structural features are mainly characterized by their internal fault and fold architectures in cross-sections that resemble the petals of a flower [15,16]. According to their internal fault structural architecture, flower structures can be classified into two main types: positive and negative structures [15–17]. A positive flower structure, also termed palm-tree structures, consists of a shallow antiform displaced by upward diverging strands of a wrench fault with mostly reverse separations. A negative flower structure, also called tulip structures, consists of a shallow synform bounded by

upward spreading strands of a wrench fault with mostly normal separations [15]. These structures are bounded by strike-slip faults on the two parallel sides [7].

The active faults on the northeast edge of the Khorat Plateau are hidden beneath loose sediments, with fault morphology eroded and quickly covered by new deposits, making fault traces hard to detect. Arjwech et al. [2] studied an active fault by excavating two trenches across a fault line identified using 2D Electrical Resistivity Tomography (ERT). Several studies [1,18–20] have successfully used the 2D ERT method to detect subsurface resistivity contrasts in unexposed sediment outcrops. However, a reverse fault, bounded by strike-slip faults on both sides of the compressive zone, was not verified. Thus, this study aims to collect additional data from 2D ERT and trenching to reassess the reverse faults, with implications for understanding the morphology affected by compression and dilation along the strike-slip zone.

2. Geological Setting

Thailand primarily consists of the Indochina and Sibumasu tectonic blocks [21]. The Khorat Plateau and the surrounding region have been significantly impacted by tectonic events linked to the prolonged Himalayan orogeny during the Miocene–Pleistocene, characterized by NW–SE compression resulting in fold and fault structures [22]. This plateau stretches from northeast Thailand, extending northward and eastward across the Mekong River into Laos, within the Indochina tectonic block [23,24]. Major active fault zones in this region predominantly exhibit strike-slip movements with NE–SW or NW–SE orientations [25]. Most active faults in Thailand are located in the North and West, while those in the Northeast are mainly found along the plateau’s edges [1,26]. Clear surface expressions of active faults are primarily visible along the plateau rim in Laos [27].

The Khorat Plateau basin is relatively flat with low, small undulating hills [28]. Most of the basin’s current margins are formed by mountain ranges. The Khorat Plateau is characterized by thick sequences of gently folded Mesozoic terrestrial non-marine sedimentary rocks known as the Khorat Group [29,30]. During the mid-Cretaceous, a deformation phase led to the E–W-trending Phu Phan uplift, which traverses the plateau and divides the Khorat Plateau basin into the Sakon Nakhon basin to the north and the larger Khorat basin to the south [31]. Fractures aligned with the major structural trend of the isolated Phu Sing Mountain range are observable in satellite imagery [32]. Isolated mountain ranges, mainly following a NW trend and bounded by regional faults, exhibit synclinal structures with gently dipping limbs at angles of 5–10° [32–34]. The fracture system aligns with the orientation of the mountain ranges, where escarpments likely represent fault-generated structures. However, clear evidence of active faulting morphology is not apparent in the field in Thailand.

The geology of the study area is predominantly covered by two members of the Phu Tok Formation of the Khorat Group. The lowest member, the Nawa member, consists of reddish-brown or reddish-orange claystone and mudstone with low resistance [35]. The Phu Tok Noi is the upper member of the late Cretaceous–early-Tertiary Phu Tok Formation. This upper member primarily features large-scale cross-bedded yellowish-red fine- to medium-grained sandstones, interbedded with reddish-yellow very-fine-grained sandstones and siltstones [26,36,37]. The paleo Mekong River carved the sandstone mountains of the Phu Wua, Phu Sing, and Phu Tok ranges, leaving them lying parallel or subparallel to the flow of the powerful river [38]. Additionally, Quaternary gravel sediments are dispersed as hilly areas along the paleo Mekong River [1].

3. Study Area and Methods

The study area is situated in Bung Kan and Nakhon Phanom Provinces in the far northeast of Thailand, near the northeastern rim of the Khorat Plateau, as illustrated in Figure 2. The Nonwangyiam and Nano sites are characterized by low-lying paddy fields flanked by rolling hills with rubber tree plantations. These rubber plantations are primarily concentrated on gravel hills. Partially exposed weathered reddish-brown mudstone can be

observed in excavated ponds within the paddy fields. Swamps or lakes are found along the fault trace to the northwest and southeast of the excavation site.

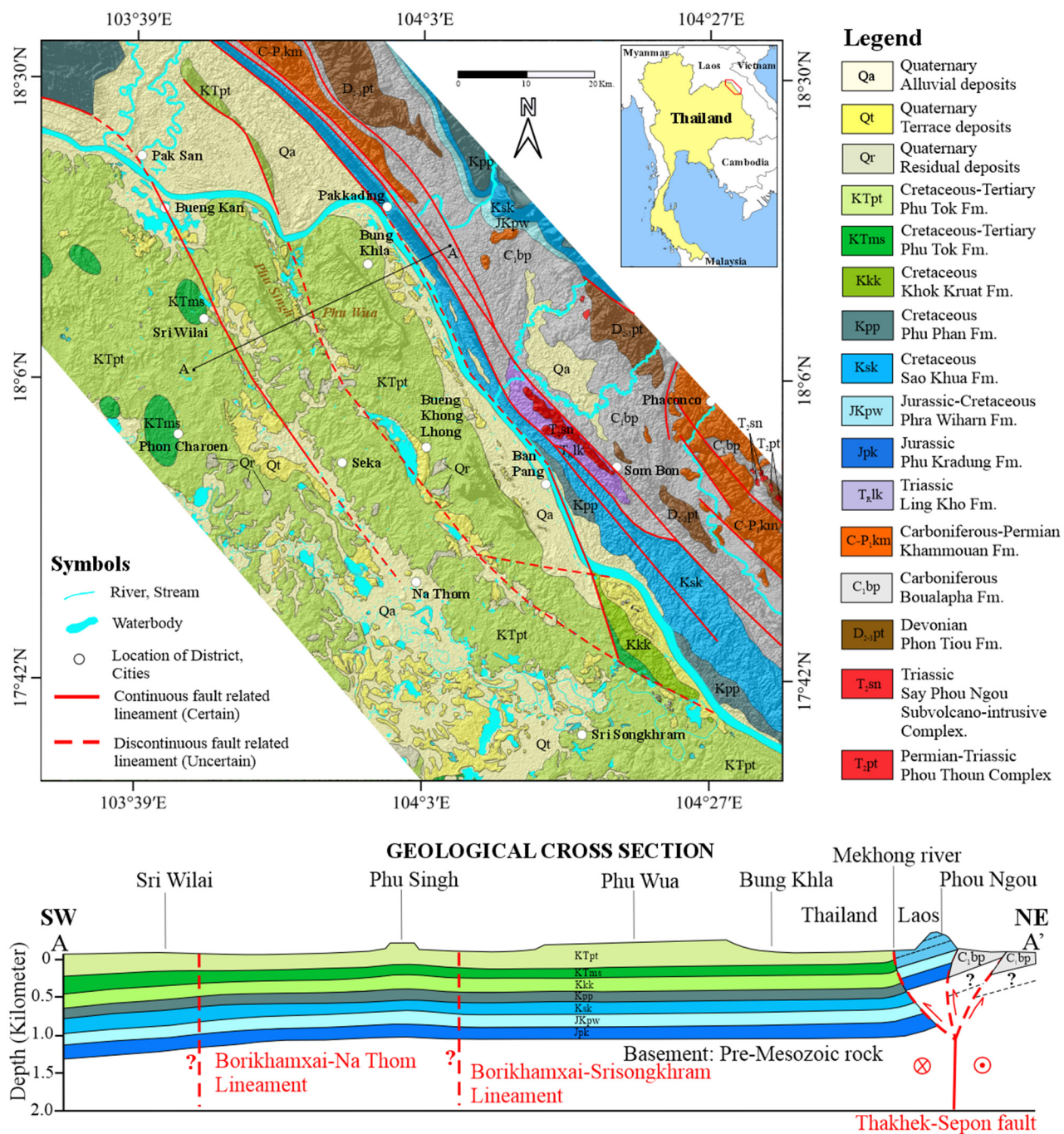


Figure 2. Geologic map of study area in Northeast Thailand and western Laos with the indicated locations of Figure 5a and a cross-section presenting interpreted faults (modified from [2]).

In Thailand, morphological features of active faults are difficult to identify. The ERT survey is ideal for this study because it provides high resolution and wide cross-sections. The data can be processed and interpreted immediately on-site, enabling quick decision-making. In the previous study, high resolution 2D ERT surveys were successful in determining the location of hidden faults in the Thakhek-Bung Kan 1 (TB1) trace. Two reverse faults (F1 and F2) were interpreted in the BK01 tomogram, but only one fault was verified by trench Nonwangyiam 1 (NWY-1), a parallel bounded fault (F2) in the BK01

tomogram was not verified yet. One reverse fault was interpreted in the BK02 tomogram. The fault was verified by trench NWY-2. Two trenches (NWY-1 and NWY-2) were excavated across the interpreted faults F1.

In this study, we analyzed a digital elevation model (DEM) and the most recent high-resolution satellite images available on Google Earth to identify morphotectonic landforms. QGIS software (open-source geographic information system (GIS) application version 3.28) was employed for the analysis of active fault traces using a 30 m resolution DEM. We revisited the Nonwangyiam site and extended the Thakhek fault analysis with one more excavation (Trench NWY-3) and interpretations. Subsequently, trench-log stratigraphy was conducted, and sediments were sampled for dating to determine the ages of sedimentary layers in the trench. Finally, paleo-seismology was studied (though not mentioned in this paper). More than 40 ERT profiles, each consisting of an electrode array with length ranging from 200 to 750 m, were conducted across the interpreted fault, the TB2 trace. We present only the 2D ERT profile BK03 from the Nano site, which displayed similar morphological features to the Nonwangyiam site. This profile revealed the most significant fault-related anomaly.

4. Results

Field investigations, including geomorphological and geological reconnaissance and ERT surveys, were conducted after DEM interpretation. Distinct fault traces with a NW–SE orientation are easily seen as sharp lineaments in satellite images and DEM on the Laos side (Figure 1). These features are evident along escarpments of Mesozoic rock-resistant beds and at the boundaries between Paleozoic and Mesozoic units (Figure 2). However, the branching faults that are clearly defined and prominent on the Laos side quickly fade into unconsolidated Quaternary sediments in Thailand. The surface traces continuing southeast from the Laos side likely represent a distinct fault. These lineaments align with natural creeks, lakes, and swamps on the Thailand side (Figures 1, 2 and 5c). Two parallel or subparallel lineaments, TB1 and TB2, intersect the Late-Cretaceous–Early-Tertiary Phu Tok mudstone and unconsolidated Quaternary sediments.

4.1. ERT Result

The ERT survey was performed using a dipole–dipole configuration with 0.75 and 2.5 m electrode spacing. The acquisition dataset was optimized to take full advantage of the available 10 channels in the SYSCAL PRO resistivity meter from IRIS Instruments (www.iris-instruments.com). The data were processed using 2D tomographic reconstruction methods employing the finite-element modeling inversion algorithms of Res2DInv software (version 4.08). The L1-norm (blocky optimization) inversion was applied, minimizing the sum of absolute deviations (residuals) and resulting in blocky profiles with vertical gradients. This geometric approach provides clear boundaries that separate low- and high-resistivity layers, thereby highlighting significant resistivity contrasts in subsurface geology. For dip-slip faults, a distinct vertical boundary was detected, emphasizing vertical flatness over horizontal flatness. As a result, robust model inversion constraints were found to be more appropriate. The ERT data for profiles BK01 and BK02 were acquired from previous studies [1,2], and the data were reprocessed. The results offer clear details for the excavation of trench NWY-3 and its geometrical features. Additionally, the BK03 profile was conducted, and its results supported these findings.

At the Nonwangyiam site in Bung Kan Province (Figure 5a–c), two profiles, BK01 and BK02, were conducted across the fault trace TB1. Each survey profile measured 235.0 m and 70.5 m, respectively, traversing low-lying paddy fields flanked by gravel hills. The 2D ERT tomograms converged with absolute errors of 2.6 and 1.9 after six iterations (Figures 3 and 4), indicating a good fit for the model inversions. The maximum penetration depths are approximately 25 m and 16 m.

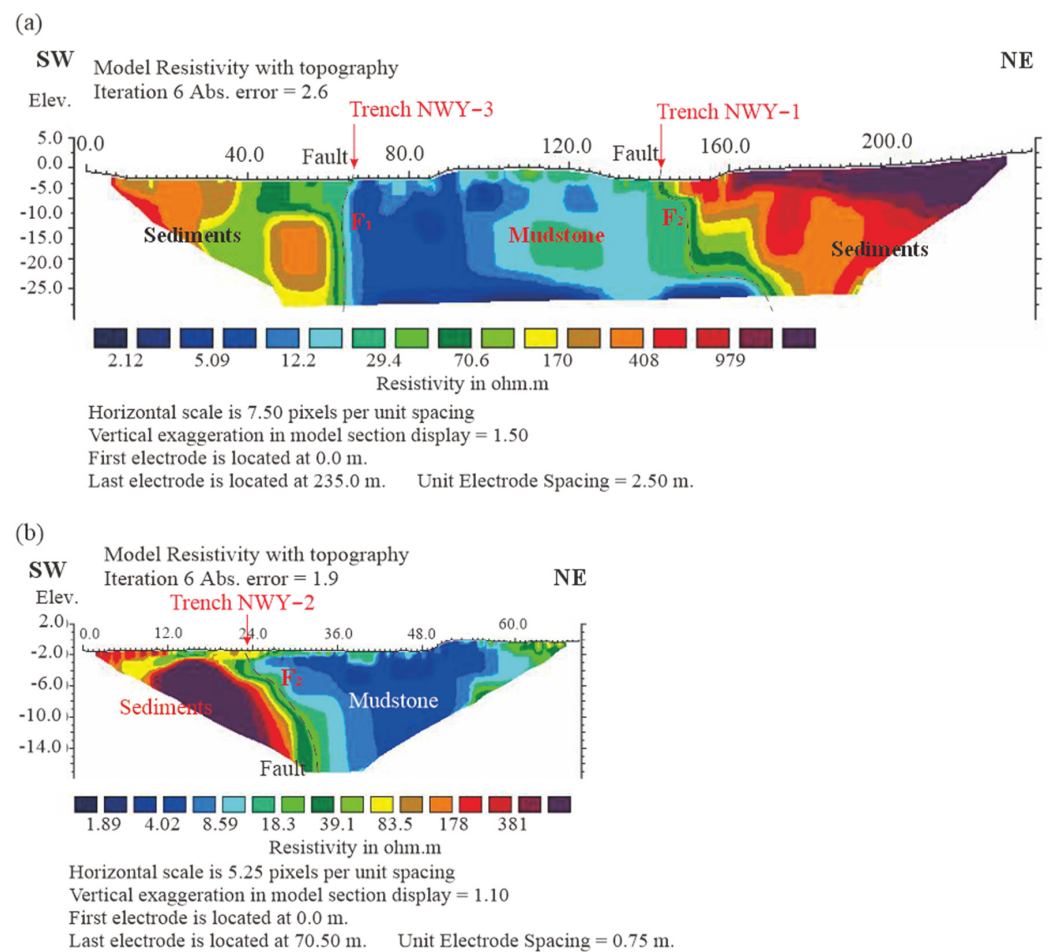


Figure 3. Two-dimensional ERT tomogram of profile BK01 (a) displaying resistivity tomography based on the L1–norm (robust) inversion method. The images show mudstone (low resistivity) flanked by coarse-grained sediment layers (high resistivity). Profile BK02 (b) displays a sharp contact between mudstone and sediment layers.

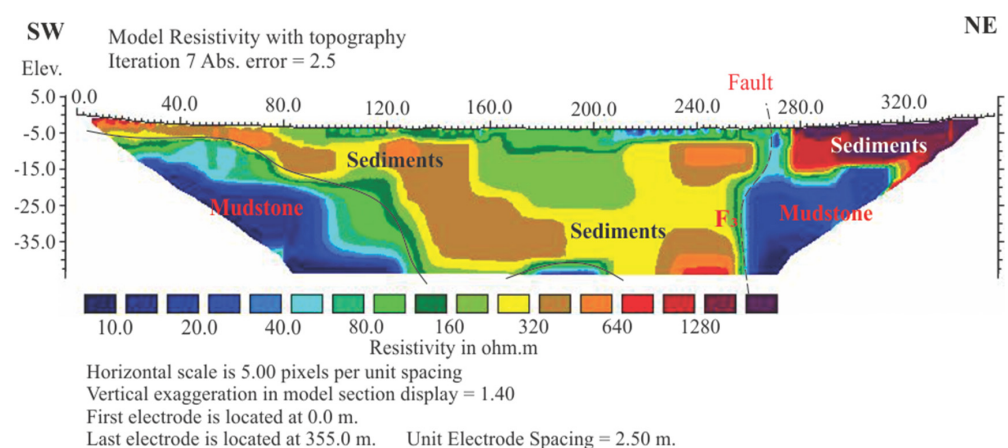


Figure 4. Two-dimensional ERT tomogram of profile BK03 displaying resistivity tomography based on the L1–norm (robust) inversion method. The image shows coarse-grained sediment layers (high resistivity) flanked by mudstone (low resistivity).

The BK01 tomogram shows two sharp vertical sections (Figure 3a,b). A heterogeneous zone of relatively low resistivity ($<50 \Omega\text{m}$) is evident in the middle of the line between 65 and 142 m, interpreted as mudstone. This zone is flanked on both sides by sharply and

nearly vertical higher resistivity ($>50 \Omega\text{m}$), interpreted as Quaternary sediments throughout the entire depth of the tomogram. The ERT tomogram clearly reveals the dip fault plane, and the contact between rock and sediments is identified as putative faults F1 at 65 m and F2 at 142 m along the survey line. The trench sites in this study are determined by anomalies F1 and F2.

The shorter profile BK02 was deployed across the interpreted F1 fault in profile BK01, approximately 150 m away from BK01. The tomogram clearly shows a sharp vertical resistivity contrast at 22 m, interpreted as the fault. The low resistivity zone is identified as mudstone, while the higher resistivity is attributed to Quaternary sands, silts, and gravel clasts, consistent with the interpretation of profile BK01.

At the Nano site in Nakhon Phanom Province, profile BK03 was conducted across the fault trace TB2 (Figure 5b). The survey profile measured 355.0 m, traversing a low-lying paddy field flanked by hills. Six iterations yielded a final absolute error of 2.5 (Figure 4). The maximum penetration depth is approximately 40 m. The tomogram shows sharp vertical sections. A relatively high resistivity zone ($>50 \Omega\text{m}$) on the northeast side is flanked by sharply and nearly vertical low resistivity ($<50 \Omega\text{m}$), interpreted as Quaternary sediments. The contact between rock and sediments is identified as the putative fault F2 at 270 m along the survey line. Consequently, the locations of faults are indicated with dashed lines.

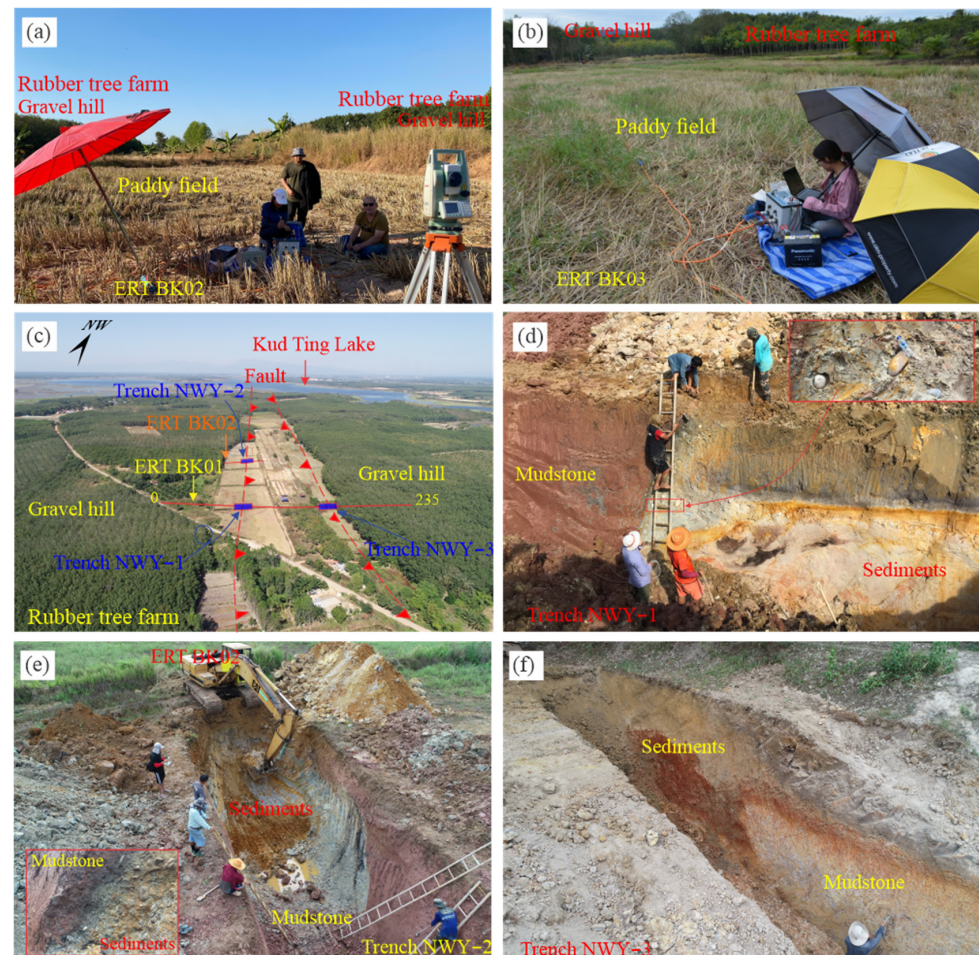


Figure 5. Photographs displaying the deployment of the 2D ERT profiles BK02 (a) and BK03 (b). An overview of the trench locations (c) and exposed walls of the NWY-1, with an inset showing the size of gravel compared to a water bottle (d), and NWY-2 (e) trenches. The inset photo in (e) shows a close-up view of the contact between mudstone and sediments, depicting the grain size distribution of unconsolidated sediments, while (f) shows the exposed walls of the NWY-3.

4.2. Trench Excavations and Stratigraphy

At the Nonwangyiam site (Figure 5c), Trenches NWY-1 (Figures 5d and 6a,b) and NWY-2 (Figures 5e and 6c,d) were previously excavated perpendicular to anomaly F2. In this study, Trench NWY-3 (Figures 5f and 7a,b) was excavated perpendicular to anomaly F1. The trench measures approximately 20 m long, 4 m wide, and 5 m deep. A 1 m² string grid was used for the entire trench, following standard paleo-seismic methods, and a lithologic log was carried out. Three depositional units (A–C) were exposed in both sidewalls. Unit A, the oldest, consists of clast-supported gravel with clay, indicative of a fluvial deposit. The gravels are typically subrounded to rounded cobbles of sandstone and quartz, with laterite accretions. Unit B is a fluvio-lacustrine deposit containing a few gravels within a clayey sand matrix. Unit C is a fluvial deposit of clast-supported gravel with clay, with laterite formed at the bottom. The succession is capped with a layer of dark topsoil composed of sand and clay.

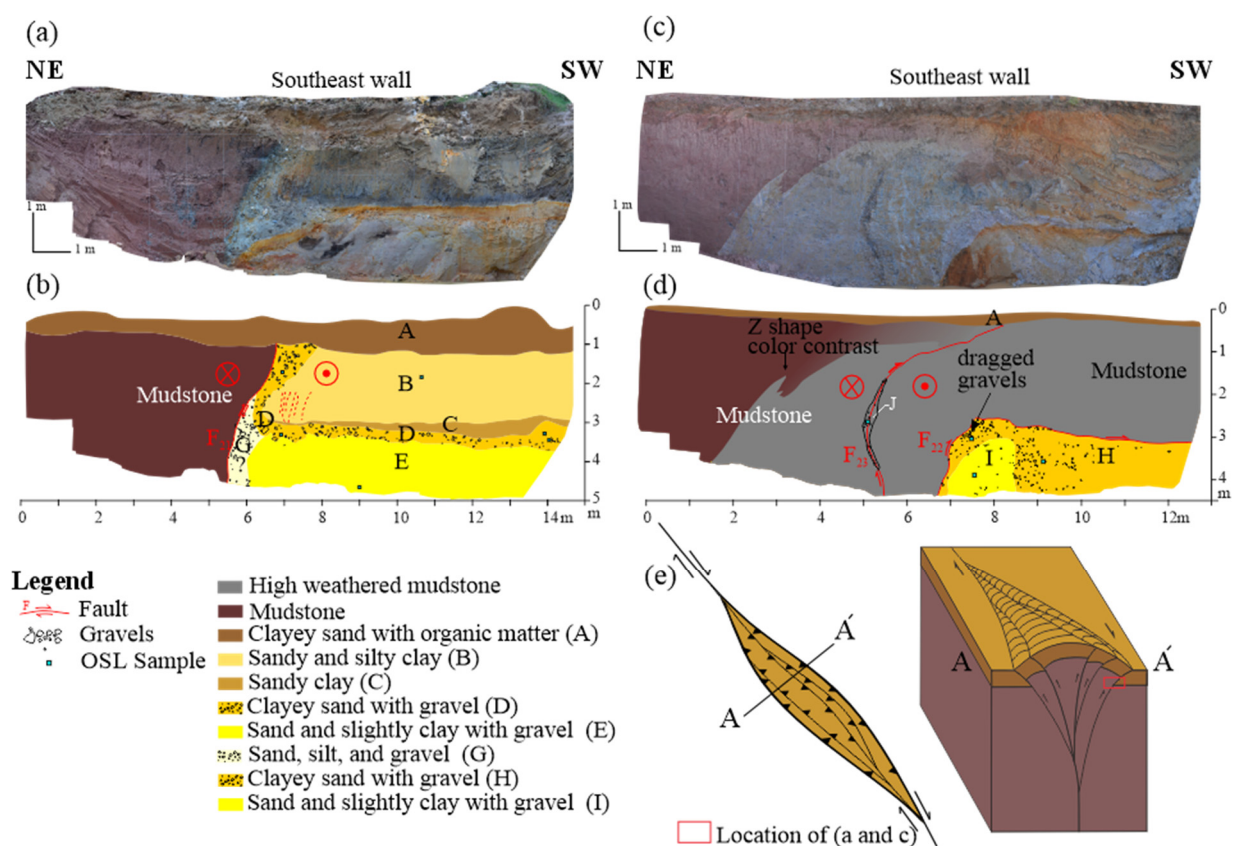


Figure 6. Photographs of the trench walls in NWY-1 (a) and NWY-2 (c), along with the stratigraphy of NWY-1 (b) and NWY-2 (d) trenches. Thrust faulting results in a main strike slip movement characterized by as a positive flower structure and antiform (e).

These units are displaced by dip-slip faults F11–F14. Reverse faulting appears to have shifted reddish, pale, blown-weathered mudstone and cut through the upper sediment layers. The vertical offset along the faults observed in the trench exceeds 2 m. The fault cuts through the strata, with the hanging wall of mudstone pushed up, cutting through the upper sediment layers. We interpret the movement within the trenches as compressional deformation of a positive flower structure produced by sinistral strike-slip movement.

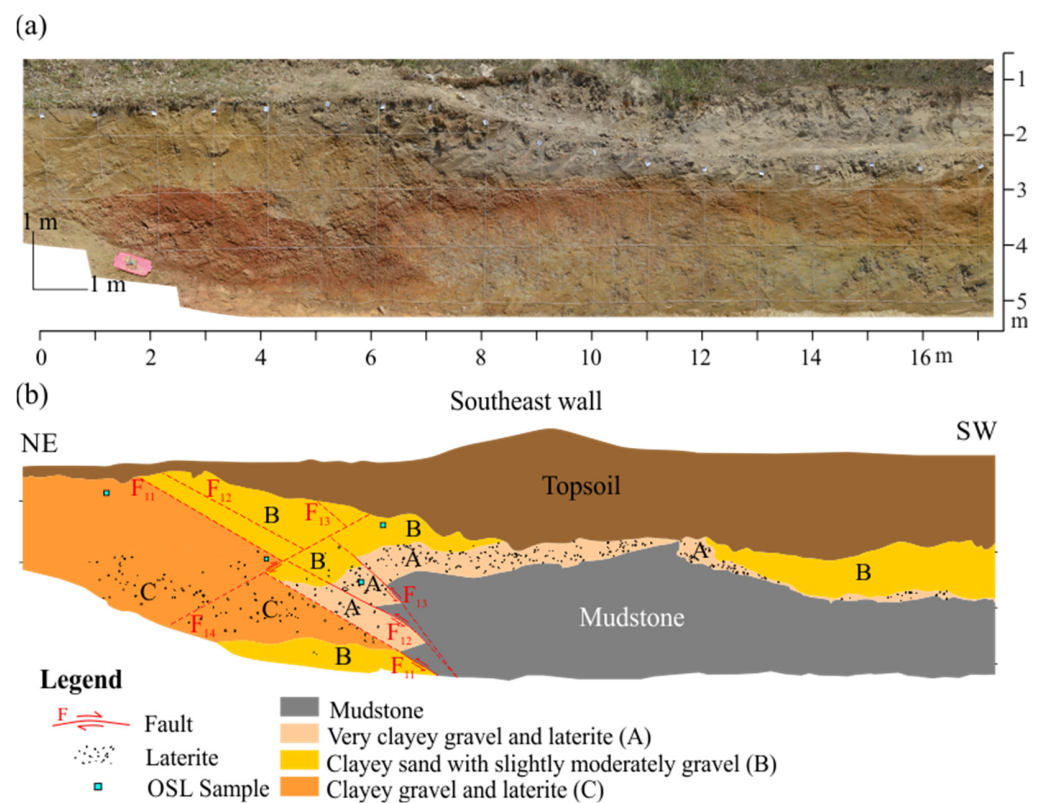


Figure 7. Photograph of the trench wall in NWY-3 (a) along with the stratigraphy (b).

5. Discussion

Two main subparallel lineaments, TB1 and TB2, trending NW–SE, were previously identified (Figure 1). Fault trace TB1 cuts through low-relief terrain to the floodplain, ending at the Song Kham River, while TB2 runs through varying terrain, passing through Bung Kong Long Lake and joining the Mekong River in the southeast. The Thakhek fault system extends into Thailand, influencing the geomorphological evolution of the Mekong River, where faulting controls flow diversions. Gravel hills, elongated remnants aligned with the interpreted faults, serve as geomorphological indicators of sediment transport processes of the river. Many boulder-strewn areas are currently used as rubber tree farms.

The combination of shear and compression due to transgression could explain the lineaments relative to the regional horizontal stress field observed in satellite images. Evidence includes R-shears along the Phu Sing Mountain ridge and the crescent-shaped Kud Ting Lake. The stress field causes compressional strain on the lower mudstone, accumulating vertical displacement over time relative to the overlying sediment layers. This structure likely corresponds to splays in the main Thakhek fault, developing local reverse faults connected at depth to form a flower structure. ERT geophysical surveys successfully identified these flower structures (Figure 3a). The trench log shows good spatial correlation with the ERT images, displaying large vertical offsets in the trench wall (Figure 6a,b and Figure 7a,b). Vertical deformation associated with the sinistral strike-slip motion caused mudstone on either side of the fault to laterally override younger sediment layers, as seen in Trench NWY-2 (Figure 6c,d). However, the 2D ERT tomogram only images the upper parts of the complex flower structure.

In wrench fault zones, both positive and negative flower structures can form. In this study, a positive flower structure was identified by the 2D ERT method and verified by excavation along the TB1 trace of the Thakhek fault. The general structure includes the predominant crescent-shaped Bung Kong Long Lake located in the TB2 trace, indicating a large pull-apart basin, interpreted as a negative flower structure in a divergent wrench fault zone under transtensional deformation. Divergent-wrench fault landforms are widespread,

exemplified by Kud Ting Lake, Nong Bang Bat Lake, Nong Chaiya Wan Lake, and Nong Bung Khra Lake along lineament TB1. These consist of a shallow synform bounded by upward-spreading strands of a wrench fault with mostly normal separations. However, positive flower structures' landforms could be eroded quickly in tropical rainforest regions and rapidly covered by new deposits, making them less evident at the Earth's surface. Therefore, sinistral or dextral movements of these branch faults cannot be identified in this study.

6. Conclusions

High-resolution 2D ERT tomograms were used to identify hidden faults along the transpressional faults TB1 and TB2. The comparison of ERT profiles with the excavated trench logs confirmed the success of the ERT survey in detecting these faults. From our integrated study, we interpret the steeply inclined faults in the 2D ERT tomogram as a positive flower structure. The middle section of the tomogram shows a low-resistivity zone corresponding to a mudstone layer with sharp contacts flanked by higher-resistivity sediment layers. Excavations of trenches NWY-1 and NWY-3 confirmed faults F1 and F2, further indicating a positive flower structure. This fault was caused by compression from strike-slip fault movement, as observed in Trench NWY-2. We extended the analysis of strike-slip fault movement using DEM and satellite images, which revealed the sagging of the large crescent-shaped Kud Ting Lake along the TB2 trace. Numerous large lakes, extending over approximately 100 km, are found along the lengths of the TB1 and TB2 traces.

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Data Availability Statement: The datasets presented here are available from the corresponding author upon request.

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