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Extensional Fault Systems in Mae Moh Basin, Lampang province, Thailand, based on 3D Seismic Data

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Abstract

The Mae Moe Basin is a major NE-SW trending failed rift basin on the remnants of the Sukhothai Arc of Northern Thailand. The Cenozoic sediments of the basin have been significantly displaced by syn-rift and post-rift deformation and erosion, which make for a labyrinthine of basin structures. In this paper, the preliminary research results of the Mae Moh mine based on 3D seismic data will be presented. The anisotropic nature of the Mae Moh mine strata seems to play a crucial role in the fault geometries present. The architectures present in the Mae Moh mine 3D seismic data show two different fault systems. The first fault system shows evidence of a variable west-northwest strike direction normal faults. The second fault system indicates normal faults linking with low-angle listric faults. Both fault systems offer evidence of linkage causing sigmodal geometries to be present in map view and show correlation through seismic attributes and horizons.

Keywords: Mae Moh Basin, Coal mine, Normal fault, Cenozoic, Thailand

1. Introduction

One of the critical elements of a sedimentary basin to contain an economically valuable fossil fuel deposit are the structures present in the subsurface, which affect the overlying depositional environments. In addition, these structures create adequate conditions to facilitate accumulation; thus, further investigation of the Sedimentary Basin's structural evolution is needed.

The Northern Tertiary basins of Thailand have previously been interpreted as strike-slip fault regimes. However, with recent advances in sandbox and clay modeling and more research on the topic, more researchers have suggested that (rift) extensional fault regimes have influenced these basins. (See Ackermann et al., 2001; Schlische and Withjack, 2009; Chantraprasert and Utitsan, 2021; Morley, 2001)

Thailand's rift basins represent extension in a very dynamic tectonic environment (Morley, 2001). Consequently, extensional stress may not have been continually imposed on the rift basins. With each control comes different but sometimes concordant fault geometries; Faults can be controlled by numerous factors such as the oblique of the pre-existing fabric's faults, the oblique orientation of those faults relative to the extensional direction, the geometries, transfer zones orientation, fault linkage, and displacement patterns (Morley & Wonganan, 2000). Equivalently, if not more substantive, is the number, relative strength, dip, strike, spacing, and type (pervasive or discrete) of fabric elements (Morley & Wonagna 2004). Such information is particularly significant to identify the geometries associated with different regimes. Thus, increased precision of structural interpretations in sedimentary basins may bolster more accurate predictions.

The study location of this research is in the northern province of Lampang, Thailand (Fig. 1A). The Cenozoic Mae Moh Basin is affected by complex faulting. The faults strike approximately N-S to NE-SW, with variable east-west dip direction. The basement comprises the Triassic Lampang Group with a complexity of folds and faults (Sompong et al., 1996).

In this paper, the structural interpretations of the Mae Moh Basin are described into three different scales: regional structure, basin structure, and pit scale structure. The pieces of literature were reviewed and added with the recent data observed during the 3D seismic investigation. 3D structural interpretations of seismic data are presented below in order to understand the structural geology of the Mae Moh Basin.

2. Geological Setting

2.1 Tectonic History

Thailand is located at the northern end of the continental crustal core of SE Asia called Sundaland (Morley, 2001), which is comprised of a progression of terranes that rifted from the Australian-Antarctica margin of Gondwana and re-assembled on the Asian margin by collisional events during Late Palaeozoic-Triassic (e.g., Metcalfe, 2002, Charusiri et al., 2002; Morley & Westaway, 2006).

The intraplate Cenozoic Mae Moh Basin is located on the remanets of the Sukhothai terrane. The Sukhothai terrane comprises two additional terranes; the Lincang Terrane to the North and the Chanthaburi Terrane to the South (Sone & Metcalfe, 2008). The terranes were initially formed as parts of the same island-arc system developed along the margin of the

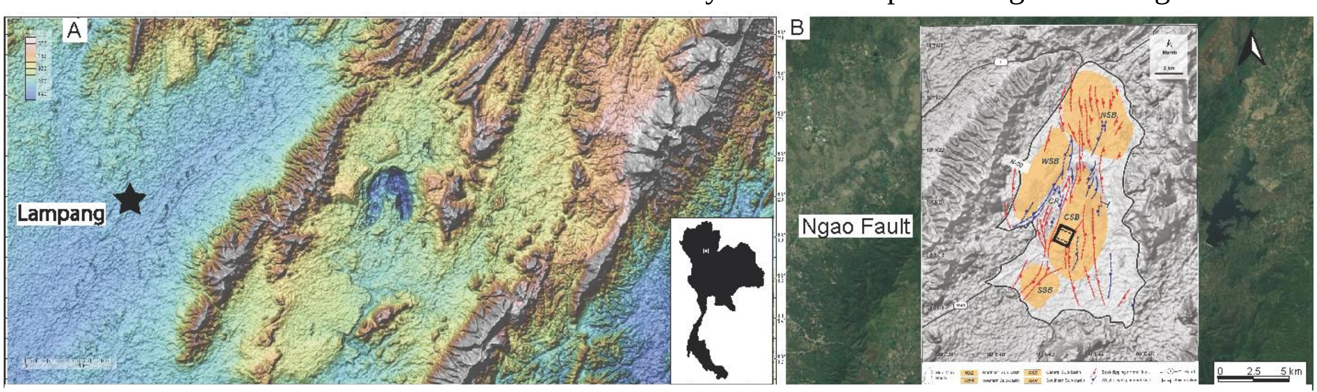

Figure 1. (A) Dem of Lampang, Thailand. Black box shows Mae Moh Mine area and orientation. (B) Basin/fault map overlain on google image. Black box shows location of 3D seismic survey. Top dash line marks location of In-line 2357 N10, bottom dash line marks location of In-line 2070 S4. Modified from Sompong et al (1996)

Indochina Terrane, which was subsequently amalgamated to Indochina due to back-arc collapse and succeeded as a continental arc in the Triassic (Sone & Metcalfe, 2008) before effected by the strike-slip faults in the Cenozoic forming the N–S sedimentary basins (Morley, 2013). Thus, the Cenozoic tectonic events are the vital key to understanding the regional structure around the Mae Moh Basin.

The Sukhothai Terrane of Barr and Macdonald (Sone & Metcalfe, 2008) describes the terrane delineated by the Inthanon Suture Zone to the west and the Nan Suture to the east. The terrane is influenced by folded and faulted sequences of sandstones and shales of the Lampang Group (Sompong et al., 1996) and igneous rocks with I-type granitoids, mostly of Permian and Triassic ages (Dew, 2018; Morley & Wonganan, 2000). The Cenozoic tectonics involves the penetration of India into Asia, which has rotated and extruded Indochina to the southeast along the NW–SE left-lateral strike-slip faults (Tapponnier et al., 1982). The clockwise rotation of Indochina affected the reverse sense of motion on the NW–SE strike-slip faults in Southeast Asia and caused the opening of the Cenozoic sedimentary basins (Tapponnier et al., 1982).

2.2 Late Cretaceous to Cenozoic Basin Evolution

Structural elements in the Mae Moh Basin are shown in Figure 1B, highlighting the NNE-SSW sigmoidal trending fault geometries.

Polachan et al. (1991) suggest that the small Cenozoic rift basins in Northern Thailand were formed as pull-apart basins due to sinistral strike-slip motion NE–SW trends and dextral motion on N–S to NW–SE trends. However, Polachan's model was not explicit on the types of stress systems contributing to reactivation. The transition in the stress regime from compression in the Eocene to that of the Middle Miocene may have been gradual (Chantraprasert & Utitsan, 2021). Some of the significant fault patterns around the basins swing from N–S to NE–SW trends and could be interpreted as forming at releasing bend geometries. However, the NE–SW fault trends appear to be much more discontinuous than proposed by Polachan et al. (1991) and do not seem to have large displacements, suggesting the pull-apart model is not appropriate (Morley, 2001; Rhodes et al., 2002).

The rift basin model is later proposed to explain the Cenozoic sedimentary basin forming (Morley, 2001); because the stress orientations and magnitudes within the rift basins of Thailand have fluctuated considerably from the Eocene to the Present (Morley, 2016), resulting in minor right-lateral slip causing episodic inversion or rotation of the extension direction (Chantraprasert & Utitsan, 2021). Thus, strike-slip faults are not responsible for opening all rift basins in Thailand; subduction rollback of the Indian plate to the west of Thailand is possibly an alternative mechanism to open the Cenozoic sedimentary basins (see Morley, 2001)

2.3 Geology of the Mae Moh Basin

The Mae Moh Basin is categorized by oblique border fault system and orthogonal intra-rift fault system. However, the border fault system of the Mae Moh Basin has not been defined in detail. It is likely that the NE-trending oblique-slip fault (Ngao Fault, see Fig. 1B) controlled the Permo-Triassic ridge and formed the western margin of the Basin (Uttamo, 2003)

Information from the Electric Generating Authority of Thailand (EGAT), such as wellbore data, outcrop data, and constructed geological cross-sections (from the Mae Moh mine) coupled with structural maps from 2D and 3D seismic data, provide a rare opportunity to study fault displacement in detail from outcrop to subsurface data (Morley et al., 2004).

The unpublished report from EGAT (Mae Moh Coal Deposit) states three distinct structural discontinuity patterns presenting in the Mae Moh Basin. The first patterns described are those of synthetic fault patterns. These patterns form a graben structure with the center of the Basin being downthrown relative to the east and west margins which are horsts. These structural discontinuities strike approximately

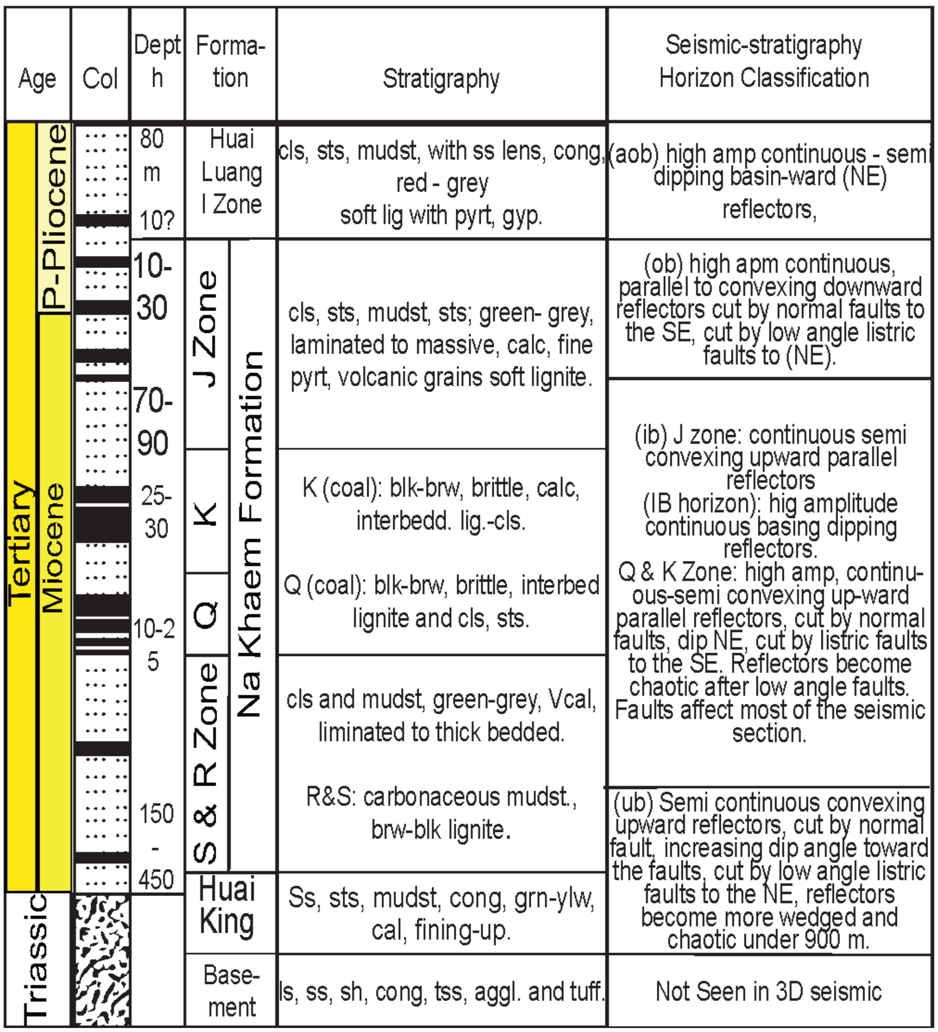

Figure 2. Stratigraphy and Seismic Classification. (cls) claystone, (sts) siltstone, (ss) sandstone, (cong) conglomerate, (mudst) mudstone, (pyrt) pyrite, (gyp) gypsum, (lig) lignite, (tss) tuffaceous sandstone, (sh) shale, (calc) calcareous, (Vcal) very calcareous, (aggl) agglomerate, (blk) black, (brw) brown, (grn) green, (ylw) yellow, (amp) amplitude. (Modified after Jitapankul et al. 1985)

north-south direction. Furthermore, the faults are generally steep (i.e., more significant than 50˚).

Additionally, on numerous occasions, the report states a single fault of large displacement is, in fact, a group of stepped faults, with each component fault only having a small displacement. These step faults were determined from the related density of borehole spacing. The second (antithetic) patterns produced structures that dip east and westwards towards the basin margins, striking north-south through the central basin, giving similar geometries as the first style. This style creates normal fault planes significantly flatter than the first phase fault pattern (e.g., 15˚ to 20˚). Throughout the basin, the outward dipping antithetic faults appear to displace the inward dipping synthetic faults. The antithetic faults are either straight or curved (convex upward).

Additionally, the third pattern of faulting was suggested to be present. The structural discontinuity is striking approximately east-west with a variable north-south dip direction. The report further states that these normal faults show evidence of being formed early in history as subsidence occurs and later continuing through deposition of younger sediments. Thus, developing growth faults from sedimentation loading. The production of growth faults has created stratigraphic thicknesses greater on the hanging wall side (Morley et al., 2004). The growth faults tend to be located towards the center of the basin and are associated with significant central graben faults.

Furthermore, faults are post-depositional and displace strata in the Haui King, Na Khaem formations (Fig. 2). However, the study from (Morley et al., 2004) states, in outcrops (Mae Moh Mine), fault zones tend to be narrow, and zones of drag on either side of the fault are also limited. Some claystone in these zones shows plastic elongation (Morley et al., 2004), which suggests that the rock behaved more plastic at the timing of faulting than previously thought. Further stating, seismic data shows the expanding of growth fault strata towards major bounding fault, hence faults populated during a syn-depositional period (e.g., Morley et al., 2004). In contrast to the border fault system, the intra-rift fault system is characterized by N-S-trending normal faults. Most of the faults with striations show pure dip-slip to high-angled oblique-slip with minimal evidence for strike-slip displacement. Based on fault-slip data, Morley et al. (2001) suggested that E-W to ENE-WSW extension dominated the evolution of the mine.

4. Data and Methodologies

4.1 3D Seismic Data

EGAT provided the 3D seismic survey (Mae Moh Mine 3D) used in this study. The survey covered an area of approximately 3.05 km^2 across the Mae Moe Mine's central sub-basin and extended at depth to 1.6 Km. Additionally, the Geodic data was WGS84, projection UTM zone 47 N, Datum plane 200 m above mean sea level. The seismic quality of the 3D survey is decent from the westernmost margin of the survey to approximately the middle and extends up to roughly ~1.2 km in-depth. Deeper than this, the seismic signal becomes chaotic and un-mappable. The seismic quality also decreases towards the east, possibly from the structural complexity and challenging conditions for data collection described in the company data acquisition. Thus, the seismic was poorly visible in these areas. In this study, the poor visible seismic reflectors were improved using Petrel's auto gain control and structural smoothing volume processing. As a result, the horizons were mapped, and structural discontinuities were more pronounced to aid with interpretations.

4.2 Seismic Horizon Interpretation

Seismic interpretation and visualization commenced using Petrel software. The seismic stratigraphy of the Mae Moh Basin was reproduced from the specs of the previous acquisition and interpretation reports (CGG Mae Moe Mine 3D 2014).

Distinguishable stratigraphic-structural boundaries in the 3D seismic dataset were interpreted in a 10 x 10 grid of inline and crosslines. Spacing between lines was 10 m, resulting in 100 m x 100 m. The smaller interpretation grid sizes were applied where complex structural discontinuities were observed, including 5 x 5 lines and some cases 2 x 2 lines (20 m x 20 m).

The horizon auto-picking tool in Petrel was utilized to interpret (horizon) lines; the threshold was set to .9 to prevent over-picking, especially across structural discontinuities. The technique used artificial neural networks to enable horizons to be tracked in three dimensions and was applied to produce the boundary of the interpreted horizons. The second process applied the manual horizon picking tool across areas of poor seismic data quality. Finally, using the interpolate polygon tool inside areas of known stratigraphic equivalent units. The technique uses complex statistical methods that estimate the value of all unknown data by a user-defined area of known horizon points, which was used to fill in the absence or poor quality of data in areas of interest. See Figure 2 for horizon interpretation criteria and classification.

4.3 Attribute Extraction & Structural Interpretations

Seismic variance, root-mean-square (RMS), and amplitude contrast were extracted on the 3D interpreted horizons. These were used to assemble fault maps and to investigate fault segmentation in depth. Attribute extractions were carried out and overlain in Petrel to highlight structural discontinuities.

Fault interpretations were made in the 3D data set by faults across multiple mapped horizons (stratigraphic units), subsequently cross-correlated with previously processed 2D seismic data set as well as borehole data to constrain interpretations. 3D fault segments were interpreted on N-NE to S-SW striking faults. Faults were not interpreted on the crossline; however, an arbitrary line was needed to identify the oblique structural discontinuities not easily identified in either cross or inline sections.

4.4 Data Limitations

The quality of seismic is generally poor from the middle to the easternmost area of the data set. The vertical resolution of the data is approximately 7-8 m or 70 Hz; additionally, reflectors seem to thin towards faults and then travel along structural discontinuities. Interpretation errors can be made when picking reflectors in the heavily faulted central area due to the structural complexity and environmental

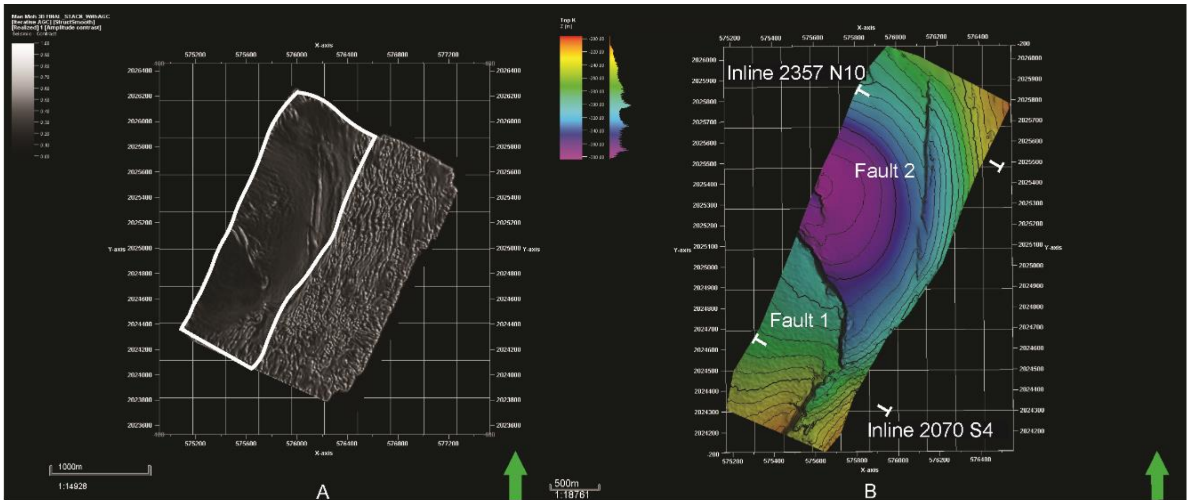

Figure 3. (A) Depth map of K (coal seam) horizon overlain with variance attribute. (B) Time slice of amplitude contrast attribute. Note the similar fault strike directions of two separate fault systems in A & B. White box shows horizon location. First fault system showing variable strike directions (NE-NW). Second fault system N-S strike direction.

obstacles obscuring the data collection process and some volume processing (overprocessing).

5. Results

This section aims to analyze the two extensional fault systems and their geometries to determine the mechanisms that contribute to the basin's formation. For this study, the seismic stratigraphy of the Mae Moh Basin is divided into four key sections, three horizons (coal seams from the previous study) and three additional horizons (see Fig. 2).

5.1 Extensional Fault System I

The first fault system (Fig. 3B) in map view shows a sigmoidal geometry pattern with variable west-northwest strike single direction fault; however, separate faults link to make one fault in cross-section view (Fig. 4). The system can be classified by splitting the upper (mapped horizons) continuous, parallel to sub-parallel basin dipping reflectors (J, IB, K, Q) to approximately 180 - 550 m below MSL (Fig. 4). The fault continues to displace the lowermost mapped horizon 550- 600 m (UB); In contrast to the upper horizons, the bottom of UB can be categorized by high amplitude, parallel to sub-parallel continuous reflectors with an increased angle of inclination towards the fault, causing a convex upward pattern. From approximately 500 m to the extent of seismic data, the faults were inferred to continue the strike trend. Thus, causing a wedge-like shape on the hanging wall of the fault, reflectors increase dip angle towards the fault (Fig. 4).

The first fault system displays much different geometric growth patterns to the north than that of the southern (Fig. 5). The fault can be classified by splitting the same horizons as in the south; however, the continuous parallel to sub-parallel reflectors increase in the dip angle towards the Basin center. Additionally, the fault geometry becomes more linear than in the south, and some places showing oblique structural discontinuities. Subsequently, losing the wedged shape pattern on the hanging wall of the fault.

A second fault system is present to the northeast of the first fault system, showing different fault architectures than that of the southwest.

5.2 Extensional Fault System II

The second fault system (Fig. 3B) in map view shows a dominant N-S strike direction single fault; however, the cross-section view shows two faults linking to produce planar style geometry. The system can be classified by splitting the upper (mapped horizons) continuous, parallel basin dipping reflectors (K, Q, UB) to approximately 290-750 m below MSL (Fig. 4). In contrast to the first fault system, the bottom of UB can be categorized by high amplitude, parallel to sub-parallel continuous reflectors dipping towards the basin margin. Above the planar fault of the second fault system, a low angle listric fault is present, producing convex upward geometries. The cutting of critical horizons classified this fault by high amplitude continuous parallel to sub-parallel reflectors dips increasing towards the Basin center.

In contrast to the first fault system, the second fault system does not differ from the north. Instead, the two fault systems interpreted seem to link creating sigmoidal geometry (Fig. 5). Therefore, the fault can be classified by splitting the same horizons as south; however, the continuous parallel to sub-parallel reflectors decreases in the basin center's dip angle. Furthermore, creating a more wedged shape across the fault with shallower dips.

6. Discussion

In northern Thailand, the tectonic evolution of each coal basin appears to be different: variables are the magnitude and timing of inversion and the onset and duration of extension (Morley et al., 2001). Two models have been proposed to explain the Late Cretaceous–Palaeogene tectonic events associated with the opening of Thailand's Northern Cenozoic basins (see Polachan et al. 1996; Tapponnier et al., 1982; Morley et al. 2001). They are the strike-slip pull-apart basin and extensional model. However, the pull-apart model is very simple and does not explain some of the geometries discussed above.

Morley et al. (2001) state the north-south-striking rift basins of the western Gulf of Thailand have undergone extension from the Oligocene to Mid-Miocene, whereas further SE the Pattani and Malay basins underwent extension during the Eocene(?) Oligocene (Morley et al. 2001). These periods cover both sinistral and dextral phases of strike-slip motion of the regional fault zones (Three Pagodas and Mae Ping fault zones) (Lacassin et al., 1997). Thus, inferring the extensional model is better suited for opening the Mae Moh Basin.

(Morley and Wonganan, 2000) conducted a detailed mapping of the fault patterns in the mine. The paper states, the eastern part of the mine displays a simple fault pattern composed of N–S striking, overlapping, generally soft-linked faults. The western part of the mine is very different. N–S striking faults are bounded by NE–SW striking faults. The N–S striking faults have zig-zagging map patterns involving NE–SW segments (Figure. 1B).

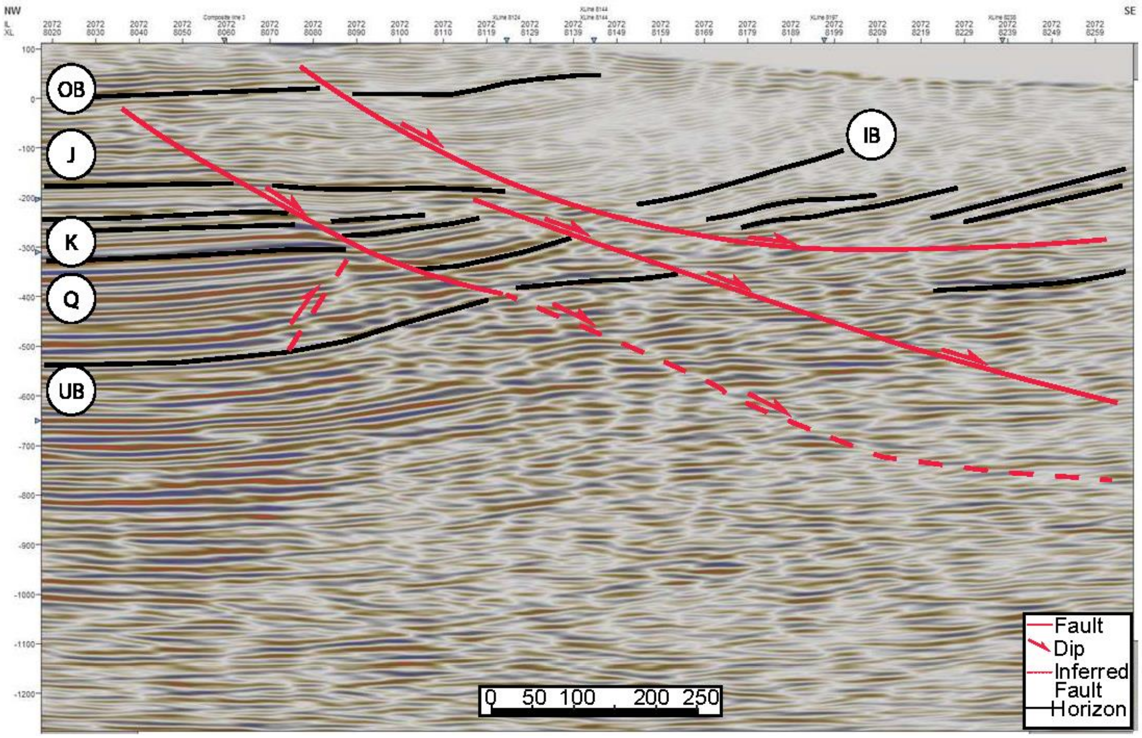

Figure 4. Inline 2070 S4. (OB) overburden, (J) J coal, (IB) internburden, (K) K coal, (Q) coal, (UB) underberden. Location on Fig. 1B.

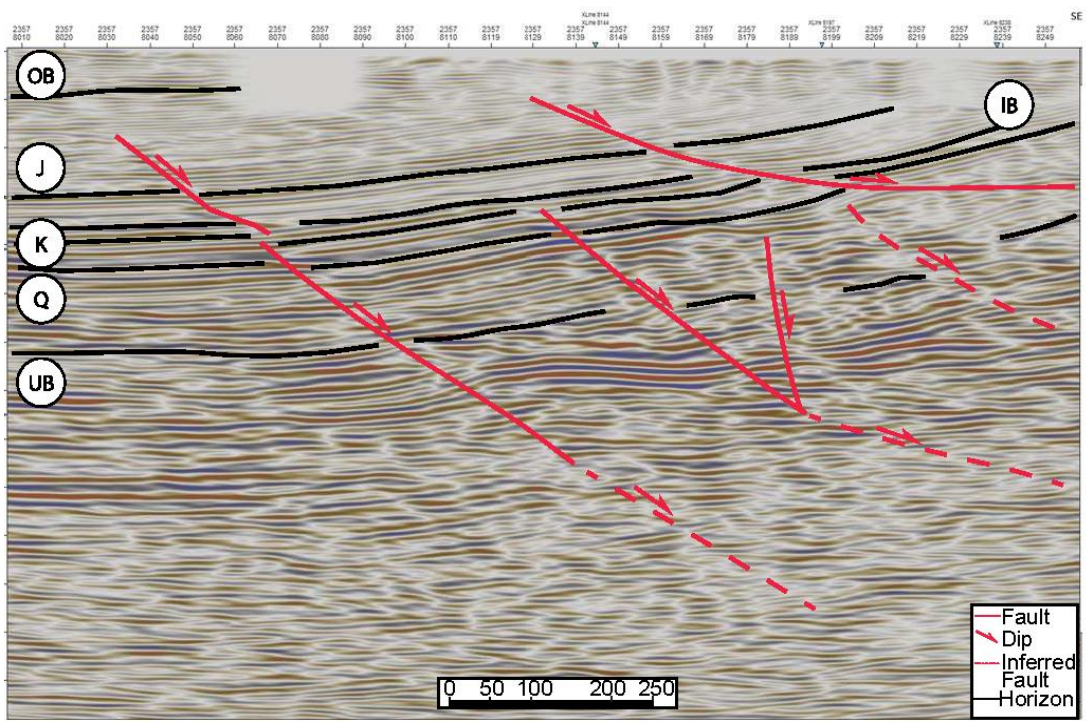

Figure 5. Inline 2357 N10. (OB) overburden, (J) J coal, (IB) internburden, (K) K coal, (Q) coal, (UB) underburden. Location on Fig. 1B)

Additionally, planar normal faults cut the Miocene sequence showing changing dip angle at the soft layer (i.e., coal seam). On the other hand, tilted beds are associated with the listric fault (Figs. 4 & 5). Bed dip angle increases towards the fault, indicating block rotation.

Furthermore, inversion features have been interpreted from outcrop and previous 2D seismic surveys (Sompong et al., 1996). However, no solid 3D seismic evidence was found at this time.

The faults present in the 3D seismic patterns compare well with fault systems in analog models of rift basins, which geometries are controlled by pre-existing structures (McClay et al., 2002; Corti, 2012). Additionally, fault patterns in the western part Mae Moh mine is also representative of sandbox models of oblique extension with a 45˚ angle (e.g., Withjack and Jamison, 1986; Tron and Brun, 1991; McClay and White, 1995; Clifton et al., 2000), and suggests that NE–SW striking oblique basement fabrics have influenced the western half of the mine, but not the eastern half (Morley et al., 2004).

In summary, normal faults are the dominant structure in the Mae Moh Mine 3D seismic data. Reverse faults are rarely found in outcrop analysis, possibly indicating extension interrupted by inversion events associated with sub-horizontal NW-SE to NE-SW maximum principal stress ($\boldsymbol{\sigma}_1$) direction (Morley et al., 2001). A further seismic investigation is needed in order to gain more data to perform a quantitative fault analysis.

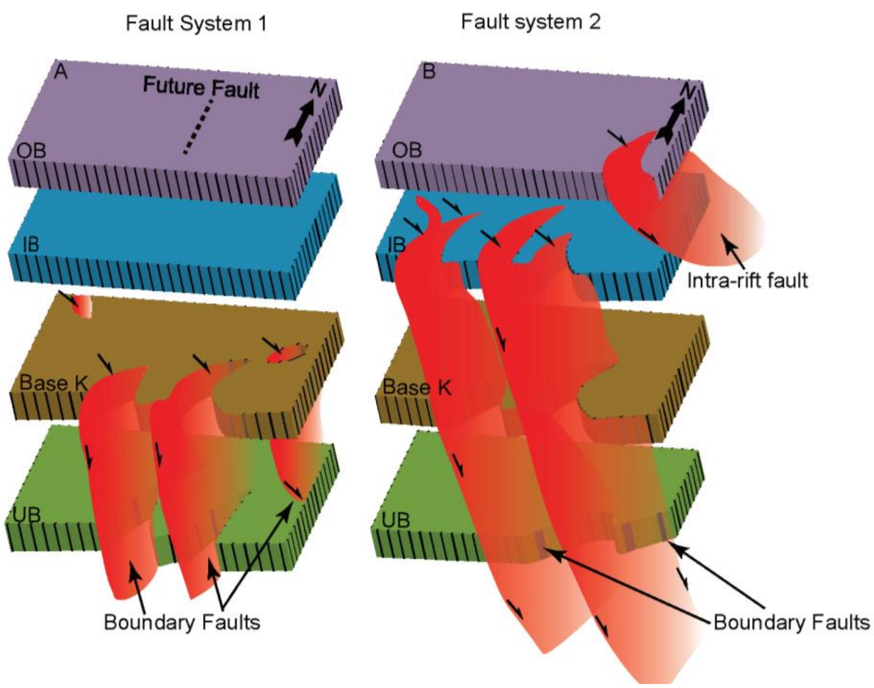

Figure 6. 3D schematic illustration of the fault systems in Mae Moh seismic survey. Horizons increase with depth. Note striations show slight slip direction. Vertical exaggeration; Boundary Faults striking primarily NE (parallel to Ngao fault) and Intra-rift fault primarily N-S. (A) early deformation with segmented faults. (B) present day with linkage of en echelon boundary fault and nucleation of intra-rift fault.

7. Conclusion

Normal faults presenting in the Mae Moh Mine seismic data represent fault populations that developed early to the late Miocene formation of a sedimentary basin (see Morley & Wonganan, 2000). The interpreted faults investigated show complex kinematic patterns creating multiple displacement highs and lows indicative of fault linkage. Similar geometries have been described for forming both strike-slip pull-apart and extensional regimes (see Polachan, 1991; Tapponnier et al., 1982; Morley, 2001).

In the Northern and Western Sub-basins, their western margin can be classified as en-echelon segmentation and overlapping fault arrays (Fig. 6A). It is possible that these faults propagated along strike and linked to the border faults (fault 1) resulting in rotation and increasingly sigmoidal fault geometry. The geometry of the eastern margin can be inferred from the NNE-striking ridge located approximately 10 km southeast of the Mae Moh mine. Likely, the ridge-parallel fault extends northwards along the strike and links with the Ngao Fault. This indicates that the oblique NNE-striking border fault system potentially controls the structural development of the Mae Moh Basin.

In contrast to the border fault system, the intra-rift fault (fault 2) system is characterized by N-S-trending normal faults (Fig. 6B). Based on fault-slip data, Morley et al. (2001) suggested that E-W to ENE-WSW extension dominated the evolution of the mine.

The geometries of the extensional fault systems address in this paper, together with displacement analyses (Morley & Wonganan, 2000), indicate that N-S oriented faults were initially segmented, forming en-echelon fault arrays within the overall NE trending Mae Moh Basin.

The high structural complexity and poor exposures in rift basins are one factor hindering the field from excepting one model that covers the multiplex fault architectures in their entirety. However, more data such as well data and field observations from recent mine faces are critical to correlate the proposed structural interpretations presented in this study quantifiably.

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