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EDITED BY

Peng Guo,
Commonwealth Scientific and Industrial
Research Organisation (CSIRO), Australia

REVIEWED BY

Jia-jia Yang,
Qingdao Institute of Marine Geology
(QIMG), China
Yan Poong,
Chinese Academy of Sciences (CAS),
China

*CORRESPONDENCE

Xiwu Luan,
✉ xluan@sdust.edu.cn

RECEIVED 26 June 2023

ACCEPTED 08 August 2023

PUBLISHED 23 August 2023

CITATION

Guo M, Luan X, Zhang H and He B (2023),
Geometric and kinematic analysis of
faults bordering the Andaman sea
continental shelves: a 3D seismic
case study.
Front. Earth Sci. 11:1247665.
doi: 10.3389/feart.2023.1247665

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Geometric and kinematic analysis of faults bordering the Andaman sea continental shelves: a 3D seismic case study

Meng Guo¹, Xiwu Luan^{2*}, Huixing Zhang¹ and Bingshou He¹

¹Key Laboratory of Submarine Geosciences and Prospecting Techniques, Ministry of Education, Ocean University of China, Qingdao, China, ²College of Earth Science and Engineering, Shandong University of Science and Technology (SDUST), Qingdao, China

To clarify the tectonic evolution of M15 block in the Andaman Sea, we perform a delicate study of fault geometry and dynamics using a 3D seismic data. The data reveal eight sequence interfaces from the Early Oligocene to the Quaternary, large scale and multi angle extensional strike-slip faults, and a series of normal faults. The two large scale faults F1 and F2 start in the Eocene and end in the Quaternary, controlling the regional structure. The NNE-SSW strike-slip F1 fault belongs to the South Sagaing fault and the NNE-SSW strike-slip F2 is the eastern Andaman fault, the strike-slip movement of which are controlled by the impact of the collision between the Indian plate and the Eurasian plate. Through the analysis of the fault development history by the method of the ancient drop and the growth index, we find that most of the large or secondary scale faults reach the maximum drop and growth index in the Miocene, indicating that the Miocene is a significant period of plate collision enhancing and faults generating. The regional stress field is dominated by E-W tension. The continental crust has expanded rapidly from the Oligocene to the Miocene which results in the rapid subsidence of the crust. This regional stress intensity becomes weak after the Miocene. The activities of the faults caused a large difference in terrain height between the west and the east in the study area, forming a pattern of the western depression and the eastern terrace. Many NNE-SSW, NE-SW or NEE-SWW trend strike-slip faults and minor faults develop in the Miocene. It echoes the event that the convergence and subduction of the Indian plate from SW to NE direction led to the right rotation and N-NNE strike-slip of the West Myanmar block in the Miocene, thus forming a regional large strike-slip fault. All of the faults affect the structure of the region.

KEYWORDS

Andaman sea, strike-slip, Sagaing fault, Mergui Basin, structure

1 Introduction

The Andaman Sea has always been considered as a region of Cenozoic extensional and strike-slip activities and is related to the Himalayan compression event. Since the Cenozoic, due to the solid tectonic movement, the geomorphic pattern of the whole Southeast Asia and even the global geomorphology has undergone dramatic changes, especially the orogeny represented by the uplift of the Qinghai Tibet Plateau has a significant impact on the changes of the global environment and climate (Zachos et al., 2001; Hall, 2002; Yin, 2010). The Andaman Sea is located at the intersection of the Indian and Eurasian plates. Influenced by

plate movement, it has complex structural characteristics, multiple fault patterns and wide distribution, forming a typical “trench arc basin” system (Diehl et al., 2013).

Controlled by the closure of the New Tethys Ocean Basin at 60–50 Ma, the collision between the Indian plate and the European plate (Garzanti and Gaetani, 2002; Najman, 2010; Wu et al., 2014), and the rifting and back-arc pull apart spreading of Andaman to the east of the Sunda subduction zone, multistage faults are widely distributed in the region (Khan and Chakraborty, 2005; Khan et al., 2017). The Sagaing fault extends southward from the Myanmar land to the Andaman Sea area. It is divided into several secondary faults at the sea inlet of the Ayeyarwaddy Delta and connected with the central expansion area. As a back-arc spreading center formed in a typical extensional environment in the Andaman Sea, the leading regional strike-slip faults are the West Andaman Fault, the Sagaing Fault and the Sumatra Fault from west to east. The characteristics of the faults in the sea area are related to the onshore area. The West Andaman fault separates the western accretion wedge zone, forearc depression zone and western highland uplift zone from the center back-arc basin. The Sumatra fault passes through the northern Sumatra basin and the southern back-arc basin from south to north, while the Sagaing fault runs through the entire eastern basin.

The strike-slip fault is the main feature of fault in the study area. With the convergence and subduction of plates, the dip angle will change and the angle near the subduction center will be smaller (Fitch, 1972; McCaffrey, 1992; Philippon and Corti, 2016; Schütt and Whipp, 2020; Yang et al., 2021; Okuwaki and Fan, 2022). This will result in large strike-slip faults with a length of hundreds of kilometers or longer, which mostly on the overriding plate and close to volcanic arcs (Manaker et al., 2008), such as the Alpine fault in New Zealand (Norris and Cooper, 2001), the Great Sumatra Fault in Sunda (McCaffrey, 2009) and the Enriquillo Plain Garden Fault (EPGF) in Caribbean (Calais et al., 1992; Mann et al., 1995). Due to the strike-slip faults are prone to large earthquakes, many people have conducted research on this issue (Sylvester, 1988; Schmittbuhl et al., 2006; Melgar et al., 2015; Chu et al., 2021; Hu et al., 2021). The relationship between different fault attributes (such as length displacement) is very important for understanding and predicting its mechanical, hydraulic, topographic and seismological characteristics (Kim and Sanderson, 2005; Gutscher and Lallemand, 2010; Ul-Hadi et al., 2013; Fossen and Rotevatn, 2016; Zhang et al., 2020; Yuan et al., 2022; Cheng et al., 2023). The change of strike-slip fault geometry is easy to observe on the surface and is often used to study the geometry of dip-slip faults (Barka and Kadinsky-Cade, 1988; Zhang and Sagiya, 2018; Zuza and Carlson, 2018). The degree of fault deformation may vary with geometric complexity of the faults (Dolan and Haravitch, 2014; Milliner et al., 2016). Strike-slip faults include both small-scale millimeter scale faults and large-scale faults that run through the entire crust (Segall and Pollard, 1983; Martel and Pollard, 1989; Dickinson, 1996; Singh et al., 2013). Its sliding distribution are commonly determined by correlating offset stream channels and offset channels are formed by the interplay of tectonic and geomorphic processes (Papaleo et al., 2017; Reitman et al., 2019). To study the distribution and features of the strike-slip faults is significant to understanding the migration and accumulation of hydrocarbon resources (Qiu et al., 2019; Tian et al., 2022).

Predecessors have also done some work on the Andaman Sea. Polachan and Racey (1994) studied the geological situation and tectonic evolution of Mergui Basin, located in the south of the back-arc basin

area. Good progress has also been made in the research on the tectonic evolution of the Alcock rise and Sewell rises in the middle of the back-arc basin and the central expansion zone (Morley and Alvey, 2015; Morley, 2017; Curray, 2005; Curray et al., 1979; Curray et al., 1982; Raju et al., 2004; Diehl et al., 2013; Morley, 2013; Mahattanachai et al., 2021). However, few studies have been conducted on the Mergui platform area centered on the M15 block and penetrated by the Sagaing fault. The tectonic evolution of the study area has not been reported yet. The development and distribution of faults play a controlling role in the regional tectonic evolution. Therefore, we study and analyze the fault structural characteristics of the M15 block in the Andaman Sea, so that make the tectonic evolution of the area clear and provide a guidance for understanding the migration and storage of petroleum.

2 Geological setting

The Andaman Sea is located in the eastern part of the Bay of Bengal, at the intersection of the Eurasian and Indian Ocean plates (Curray, 2005). The area is about $7.98 \times 104 \text{ km}^2$, 1200 km from north to south, and a width of 645 km from east to west. The average water depth is about 1000 m, but the water depth in the central area (about 5% of the sea area) exceeds 3000 m, and water depths very locally exceed 4000 m (Morley, 2017). As a marginal sea in Southeast Asia, it is a convergent continental margin (Luan et al., 2021) (Figure 1), stretching from the Malay Peninsula in the east to the Bay of Bengal in the west, from southern Myanmar in the north to northern Sumatra Island in the south (Curray, 2005; Srisuriyon and Morley, 2014). The study area, block M15 (Figure 1), is located in the eastern part of the Andaman Sea, with a latitude range of $11^{\circ}40'00''$ – $12^{\circ}19'07''$ and a longitude range of $96^{\circ}23'15''$ – $97^{\circ}01'48''$. The temporal sampling rate of seismic data is 2 m, and the area of 3D survey data is about 4000 km^2 . The Andaman Sea is a Cenozoic Ocean basin, and the regional sedimentary strata are mainly Cenozoic strata (Table 1).

3 Data and methods

The survey area is about 200 km from the Mergui port in Myanmar, with a depth of more than 100 m. The maximum depth of the western boundary of the survey area is about 1500 m. The depth gradually deepens and varies significantly from eastern to western boundaries. The data acquisition was completed by the COSL seismic exploration vessel HAIYANGSHIYOU 721 (abbreviated as HYSY721). The seismic sampling rate is 2 m, and the 3D survey data area is about 4000 km^2 consisting of 117 prime sail lines with an average sail line length of 75.725 km. HYSY721 uses twelve 7050 m streamers and two alternately fired 4030 cubic inch air gun arrays in configuration-acquired data.

We use well-imaged high-resolution 3D seismic data to study the fault system in the region. Firstly, the sequence of the M15 block is divided by seismic interpretation profile and relevant geological data in the study area. Secondly, the six significant faults in the region are quantitatively analyzed by the ancient drop method and growth index method. Then, the dynamic origin of the faults is analyzed, and its influence on the regional tectonic evolution is analyzed.

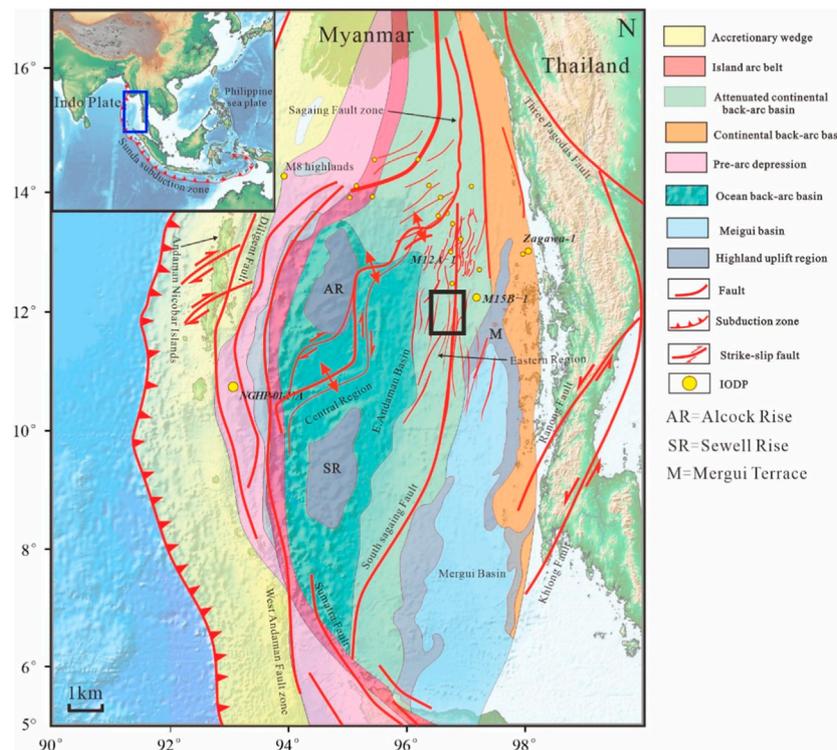


FIGURE 1 Map showing major geomorphologic features along the Andaman Sea. The study area is marked by the rectangle with the outline.

TABLE 1 Regional sedimentary structures.

Epoch	Comments	Depositional environment	Reflection geometry			Horizon
			Reflection configuration	Reflection amplitude	Reflection continuity	
Quaternary	Normal deposition with no or less tectonic effect	Sag-fill	Parallel	Moderate to high	Continuous	SF
Pliocene	L Basin fill under tectonics effect	Basin fill	Wavy	Low to moderate	Continuous	T1
	E MTD (Mass transport deposition)	Progradational	Chaotic	Low	Discontinuous	T2
Miocene	L Basin fill	Basin fill	Wavy	Low to moderate	Continuous	T3
	M MTD (due to uplift of invisible bank)	Sigmoidal progradation	S-shaped	Moderate to high	Continuous	T4
	E MTD	Onlap fill	Semi-transparent Chaotic and moderately wavy	Low	Discontinuous	T5
Oligocene	Sand deposits	Onlap fill	Moderately wavy	High	Moderately continuous	T6
						Tg

4 Seismic stratigraphy

Referring to the relevant stratigraphic sequence division (Ye et al., 2022; Chen et al., 2023), we divided the stratigraphic sequence in more detail and identified seven stratigraphic sequences (from old to new) in the seismic data profiles: the Early Oligocene, the Late Oligocene, the Early Miocene, the Middle Miocene, the Late

Miocene, the Pliocene and the Quaternary, which are defined by eight sequence interfaces named Tg, T6, T5, T4, T3, T2, T1 and SF, respectively. We also identified six large strike-slip faults and secondary faults, named F1, F2, F3, F4, F5 and F6, respectively. The distribution of them is shown in Figure 2. The color of Figure 2 represents the time of T6 horizon. In order to clearly show the faults development history, we select three seismic profiles (Figure 3A;

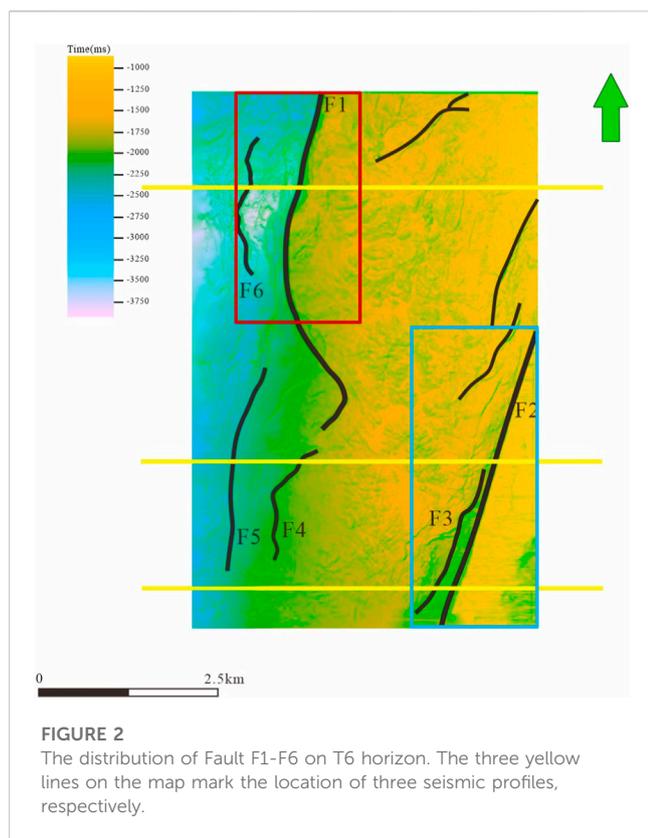


Figure 3B; Figure 3C), the position of which are shown in Figure 2, the yellow lines named line1, line2 and line3. From Figure 3A, we can see that there is a very bit fault named F1 passing through the basement Tg until SF. It is easy to see that the F1 fault was active before the Oligocene. Through analysis, we know that the F1 fault is the known South Sagaing fault. It is the Sagaing fault that controls the tectonic movement in the area, and the Sagaing fault was formed by plate movement before the Eocene. After the Eocene, the Andaman Sea suffered from land and land subduction, and the Myanmar microplate collided with the Indian plate, resulting in the counterclockwise rotation of the Indian plate, while the Myanmar microplate further moved northward, eventually coupling with the Indian plate boundary. Although there is no sufficient evidence to prove that the F1 fault belongs to the same fault as the Sagaing fault, we still call it the South Sagaing fault because it has the same strike as the dextral strike slip Sagaing fault. Besides, in the process of fault analysis for the seismic profiles, it is found that the F1 fault is obviously connected with the South Sagaing fault in the north and south of the study area, which further proves that the F1 fault belongs to the South Sagaing fault. The activity of the fault caused a large difference in terrain height between the east and the west in the study area, forming a pattern of the separation of the western depression, the eastern slope zone and the eastern terrace.

The F2 fault (Figure 3B; Figure 3C) we call it the eastern Andaman fault separates the Mergui Ridge from the eastern platform. Affected by the F2 fault, the Oligocene strata on the right side of F2 were uplifted and received some denudation, leading to the thickness decreased significantly. Moreover, the strike-slip and rifting in the north of Mergui Basin further increased the thickness difference between the east and west sides

of the fault (Luan et al., 2023). In the Early Miocene and middle Miocene, rifting and strike-slip occurred in the northern part of the Mergui Basin and the degree of back-arc expansion increased. At the same time, there was a large-scale eruption of volcanic magma, coupled with the uplift of the volcanic island arc, and thus the regional terrain difference also increased. From Figure 3B and Figure 3C, we can also see that the changes of the strata (T3-SF) were not so obvious after Miocene. It is due to the activities of the faults attenuated.

NNE-SSW strike-slip faults and several NEE-SWW secondary faults (such as F3-F6 faults in Figures 3A–C) control the structural development in the region. A series of normal faults are also developed in M15 block of Andaman Sea. In order to clearly show the trend of the faults, we extract the coherence attributes of T6 horizon in the red rectangle area (Figure 4A) and the blue rectangle area (Figure 4B) of Figure 2. From Figure 4, we can clearly see the F1 fault, the F2 fault and other secondary or smaller faults. The faults mostly are distributed in NNE-SSW, NE-SW or NEE-SWW directions. The secondary faults, mainly showing extensional displacement, are very closely distributed in the basin and tend to form arrays with dominant dip or conjugate fault groups. The NNE-SSW trending Sagaing fault in the study area is consistent with the further northward trending Sagaing fault. These faults interact with each other to form the current tectonic structure.

5 Discussion

5.1 Fault families around study area

Faults developed in the study area comprise four fault families based on their geometry, orientation, distribution and relationship with main structures (Figure 5).

The study area has produced large-scale and multi-angle extensional strike-slip faults. Through refined interpretation of seismic profiles and identification of faults in the study area, it is believed that the area mainly includes negative flower shaped faults, “Y” type composite faults, domino-type fault zones and graben horst structural combination styles, which are widely distributed in the whole study area.

- 1) The negative flower structure is associated with the strike-slip fault under the tensile and torsional stress field conditions (Figure 5A; Figure 5C). The fault forms a syncline structure above the strike-slip fault. The flower structure is dominated by positive slip distance, and the cross-section is steep and gentle. The stratum between the faults is a graben structure. The folds and faults derived simultaneously on the flank are arranged in the echelon.
- 2) Domino fault zone: a series of faults with a consistent or nearly consistent dip in the profile and parallel or nearly parallel strike in the plane from the domino structural style (Figure 5B).
- 3) “Y” type fault is often developed in an extensional fault depression basin (Figure 5A). The intersection of the main fault and the reverse dipping secondary fault presents a “Y” shape. The main fault is significant in scale and has been developed for a long time. The fault usually passes through the lower sedimentary layer, which is generally a basin-

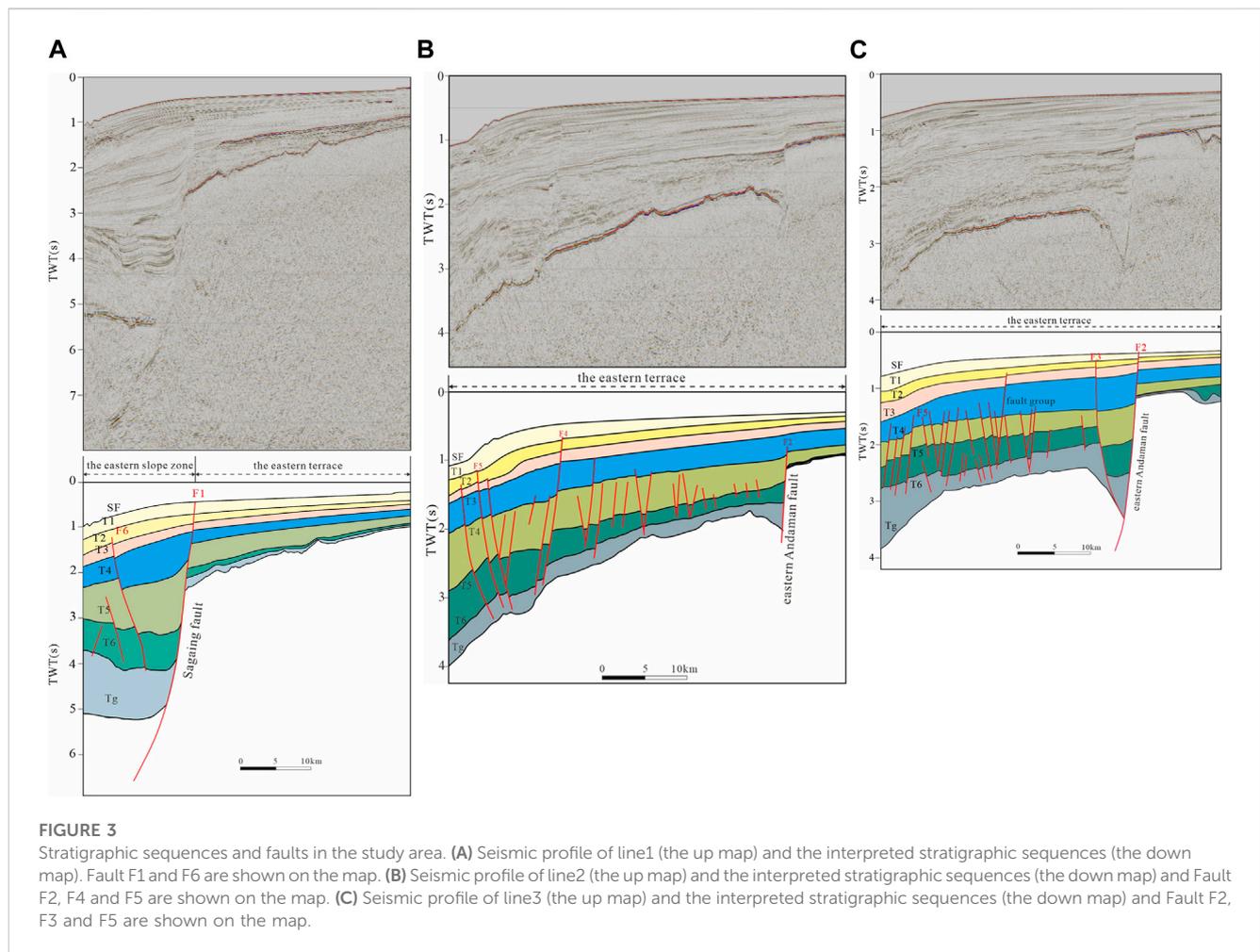


FIGURE 3 Stratigraphic sequences and faults in the study area. (A) Seismic profile of line1 (the up map) and the interpreted stratigraphic sequences (the down map). Fault F1 and F6 are shown on the map. (B) Seismic profile of line2 (the up map) and the interpreted stratigraphic sequences (the down map) and Fault F2, F4 and F5 are shown on the map. (C) Seismic profile of line3 (the up map) and the interpreted stratigraphic sequences (the down map) and Fault F2, F3 and F5 are shown on the map.

controlling or belt-controlling fault, and controls the depression and boundary of the region. The secondary fault is generally located in the shallow section of the stratigraphic depression side, opposite the tilt direction of the main fault.

4) Graben and horst: the two sides of the graben are surrounded by faults, and the middle is a falling fault block common in fault basins. The horst is opposite to the graben; the middle part is a rising fault block, and the fault blocks on both sides are relatively falling. Graben is more developed in the areas where the crust is stretched, and graben horsts are often associated with development, which occurs alternately under the control of faults. A representative horst combination can be found in Block M15 (Figure 5C).

5.2 Quantitative analysis

In this section, we select six representative faults from the four fault families to compile. These data are used to evaluate the growth history of faults.

The fault system is divided into two levels. The first level fault mainly controls the slope break zone boundary between the eastern Andaman Sea platform and the western depression or eastern slope zone. It controls the formation and evolution of oil and gas in the

region. The secondary fault mainly controls the characteristics of the secondary depression and graben horst in the area, leading to the uplift and subsidence of the stratum. The secondary fault significantly restricts oil and gas accumulation and storage. In the study area, faults have an important influence on the sedimentation and distribution of provenance.

The F1 and F2 faults are the primary boundary significant faults controlling the eastern part of the Andaman Sea. They extend long and have a large scale. The profile shows that they penetrate the T6 reflector downward. The quantitative analysis of the F1-F6 faults in the study area is carried out by using the method of ancient fall and growth index to study the characteristics of fault activity in the area (Figure 6).

F1 is the Sagaing fault. It controls the regional structure. We can see from Figure 6A that the fault began in the Eocene and then started to grow. In the Oligocene, it reached the maximum ancient drop, 1456.17 m with the maximum growth index, 5.87. After the Oligocene, the ancient drop and growth index showed a decreasing trend as a whole. This is because the strata in the west of the fault had been in subsidence and the degree of subsidence was severe in the Oligocene, leading to the maximum growth index and ancient drop. After that, the subsidence became slowly.

F2 is the East Andaman Fault. The fault trend in the region is NNE-SSW; The west of F2 is the eastern platform, where the traps

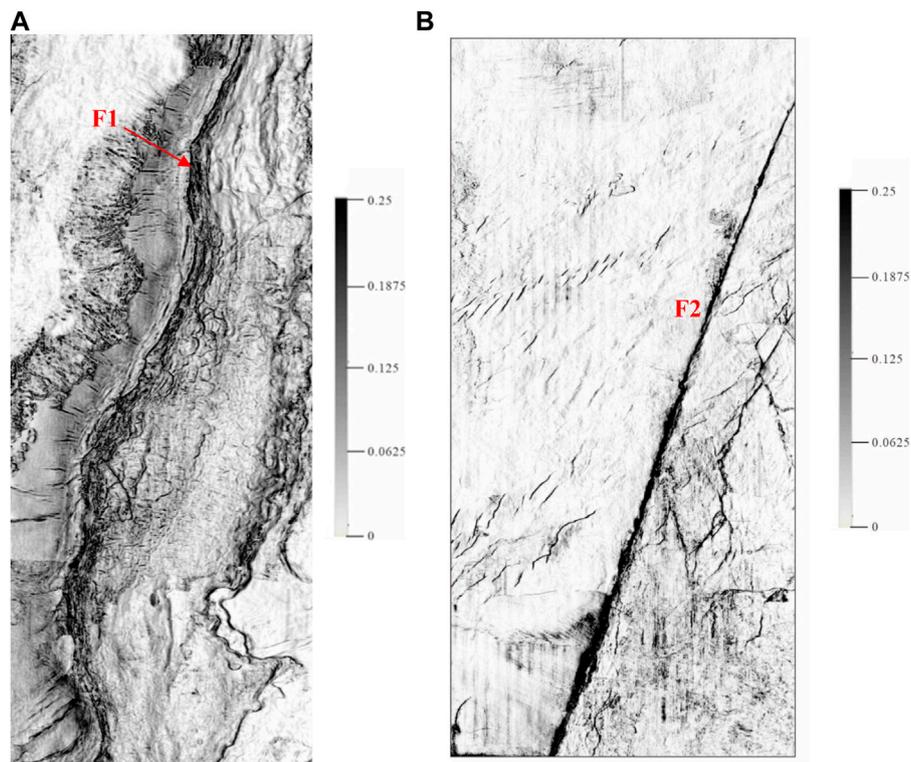


FIGURE 4
 Faults distribution in the study area. (A) The coherence attribute slice of T6 horizon in the red rectangle area of Figure 2. (B) The coherence attribute slice of T6 horizon in the blue rectangle area of Figure 2.

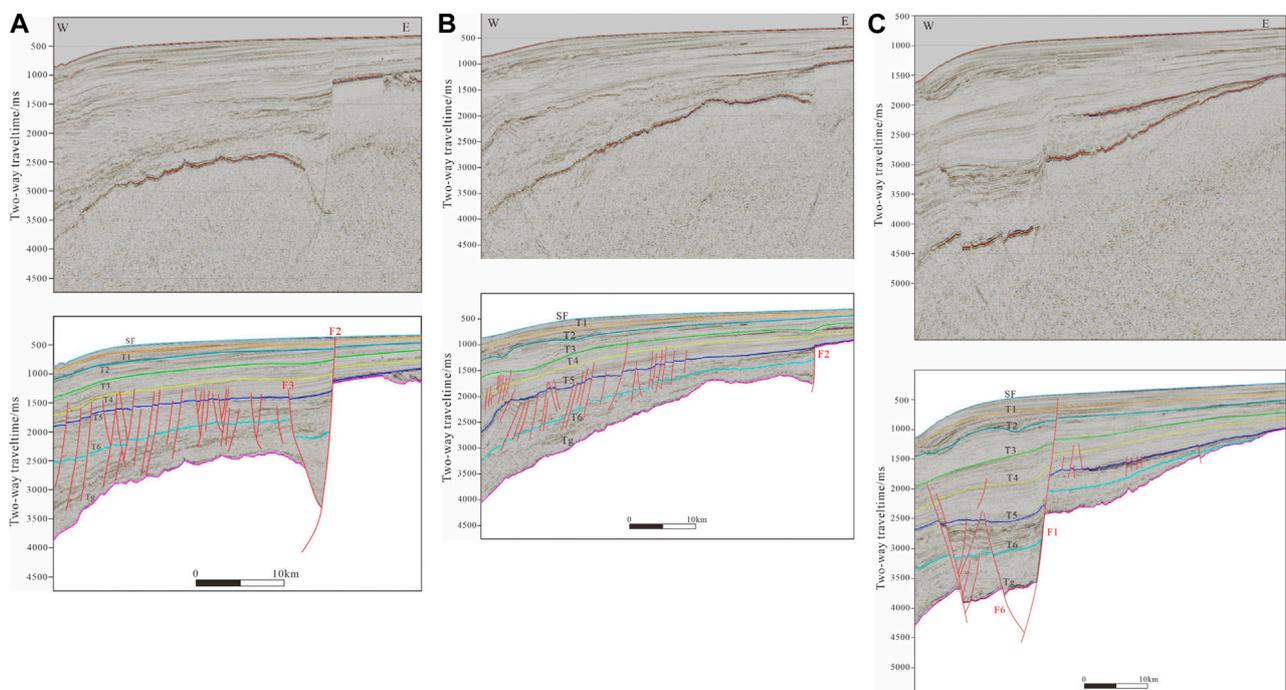


FIGURE 5
 Geological sections and faults across the M15 block of Andaman Sea ((A–C) is the profile of the study area from south to north).

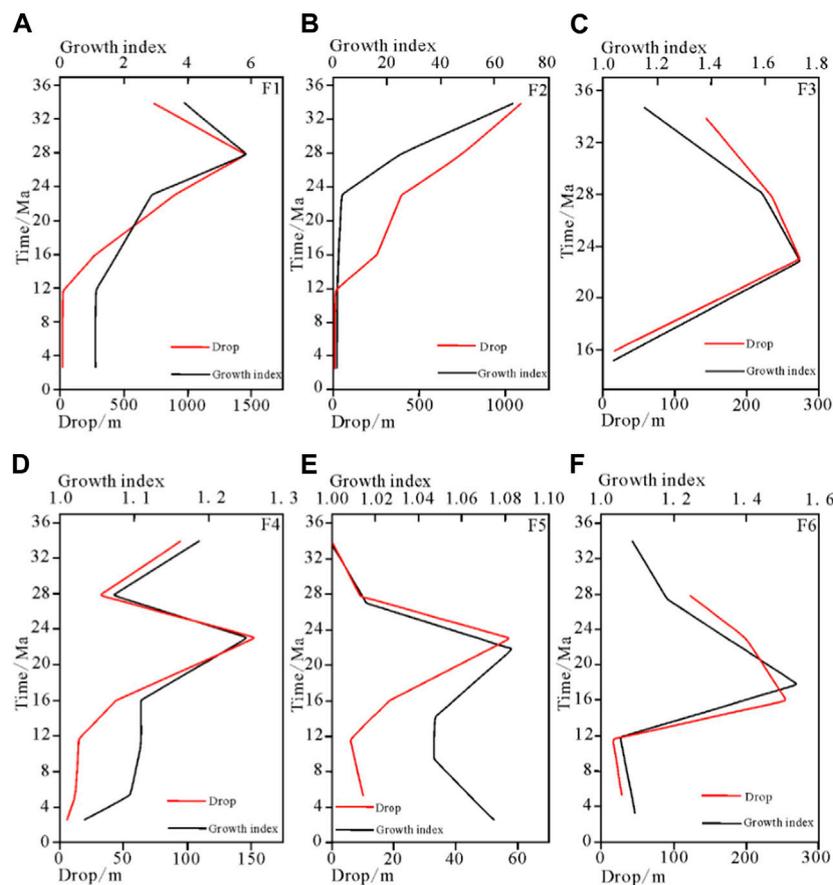


FIGURE 6
Analysis of the ancient drop and the growth index of F1–F6 faults ((A–F) correspond to F1–F6 respectively).

are relatively well-defined. The east side of F2 is Mergui Ridge. [Figure 6B](#) shows the ancient drop and growth index change dramatically before the Miocene, illustrating that a significant difference in strata drop and thickness before and after the Miocene. The reason is that the F2 fault was more active before the Miocene than after it, characterized by higher localized basement and thinner strata due to denudation.

It can be seen from the figures ([Figures 6C–F](#)) that the faults ancient drop and growth index are generally represented as one activity peak in the Middle Miocene. Since the Late Oligocene, the faults ancient drop and growth index in the study area have gradually increased, indicating that the faults activities have gradually increased; In the Early Miocene, the faults ancient drop and growth index reached the maximum, indicating that the faults activities reached the peak, which was the most active period of tectonic activity; After the Early Miocene, the faults ancient drop and growth index decreased, indicating that the activity rate of faults and tectonic decreased gradually.

Since the Oligocene, the fault ancient drop and growth index trend tend to be consistent. The fault ancient drop and growth index reached the maximum in the Early Miocene, indicating that the fault activity reached the maximum in this period. At this time, due to the collision between the Indian Plate and the Myanmar microplate, the Sagaing fault started to dextral strike-slip, the Myanmar Basin

experienced tension and fracture, the Andaman Sea expanded, and the Mergui basin was formed. At the same time, large-scale marine transgression began to occur, characterized by progressive sedimentation of sandstone and mudstone from river facies and delta facies to shallow sea facies, leading to an increase in the thickness difference between the hanging wall and footwall of the fault. The reason for the thinning of the hanging wall of the fault may be due to the effects of ocean current scouring, seawater erosion, etc. Therefore, the fault growth index increase may be caused by the combined effects of sedimentation and seabed erosion. After that, the ancient drop and growth index decreased. In the Late Miocene, the ancient drop and growth index reached the lowest, and the fault activity gradually weakened. This indicates that a large-scale strike-slip pull-apart movement along the Sagaing fault was from the Early Miocene to the Early Pliocene. The East Andaman Sea Basin gradually developed, and the Mergui Basin then turned into a depression stage.

From the Early Pliocene to the present, the Myanmar microplate continued to move northward and collided with the Himalayan fault of the Eurasian plate. Due to the blocking effect of the Himalayan fault, the region underwent structural inversion. A series of negative flower structures, “Y” type faults and other structural styles were produced by torsional compression and extrusion and the region is

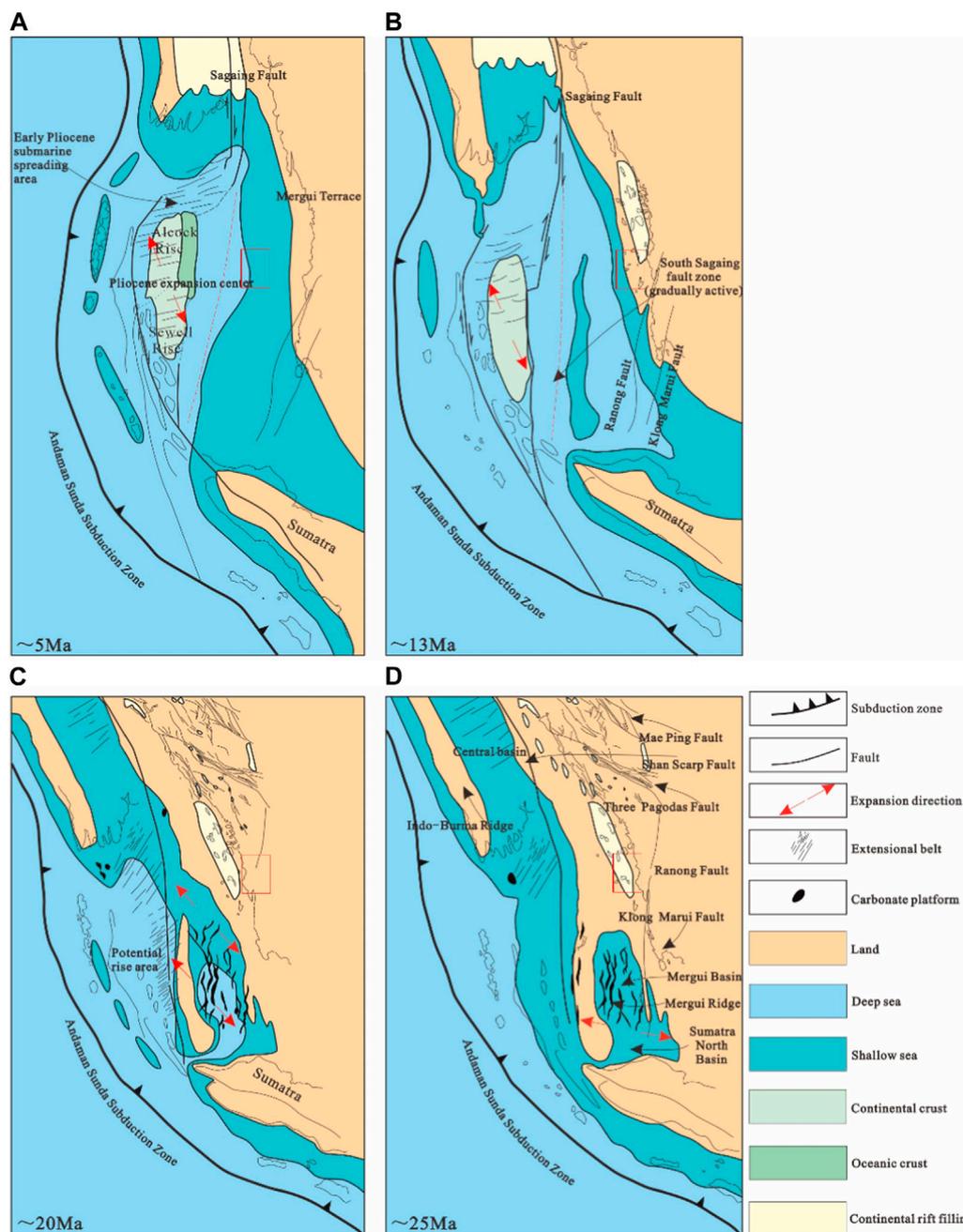


FIGURE 7 Structural evolution model of Andaman Sea (According to the revision of literature (The age of (A–D) is from new to old) (Srisuriyon and Morley, 2014)).

in an east-west torsional compression tectonic stress environment. During this period, the Andaman Sea was in the stage of regression.

5.3 Regional dynamics of growth faults

It can be seen from the above analysis that a large number of NNE-SSW, NE-SW and NEE-SWW trending faults were developed during the Late Oligocene and the Early Miocene. During the Oligocene, the growth index and ancient fall of the study area

were both at low values, indicating that the collision between the Indian plate and the Eurasian plate was a soft collision at this time, and the fault gradually began to form. The characteristics of the primary and secondary faults have yet to appear. The Sagaing fault started to dextral strike-slip and the Mergui basin was formed. At this time, the study area (red rectangle in Figure 7) belongs to a continental crust environment (Figure 7D). The continental crust began to expand, resulting in rapid subsidence of the stratum, which lasted until the Early Miocene, and then the subsidence slowed down, and Graben and half-graben almost filled the sea level

(Curry, 2005). The Miocene is an important period of fault development in the study area, and the plate movement at that time is relatively active. During this period, the plate collision gradually strengthened, and the volcanic arc was uplifted, and the fore-arc and back-arc basins in Andaman Sea areas began to take initial shape, and the strike-slip fault extended southward to the north of the Mergui basin (Figure 7C). The back-arc basin affected the formation of the study area. With the change in the extension direction of the fault, the strike-slip fault developed to the Mergui basin. This change promoted regional tension deformation, and the growth index and ancient fall gradually increased during this period, reaching the peak in the Middle Miocene (Figure 6). The coupling effect between Indian and Australian plates has a significant influence on the fault activities in the study area, which is the main reason for the development of faults; The accelerated uplift of the volcanic island arc leads to the gradual increase of the thickness difference of the stratum in the Andaman Sea area (Figure 7B). In the Late Miocene, with the coupling of the Indian plate and the West Myanmar block, the Sagaing fault began to move, and large-scale strike-slip pull apart movement occurred along the Sagaing fault, and the “trench-arc-basin” system of the Andaman Sea gradually developed. Now, the study area is in marine environment (Figure 7A).

The development of faults controls the discharge of fluids and the migration of oil and gas. The strike-slip form of the Sagaing fault in the back-arc depression of the study area determines the direction of E-W and NNE-SSW tensile stress (Singha et al., 2019). The tension in the E-W direction has led to the occurrence of strike-slip movements and N-S trending Sagaing fault, resulting in the formation of central extension zones and near N-S trending regional faults. When the local formation pressure gradually increases and finally reaches the formation fracture pressure, the formation will break. At this time, due to the occurrence of the fracture, the fluid will start to release upward through the fracture (Mohan et al., 2006).

6 Conclusion

From the detailed analysis of seismic data, we reach the following conclusions:

- 1) It is found that a series of NNE-SSW strike-slip faults and NE-SW or NEE-SWW faults are mainly developed in the study area. Strike-slip faults control the depression and uplift in this area, forming a geomorphic morphology of high east and low west, which echoes the collision between the Indian plate and the Eurasian plate.
- 2) The fault mainly developed between the Late Oligocene and the Early Miocene. Since the Late Oligocene, the collision between the Indian and Eurasian plates has become more robust. At the same time, the coupling between the Indian plate and the Myanmar microplate has led to a significant dextral strike-slip

movement of the Sagaing fault. F1 Sagaing fault and F2 East Andaman fault developed before the Oligocene. The continuous activities of the primary and secondary faults until the Early Miocene promoted the formation of the tectonic framework in the study area.

- 3) The regional stress field affects the fault's development. The stress field in the region is dominated by E-W tension. The continental crust has expanded rapidly since the Oligocene, resulting in rapid subsidence, which lasted until the Early Miocene and then slowed down. This regional stress intensity was significantly greater from the Late Oligocene to the Early Miocene than that after the Early Miocene, so many near NNE-SSW growth normal faults were developed in the study area before the Early Miocene.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MG and XL contributed to conception and design of the study. MG wrote the first draft of the manuscript. HZ and BH reviewed and modified the manuscript. All authors contributed to the article and approved the submitted version.

Funding

This study is supported by National Natural Science Foundation of China (Nos. 92055211 and 42249801), China-ASEAN Maritime Cooperation Fund Project (No. 12120100500017001).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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