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Submarine landslide and associated polygonal faults development: a case study from offshore Norway

Anh Ngoc Le *, Ngan Thi Bui

Hanoi University of Mining and Geology, Hanoi, Vietnam

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ABSTRACT

Submarine slide and polygonal faults have been investigated using high-resolution 3D seismic data, over an area of 2,300 km^2. The study area is located on the continental slope, offshore Norway. Submarine sliding covers more than half of the study area, and is part of the Storage slide. The slide developed a series of extensional faults at the upper extensional zone which is gradually changed to chaos seismic facies, interpreted as mass transport deposits. There is no clear evidence of compression/contractional zone downslope. Polygonal faults are highly developed in the KS1 and KS2 interval, corresponding to the Lower Miocene age. The fault has small offset of c. 10÷30 ms TWT, spacing ranges between c. 500 m and 1 km. Within this faulted interval, faults tend to develop intensively below the submarine sliding and much less out of that area. Bright amplitude anomalies are observed within the north south – elongated anticline structure. It has been mapped over an area of c. 135 km^2 coinciding with the top anticline. Among those, there are two obvious negatives, bright amplitude reflectors which are relatively flat at 2670 ms TWT (flat spot 1) and 2800 ms TWT (flat spot 2). These flat spots are interpreted as hydrocarbon-brine contacts. Flat spot 2 is bounded by the structure contour but there is no evidence for the unconformable with the lithologic reflections from the trap boundary, thus this still needs to be confirmed by well data. Bright amplitude anomalies suggest the existence of hydrocarbon in the trap, in addition, the occurrence of polygonal faults is linked to seal potential covering the underneath petroleum reservoir, proving the great hydrocarbon potential in this area.

1. Introduction

The study area is located near the head of the Storega slide. Submarine sliding is documented in many basins but the largest and most famous slide is the Storega slide. Recent studies indicated that c. 2,500÷3,500 km^3 of sediment had been removed from the slide scar. This even happened 8,200 years ago (Bryn et al., 2005). The movement of large-scale sliding is caused by climatic

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*Corresponding author
E - mail: lengocanh@humg.edu.vn
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variability, at the end of glaciation or soon after the deglaciation (Haflidason et al., 2005).

Polygonal fault systems have been documented in many basins worldwide as a feature formed by the non-tectonic regime. They are normal faults with polygons geometry in the plan view (Berndt, 2005, Cartwright et al., 2007; Løseth et al., 2011; Le, 2021; Gay et al., 2021). The faults are supposed to be formed by sediment loading and heterogeneous volumetric compaction results in small-scale normal faults (Berndt, 2005; Neagu et al., 2010). Polygonal fault systems are interpreted as layer-bound of deformation and its restricted in the low-permeability slope and basin plain lithofacies (Cartwright et al., 2007; Gay et al., 2021).

For oil and gas potential or play analysis, polygonal faults are on debate centers on which faults act as seal or as fluid pathways. Polygonal faults should be considered sealing potential as a time-dependent parameter (Alexander and Handschy, 1998). The long-term behavior of fault planes as flow conduits controls by the permeability of the fault rocks. The damaged zones are more permeable than their host sequences and can be major flow pathways (James, 1997). The direct evidence of significant fluid migrating upward along fault planes is the link of pockmarks craters that line up above the upper end of fault planes (Ligtenberg, 2005). However, most damaged zones are characterized by lower permeability than their host rocks, and gradually leak at low rates (Knipe, 1997). In addition, the fact that many oil and gas accumulations are successfully trapped by a top seal that is polygonally faulted indicates that leakage through these faults is inadequately rapid to destroy the accumulations. In this paper, the occurrence of polygonal faults will be investigated in conjunction with the occurrence of the submarine landslide and reservoir potential.

2. Geological setting

Located on the continental margin of the Norwegian sea, the studied area belongs to the Møre basin, one of the major basins of the Norwegian sea, with a very thick Cretaceous basin fill. The general tectonic development comprised a long period of extension and rifting that ended in early Eocene time by the continental separation (Brekke, 2000).

The studied area is located on the head of the Storage slide, one of the largest submarine slides discovered (Figure 1). The slide was first documented in 1970s (Jansen et al., 1987). The large volume of sediment had been removed from the slide scar by the main event dated 8,200 years ago, leading to a tsunami that struck the west coast of Norway (run up 10÷12 m), Scotland (4 ÷6 m), Shetland (20÷30 m), and the Faroes (> 10 m) (Bondevik et al., 2003; Bryn et al., 2005).

The area has experienced several rifting phases in the mid-late Jurassic, the Late Cretaceous and before continental break-up in the Early Eocene. There are at least five phases of uplift from the Cenozoic including (Brekke, 2000): (1) Latest Maastrichtian and earliest Paleocene; (2) Early Eocene; (3) Late Eocene/Early Oligocene; (4) Early-mid Miocene; (5) Plio-Pleistocene. The latest Maastrichtian-Early Paleocene phase is supposed to be the time to generate the Møre Basin which received clastic material from the Norwegian mainland to the deep marine areas.

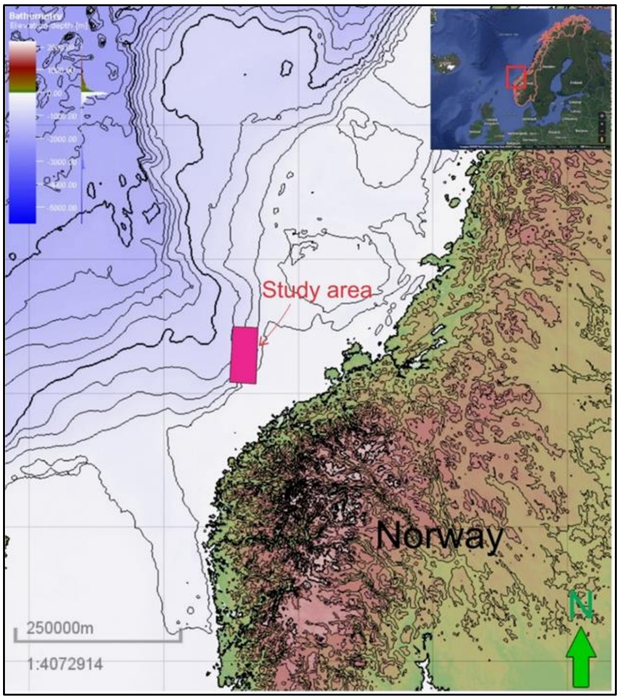

Figure 1. The study area is located offshore Norway, in the Møre basin with a water depth range from 300 to 1,200 m, covering an area of 2,300 km^2*.*

3. Dataset and Methodology

This study uses high-quality 3D seismic data offshore Norway (Figure 1). The study interval is 4,000 ms TWT corresponding to the Paleogene to present sequences. The seismic data is displayed as zero phase, SEG reverse polarity. The 3D seismic survey covers an area of 2,300 km^2. The 3D seismic survey includes inline and crossline at a spacing of 25 m, the dominant frequency in the range of 36÷46 Hz. Assuming a velocity of 1,700÷2,000 m/s, the vertical seismic resolution can be calculated as a quarter of the dominant wavelength, which would be c. 10÷12 m.

Interpretation has been carried on using standard seismic stratigraphic techniques (Michum Jr, 1977; Vail et al., 1977). Based on the reflection terminations and seismic facies characteristics, Three main key surfaces have been mapped, dividing the seismic volume into chronostratigraphic packages. These packages are used to analyse the occurrence of submarine landslides, polygonal faults, and amplitude anomalies and focused on the study of polygonal faults.

4. Results

4.1. Submarine landslide

Submarine landslides are observed with the headwall slope gradient of 25÷35^0 (Figure 2).

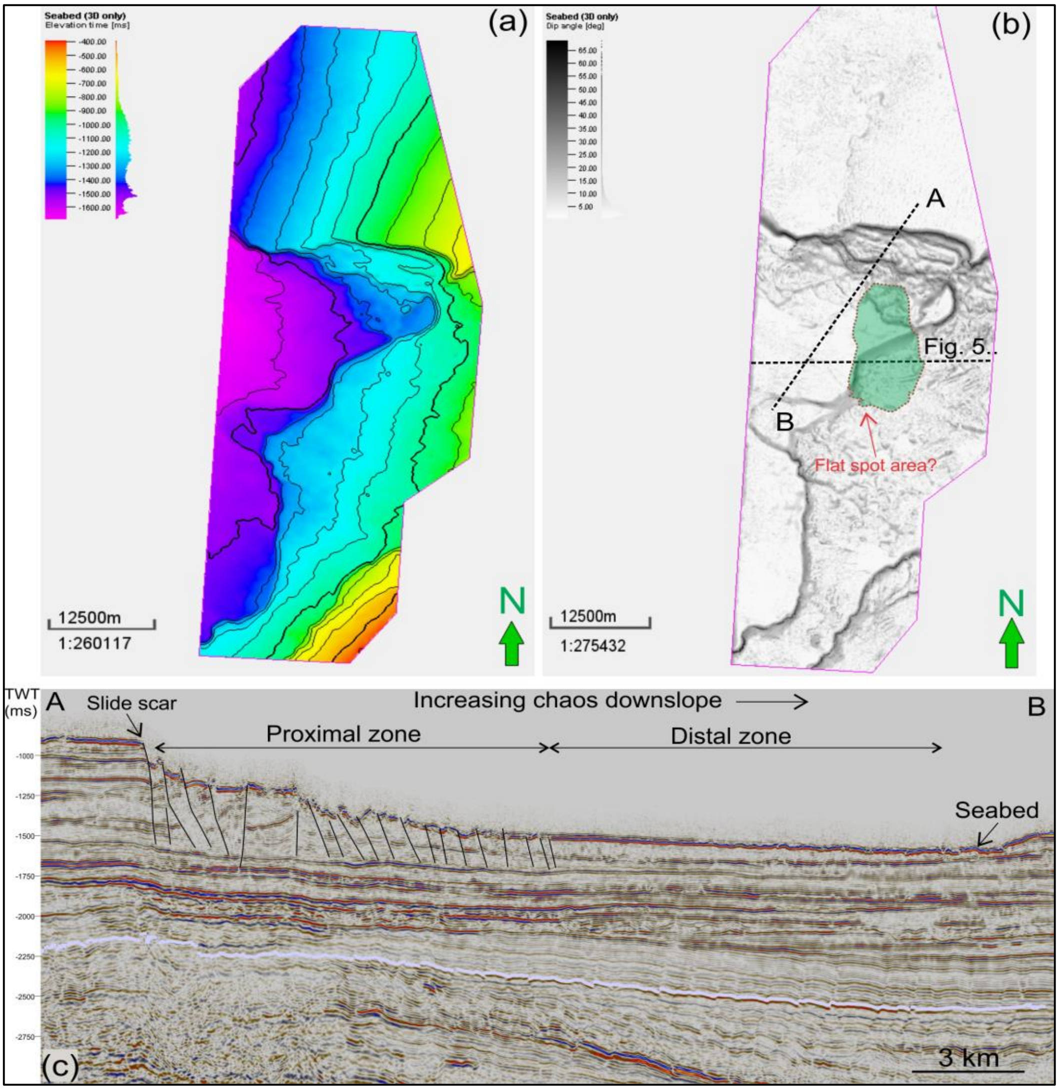

Figure 2. Submarine landslide is shown in the time structure map of the seafloor (a), and seafloor dip map (b), a seismic section reveals the increasing chaos facies basinward (c).

The slide is well defined as an upper extensional zone (proximal) with a series of east-west normal faults dipping south and a down-slope contractional zone with chaos seismic facies which is interpreted to be mass transport deposit caused by internal deformation mechanism (distal zone). As the sediment breaks away and moves down from the scarp, it generates many faults which are closely spaced away from the scarp. The bedrock has been rotated and can be classified as rock fall (slump) (Figure 2). The displacement of the faults is gradually decreasing toward the distal area. The maximum offset is c. 100 ms TWT. There is no clear evidence of the compression at the distal zone but the chaos seismic facies dominantly in this area indicated the unconsolidated flow or debris flow area in the area.

Submarine landslide is known as gravitational collapse structures which can range from centimeters to hundreds of kilometers and can influence both loose sediments and solidified sediments under marine and nonmarine conditions (Færseth and Sætersmoen, 2008). According to these authors, horizontal stress is exerted at the head slide as a mass of sediment slides, and it increases simultaneously as it slides towards the toe. In this case, there is no compression feature in the distal area which support the gradual release of the energy of the submarine slide.

4.2. Polygonal faults

Polygonal faults are observed c. 1000 ms below the seafloor. Three key surfaces have been mapped KS1, KS2, and KS3 (Figures 3 and 5) which divide the polygonal unit into the upper and lower interval. These are high amplitude reflections. The KS1 corresponding to the top of the polygonal fault unit marks the change from highly faulted interval below to low amplitude, continuous to discontinuous reflections above. The KS2 separates the unit into upper and lower intervals where the fault population is denser in the upper interval compared to the lower interval. The KS3 is possibly corresponding to the base of the anticline/reservoir and marks the change from chaos seismic facies below to disrupted, low to high amplitude reflections above.

The average thickness of KS1 and KS2 is about 950 ms. The unit is thinner in the north-south striking dome area (Figure 4a). The most obvious characteristic of the faults is that the faults have different strike directions, creating polygonal patterns which are supposed to be dominated by very fine sediments (Figure 4). Spacing and pattern of the polygonal geometry similarly differ from one map to the other (Figure 4). The population of the faults is denser in the upper interval compared to the lower interval (Figure 5). In addition, on the KS3, fault strike tends to connect and forms some east-west striking faults in the north area (Figure 4d). Some faults can be traced out of the top unit but mostly bounded within the polygonal fault unit. Fault spacing ranges between c. 500 m and 1 km, with a small offset of c. 10÷30 ms TWT. Within this unit, toward the southeast area, polygonal faults are difficult to observe as the dominant of discontinuity to chaos seismic facies (Figure 5).

4.3. Amplitude anomalies

Within the lower unit bounded by KS2 and KS3, amplitude anomalies are observed within the north south – elongated anticline structure (Figure 1), below the submarine landslide area. The amplitude anomalies are characterized as locally high amplitude, continuous reflections of up to 400 ms TWT thick, covering an area of c. 135 km^2 (Figure 5). Among those, there are two obvious negatives, bright amplitude reflectors which are relatively flat associated with the top of the anticline. These reflectors have been identified at 2,670 ms TWT (flat spot 1) and 2,800 ms TWT (flat spot 2). These are considered flat spots produced by hydrocarbon-brine contact. Flat spot 2 has been mapped revealing that it is bounded by the structure contour (Figure 3). However it doesn't show the unconformable with the lithologic reflections from the trap boundary, thus this is not clear for the occurrence of the flat spots until it can be confirmed by well data.

Despite the consideration of the flat spots, the occurrence of high amplitude reflections still supports the presence of hydrocarbon accumulation in the trap.

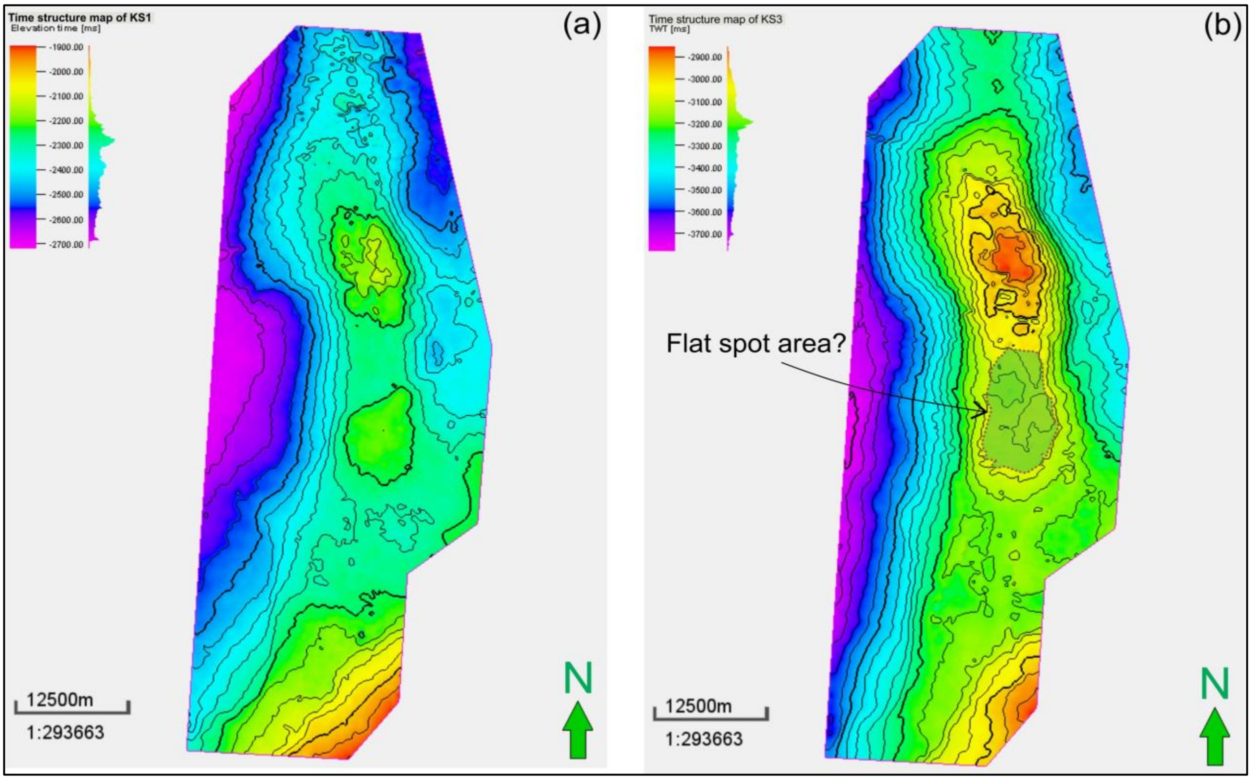

Figure 3. The time structure map of KS1 (a) and KS3 (b) reveals the north south - elongated anticline structure.

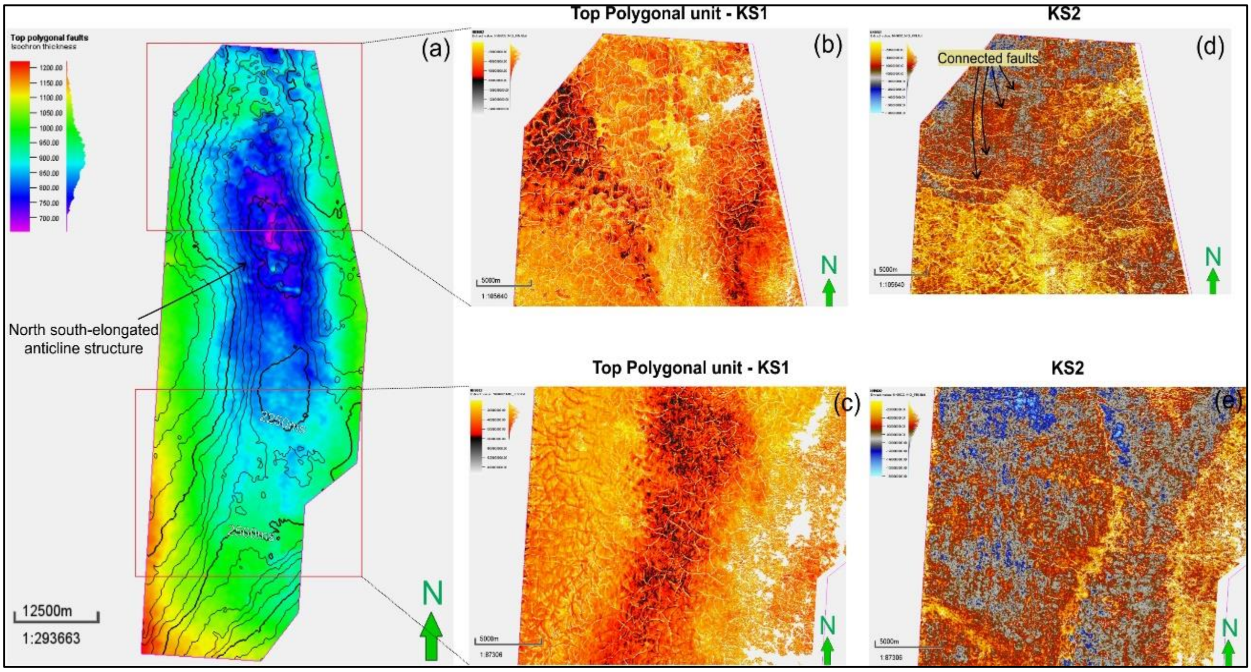

Figure 4. Isochron thickness map of the KS1 and KS3 overlap on the top surface of the polygonal fault unit (a). The extract amplitude map of the KS1 (b, c) and the KS3 (d, e) show the polygonal fault pattern which is different from KS1 to KS3 surface.

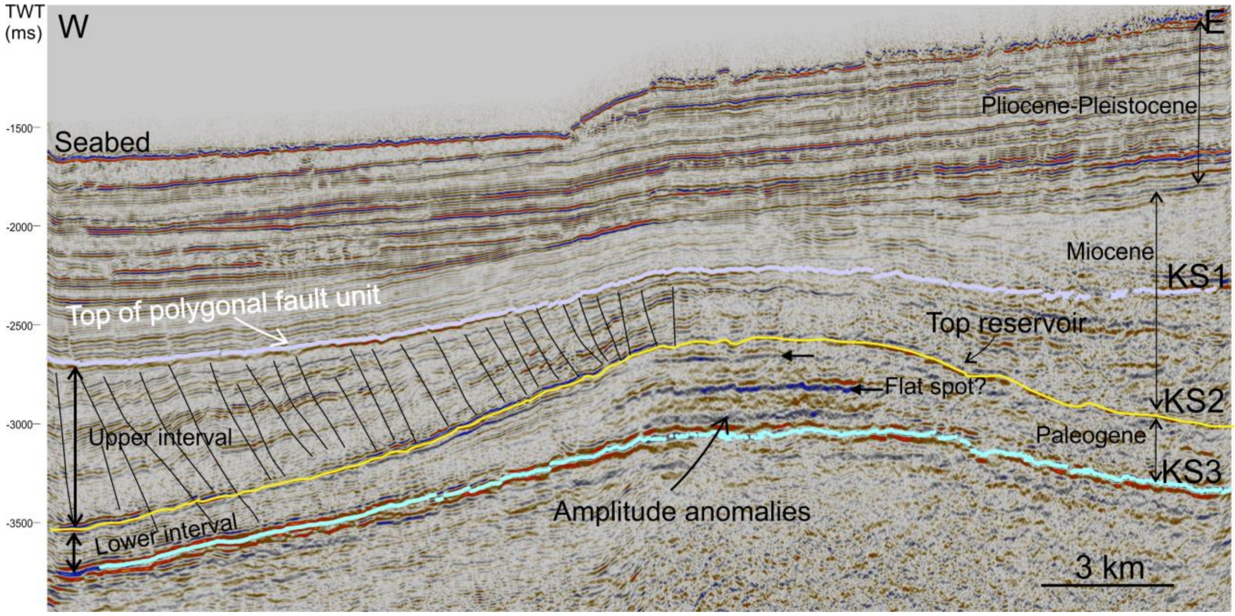

Figure 5. A seismic cross-section illustrated the occurrence of polygonal faults within the KS1 and KS2 interval. Faults tend to be denser below the submarine slide and are hard to observe in the southeast part of the study area which is dominated by discontinuous, low amplitude seismic reflections. Amplitude anomalies are observed which is possibly a DHI for the anticline trap.

5. Discussion

Polygonal faults are highly developed in the upper interval and tend to be denser in the eastern part of the anticline, below the submarine landslide. The occurrence of polygonal faults is interpreted for fine-grained sediments interval.

The rapid emplacement of debris flows or changes in the regional sedimentation rate is thought to be the primary causes of the development or abrupt end of polygonal faults (Gay and Berndt, 2007). In this study, the occurrence of the fault tends to be triggered by several uplift phases in Kainozoi, and also the unstable of the seafloor caused submarine sliding thus producing rapid emplacement of debris flows. Polygonal faults may have formed mainly in the upper interval of KS1 and KS2 but have been active and inactive several times, leading to the presence of polygonal below and above this interval.

North-south trending anticline which is marked by the KS2 at the top and KS3 at the base may play a great hydrocarbon trap for the area. The occurrence of high amplitude corresponds to the top of the anticline structure is supposed to be present for the hydrocarbon accumulation. The upper interval overlaps the reservoir which is highly polygonal faulted on the left limb of the reservoir suggest the existence of a mud-dominated formation and can act as a good seal. Polygonal faults are also documented in the neighboring basin, Vøring Basin. The faults are abundant in the upper Miocene to the seafloor. If the faulted layers are highly interconnected, fluids can migrate to shallower depths and generate vertical pipes and pockmarks on the seafloor. (Gay and Berndt, 2007). In this studied area, pockmarks are not observed on the seafloor due to the seafloor instability. In addition, the faults tend to be bounded within the KS1 and KS2 interval thus there is no migration pathway for the hydrocarbon to reach the seafloor.

The most significant feature of the studied area is the occurrence of the anticline associated with the amplitude anomalies. Polygonal faults only developed in one limb of the anticline, suggesting good seal potential.

6. Conclusion

Polygonal faults have been broadly observed in the study area, in the lower-mid Miocene sequence, covering almost the entire area. The faults tend to be more well developed in the eastern part, downslope direction. Fault spacing ranges between ~ 500 m and 1 km with a small offset of ~ 10÷30 ms TWT. The well-developed polygonal faults above the north south – elongated anticline structure indicated the occurrence of fine-grained sediment which can act as a good seal potential. In addition, the widespread amplitude anomalies associated with the top of the anticline strongly support the high potential of hydrocarbon accumulation in the studied area.

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Contribution of authors

Anh Ngoc Le - conception, design, interpretation, draft the article and revise for submission. Ngan Thi Bui - data analysis, seismic interpretation, mapping, and drawing figures, discussions.

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