Research Article

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Seismic characteristics of polygonal fault systems in the Great South Basin, New Zealand

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Abstract: A well-developed multi-tier polygonal fault system is located in the Great South Basin offshore New Zealand's South Island. The system has been characterised using a high-quality three-dimensional seismic survey tied to available exploration boreholes using regional two-dimensional seismic data. In this study area, two polygonal fault intervals are identified and analysed, Tier 1 and Tier 2. Tier 1 coincides with the Tucker Cove Formation (Late Eocene) with small polygonal faults. Tier 2 is restricted to the Paleocene-to-Late Eocene interval with a great number of large faults. In map view, polygonal fault cells are outlined by a series of conjugate pairs of normal faults. The polygonal faults are demonstrated to be controlled by depositional facies, specifically offshore bathyal deposits characterised by fine-grained clays, marls and muds. Fault throw analysis is used to understand the propagation history of the polygonal faults in this area. Tier 1 and Tier 2 initiate at about Late Eocene and Early Eocene, respectively, based on their maximum fault throws. A set of three-dimensional fault throw images within Tier 2 shows that maximum fault throws of the inner polygonal fault cell occurs at the same age, while the outer polygonal fault cell exhibits maximum fault throws at shallower levels of different ages. The polygonal fault systems are believed to be related to the dewatering of sedimentary formation

during the diagenesis process. Interpretation of the polygonal fault in this area is useful in assessing the migration pathway and seal ability of the Eocene mudstone sequence in the Great South Basin.

Keywords: seismic interpretation, polygonal fault system, Great South Basin

1 Introduction

Since polygonal fault systems (PFSs) have been discovered in sedimentary basins worldwide, many PFSs have been studied with respect to petroleum exploration, such as their seal capacity and as a paleo-stress indicator [1–5]. Henriot et al. (1991) first described PFS in the North Sea Basin as fracture networks in the Palaeogene clays based on two-dimensional (2D) seismic interpretation [6]. Later, Cartwright (1994) analysed three-dimensional (3D) seismic data in the same area and illustrated polygonal fault geometry on seismic time slices [7]. In general, polygonal faults are a dense pattern of normal faults formed by compaction and dewatering of a sedimentary formation [8]. They are characterised by vertically and laterally extensive arrays in the host rock and are usually formed in the first few hundred meters of burial [3,9,10]. The occurrence of PFSs is often linked to very fine-grained sedimentary succession that is confined by stratigraphy or lithology, giving a polygonal fault interval or tier [8,9]. Lateral and vertical propagations of polygonal faults are defined by changes in lithology, especially muddy properties within the interval, which may relate to depositional environments (e.g. [3,11]). Tier boundaries are recognized by the disappearing of polygonal faults in the seismic data, which may mark the changing of lithological properties or the changing of individual polygonal fault geometry [12,13]. Thus, PFSs might be useful to highlight lithological variation related to depositional environments. For instance, in frontier exploration areas of petroliferous basins where well information is lacking, it

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is difficult to map out the depositional environments and lithological variation from seismic data independently. PFSs can be recognized both laterally and vertically and could be used to delineate and assign as a facies model for geological or petroleum systems modelling. PFSs have been described elsewhere from New Zealand and in the Great South Basin (GSB) (Figure 1). PFSs in the Great South and Canterbury Basins have recently been reported by several studies (e.g. [14–17]). Morley *et al.* (2017) studied the honeycomb structures associated with the PFS in the GSB [15]. The honeycomb structures are characterised by extensive circular to polygonal depressions. Morley *et al.* (2017) observed two PFS tiers, which are referred to as Tier 1 (southern area) and Tier 2 (northern area), but they did not focus on details of the PFS characteristics such as fault throw analysis and depositional environment at the PFS interval [15]. Li *et al.* (2020) also studied the characteristics of the PFSs in the GSB using fault enhancement and skeletonization processes [17]. However, they focused on the southeastern part of the 3D seismic data; hence, the north-western area is not well-documented. Morley *et al.* (2017) and Li *et al.* (2020) suggested that the honeycomb structure and PFS in this basin are related to the opal-A/CT transformation, which is characterised by a high amplitude reflection [15,17]. Without well data to constrain the lithology of the sedimentary succession, lacking depositional environment interpretation and lacking temperature calculation at the opal-A/CT transformation interval, the proposed opal-A/CT transformation may be somewhat uncertain.

Nowadays, the GSB contains several potential petroleum plays [18], and even though the petroleum fields are not at an economic stage, they are still attractive for further exploration. To increase the understanding of petroleum resources in this basin, it is necessary to investigate the basic geological information such as seal ability, fluid migration and trap. PFSs usually occur within fine-grained sedimentary successions, which often form seals for petroleum reservoirs. In this study, 3D seismic data and seismic attributes are utilized to map and characterise the PFSs in the GSB. The PFSs in this study area are mainly confined within the Paleocene to Eocene fine-grained sedimentary successions (Figure 2). Sand injections are reported to occur within Late Paleocene succession beneath the PFSs in this study area [19]. Sandstone injections constitute prolific petroleum reservoirs. This study presents the quantitative method for throw–depth (T – Z) plots along the polygonal faults in the GSB. The depositional environment and stratigraphic interpretations are useful

Figure 1: Location map of the GSB and study area. The GSB 3D seismic survey is highlighted as a black polygon and the 2D seismic lines are highlighted as blue lines (modified from [48]).

to highlight the possible lithology at the interested interval. The goal of this study is to image and recognize geologically and geomorphologically meaningful patterns of the PFS from seismic data. Fault throw analysis is performed for understanding the PFS evolution with discussion on fault initiation, propagation and linkages in three dimensions.

2 Geological setting

The GSB is situated in the southeast offshore New Zealand's South Island. The basin is located beneath the modern shelf area and covers an offshore area of approximately 85,000 km² with water depths of 300–600 m (Figure 1). Rifting of Zealandia from Australia and Antarctica was initiated from the break-up of eastern Gondwana at approximately 105–100 Ma that eventually led to the formation of sedimentary basins across the older pre-rift basement rocks in New Zealand

Figure 2: Regional seismic line shows the seismic stratigraphy and age correlation of the study area. Polygonal faults are restricted to the Eocene mudstone sequence of the Laing Formation. See the seismic profile location in Figure 1.

[20–25]. A pre-Eocene movement of Alpine fault was proposed to develop before 45 Ma may have formed a paleo-high that contributes the sediment sources into the Canterbury Basin through early Oligocene channels [26,27]. During this rifting event, the GSB was dominated by a series of grabens and half-grabens trending in the northeast–southwest direction [28,29]. The basement rocks include silicic to intermediate plutonics and metasedimentary rocks [30,31].

The oldest known sedimentary sequence in the GSB is the Hoiho Group (Late Cretaceous, syn-rift) [29]. Biostratigraphic studies of the Hoiho-1, Kawau-1A, Tara-1, Pukaki-1, and Rakiura-1 wells within the basin suggest the deposition of the Pakaha and Rakiura Groups in a non-marine coastal plain environment to a slight marine influence on a lower coastal plain environment during the Late Cretaceous to Late Eocene [29]. The Penrod Group consists of mainly carbonate sediments of mid-Oligocene and younger age. It should be noted that this study focuses on the Rakiura Group where PFSs are observed (Figure 3).

The Rakiura Group was deposited during the Eocene and was divided into the Laing and Tucker Cove Limestone Formations (e.g. [15]). Seismically, the Rakiura Group is interpreted to represent slope-basin floor and turbidite fans, bathyal carbonates and clastics and submarine canyon deposits [32]. The top of the group is marked by a regional unconformity that separates the

Rakiura Group from the Penrod Group sediments. Laing Formation was deposited in a shelf to the upper bathyal environment, and it extends over most of the basin with a thickness of approximately 2 km in some places. During the Early Eocene, the basin was shallowed toward the northwest with the formation of a thick prograding clastic wedge. By the end of the Eocene, the basin became a deeper marine setting according to a relative sea-level rose so that the depositional environment in the north-western portion of the basin was in an upper bathyal setting while the depositional environment in the eastern part the basin was deeper in a mid-bathyal setting [33]. Laing Formation was then overlain by Tucker Cove Formation that consists of soft to firm, white to light grey, fine-grained, foraminiferal limestone with chert nodules and traces of pyrite and glauconite [32,34]. The stratigraphic framework of the GSB is presented in Figure 3.

3 Dataset and methods

The GSB 3D seismic data used in this study covers a surface area of 1,344 km². The seismic volume is a zero-phase, full offset, post-stack time-migrated volume. An increase in acoustic impedance is indicated by positive amplitudes (peak). The seismic data have a bin spacing

Figure 3: Stratigraphy of the GSB, modified from [49].

of 12.5 m × 25 m in crossline and inline directions, respectively. The interval of interest is characterised by a dominated seismic frequency of 40–60 Hz, resulting in a vertical resolution of about 8–12.5 m, using an average sediment velocity of 2.0 km/s. The horizontal resolution of about 16–25 m ensures confidence in the geomorphological interpretation of the PFS features. Additionally, regional 2D seismic reflection profiles were also used to extend the interpretation from the exploration wells that were drilled adjacent to the 3D seismic survey to constrain the lithostratigraphy in the study area (Figure 2). Seismic sequences and key horizons were first identified, mapped and interpreted in a sequence stratigraphic framework on the 2D and 3D seismic data by calibrating to the Pakaha-1 well (Figure 2).

Seismic attributes were also analysed from the selected surface maps using a short time window of,

on average, 20–50 ms two-way travel time (TWT). Seismic attributes used in this study are root-mean-square (RMS), variance, and azimuth attributes. RMS seismic amplitude attribute averages and normalizes amplitude information in an interval and is a useful indicator of the bulk lithology and depositional environments [35]. The variance attribute is the inverse of the coherence attribute and is useful for edge detection. Discontinuities in strata reflections such as faults or channel edges are highlighted by variance attribute [36]. The azimuth attribute in the direction of the gradient vector calculated at each grid point of the interpreted (time) horizon, which is helpful for identifying fault patterns in 3D seismic data [37]. The azimuth attribute also helps to highlight the dip direction of the fault planes and strike curvature particularly in the circular polygonal fault zone.

Fault orientation and fault throw characteristics of the PFSs in this area are studied within a polygonal fault cell. The primary aims of fault throw analysis are to further investigate the activity of the PFSs in the Great South Basin and to determine whether the faults show multiple reactivation histories. T - Z plots are a measurement of throw along fault dips from lower fault tip to upper fault tip or across the trace of faults [38]. This measurement is commonly used as a measure of polygonal fault movement (e.g. [39]). In 3D, the throw is calculated for individual fault crossing five seismic horizons within the Eocene interval. Hanging wall and footwall contacts are marked on the fault for each seismic horizon, with the resulting amounts of displacement shown by colour changes on the fault plane. Therefore, fault growth can be implied from its 3D throw colour map.

4 Results

4.1 Description of key stratigraphic surfaces

4.1.1 Top Eocene

The Top Eocene is interpreted on a negative polarity event (a trough), which is characterised by a high amplitude and continuous reflection (Figure 4a). This surface is easy to map over the study area. The surface marks a change from a parallel reflection geometry below to a chaotic reflection pattern above. The PFSs are clearly seen on this surface.

4.1.2 Top Middle Eocene

The Top Middle Eocene is interpreted on a positive polarity event (a peak) and is easy to map on a peak throughout the study area (Figure 4b). Polygonal faults are observed and cut through this surface, mostly in the southeastern part of the seismic data, but are difficult to observe on the map view in the northern part. To the west, this surface onlaps against older clinoform reflections presented in Figure 4b. A fan-shaped high amplitude area is observed within a basin deposit as evidenced by the RMS amplitude map (Figure 4b). This fan-shaped area is interpreted to be a basin floor fan.

4.1.3 Top Paleocene

The Top Paleocene is interpreted on a negative polarity event and is associated with lower polygonal fault tips in the southeastern part of the study area (Figure 4c). The surface is interpreted to be a flooding surface at Late Paleocene. In the map view, the variance and RMS amplitude attribute maps highlight high-amplitude features trending in NW-SE, with curvilinear channel-like geometries within the slope area (Figure 4c).

4.1.4 Description of the PFSs

All PFSs observed within the 2D and 3D seismic data are related to the Laing and Tucker Cove Formations, which are mainly composed of marls, muds and clays (Figure 3). The polygonal faults are well imaged in the 3D seismic volume, which allows us to define and describe their geometry both in the planform and cross-sectional views. The PFSs in the study area are divided into two intervals, called Tier 1 and Tier 2, based on the vertical extents of their upper and lower fault tips (Figure 5a). The basal boundary of the polygonal faults is indicated by the first reflector below the lowest fault tips. In this study area, the lower fault tips of Tier 1 and Tier 2 are limited approximately in the Middle Eocene and the Early Eocene successions, respectively. The upper fault tips in both tiers are terminated at the Late Eocene horizon (Figure 5b and c). In general, both tiers consist of regular normal faults with an almost equal number of oppositely dipping faults. From map view, the PFS network changes from fully polygonal to a much more linear pattern towards the shallow slope area and is not visible on the upper slope area, which marks the upper boundary of the PFS or is under the seismic resolution (Figures 5a and 6a).

4.1.5 Tier 1 PFS

Tier 1 is observed within the marl succession of the Late Eocene (Figure 5a and b). In section view, faults are planar with typically have fault height of approximately 100–200 ms TWT. The thickness of this interval is approximately 200 ms TWT and the interval shows a high degree of faulting in the uppermost part (Figure 5a). The polygonal faults have small throws (<25 ms TWT) and display similar characteristics on seismic profiles by small fault height and steep-dipping fault. In map view, Tier 1 shows a dense pattern and highly mature system with almost no free lateral tips exhibited with orthogonal to oblique intersection angles. The overlying and

Figure 4: Seismic attribute maps of selected key horizons: (a) Top Eocene, (b) Top Middle Eocene and (c) Top Paleocene. Each map covers the same area and shows the presence and absence of PFSs which are influenced by depositional environments. Blue line represents the limitation of the polygonal fault zone, which dominates in the southeast (basinwards). Black and red lines mark the boundaries of shelf and slope areas, respectively. The PFSs are restricted in the very fine-grained sediment area and more lateral propagated landward by shifting the bathyal deposition.

underlying intervals are represented by continuous reflections with little to no polygonal faulting (Figure 5a). The polygonal faults in this tier are died out mostly at the top of the Laing Formation. Although a rose diagram in Figure 6b indicates the diverse orientations of their strikes have a background radial distribution of fault strikes (Figure 6b), there are two superimposed strong preferred orientations of NNE- and WNW-striking faults. These majority faults preferentially dip to the SSE and NNW directions.

4.1.6 Tier 2 PFS

Tier 2 consists of large polygonal faults with a fault height ranging from 500 to over 1,000 ms TWT (Figure 5a and c). Generally, the polygonal faults in this tier have larger

throws (up to 60 ms TWT) than Tier 1. Tier 2 is mostly dominated within the Laing Formation and is stratigraphically restricted to the Paleocene-to-Late Eocene interval (Figure 5c). The faults are commonly truncated at the Late Eocene horizon (Figure 5c). The difference between Tier 1 and Tier 2 is that there is a variety in fault size with many minor small faults randomly occurred at different levels within Tier 2. It is obvious in seismic profiles that the maximum fault height of Tier 2 indicates the thicker fine-grained sedimentary successions (Figure 5c). In the map view, Tier 2 is characterised by a series of convergent pairs of normal faults (Figure 6a). Polygonal intersections of these conjugate fault pairs define a polygonal fault cell. Within the polygonal fault cell, faults commonly trend to intersect with the cell-bounding conjugate faults (Figure 6a). Generally, the fault strikes in this tier show multiple orientations, although there are strongly preferred

Figure 5: (a) Variance map of the horizon slice 40 ms below the Tucker Cove Formation (Late Eocene) shows highly faulted sediments that consist of small-scale normal faults (inset seismic profile shows locations for [b] and [c]). (b) Tier 1 PFS consists of regular and almost even numbers of oppositely dipping planar faults. They formed within the upper Eocene section. (c) Tier 2 PFS consists of a series of conjugate normal faults with forming polygonal fault cells in map view. The base of Tier 2 PFS lies within EE near the Top Paleocene horizon.

orientations in NE, NW and ENE directions (Figure 6b). These faults preferentially dip to the NW and NE quadrant.

4.1.7 Maximum fault throw

To understand the formation of the polygonal fault system in this area, several random faults are mapped in the selected area using maximum fault throw analysis (Figure 7). The height and length are extracted from the selected polygonal faults, as well as the T - Z plots and 3D throw colour maps to understand the propagation history of these faults. The profile of T - Z plots may indicate: (1) isolated growth fault (i.e. a ‘c-shape’ profile geometry), (2) fault reactivation (i.e. a “stepped” profile geometry) or (3) dip-linkage fault (i.e. a ‘B-shaped’ profile geometry) as presented in Figure 7a. Due to the small fault throw and small fault height of Tier 1, only Tier 2 is used to analyse a 3D fault throw in this study.

The maximum fault throws from T - Z plot of Tier 1 is located at 1,200–1,300 ms TWT within the Middle-to-Late Eocene (Figure 7b). The T - Z plot in this tier is characterised by a c-type profile indicating that it is likely to form during the Late Eocene post-dated to the Tier 2 (Figure 7b and c). The T - Z plot from Tier 2 indicates a c-type profile with

maximum fault throws located in the Early Eocene Laing Formation approximately at 1,800–2,000 ms TWT (Figure 7c). The T - Z plots in both tiers indicate a c-type profile suggesting isolated fault development with fault propagation both upward and downward from the maximum throw point as presented in Figure 7 (see ref. [40]).

In this study, 3D fault throw analysis of a polygonal fault cell is performed, which is located in the southern part of the 3D seismic survey (Figure 8a). The inner polygonal faults are composed of two polygonal fault segments (Fault 1 and Fault 2; Figure 8b). The outer polygonal fault set composes of four polygonal fault segments (Fault 3, Fault 4, Fault 5 and Fault 6; Figure 8c). For better 3D fault throw analysis, Fault 1 and Fault 3 were split into Fault 1a, Fault 1b, Fault 1c, Fault 3a and Fault 3b according to their strike orientations. The average strike and dip directions of polygonal faults change significantly within the cells in Tier 2 (Figure 8). The maximum fault throws of the inner polygonal fault cell appear continuously at the same horizon of Early Eocene (EE) (Figure 9a). The maximum fault throws of the outer polygonal fault cell randomly appear at different horizons from EE to Middle Eocene (ME) (Figure 9b). An abrupt change in fault throws across the outer-cell faults is likely because of the intersection with the adjacent faults along strike and depth that characterise Tier 2.

Figure 6: (a) 3D perspective view of variance map of the horizon slice 40 ms below the Late Eocene horizon shows polygonal fault cells formed by multi-directional fault network (see red rectangle). (b) Rose diagrams show strikes and dip directions of the polygonal faults in the study area. Selected polygonal faults in Tier 2 PFS (in the red rectangle) are interpreted and used to perform 3D fault throw analysis.

5 Discussions

5.1 Deposition and sedimentation within the PFSs

There is no evidence of tectonic deformation controlling sediment accommodation within this basin during the Paleocene–Eocene time, and so, it is likely that the

relative sea level is the main factor that controlled sediment deposition. However, there are some tectonic movements dominated by horizontal shorting and uplift along the Alpine plate boundary occurring in the west (present-day) of the GSB basin [20,41]. Generally, the post-rift sedimentary successions in this area are dominated by marine influence with Paleocene to Eocene deltaic progradation in the west of the basin [15,18]. Due to a lack of tectonic deformation in the study

Figure 7: (a) Schematic diagrams of T - Z plots showing isolated growth fault, reactivated fault and dip-linkage fault (modified from [40]). Examples of T - Z plots identified in the Tier 1 PFS (b) and Tier 2 PFS (c). Studied faults in both tiers exhibit c-type profile.

area, the transition from the regressive sedimentary wedge to the widespread deposition of mudstone in the eastern area may occur with an influence of sea-level

fluctuations. This is possibly a direct influence on the formation of a prograding delta system and mounded contourites in the western part of the GSB since the

Figure 8: (a) Zoomed view of a single polygonal fault cell shows the polygonal fault planes used to analysed 3D fault throw. 3D fault throw colour maps of (b) inner-cell faults and (c) outer-cell faults (looking up from the bottom of the polygonal fault cell). See Figure 6 for the location. Faults 1–5 are dipping away from the cell. Faults 4 and 6 represent a pair of conjugate fault set at the cell boundary. Maximum fault throws mainly focus on the E-W to NE-SW striking fault segments of both inner and outer faults.

Figure 9: 3D fault throw colour maps of (a) inner faults and (b) outer faults (looking perpendicular to fault strike), see location in Figure 8. Multiple points of maximum offset can be observed laterally around EEEE on the inner fault planes. Fault throw decreases vertically. The maximum fault throws of the outer polygonal fault cell isolated occur at different levels from EE to ME.

Paleocene time (e.g. [15,17]). Although sea-level fluctuations may be a possible main control for sediment deposition in this area. Pre-Eocene tectonic movements along the Alpine fault in the west of the GSB may cause an increase in sediment input to the study area according to the prograding systems in Figure 10 [25,26]. In this study, it remains unclear if the Alpine movements could have been contributed sediments within the study area. We are unable to either accept or to refute the influence of the Alpine movements on sediment supply; consequently, it would be a combination of processes related to the Alpine movements and sea-level fluctuations.

The paleogeographic maps of the Paleocene to Late Eocene are presented in Figures 4 and 10. The large-scale clinoform facies suggests that paleo-shelf areas were in the northwestern part of the study area, while deep marine sediments deposited in the southeastern part of the study area where Tier 2 polygonal faults are observed (e.g. [19]). Since Paleocene time, a long marine transgressive period provided the thick, very fine-grained deposits and the lateral progressive landward of the paleo-shelf breaks. This period is in accordance

with an extension of the PFS located within very fine-grained sedimentary successions (Figure 4). Hence, seismic stratigraphic observation suggests that transgressive sedimentary deposits are a significant contributor of favourable sediments such as fine-shale and carbonate sediments for developing the polygonal fault formation within this area.

5.2 Distribution of PFS

In this study, the distribution of the PFSs is restrictedly developed in the area where transgressive sedimentary successions or fine-grained sediments dominated (Figure 4). The PFSs did not develop in the progradation sequence where coarse-grained sediments dominate. In addition, the boundary of the polygonal fault tier is controlled by changes in the lithological composition, possibly due to lateral sedimentary facies change as suggested by [3,8,12] (Figure 10). Therefore, the depositional process of pelagic sediments is one significant factor in the formation of the PFSs. The polygonal faults are limited to the top and bottom of clinoform

Figure 10: Un-interpreted and interpreted 3D seismic profiles show sequence boundaries and system tract interpretation within PFS. SF = sequence boundary. MFS = maximum flooding surface.

reflections, suggesting that they cannot penetrate through a thick sand interval (Figure 10). Seismically, a major impact on the lowstand deposition (e.g. slope fan) is that it acts as a buffer interval and delays, or prevents, polygonal fault propagation (Figures 4 and 10).

5.3 PFS formation

Generally, seismic characteristics of the PFSs in the GSB are similar to previous studies (e.g. [15,17]). Tier 1 PFS exhibited a higher fault density than Tier 2 PFS. The thin fine-grained sediments in which the Tier 1 PFS develops and overlies the coarse-grained sediments probably are the main factor for the development characteristics of Tier 1 PFS (Figures 4 and 10). The c-type profile is most common in this area within both tiers. The c-type profiles indicate that faults nucleate near the middle of

the polygonal fault tiers and propagate unimpeded upwards and downwards, before encountering sandstone-rich layers, which acted as mechanical barriers to fault propagation.

Polygonal fault segments extracted from the polygonal fault cell in the Tier 2 PFS exhibit roughly flat-top conical shapes. Each cell is separated by a series of convergent fault set where both inner and outer faults are dipping away from their cell centre (Figure 8). According to 3D fault throw analysis, the Tier 2 PFS initiated at the EE forming the inner faults. Then, sediments in this interval continue lateral shrinkage resulting in the development of the outer faults with smaller maximum throw at a younger level. This lateral spontaneous shrinkage of sediments with the expulsion of fluid can create polygonal faults (e.g. [42]). This suggests a compactional origin due to dewatering within the PFSs rather than shear failure related to opal A/CT

Figure 11: Simplified chronostratigraphy and some key mineral composition derived from Pakaha-1 well report are shown along the two polygonal fault tiers.

transition. In addition, Laing Formation, where the Tier 2 PFS initiated, is dominated by clay that allows a great amount of fluids to expel (Figure 11). We therefore proposed that the PFSs in the study area are more likely to be related to the dewatering of sedimentary successions during the diagenesis process. Although we proposed that the PFSs are formed by dewatering of sedimentary successions, it should be noted that the dewatering of sedimentary successions often occurs when montmorillonite is predominantly rich in clay. Thus, it is still necessary to further study whether there are other factors that can induce the PFSs in this area such as drilling and detailed core sampling within Laing and Tucker Cove Formations.

Overall strike orientations and maximum fault throws, which concentrate on the E-W to NE-SW striking fault segments, possibly indicate an influence of the

SE-dipping basal slope underneath the faults during early fault development. For the entire region, the overall polygonal faults may have preferential strikes parallel to the SE-dipping slope [e.g. 17].

5.4 Comparison with other polygonal systems

The relationship between polygonal faults and the depositional environment is complex. In general, polygonal faults are observed within fine-grained, hemipelagic to pelagic sediments in a bathyal setting [3,9,38,43]. The PFSs interpreted from 3D seismic data in this area are similar to most published PFSs in the GSB and other sedimentary basins worldwide that PFSs

are restricted to pelagic sediments during a transgressive marine period (e.g. [2,3,9,14,15,17,38,43]). It is important to note that although the depositional environments of the interval hosting the PFSs in this study area are similar to that in most published PFSs worldwide, the faulted intervals in some basins are exclusively clastic sediments, such as in the North Sea and Barents Sea [9,44].

A better understanding of the PFSs in the GSB may be useful for future petroleum exploration and production in the region [45]. It is widely known that PFSs may represent seals or permeable conduits for fluid flow in the subsurface (e.g. [43,46,47]). Honeycomb structures or circular depression features are observed within the Laing Formation and are interpreted to form by silica diagenesis at opal-A/CT transition boundary [15]. Similar to this basin, Hoffman et al. (2019) found circular depression features associated with polygonal faults and believed that polygonal faults are a fluid conduit for circular depression in the Canterbury Basin, New Zealand [16]. The PFS formation is believed to relate to the dewatering of fine-grained sedimentary successions in the GSB. We, therefore, interpret that PFS may be a fluid conduit contributed to the circular depression features in the GSB, similar to the Canterbury Basin. Chenrai and Huuse (2020) observed sand in this study area and described that sand injections are developed near Paleocene channel margins and are often seen to be adjacent to downward terminations of polygonal fault tips in the southern part of the study area [19]. The occurrence of the PFSs is suggested to postdate the sand injections and may act as a local fluid conduit at the top of the sand injection bodies [19]. Thus, the Laing Formation, where polygonal fault developed, may not be the seal for the Paleocene channel in the study area.

6 Conclusions

Analysis of the 3D seismic data in the GSB revealed that the PFSs are from the Paleocene-Eocene sedimentary successions, and they could be divided into two tiers including Tier 1 PFS and Tier 2 PFS. The distribution of polygonal faults shows a direct relationship to a very fine-grained environment within the basin. The seismic stratigraphic analysis also suggested that a transgressive system tract is a significant process in polygonal fault development as a host interval. Fault nucleation and fault throw analysis indicate faulting commenced during EE creating Tier 2 PFS, with reactivation and expansion

possibly occurring in ME forming the Tier 1 PFS. A key observation arising from fault throw analysis in this study is that the maximum fault throws within inner polygonal fault cells occur at the same seismic horizon or the same age. Then the polygonal fault development is expanded laterally creating the outer polygonal faults with multiple depths of fault throw maxima. Interpretation of the polygonal fault in this area is useful in assessing the migration pathway and seal ability of the Eocene mudstone sequence in the GSB and elsewhere in the world.

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