A Review of the Global Polygonal Faults: Are They Playing a Big Role in Fluid Migration?

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Polygonal faults (PFs) have been widely found in over 100 sedimentary basins worldwide, mainly in marine setting on continental margins and intracratonic sedimentary basins. PFs are characterized by layer-bound minor normal faults arranged in polygonal patterns and multi-direction strikes, most of which were developed in fine-grained sediments rich in claystone. The genesis mechanisms of PFs have been recognized as non-tectonic, mainly including shear failure, syneresis, density inversion, low coefficients of friction and gravity sliding theory. Previous studies often regarded PFs as conduits playing a role in favouring fluid migration, which were also regarded as fluid source expelled during PF generation. However, some researchers proposed that the PF-bearing layer is generally impermeable and may act as a seal. To better understand the role of PFs in fluid migration and their contrition to the shallower hydrocarbon accumulation, a geophysical review of global PFs case studies is conducted in this paper. A comprehensive analysis is carried out based on abundant case studies, with key parameters analyzed including the PFs characteristics (e.g., buried depth, lithology, size, etc.), formation mechanisms of PFs, tectonic-sedimentary setting, and the spatial relationship of PFs, nearby major fluid migration pathways and high amplitude anomalies. The compilation of global PF case studies of shows that hydrocarbon fluids from the deep is more likely to migrate upward through normal big faults, gas chimneys or unconformities surface around PFs. In most cases, PFs play limited roles in fluid migration, such as in South China Sea where hydrocarbon accumulations have been observed under the PFs and the PF-bearing layer may act as a seal trapping the free gas underneath. Generally, the role of PFs in fluid migration should be determined through a comprehensive analysis of the characteristics of PFs, surrounding amplitude anomalies, hydrocarbon distribution, and even the sealing ability of PFs which needs further study. It is more likely that the PFs play a limited role in vertical fluid migration and related shallower hydrocarbon accumulation and distribution.

Keywords: polygonal faults, fluid migration, genesis mechanism, dewatering, seismic data

INTRODUCTION

Polygonal faults (PFs) are the network of layer-bound minor normal faults, which are generally characterized by polygonal planform geometry and variable strike directions (Lonergan et al., 1998a; Berndt et al., 2012; Laurent et al., 2012; Ding et al., 2013; Li et al., 2020). PFs were first found in the Lower Tertiary sediments in Belgium, but the polygonal planform pattern was not determined at the beginning due to the absence of 3D seismic data (Henriet et al., 1991). Cartwright (1994 ab) adopted the time slice technique to first characterize the planform pattern of the PFs in the North Sea Basin. Since then, PFs have gained attention as one of the most debated and mystical geological structures from researchers, and have been recognized in over 100 sedimentary basins worldwide till now (e.g., Seebeck et al., 2015; Ireland et al., 2021; **Figure 1**). PFs were proposed to be extensional non-tectonic in genesis occurring at comparatively shallow depth (Cartwright, 1994 ab, 2011). They are commonly featured by small fault throw (usually10-50 m), slight fault displacement (mostly< 100 m), steep in dip angles (typically 40–70°), short horizontal extension in a single fault (commonly < 1500 m), and multi-direction strikes without preferential direction (Cartwright, 1994a, 2011; Cartwright and Dewhurst, 1998; He et al., 2010; Berndt et al., 2012; Ding et al., 2013; **Figure 2**). In addition to PFs, non-tectonic fractures can also occur in shale, formed during shale diagenesis and hydrocarbon generation and expulsion (Meng et al., 2021). This kind of fractures can occur at deeper depth, caused by the fluid pressure buildup, local stress distortion, and abrupt changes in matrix porosity and rock mechanical properties due to the intrinsic properties of shales. But they may be invisible in seismic due to their small scale and the resolution limitation of seismic data.

Previous studies often regarded PFs as dominant pathways for fluid migration, the presence of which was often interpreted to have facilitated vertical migration of oil and gas, therefore playing a vertical role in the shallower hydrocarbon accumulations (Larter et al., 2000; Gay et al., 2006; Hustoft et al., 2007; Ding et al., 2013; Alrefaee et al., 2018; Velayatham et al., 2021). For example, Alrefaee et al. (2018) mentioned that the PFs in the Northern Carnarvon Basin acted as the conduits for the hydrocarbon migration, and Ding et al. (2013) stated that the PFs in the Sanzhao sag of the Songliao Basin in China played a significant role in oil migration. However, no direct detailed evidence has been provided in these publications to prove the roles of PFs in facilitating vertical fluid migration. On the contrary, high amplitude seismic reflections indicating free gas distribution was observed underneath the PF-bearing layer in the continental margin of the South China Sea, suggesting that the PF-bearing layer may act as a seal and the PFs may not be favorable fluid migration conduits at present (Sun et al., 2010). After careful examination of lots of PF case studies, it has been recognized that the evidence for the role of PFs in fluid migration is not solid enough in most cases, and more comprehensive studies should be carried out to evaluate the role of PFs in fluid migration. In this paper we focus on the role of PFs in fluid migration by conducting an examination of enormous global cases of PFs, and key parameters are analyzed such as the genesis mechanism and characteristics of the PFs (e.g., buried depth, lithology, size, etc.), surrounding amplitude anomalies, hydrocarbon distribution and even the permeability of the faults and nearby sediment layers. Based on above analysis the general role of PFs in fluid migration is evaluated, as well as the
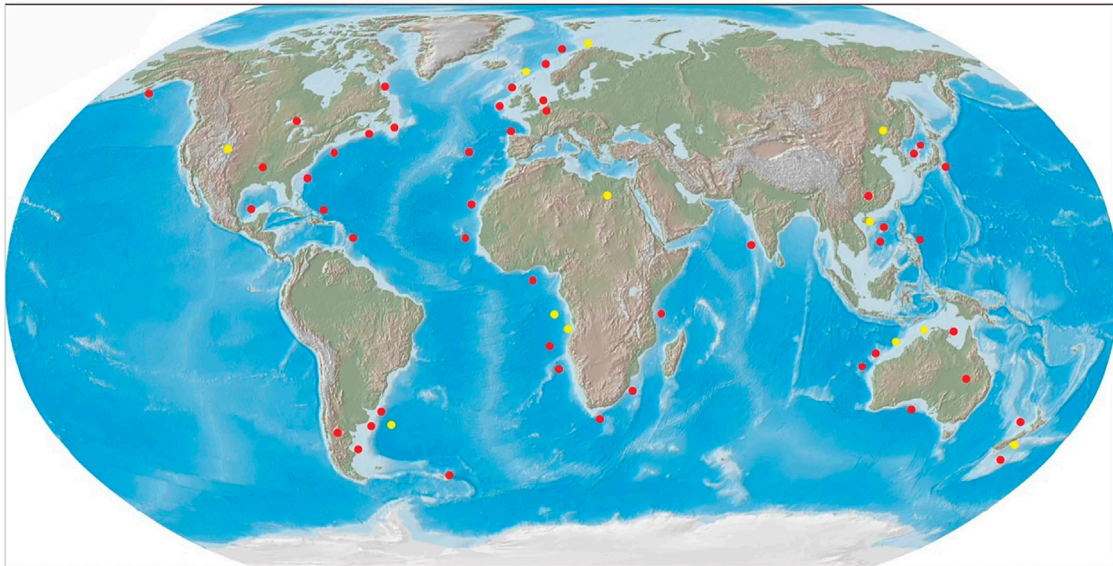

FIGURE 1 | Global distribution of the polygonal faults discovered all over the world (modified after Cartwright, 2011). In this study PF occurrences discovered after 2010 (yellow dots) are added which is a supplement of previous compilation (red dots; Cartwright, 2011).
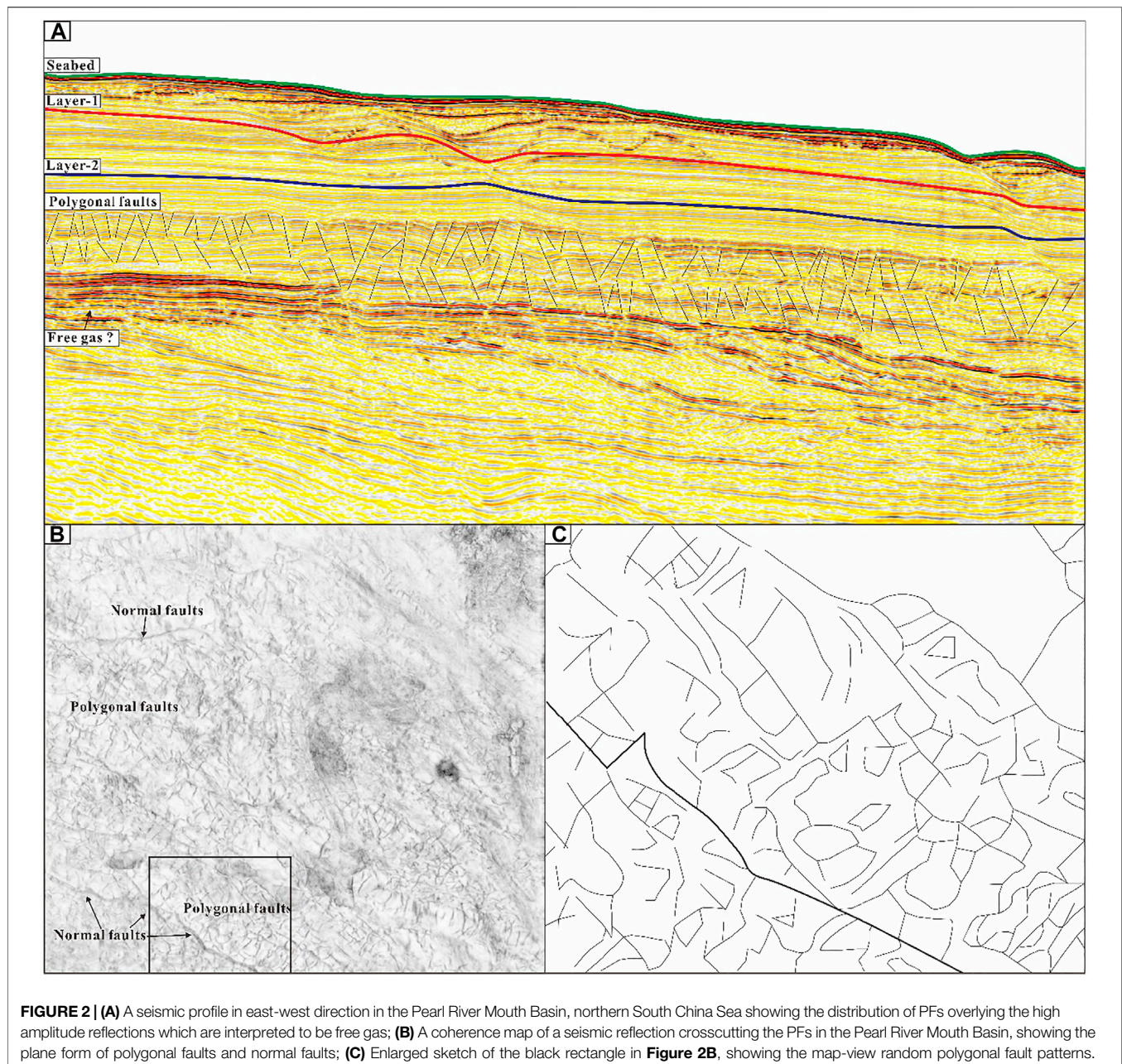
FIGURE 2 | (A) A seismic profile in east-west direction in the Pearl River Mouth Basin, northern South China Sea showing the distribution of PFs overlying the high amplitude reflections which are interpreted to be free gas; **(B)** A coherence map of a seismic reflection crosscutting the PFs in the Pearl River Mouth Basin, showing the plane form of polygonal faults and normal faults; **(C)** Enlarged sketch of the black rectangle in **Figure 2B**, showing the map-view random polygonal fault patterns.

contribution to the shallower hydrocarbon or gas hydrate accumulation.

GENESIS MECHANISMS OF POLYGONAL FAULTS (PFS)

A compilation of the genesis mechanisms of PFs is summarized in this paper based on publications of global PF case studies, with five main mechanisms recognized including density inversion, gravity sliding theory, low coefficients of friction, syneresis, and shear failure (**Table 1**). 'Gravity sliding theory' was first proposed by Higgs and McClay (1993), according to which the gravitational

stresses produce a strong alignment of fault strikes during a downslope sliding of deposits (Cartwright et al., 1994 ab; Goulty, 2008). However, many PF-bearing layers are smooth with an extremely small dip of almost zero, suggesting that this theory may not explain the formation mechanisms of many PF cases (Cartwright et al., 2003; Goulty, 2008).

The 'low coefficients of residual friction' mechanism was proposed by Goulty (2002), and it was proposed that the nucleated PFs can continue to grow by low coefficients of friction, creating compaction and repeated slip of sediments with increasing overburden stress (Goulty, 2008; Han et al., 2016). The mechanism of low friction coefficients along faults can only explain the formation of PFs after initial slip, but cannot

TABLE 1 | A compilation of genesis mechanisms of polygonal faults in different study areas.

Genesis mechanisms	Description	Key study area	References
Density inversion	After drainage during compaction, the top and bottom of the mudstone becomes dense forming low permeable sealed layers. The water in the middle of the mudstone cannot be expelled, generating overpressure. When it is critically overpressured, hydraulic fractures may occur with faults and collapses forming at the top, leading to the formation of PFs.	North Sea Basin, Lake Hope region, Farafra Oasis of Western Desert of Egypt	Henriet et al. (1988,1991) Cartwright (1994a), Cartwright (1994b) Cartwright and Lonergan (1996) Watterson et al. (2000) Tewksbury et al. (2014)
Gravity sliding	Downslope gravitational collapse produces a strong alignment of fault strikes perpendicular to the direction of sliding towards the depoleft.	Outer Moray Firth of northern North Sea	Higgs and McClay (1993) Clausen et al. (1999)
Low coefficients of friction	Low coefficients of friction can increase the displacement on localized fault surfaces and the concentrated stress around the dislocation loop may bound the slip zone. It may enable the outward propagation of the polygonal fault after initial slip which eventually coalesces with others into a polygonal fault system.	Eormanga Basin, North Sea Basin	Goulty (2002) Goulty and Swarbrick (2005) Goulty (2008)
Syneresis	Syneresis occurs during the early stage of compaction and dewatering, and the three-dimensional contraction of smectite-rich gels favors the PF formation. This genesis mechanism is driven by the interparticle attractive forces between clay particles, and mainly occurs in layers composed of smectitic claystone and carbonate chalks.	Stable Subbasin, North Sea Basin, Qiongdongnan Basin	Cartwright (1996) Lonergan et al. (1998b) Hansen et al. (2004) Wu et al. (2009) Sun et al. (2010) Han et al. (2016)
Shear failure	The conversion of opal-A to opal-CT reduces the bulk rock volume and induces differential compaction and shear failure during regional diagenetic processes of siliceous sediments. It is accompanied by stress changes, and therefore can cause PFs initiation.	Vøring Basin, Møre Basin, Sanzhao Sag of Songliao Basin, Great South Basin	Cartwright. (2011) Davies and Ireland (2011) Ding et al. (2013) Li et al. (2020)

account for fault nucleation (Goulty, 2002; Goulty and Swarbrick, 2005). In addition, this theory is not applicable for PFs developed in porous sandstones because shear band in sandstones is usually developed through a strain-hardening process that eventually weakens the strain (Antonellini et al., 1994; Aydin et al., 2006; Antonellini and Mollema, 2015).

'Density inversion' was interpreted to be caused by the differential compaction between the underlying over-pressured low-density strata and the overlying normally pressured layer (Henriet et al., 1991; Cartwright, 1994 ab). It was often accompanied by shale flowage and hydrofracturing, during which processes the PFs were formed. For example, the PFs in the Lake Hope region of South Australia was interpreted to be triggered by gravitational instability of a low-density over-pressured layer at the bottom of the PF-bearing sequence (Watterson et al., 2000). This has been proved by experimental results as the pattern of ridges defining the polygon boundaries is consistent to the experimental spoke and hub patterns formed at the boundaries between viscous materials with density inversion. The 'density inversion' theory has also been proved by Nicol et al. (2003), who proposed a density inversion model showing similar fault geometry, linkage and capture. However, this theory only suits the PFs developed in over-pressured low-density layers and cannot explain the PFs in normally pressured strata (Goulty, 2002; Ding et al., 2013).

'Syneresis mechanism' indicates the PF formation caused by dewatering contraction, probably due to spontaneous contraction of colloidal sediments which often occurs during early compaction (Dewhurst et al., 1999a; Dewhurst et al., 1999b;

Berndt et al., 2012). This theory can better explain the map-view polygonal geometry as the small normal faults intersect with each other (Ding et al., 2013). The PFs found in the Tertiary strata of the North Sea is interpreted to be formed under this genesis mechanism (Dewhurst et al., 1999a). In this area, the lithology of the PF-bearing successions is dominantly composed of smectitic claystone and carbonate chalks, and the three-dimensional contraction of smectite-rich gels favors the PF formation, which is driven by the interparticle attractive forces between clay particles. At present the syneresis mechanism is widely accepted especially for PF occurrence areas rich in colloidal sediments.

'Shear failure', also known as 'volumetric contraction', is regarded to be caused by a decrease in horizontal stress due to mineral-specific dissolution associated mostly with opal A-opal CT-quartz transitions during sediment diagenesis (Davies and Ireland, 2011; Laurent et al., 2012; Li et al., 2020). This mechanism has been widely adopted to explain the formation of PFs (Cartwright, 2011; Ding et al., 2013), such as in the Sanzhao Sag in East China, Vøring Basin Offshore Norway and Great South Basin in New Zealand (Han et al., 2016; Li et al., 2020). However, the shear failure mechanism is not applicable for the PF formation in areas without biogenic silica and smectite, such as in the chalk layer of Cretaceous Khoman Formation near Farafra Oasis in the Western Desert of Egypt (Tewksbury et al., 2014).

Generally, no consensus on the genesis mechanism of PFs has been reached until present and it is possible that there are several different genesis mechanisms for the global PF occurrences which

TABLE 2 | A compilation of global case studies of PFs showing information on location, buried depth, geological time, lithology, thickness, size, related hydrocarbon reservoirs, and the role of PFs in fluid migration.

Locations	Buried depth	Geologic time	Lithology	Thickness	Size	Nearby reservoir	Previous recognitions of the role of PFs in fluid migration	References
The middle of the North Sea Basin	No report	Palaeocene-Late Miocene	Mudstone	~100–200 m ~200–300 m ~400–500 m	Mean length: 1–2 km Line spacing:25 m Throw: 10–70 m	No report	No report	Lonergan et al., 1998a Dewhurst et al. (1999a)
Mid-Norwegian Margin	~600–1100 m (below seabed)	Miocene	Fine-grained hemipelagic siliceous ooze	~400–500 m	Throw: 20–30 m	GHSZ exists above PFs	Dewatering occurred during the development of PFs may be regarded as a fluid source that contributed to shallower gas hydrate system.	Berndt et al., 2003 Hustoft et al., 2007
Western Lake Superior	a few meters (below lakebed)	Early Holocene	Glaciogenic clays	<30 m Mainly 10–15 m	Throw < 1 m	Np report	The presence of seabed pockmarks indicates the pore fluid escape from the water-saturated near-surface sediments to the seabed through the PFs.	Cartwright et al. (2004)
Lower Congo Basin offshore Pointe Noire, Congo	~50–800 m (below seabed)	Pliocene	Fine-grained sediments	~700 m	Offsets:5–30 m Average spacing 100–500 m	Reservoir exists below PFs; gas hydrate accumulation exists above the PFs	The presence of seabed pockmark indicates fluid can escape from the free gas zone (FGZ) underlying the gas hydrate stability zone (GHSZ) to the seabed through the PFs.	Gay et al. (2006)
Sanzhao Sag in the Songliao Basin, East China	~100–180 m ~380–500m; (below seabed)	Late Cretaceous	Shaly sandstone; fine mudstone	~100–150 m ~200–250 m	Extending length 0–5 km (mostly < 2 km) Throws < 50 m	Reservoir exists above and below PFs	①Oil source comparison shows hydrocarbons above and below the PFs are from the same source, indicating that the PFs may have acted as migration pathways ②The PFs are laterally sealed, and can form favorable hydrocarbon traps when combined with sand bodies ③Drilling data show that the presence of PFs can enhance reservoir performance. (Continued on following page)	He et al., 2010 Ding et al., 2013

TABLE 2 | (*Continued*) A compilation of global case studies of PFs showing information on location, buried depth, geological time, lithology, thickness, size, related hydrocarbon reservoirs, and the role of PFs in fluid migration.

Locations	Buried depth	Geologic time	Lithology	Thickness	Size	Nearby reservoir	Previous recognitions of the role of PFs in fluid migration	References
Qiongdongnan Basin, South China Sea	~1800m (below seabed)	Middle-late Miocene	Fine-grained mudstone	~252 m	Length: 150–1500 m Throws: 10–40 m Dip: 25–90°	Reservoir exists below PFs	①The incised valleys above the PFs indicate that PFs can act as migration pathways ②PFs may reduce the seal integrity of the PF-bearing layer.	Sun et al., 2010 Han et al. (2016)
Lower Congo Basin offshore Congo River	~100–500 m (below seabed)	Pliocene	Fine-grained clay rich in biogenic silica	~200–300 m	Diameter of fault cell< 100 m	Reservoir exists below PFs	Abrupt termination of the high reflectivity zones against PFs indicates that the PFs can act as barriers for fluid flow.	Andresen and Huuse, (2011)
Hatton Basin, NE Atlantic Ocean	~30–50 m (below seabed)	Late Eocene	Calcareous biogenic ooze	~250 m	Several hundred meters across	Reservoir exists below PFs	The close correlation between the alignment of the seafloor polygonal depressions and underlying PFs indicates PFs can act as fluid escape pathways.	Berndt et al. (2012)
Gjallar Ridge Vøring Basin, offshore Norway	~16 m (below seabed)	Late Miocene-Late Pliocene	Claystone with biogenic ooze	~200–300 m	Offsets < 30 m Average dip: 50–60°	Reservoir exists below PFs	Once a polygonal fault network is connected and fault units are hard-linked, the PF system forms preferential pathways for vertical fluid migration.	Laurent et al. (2012)
Hammerfest Basin	~500–700 ~1000–1150 m (below seabed)	Late Cretaceous	Shale with coarse clastic material	~125 m	Throw: 5–20 m Space: 300–500 m Strike: 80–90°	Reservoir exists below PFs	The high amplitude anomalies indicating gas pockets indicate that the PFs and PEEFs provide migration pathway for ascending fluids.	Ostanin et al. (2012)
Pearl River Mouth Basin,	~1150–1600 m	Early Miocene	Fine-grained sediments	~250 m	Long: 100–1,400 m Spacing: 200–800 m Throw: 10–30 m	Gas hydrate accumulation exists above PFs; deep large gas reservoir exists below PFs	The large gas reservoir directly underlies the PFs without leaking, indicating that the PF-bearing layer can act as a seal trapping the free gas underneath.	Sun et al. (2012)

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TABLE 2 | (*Continued*) A compilation of global case studies of PFs showing information on location, buried depth, geological time, lithology, thickness, size, related hydrocarbon reservoirs, and the role of PFs in fluid migration.

Locations	Buried depth	Geologic time	Lithology	Thickness	Size	Nearby reservoir	Previous recognitions of the role of PFs in fluid migration	References
Faroe-Shetland Basin	~200–900 m (below seabed)	Eocene-Oligocene	Claystone	~600–700 m	Throw: A few meters to more than 100 m	No report	No report	Bureau et al. (2013)
Near Farafra Oasis, Egypt	Outcrops	Cretaceous	Chalk	~220 m	Throw: 2–3 m Dips: ~80°	No report	Vein systems and grooved fault surface indicate that PFs can serve as fluid conduits.	Tewksbury et al. (2014)
Arches National Park in south-eastern Utah	Outcrops	Middle Jurassic	Sandstone	~1–2 m	Edges long:1–5 m Offsets: < 1 m Wide: a few meters	No report	PFs reduce the permeability of sandstone and may therefore weaken the potential reservoir quality.	Antonellini and Mollema, (2015)
Lower Congo Basin offshore Luanda, Angola	~60–500m, mainly 150 m (below seabed)	Pliocene-Pleistocene	Fine-grained sediments	~100–300 m	Throw: 10–20 m	No report	No report	Morgan et al. (2015)
Petrel Sub-basin, Bonaparte Basin, Australia	~300–1200 m (below seabed)	Middle-late Cretaceous	Micaceous mudstone	~650 m	Space 100–1200 m	CO_2 storage and hydrocarbon reservoirs exist below PFs	①The PF outcrop displays calcite veins which indicates that the PFs promoted fluid flow through the seal ②The low reflection strengths, acoustic turbidity, and bright spots beneath the PFs can be regarded as the indirect evidence for fluid escape.	Seebeck et al. (2015)
Offshore Uruguay	~800–1500 m (below seabed)	Pliocene-Pleistocene	Fine-grained mudstones rich in hydrocarbon	~300–650 m	Throw: 2–30 m	Reservoir exists below PFs	①Seal integrity can only be destroyed by PFs to a limited degree ②The PF-bearing layer is fine-grained and low permeable, and may act as seal to trap a hydrocarbon accumulation underneath.	Turrini et al. (2017)
Carnarvon Basin, Australia	No report	Palaeocene-Eocene	Calcareous clay	~90 m ~180 m	Length: 70–620 m Throw: 10–40 m	Reservoir exists above PFs	PFs destroyed the continuity of the fine-grained sedimentary layer, and the PFs may act as conduits for upward hydrocarbon flow.	Alrefaee et al. (2018)

TABLE 2 | (*Continued*) A compilation of global case studies of PFs showing information on location, buried depth, geological time, lithology, thickness, size, related hydrocarbon reservoirs, and the role of PFs in fluid migration.

Locations	Buried depth	Geologic time	Lithology	Thickness	Size	Nearby reservoir	Previous recognitions of the role of PFs in fluid migration	References
Canterbury Basin, New Zealand	~850–1250 m (below seabed)	Palaeocene-Eocene	Clay-rich mudstone	~200–300 m	Dip: 20°–40° Spacing: 200–300 m Throw: 10–30 m	No report	The occurrence of paleo-pockmarks above the top of the PF-bearing layer indicates the fluid expulsion during PF formation.	Hoffmann et al. (2019)
Great South Basin, Zealand	~1,000–2000m (below seabed)	Eocene	Siltstones, shales and marls	~750–1000 m	Dip:45–55° Displacement: tens of meters to a hundred meters	No report	No report	Li et al. (2020)
Ceduna Sub-Basin, Bight Basin	~750–1550 m (below seabed)	Late Cretaceous	Fine-grained sediments	~450–500 m ~600–700 m	Throw: ~9–25 m	Reservoir exists below PFs	Spatial relationship of the fluid escape features and underlying PFs indicates that PFs have acted as fluid migration pathways in the geological past.	Velayatham et al. (2021)

should be determined by the local lithological, diagenetic or stress conditions. "Density inversion", 'syneresis' and 'shear failure' are the main formation mechanisms which are widely accepted as responsible for the formation of PFs in different areas. To determine the specific formation mechanism of PFs in certain areas, a comprehensive analysis should be carried out investigating key parameters such as lithology, pore fluid and strain conditions.

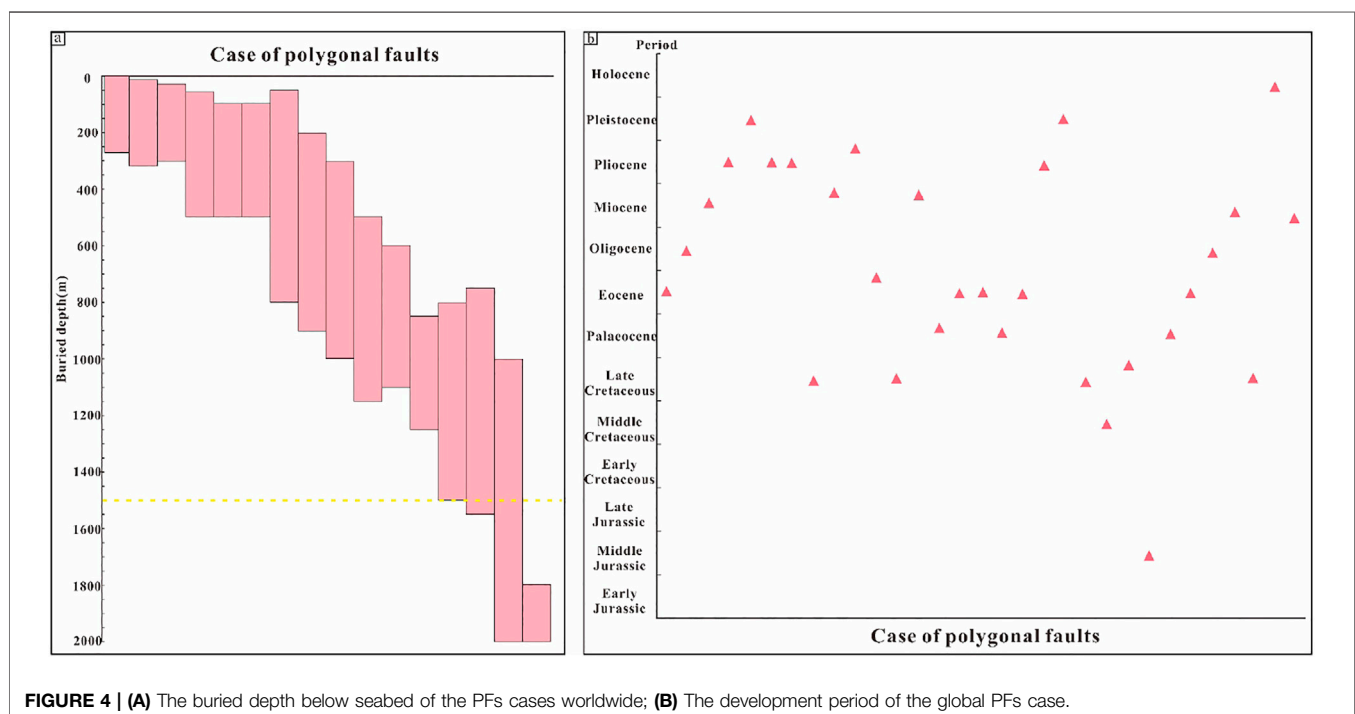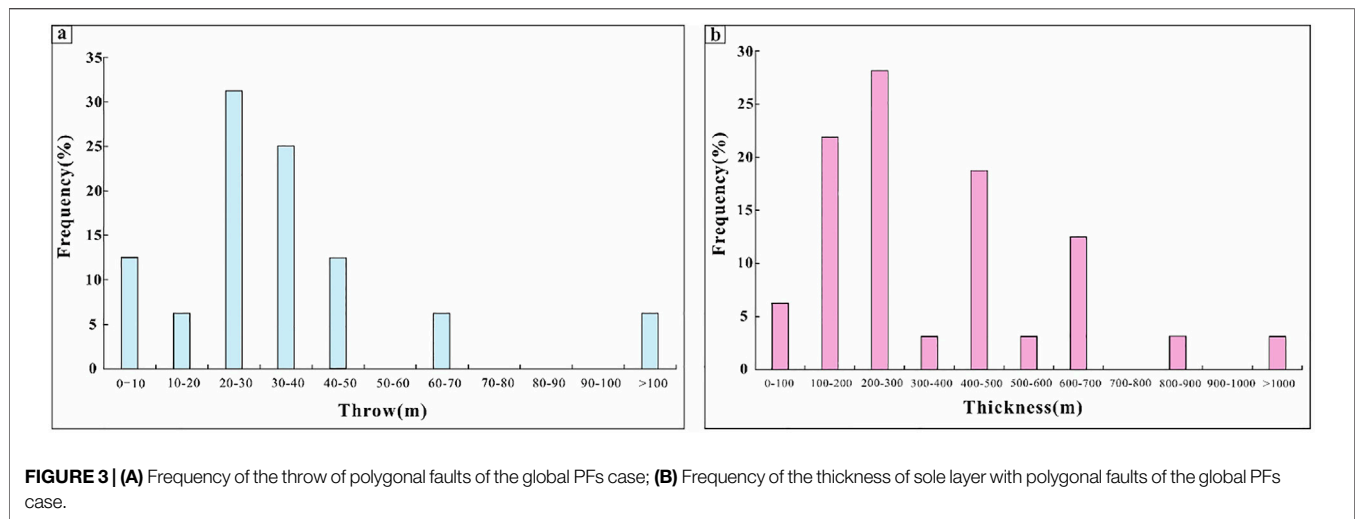## SEDIMENTARY-TECTONIC SETTING OF POLYGONAL FAULT DEVELOPMENT

PFs are layer-bound deformation structures mainly formed in shallow soft sediments of marine settings such as passive continental margins (Tewksbury et al., 2014; Seebeck et al., 2015; Turrini et al., 2017; Hoffmann et al., 2019; Velayatham et al., 2021), some intracratonic sedimentary basins and foreland basins (Cartwright, 2011; Morgan et al., 2015; Li et al., 2020; **Figure 1**). Some PFs have also been observed in lacustrine environment (Cartwright et al., 2004; He et al., 2010; Han et al., 2016). Most PFs were found in strata of fine-grained sediments (e.g., mudstone, shale, claystone, or carbonate chalk), younger than Middle Cretaceous period (**Table 2**; Hansen et al., 2004; Andresen and Huuse, 2011; Tewksbury et al., 2014; Yang et al., 2017; Alrefaee et al., 2018). However, Sun et al. (2010) and Hansen et al. (2004) stated that PFs may also occur in comparatively older pre-Cretaceous

sediments, but they cannot be imaged clearly in seismic data probably due to the limitation of seismic resolution. A case study in Arches National Park in south-eastern Utah displayed the outcrops of PFs in the upper sandstone layer of the Middle Jurassic (**Table 2**), and the preservation of PFs in a comparatively older strata was probably due to their shallow burial depth in an uplifted erosional environment (Antonellini and Mollema, 2015).

Hansen et al. (2004) used 3D seismic attribute maps to show the intersecting pattern between PFs and tectonic faults, suggesting that the propagation of PFs has been disturbed by the tectonic faults. Ostanin et al. (2012) also emphasized the tectonic impact on the growth of PFs, and the dominant strike direction of the PFs is consistent with the strike direction of the regional tectonic faults. Therefore, even though the PFs are non-tectonic, the tectonic influence on the growth and propagation of PFs cannot be ruled out. The development and distribution of PFs are primarily determined by the lithology of the PF-bearing layer and their buried depth, and the regional stress affects the propagation and dominant direction of both tectonic faults and PFs.

CHARACTERISTICS OF POLYGONAL FAULTS

Based on publications of global PF case studies, a compilation of PFs was carried out with key parameters analysed including PF

FIGURE 3 | (A) Frequency of the throw of polygonal faults of the global PFs case; **(B)** Frequency of the thickness of sole layer with polygonal faults of the global PFs case.

FIGURE 4 | (A) The buried depth below seabed of the PFs cases worldwide; **(B)** The development period of the global PFs case.

locations, geological time, buried depth, lithology, thickness, size, related hydrocarbon reservoirs, and their interpreted roles in fluid migration (**Table 2**).

General Geometry and Location of the Polygonal Faults

PFs are often characterized by small fault throw (**Figure 3A**), small lateral extension and various displacement value (from a few meters to over 100 m), mainly developed in shallow-buried strata which are over 100 m thick and deposited after the Middle Cretaceous period (mainly Tertiary, **Figure 3B**, **Figure 4B**; Cartwright, 2007; He et al., 2010; Berndt et al., 2012; Ostanin

et al., 2012; Li et al., 2020). They have neither dominant strike nor dominant tendency, existing as networks of minor normal faults (Watterson et al., 2000; Alrefaee et al., 2018; **Figure 2**). The throws of PFs developed in most of the PF areas are smaller than 50 m, such as in the Lower Congo Basin (10–20 m, Morgan et al., 2015), in the Hammerfest Basin (5–20 m, Morgan et al., 2015), in the Qiongdongnan Basin (10–40 m, Han et al., 2016), and in the Near Farafra Oasis, Egypt (2–3 m, Tewksbury et al., 2014). In addition, some PFs with larger throw of >100 m have also been found such as in the Faroe-Shetland Basin (Bureau et al., 2013). The extending length of PFs in most of the PF areas is generally smaller than 2 km, such as in the Northern Carnarvon Basin (70–620 m, Alrefaee et al., 2018), in the North Sea Basin

(1,000–2000 m, Lonergan et al., 1998a), and in the Pearl River Mouth Basin (100–1400 m, Sun et al., 2012).

With the increase of burial depth, the dip angle of PFs decreases gradually, interpreted to be caused by compaction and flattening of the fault planes due to increasing vertical stress (Lonergan et al., 1998b; Stuevold et al., 2003; Shoulders et al., 2007). For example, some PFs from offshore Norway appear to have relatively steep dip angle of ~80° at the shallower level, but they show strongly listric at deeper depth with comparatively smaller dip angle of ~60° (Cartwright, 2011). PFs are layer-bound deformation structures mainly formed in shallow soft sediments of marine settings. Most of the PFs discovered worldwide are located at depth smaller than 1,500 m below the seabed (mbsb) with only a small proportion of PFs occur at depth ranging from 1,500 to 2000 mbsb, at which depth the early stages of compaction probably caused the initiation of PFs (**Figure 4A**). At even deeper depth, the PF-bearing layer experienced strong diagenesis which makes the PFs difficult to be imaged in seismic. What is more, small sized PFs have been found in a few meters below the present-day lakebed in the Western Lake Superior, with a thickness range of 10–15 m and fault throw of < 1 m (Cartwright et al., 2004). Two outcrops of PFs have been observed in the Jurassic layers in the Arches National Park in south-eastern Utah and the Cretaceous layers in the Near Farafra Oasis, Egypt (Tewksbury et al., 2014 Antonellini and Mollema, 2015). The layer-bound PFs are mainly developed in marine claystone, and therefore the thickness of the PF-bearing strata is mainly controlled by the sediment distribution deposited in certain sedimentary environment (Cartwright and Lonergan, 1997; Goulty, 2008). Most PFs around the world were developed in layers of < 700 m thick, with quite a few occurring in layers of only several meters thick (**Table 2**; **Figure 3B**). For example, the outcrops of PFs was observed in Arches National Park in south-eastern Utah, the layer thickness of which is < 2 m (Antonellini and Mollema, 2015).

Lithology of Polygonal Fault-Bearing Layer

PFs are usually found in layer-bound successions consisting mainly of fine-grained sediments (e.g., mudstone, shale, claystone, or carbonate chalk), which may be related with the genesis mechanism of PFs (Andresen and Huuse, 2011; Cartwright, 2011; Yang et al., 2017; Alrefaee et al., 2018; Ireland et al., 2021). "Syneresis" due to spontaneous contraction of colloidal sediments and "shear failure" caused by mineral-specific dissolution have been widely accepted to explain the PF formation mechanism in fine-grained sediments (Han et al., 2016; Li et al., 2020). Besides, small outcrops of PFs have been found in the Entrada sandstone strata of Middle Jurassic in the Arches National Park in south-eastern Utah (Antonellini and Mollema, 2015). Since sandstone are relatively coarser and permeable, genesis mechanisms such as "syneresis" and "shear failure" cannot explain the PF formation in sandstone layers. The "density inversion" was proposed to account for the PF formation in the Entrada Sandstone (Antonellini and Mollema, 2015). The over-pressured sequences (Carmel Formation) is overlain by normally pressured layer (Entrada Sandstone), which caused

accompanied shale flowage and hydrofracturing therefore leading to the formation of PFs in sandstones. In addition, the geometry, distribution and intensity of PFs are mainly determined by lithological features such as grain size, hardness, diagenesis, clay mineralogy and organic matter content (Dewhurst et al., 1999 ab; Hansen et al., 2004; Turrini et al., 2017). When the PF-bearing layer is homogeneous in thickness and lithology, faults cross cut each other uniformly at an angle of 60° (Cartwright, 2011; Li et al., 2020). Otherwise, the geometry of the PFs is featured by irregular polygons when the PF-bearing layer is heterogeneous in thickness and lithology, which represents the situation of most global PF cases.
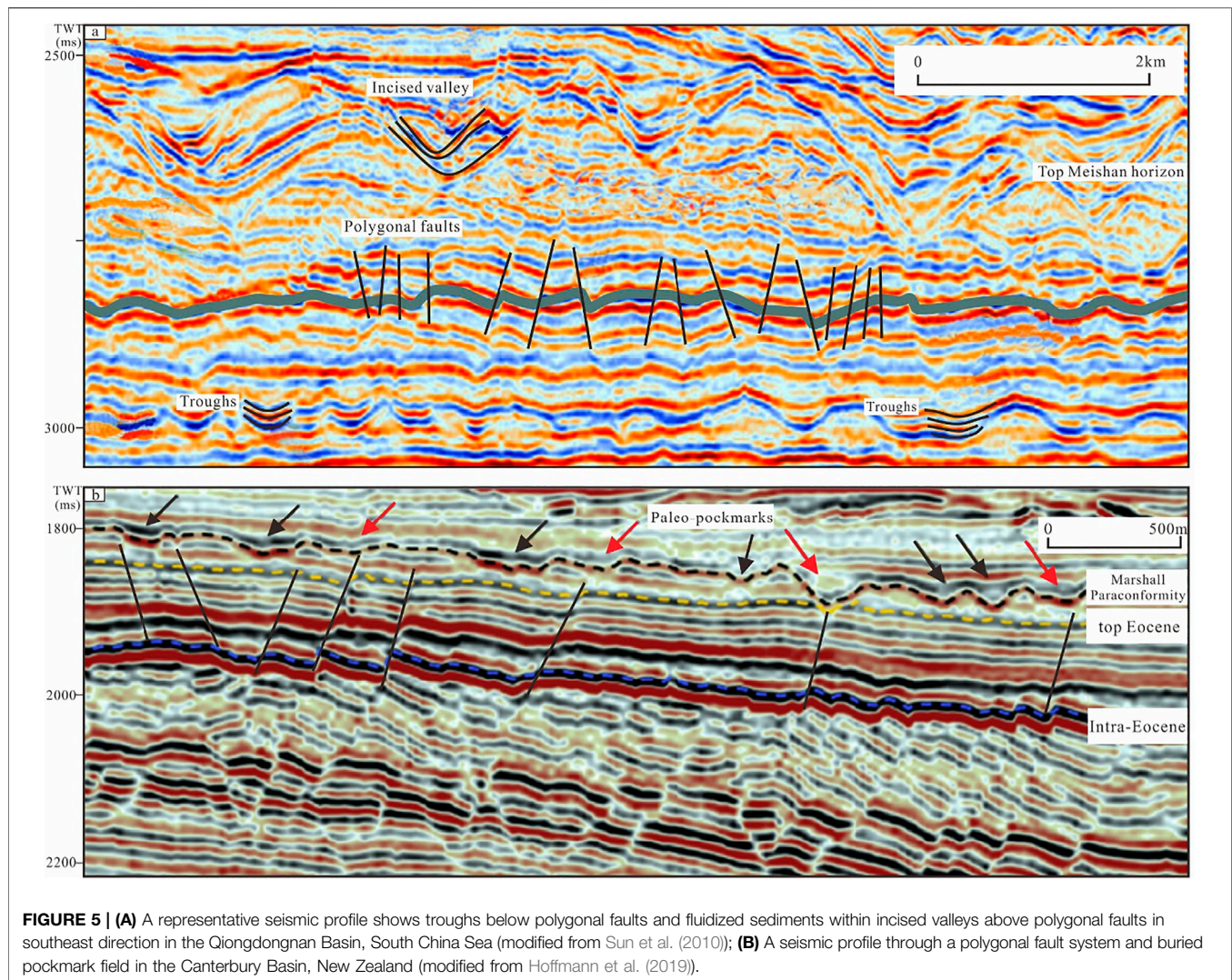
Although most PFs occur in fine-grained sediments, their formation and characteristics are also affected by nearby coarse sand bodies density (Victor and Moretti, 2006; Shoulders et al., 2007; Liu et al., 2008; He et al., 2010). In the south-east area of the Sanzhao sag, the PFs are well developed in areas of smaller sand/layer thickness ratio and poor physical property. On the contrary, the PFs are sparsely developed in the northern area of Sanzhao sag where is featured by larger sand/layer thickness ratio and good physical property (He et al., 2010). The sand bodies overlying the PFs favour the discharge of fluids from the PF-bearing mudstone layer, inhibiting the formation of overpressure and therefore causing sparsely developed PFs.

DISCUSSION

Previous Recognitions of the Roles of Polygonal Faults

According to previous studies, the presence of PFs has been proposed to play a role in both favouring fluid migration and as a fluid source during the early stage of PF generation (Hustoft et al., 2007; Sun et al., 2010; Tewksbury et al., 2014). Many researchers commonly believed that PFs facilitate fluid migration by generating more failures and destroying the integrity of fine-grained layers, and regarded PFs as dominant channels for fluid migration and re-migration (Ding et al., 2013; Seebeck et al., 2015; Han et al., 2016). For example, Laurent et al. (2012) has proposed that the PFs in Gjallar Ridge offshore Norway can act as preferential fluid migration pathways when they are connected closely. Alrefaee et al. (2018) interpreted the PFs in Northern Carnarvon Basin in Australia as the fluid migration pathways based on seismic imaging of the discontinuity of the fine-grained sediments. In the Sanzhao Sag of the Songliao Basin, the oil source comparison of hydrocarbon reservoirs above and below PFs shows that they were from the same source rock, and this was regarded as the evidence that PFs acted as the fluid migration pathways (He et al., 2010; Ding et al., 2013). According to Sun et al. (2010), the development of PFs in the fine-grained Huangliu Formation and Meishan Formation in Qiongdongnan Basin destroyed the sealing property and increased the permeability, resulting in the upward secondary migration of oil and gas from the lower hydrocarbon reservoir.

Considering the dewatering process during the initial period of PF formation, the PF-bearing layer may be a fluid source where
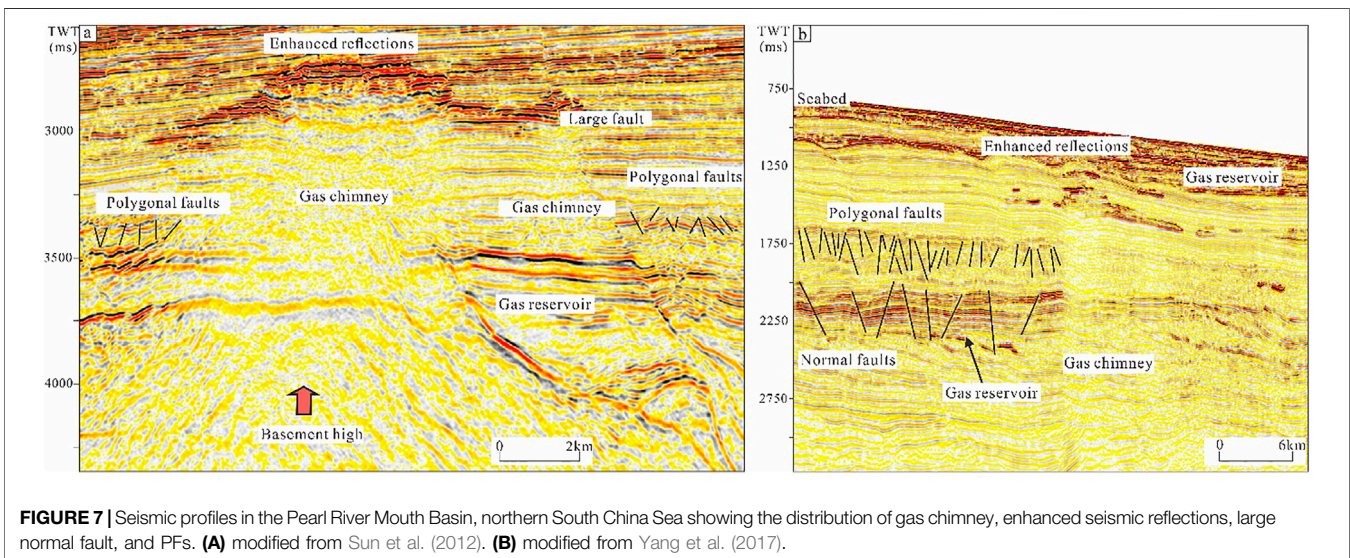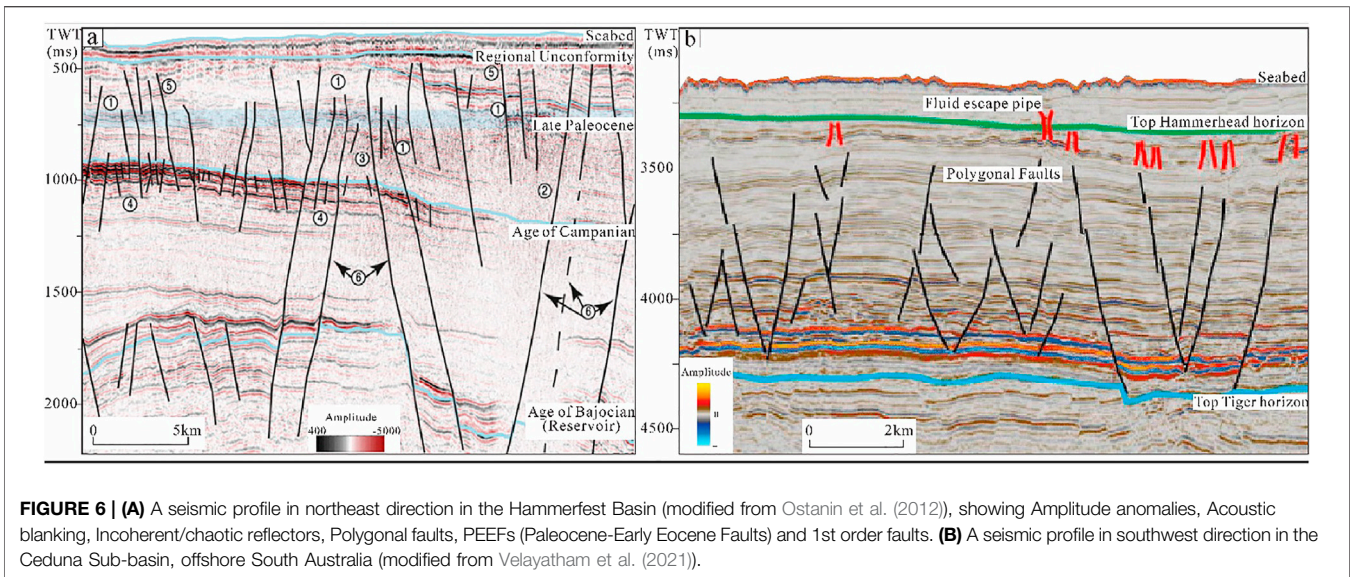
FIGURE 5 | (A) A representative seismic profile shows troughs below polygonal faults and fluidized sediments within incised valleys above polygonal faults in southeast direction in the Qiongdongnan Basin, South China Sea (modified from Sun et al. (2010)); **(B)** A seismic profile through a polygonal fault system and buried pockmark field in the Canterbury Basin, New Zealand (modified from Hoffmann et al. (2019)).

fluids were expelled to nearby sediments. For example, the sediment dewatering during PF generation in the Kai Formation and the underlying Brygge Formation in Mid-Norwegian Margin were regarded as responsible for providing the fluid source for the gas hydrate formation in the shallower Vøring margin (Berndt et al., 2003; Hustoft et al., 2007). PF generation is commonly associated with underlying troughs and overlying incised valleys, and it was proposed that the fluid produced by dewatering in the early stage of PFs formation may escape and migrate upward causing the troughs due to related consequent volume loss and subsequent collapse (Sun et al., 2010). The overlying incised valleys were caused by fluid escape which was expelled from underlying PF-bearing mudstone layer (**Figure 5A**).

Sediment compaction and pore water drainage occur during PF formation, resulting in the formation of pockmark in Canterbury Basin (Berndt et al., 2003; Gay et al., 2004; Gay and Berndt, 2007; Goulty, 2008). But that is not the only factor for the pockmark formation because 6 out of 11 pockmarks are not spatially consistent with the PF locations (**Figure 5B**). Other possibilities cannot be excluded such as bottom currents and differential compaction. In addition, PFs are often laterally impermeable, which may prevent lateral fluid migration and may form fault-lithologic traps when combined with nearby sand bodies (He et al., 2010; Andresen and Huuse, 2011).
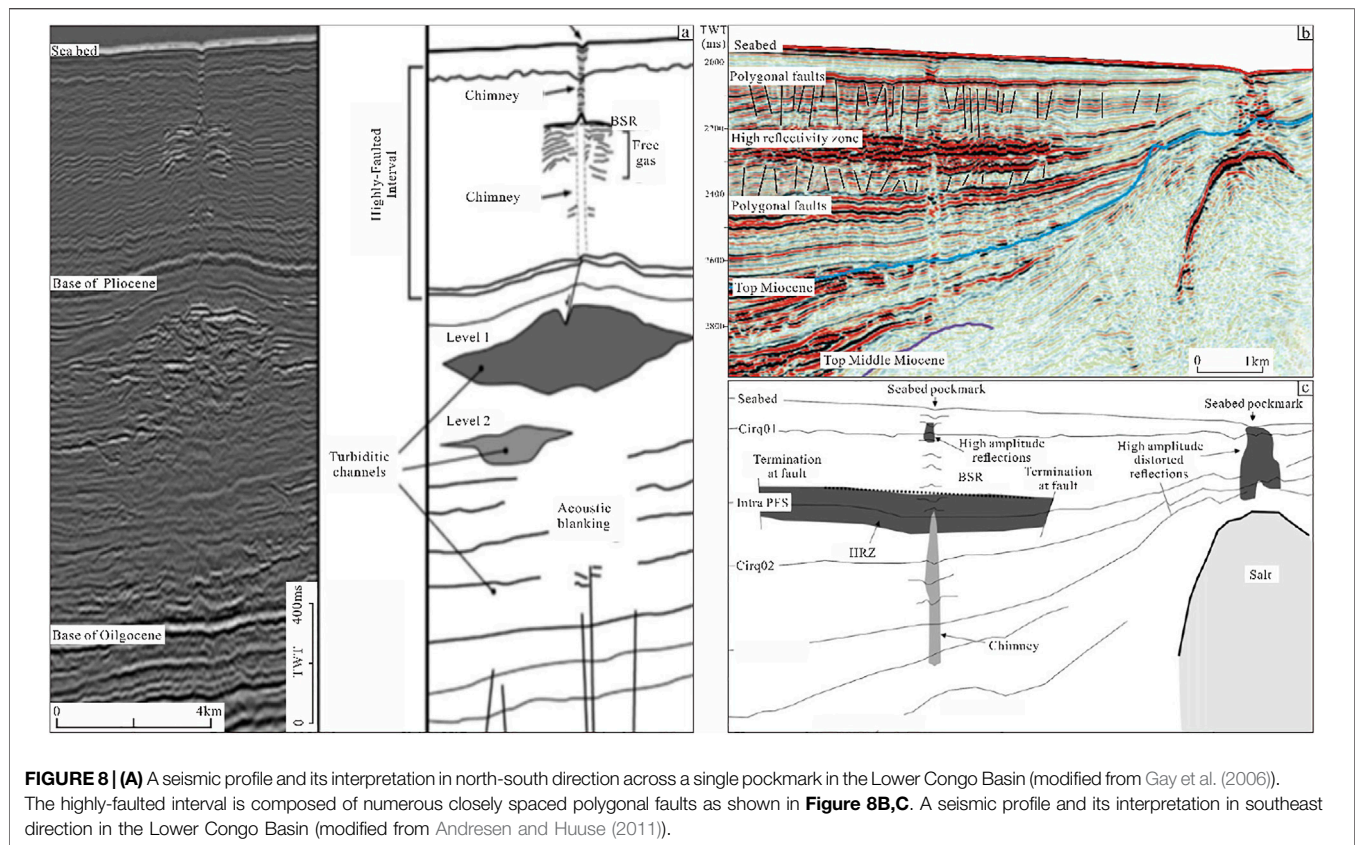
Implications for Hydrocarbon Accumulation

Previous studies often regarded PFs as fluid migration pathways for shallower hydrocarbon or gas hydrate accumulations (Ding et al., 2013; Alrefaee et al., 2018; Velayatham et al., 2021). However, other fluid conduits cannot be ruled out such as the major faults, gas chimneys unconformities surface, or lateral migration along permeable layers to the structural highs. According to Ostanin et al. (2012), the widely distributed PFs found in Hammerfest Basin within Campanian layers may act as pathways for vertical hydrocarbon migration. However, the localized high amplitude anomalies are more likely to be distributed along the Palaeocene-Early Eocene Faults and the major deep 1st order faults (**Figure 6A**). We propose that the hydrocarbon fluid from the deeper reservoirs may initially

FIGURE 6 | (A) A seismic profile in northeast direction in the Hammerfest Basin (modified from Ostanin et al. (2012)), showing Amplitude anomalies, Acoustic blanking, Incoherent/chaotic reflectors, Polygonal faults, PEEFs (Paleocene-Early Eocene Faults) and 1st order faults. **(B)** A seismic profile in southwest direction in the Ceduna Sub-basin, offshore South Australia (modified from Velayatham et al. (2021)).

FIGURE 7 | Seismic profiles in the Pearl River Mouth Basin, northern South China Sea showing the distribution of gas chimney, enhanced seismic reflections, large normal fault, and PFs. **(A)** modified from Sun et al. (2012). **(B)** modified from Yang et al. (2017).

migrate along the 1st order faults and then continue to migrate along the PEEFs to form the high amplitude anomalies. These enhanced amplitude anomalies may be due to the presence of hydrocarbons or diagenesis effect, both of which are related to the fluid migration (O'Brien et al., 2005). Velayatham et al. (2021) proposed that the PFs in the Ceduna Sub-basin, offshore South Australia may act as fluid migration pathways due to the spatial association of the PFs with shallower pipes (**Figure 6B**). However, after careful examination of the seismic profiles and plan view maps in the Ceduna Sub-basin, it seems insufficient to determine the fluids that escaped along the pipes were from underneath PFs which provided the fluids (Velayatham et al., 2021). Other possibilities of fluid supply should not be excluded such the migration along the major deep faults or lateral permeable sedimentary layers. Based on comprehensive analysis of enormous global PF case studies, we

propose that in most PF cases the PFs play very limited roles in facilitating vertical long-distance fluid migration.

Many PFs occur in the fine-grained sediments layer of the Pearl River Mouth Basin in the northern South China Sea, but they may have played limited role in fluid migration (Sun et al., 2012; Yang et al., 2017). According to Sun et al. (2012) and Yang et al. (2017), the fluid migration system is mainly composed of gas chimneys and major large faults, and the enhanced seismic reflections representing shallow gas accumulation are mainly located on top of the gas chimneys (**Figure 7**). Meanwhile, the PF-bearing layer lacks local amplitude anomalies, and high amplitude gas reservoirs even exist underneath the PFs, both indicating that the PF-bearing layer should be impermeable at present and may hinder upward migration of the underlying fluids.

FIGURE 8 | (A) A seismic profile and its interpretation in north-south direction across a single pockmark in the Lower Congo Basin (modified from Gay et al. (2006)). The highly-faulted interval is composed of numerous closely spaced polygonal faults as shown in **Figure 8B,C**. A seismic profile and its interpretation in southeast direction in the Lower Congo Basin (modified from Andresen and Huuse (2011)).

In the Lower Congo Basin, Gay et al. (2006) stated that the PFs allow deeper fluid migration to reach the seabed because of the upward deflection of the base of the gas hydrate stability zone (indicated by bottom-simulating reflector BSR in seismic), which was interpreted to be caused by a localized positive heat flow anomaly related to the PFs (**Figure 8A**). However, it has been noticed in this study that the deflection of the BSR solely appears around the chimney zone rather than throughout the whole PF-bearing layer. In the same area, Andresen and Huuse (2011) described the high reflectivity zone between the two PF-bearing layers which represents free gas accumulation. On the contrary, the vertical configuration of the free gas zone and the PF-bearing layer suggests the limited role of PFs as fluid migration conduits. It is more possible that the PF-bearing layer act as a seal trapping the free gas underneath. Additionally, localized high amplitude anomalies only exist along the gas chimney, indicating the positive role of gas chimney in fluid migration (Andresen and Huuse, 2011; **Figure 8B,C**). In this study, we interpret the high reflectivity zone between the two PF-bearing layers as sandstone-rich porous reservoir bodies which deposited as turbidite sandstone body in a background of fine-grained marine sediments. In this condition, good configuration of reservoir-seal led to the accumulation of free gas zone, with gas chimney being the major conduits transporting free gas from the deep. Considering the role of sandstone bodies as a barrier to PF propagation, the distribution and geometric attributes of PFs can be used to delineate sandstone bodies in the PF-bearing layer, which can

be applied in date-poor areas (Jackson et al., 2014; Turrini et al., 2017).

Sealing Ability of the Polygonal Faults

The activity of the PFs is intermittent which can last over several millions of years, and therefore the role of PFs in fluids migration may be spatially and temporally variable (Berndt et al., 2003; Gay and Berndt, 2007; Berndt et al., 2012). The integrity of a fine-grained seal can be destroyed by the initial dewatering of host sediments, slip activity of the PFs, or the reactivation of PFs due to the contraction during tectonic rifting period, which results in the transient fluid leakage (Gay et al., 2006; Gay and Berndt, 2007; Hustoft et al., 2007; Seebeck et al., 2015). However, the PFs should be inactive and therefore probably impermeable in a larger geological time-scale. Additionally, the PF-bearing layers are often composed of primarily very fine-grained smectitic claystones or carbonate chalks, with generally low permeability ($<10^{-17}$ m^2) (Hibsch et al., 2003; Hansen et al., 2004; Tewksbury et al., 2014; Antonellini and Mollema, 2015).

It is widely acknowledged that the existence of PFs potentially increases the overall vertical permeability of fine-grained strata, slightly higher than the permeability of the host lithology (Evans et al., 1997; Gay et al., 2004; Faulkner et al., 2010; Ilg et al., 2012). However, this may not be large enough to allow fluid to flow smoothly through the PF-bearing layer. For example, the PFs in offshore Australia exist in the cap rock above the potential CO$_2$ reservoirs (Seebeck et al., 2015), suggesting the role of the

PF-bearing layer as a seal. In contrast, the presence of PFs in coarse-grained sediments (e.g. porous sandstones) may reduce the permeability of PF-bearing layer, probably due to the deformation bands with cataclasis (Antonellini and Mollema, 2015). For example, the permeability of deformation band with cataclasis of the PFs is ~10^{-15} m^2 at Arches National Park, while the permeability of deformation bands without cataclasis can reach 10^{-14} to 10^{-13} m^2 in the same area (Antonellini et al., 1994).

To summarize, the PFs developed in the sealing strata of fine-grained sediments may have improved the permeability for certain degree, but were still not favourable for fluid migration. Alternatively, the presence of PFs may even improve the sealing ability over time when clay smeared along the fault surfaces (Lonergan et al., 1998a; Turrini et al., 2017). In addition, Cartwright et al. (2007) proposed that the rate of fluid migration through PFs is relatively low on geological time scales, and therefore the presence of PFs alone cannot cause extended leakage from deeper hydrocarbon reservoirs. Generally, the role of PFs in fluid migration may be limited due to the PF-bearing layers act more as seals in most of the global PF cases.

CONCLUSION

A geophysical review of global PFs case studies was conducted in this paper to better understand the role of PFs in fluid migration and their contrition to the shallower hydrocarbon or gas hydrate accumulation. Five main conclusions are made based on a comprehensive analysis of the geophysical characteristics of the PFs Chen et al., 2011, Davies et al., 2009, Gay et al., 2007, Shin et al., 2008, Shin et al., 2010.

1. Three genesis mechanisms may account for the PF formation in most cases, including density inversion, syneresis and shear failure. A comprehensive analysis of lithology, pore fluid and strain conditions are needed to determine the specific PF formation mechanism for a specific study area.
2. PFs are non-tectonic and layer-bound, mainly developed in shallow-buried fine-grained strata of >100 m thickness and deposited after the Middle Cretaceous period. PFs are characterized by steep dip angles (40–70°), multi-direction strikes, small fault throws (most <50 m), small lateral extensions (most < 2 km) and various displacement values (10–100 m).
3. Examination of many case studies shows that the PFs may play a limited role in fluid migration based on the spatial relationship

of the PFs, nearby major fluid migration pathways and high amplitude anomalies. On one hand, the PFs developed in the fine-grained strata may improve the permeability for certain degree, but may be not favourable for fluid migration. On the other hand, the presence of PFs may even improve the sealing ability when the clay smeared along the fault surfaces.

4. The sealing ability of PF-bearing layer can be destroyed by the initial dewatering of host sediments, slip activity of the PFs, or the reactivation of PFs, causing a transient period of fluid leakage. But in a larger geological time-scale, the PFs should be inactive and therefore probably impermeable.
5. Considering the limited role of PFs in fluid migration, it is proposed that the PFs may not contribute a lot to the shallower hydrocarbon or gas hydrate accumulation, and other major conduits are needed such as deep faults, gas chimneys, diapirs.

AUTHOR CONTRIBUTIONS

JY: Writing, Editing, Conceptualization, Methodology. YX: Software, Writing- Reviewing and Editing. ZY: Conceptualization, Supervision. SL and MW: Project administration, Investigation. SD: Data curation, Writing-Original draft preparation. YC and ML: Data curation, Writing- Reviewing and Editing.

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