Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2021) 30: 899-915
© TÜBİTAK
doi:10.3906/yer-2104-13

Structural characteristics of transtensional fault system and its implication for hydrocarbon accumulation in S Block, South Asia area

Yuwen DONG[1,2], Iftikhar SATTI[3,*], Maman HERMANA[4], Xu CHEN[1,2]

[1]Cooperative Innovation Center of Unconventional Oil and Gas (Ministry of Education & Hubei province) Yangtze University, Wuhan, China
[2]Hubei Key Laboratory of Petroleum Geochemistry and Environment, Yangtze University, Wuhan, China
[3]Institute of Geology, University of Azad Jammu & Kashmir, Muzaffarabad, Pakistan
[4]Department of Geosciences, University Technology PETRONAS, Perak, Malaysia

Received: 14.04.2021 • **Accepted/Published Online:** 07.09.2021 • **Final Version:** 22.11.2021

Abstract: Transtensional faults are well developed in the S Block of the South Asia area, which have an important impact on the hydrocarbon accumulation. However, the transtensional fault structure is very complex. Based on drilling and seismic data interpretation results, faults are divided into three typical types in the Lower Cretaceous, which can help to understand the complex fault system. The main faults are distributed in the NNW-SSE direction and parallel arrangement with dextral strike-slip shear characteristics, which determines the development of the tectonic belt. The secondary faults are often associated with the main faults, often composed of multiple branch faults. The complexity of the fault system is further aggravated by the small interlayer faults. Based on balanced cross-section technique analysis, the fault evolution has experienced five geological periods, which is closely related to the Indo-Pakistan plate tectonics and the Indus Basin evolution. In the diagonal extension stage of the Late Cretaceous, the fault activity was very strong, which had a significant impact on the tectonic pattern of "horst-graben structures and locally complex faulted blocks" in S Block. It is found that transtensional fault assemblage patterns are regular and diverse. It consists of six kinds of plane assemblage and seven kinds of profile assemblage patterns. Plane assemblage patterns include en echelon, broom, feather, comb, horsetail and diamond shape, while profile assemblage patterns consist of horst-graben faulted type, consequent faulted type, antithetic faulted type, "Y" and reverse "Y" type, "X" type and negative flower type. Different transtensional fault assemblage patterns form various kinds of hydrocarbon trap types, including faulted block, faulted nose, faulted anticline and composite traps. Fault activity and evolution promote the hydrocarbon generation, control the formation of tectonic zones and favorable traps and play an important control role in hydrocarbon migration and accumulation. Therefore, in this study the main exploration and evaluation targets are faulted reservoirs in the study area.

Key words: Fault structure, hydrocarbon accumulation, Cretaceous, horst-graben, reservoir

1. Introduction

The fault system is the basic tectonic deformation of the sedimentary basin, which runs through hydrocarbon generation, migration and accumulation (Li et al., 2013; Saffer, 2015; Abukova et al., 2019). Therefore, it is necessary to analyze the fault structure characteristics in the petroliferous basins, which is of great practical significance for hydrocarbon accumulation. Scientific fault system research is based on the earth dynamics background, as well as the consistence with the dynamics of forming basin. It can be divided into extensional tectonic pattern, compressive tectonic pattern, sliding tectonic pattern, reverse tectonic pattern and so on (Lafosse et al., 2017; Johnson et al., 2018; Odluma et al., 2019). In general, each tectonic pattern has its typical feature. However, due to the strength of the tectonic activity, tectonic activity stage, difference of activity duration and the lithology changes of formation, the tectonic pattern are quite complex. The transtensional fault structure is mainly composed of extensional action, superimposed strike-slip action. The transtensional fault concept was first proposed in the 1970s (Harding et al., 1979) and the strike-slip twisting was introduced to explain the evolution of hydrocarbon traps, basins and orogenic belts. At present, research about the causes of the tectonic pattern, assemblage types and relationship with oil and gas accumulation is abundant, which effectively promote the oil and gas exploration around the world (Shaun et al., 2006; Li et al., 2013; Yu et al., 2014; Castro et al., 2015; Li et al., 2015; Li et al., 2016; Underschultz et al., 2016; Audrey et al., 2017; Qin et al.,

* Correspondence: iasatti@gmail.com

2017; Feng et al., 2018; Robson et al., 2018; Nabavi et al., 2019; Wu et al. 2020). It is found that the S Block in the southern area of the Indus Basin is the main oil exploration basin in South Asia. The transtensional fault structure is well developed in S Block and many fault reservoirs have been discovered, which indicates that the fault activity is closely related to oil and gas accumulation (Kai et al., 2017; Xu et al., 2017). Due to the lack of contiguous high-precision 3D seismic data, the previous studies mainly focused on regional structural analysis, sedimentary facies and hydrocarbon accumulation (Huang et al., 2005; Lin, 2008; Carmichael et al., 2009; Asif et al., 2013; Liu et al., 2013; Ravi et al., 2013; Li et al., 2015; Nosheen et al., 2017; Qian et al., 2017). However, so far, less research has been done on fine fault structure interpretation and its relationship for hydrocarbon accumulation, which restricts the hydrocarbon continuous exploration and evaluation in the south of the basin to a certain extent. It is worth mentioning that S Block has achieved full 3D seismic data observation coverage in 2018, providing the possibility for the detailed fault structure research and its implication for hydrocarbon accumulation.

In this paper, based on the recent research results, the transtensional fault assemblage patterns and the favorable trap types are discussed after the transtensional fault classification and evolution analysis, as well as the oil and gas accumulation conditions and enrichment regulation are analyzed. The achievements provide technical support for the exploration of potential oil and gas in the study area and can be referential to the oil and gas exploration in a similar basin.

2. Geological setting

The Indus Basin located in the south of the Himalayas is petroliferous, and it is the largest sedimentary basin in Pakistan (Kai et al., 2017). It is a Mesozoic-Cenozoic sedimentary basin formed on the Paleozoic granite basement, with an area of about 36×10^4 km^2. The sedimentary thickness ranges from 3 to 8 km. The basin is composed of the westward inclined continental shelf. The western part is the fold orogenic belt, including the Sulaiman and Kirthar fold belt. The adjacent fold belt in east is the Sulaiman foredeep belt and Kirthar foredeep belt. The eastern depression can be divided into two parts, the north part includes Sulaiman slope and Punjab platform, and the south part includes Tal slope and Sindh platform. The north part and south part are separated by the Mary-Kirthar High (Ravi et al., 2013; Lintao et al., 2015; Kai et al., 2017) (Figure 1).

Several studies show that the basin has experienced many stages of tectonic movements since the Mesozoic, and the fractured structures are well developed (Liu et al., 2013; Li et al., 2015; Chen et al., 2017). Due to the huge differences in formation and tectonic evolution between different tectonic units, the petroleum geological conditions are complex, and the hydrocarbon accumulation conditions are quite different (Figure 1).

S Block is located in the southeast part of the Tal slope, which is uplifted in the southeast and subsidence in northwest. It is a favorable area for hydrocarbon accumulation. Four sets of sands are well developed in the Lower Cretaceous, including A sand, B sand, C sand and D sand, and they are the main reservoirs for petroleum exploration. The main source rocks are Jurassic Limestone, Cretaceous shelf and prodelta shale. The main cap rocks are thick Late Cretaceous mud. Up to now, several oil and gas fields are discovered in the Lower Cretaceous delta sandstone, which is an important hydrocarbon exploration area of Indus Basin (Carmichael et al., 2009; Asif et al., 2013; Ahmad et al., 2015; Adeel et al., 2016; Nosheen et al., 2017) (Figure 2).

3. Database and methods

In this paper, the transtensional fault assemblage patterns of Lower Cretaceous are characterized using subsurface geology, drilling data and 2D and 3D seismic data. The length of 2D seismic data is more than 10,000 km. 3D seismic data covers an area of 1500 km^2. Wireline logs are from about 200 unevenly spaced wells, and the reservoir data includes oil test data, oil field development data and so on.

Seismic calibration is employed based on the correlations between rocks and logs, and the seismic data is subsequently interpreted. The four main layers are marked and interpreted in 2D&3D seismic data for regional tectonic evolution analysis. These layers consist of: top of Jurassic, top of lower and upper Cretaceous, the top of Eocene. Because the Lower Cretaceous (including A sand, B sand and C sand) is the main target layer for petroleum exploration; the subdivided layers are detailed interpreted on 3D seismic data.

According to a series of fault factors such as fault strike, fault throw, fault extension length and its cutting relation to stratum, the fault classification and distribution are discussed, which clarifies the complex fault structures, especially the transtensional fault characteristics.

Based on the detailed 2D and 3D seismic interpretation results and balanced cross-section technique analysis, the fault structure evolution in each stage is discussed in detail. The fault assemblage pattern on the plane and profile are analyzed, which is the key to the formation of hydrocarbon traps.

Lastly, the relationship between the transtensional fault activity and hydrocarbon accumulation is discussed and the oil and gas accumulation condition and enrichment regulation are analyzed. Based on the above analysis

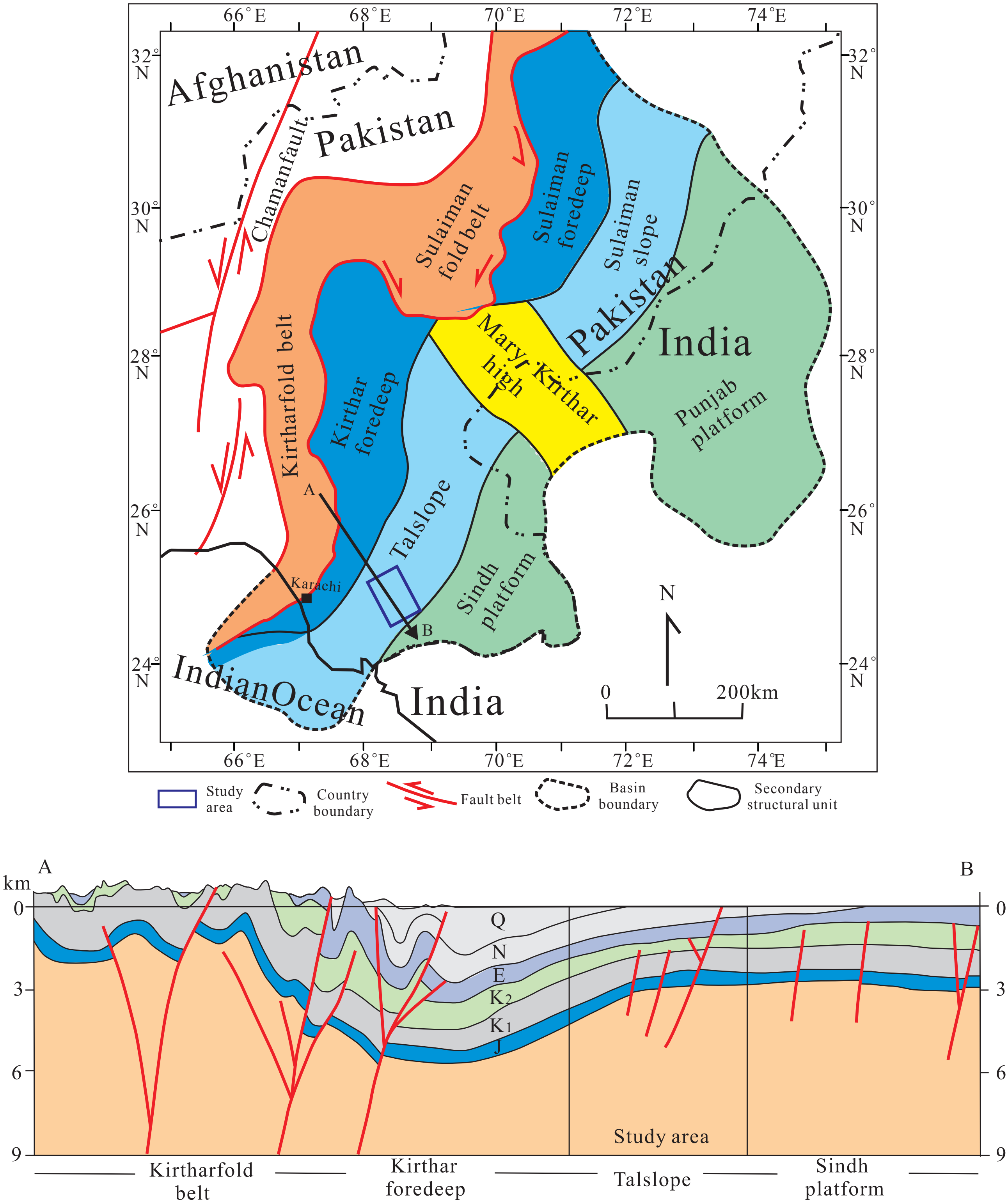

Figure 1. Structural elements of Indus Basin and location of the study area (a) and regional stratigraphic framework from northwest to southeast (b) (modified from Zuxi et al., 2005).

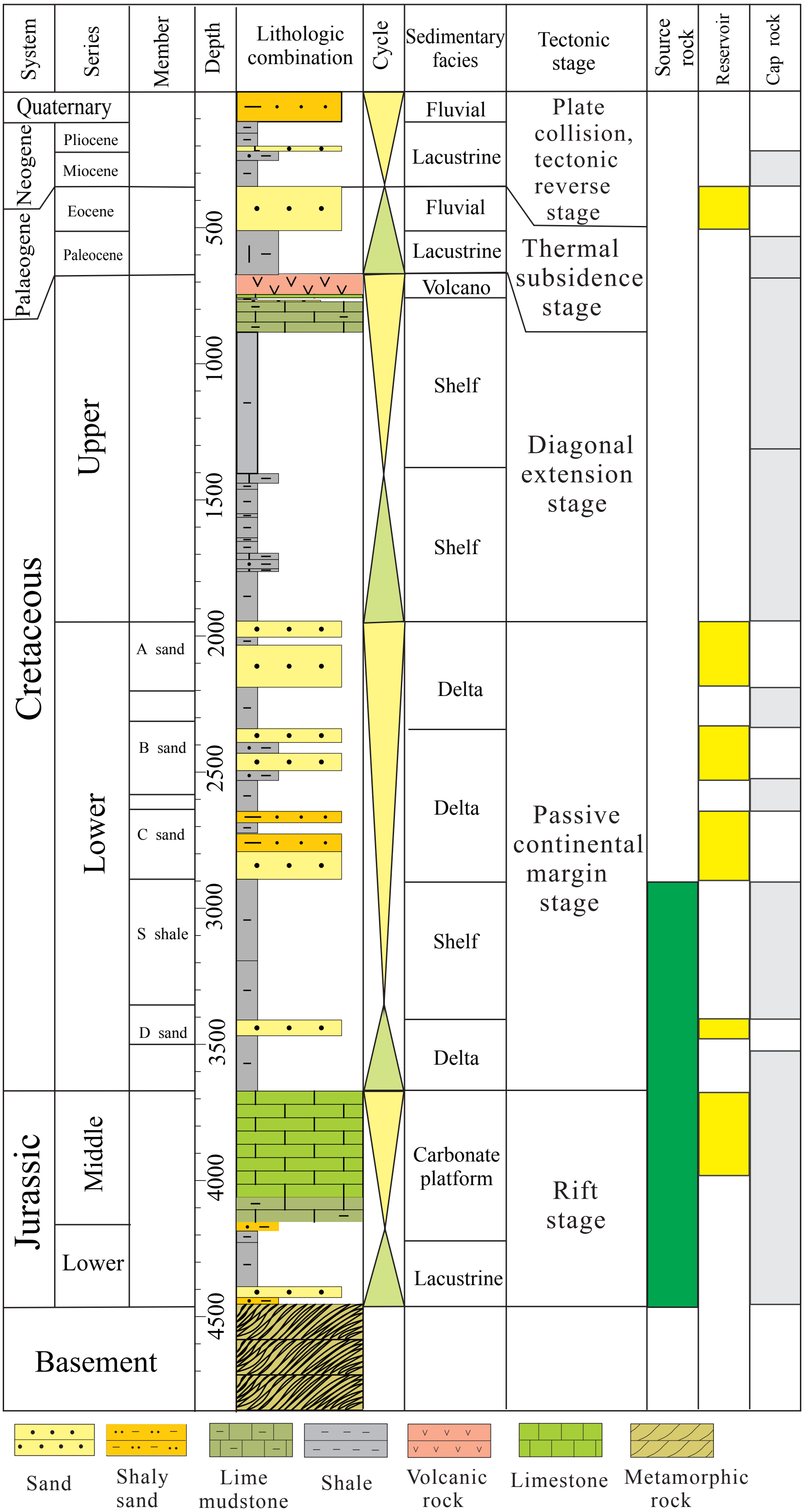

Figure 2. Stratigraphic column of the study area.

results, the preferential hydrocarbon exploration zones are put forward for hydrocarbon exploration deployment.

4. Results

4.1. Falt classification and characteristics

In the Cretaceous, due to the effect of shift and rotation of the Indian plate, the tectonic stress was mainly stretched and tensional in east-westward direction with dextral strike-slip shear characteristics and the transtensional faults were well developed, trending from northwest to southeast (Figure 3). In all, the Cretaceous fault system in the S Block is well developed, and the fault contact relationship is complex (Teng et al., 2017; Acharyyaa and Saha, 2018; Feng et al., 2018; Robson et al., 2018; Shabeer et al., 2018; Nabavi et al., 2019). From the latest seismic interpretation result and based on a series of fault factors, such as fault strike, fault throw, fault extension length and its cutting relation to stratum, the fault system is divided into three types: Type I (main faults), Type II (secondary faults) and Type III (interlayer small faults) (Table).

Type I (major fault filled with red color):

From the plane map of the fault system (Figure 3), the fault extends far in the plane, generally between 30 and 100 km. The fault strike is arranged parallelly from northeast to southwest direction. Each group of fault systems is characterized by multisegment and bifurcation combination, forming a deep and large fault system development zone. According to the interpretation of the seismic section (Figure 4), the fault cutting depth is large, penetrated Jurassic to Cretaceous, and mostly terminated near Paleogene and the vertical fault throw is large (about 300~1200 m). The dip angle of the fault ranged from 50° to 70°, and decreased with the increase of buried depth. It is easy to find that Type I faults determine the development and distribution of the tectonic zone, forming the tectonic framework of grabens alternating with horsts, influencing the overall oil-gas bearing feature of the study area.

Type II (secondary fault filled with blue color):

It is mainly associated with the main fault zone, and the development scale is less than the major fault, mainly developed in the Lower Cretaceous, often composed of multiple branch faults and is mostly terminated in the Upper Cretaceous. The vertical fault throw is between 50 and 300 m. The dip angle of the fault ranged from 50° to 70° and decreased with the increase of buried depth. On the plane, the fault strike is nearly from north to south or from northwest to southeast and extension distance is between 5 and 30 km. Type II fault, as the adjusted faults, often cut the main fault system during the fault formation and evolution, which make the structure more complicated, and form various structure traps. This kind of fault determines the amount and potential of the hydrocarbon accumulation zone (Figures 3 and 4).

Type III (interlayer small fault filled with pink color):

They are latter faults or derived faults, developed in the Lower Cretaceous, however, not developed in the Upper Cretaceous. The vertical fault throw is smaller than 50 m and the extension distance is less than 5 km. The fault strike is nearly from northwest to southeast and this kind of fault makes the structure more broken and complicated (Figures 3 and 4).

4.2. Plane assemblage pattern of transtensional faults

Tectonic stress was generally released at the fault development area. Affected by the interaction of fault systems of different grades and properties, the inside fault structures are broken. However, the plane assemblage patterns of transtensional faults are regular and diverse (Figure 5), including en echelon, broom, feather, comb, horsetail and diamond shape assemblage patterns, the respective characteristics are described as follows:

(1) En echelon: Under the major strike-slip faults action, the secondary faults arrange paralleled along the same direction on the planar, and the fault strike is from NE to SE. The angle of the twist zone is equal to the fault strike, which is the typical character of twisting stress activity. This kind of pattern is mainly distributed in the northwest of the study area, paralleling to fault system, forming a series of fault noses with lower relief, which is the potential hydrocarbon accumulation area (Figure 5a).

(2) Broom shape: It is the product of the tectonic rotation effect, which looks like a broom on the planar. The faults are converged in one end, and the other end consisted of the scattered arc-shaped faults. This kind of fault assemblage pattern is widely developed in the study area with different scales, forming a series of fault blocks where are beneficial for the hydrocarbon accumulation (Figure 5b).

(3) Pinniform: Due to a series of branch faults cut by a large fault, the fault pattern looks like a feather shape. The dip of the branch faults is similar as the main fault, and the branch faults are terminated on the main fault. This kind of fault is the result of the simultaneous action between the same direction and the backward strike-slip faults. Fault blocks are well developed at the intersection between the main fault and branch faults, where they are liable to accumulate hydrocarbon (Figure 5c).

(4) Comb shape: A series of the secondary and small faults are truncated by the major strike-slip faults in one direction, and the fault thrown and extension distance of the small faults are short. It always shows tiny tortuosity or dislocation in the seismic section. It looks like a comb on the planar. The fault block traps are easy to form at the intersection location of two group faults (Figure 5d).

(5) Horsetail shape: This kind of fault pattern is located at the end of strike-slip faults, formed some secondary faults for the decreased tectonic stress. The secondary

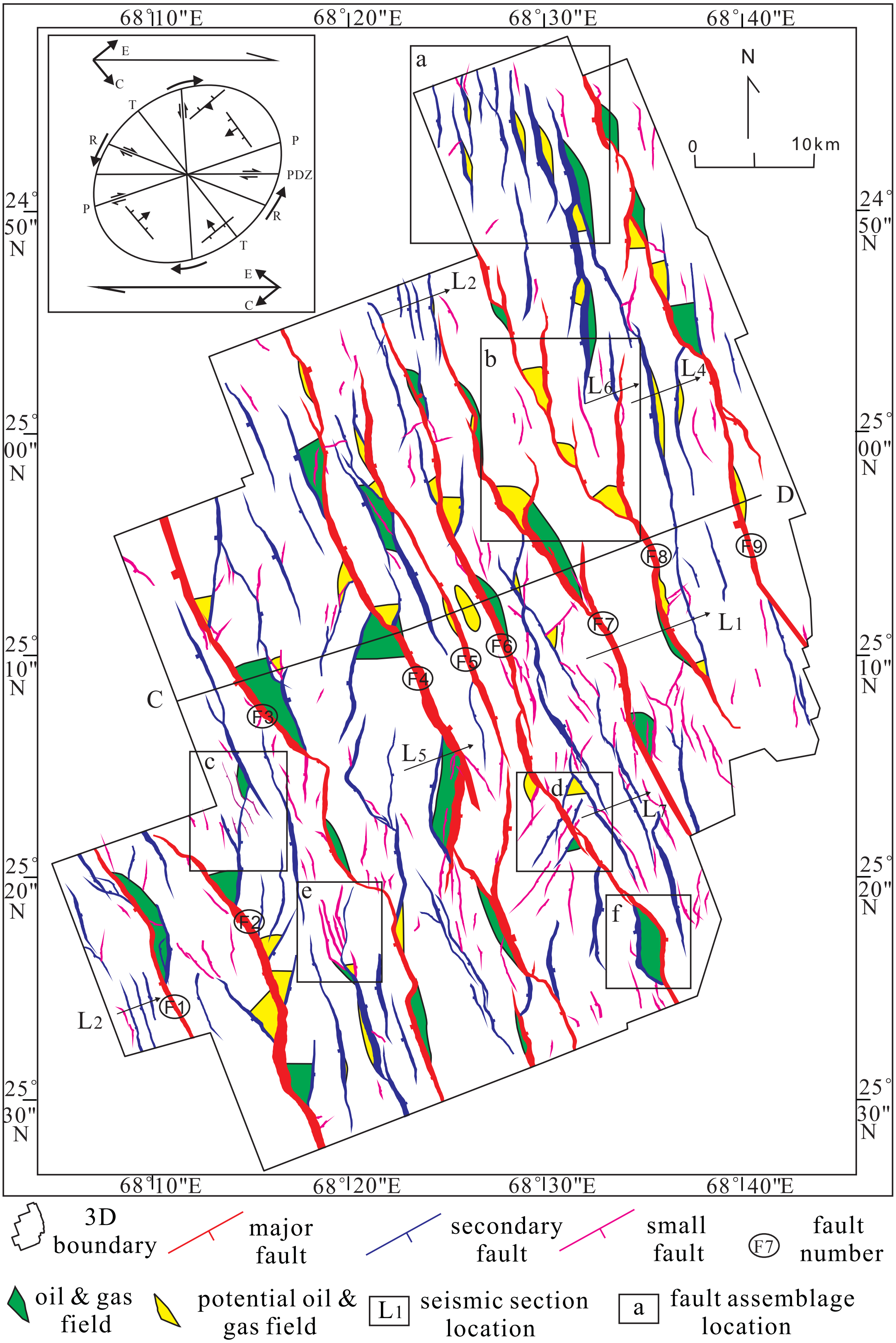

Figure 3. Fault system and discovered oil field map of the Lower Cretaceous. Note: The picture on the top left is a dextral slip shear model map. PDZ: the priority displacement zone, E: extended component, C: compressional component, T: tensional fracture, P: synclastic shear fracture, R: riedel shear fracture.

Table. Fault system classification of the Lower Cretaceous.

	Fault throw (m)	Extension length (km)	Fault strike	Characteristic
Type I: major fault	300~1200	30~100	NNW-SSE	Influence the development and distribution of the tectonic zone, which results in the tectonic framework of graben alternating with horst. The prime source fault
Type II: secondary fault	100~300	10~30	N-S, NNW-SSE	Adjusted faults controlled the trap formation. Secondary source fault.
Type III: interlayer small fault	<100	0~10	NNW-SSE, N-S	Small faults, derived faults or latter faults, which make the structure more complex

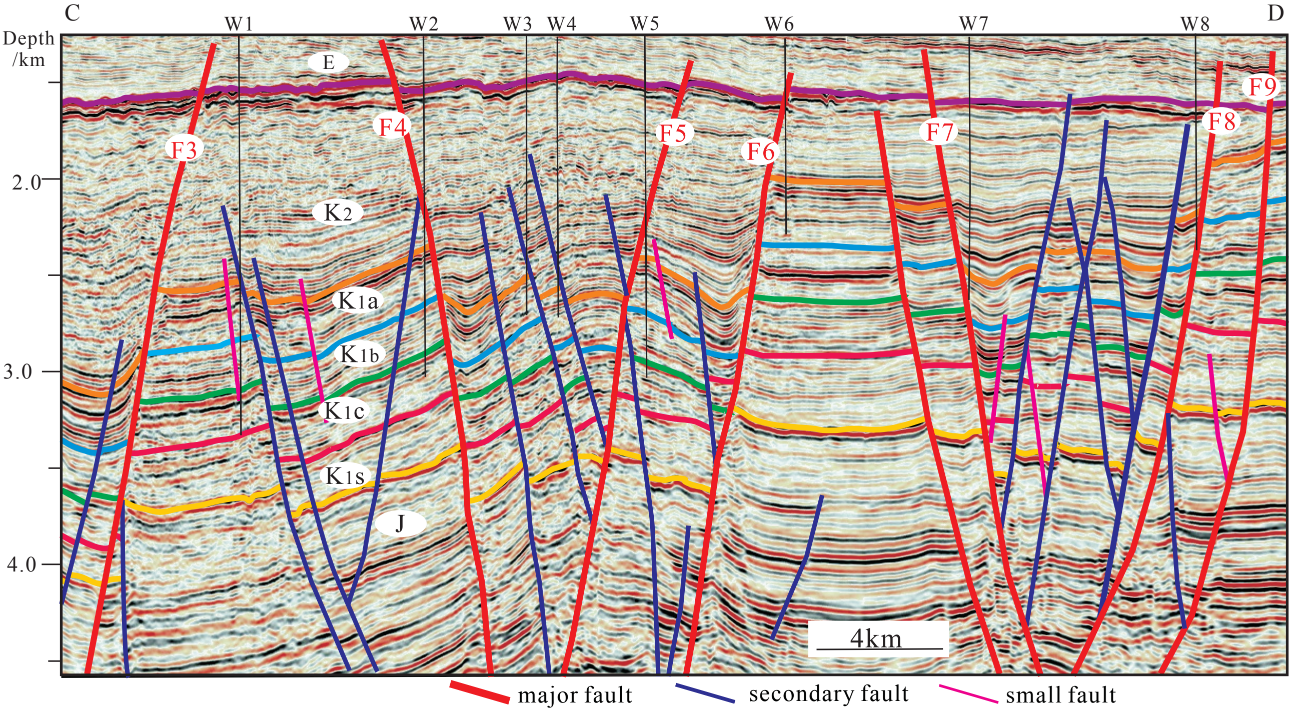

Figure 4. Seismic interpretation section showing the transtensional fault structure (The section location is shown in figure 3 “line CD”).

faults gradually dispersed and disappeared on the planar, and the horsetail shaped assemblage pattern is formed, which is potential for the hydrocarbon accumulation (Figure 5e).

(6) Diamond shape: The difference in the power and direction of the acting force on each side of the block is caused by the diagonal extension, which leads to form discrete tension and compression. Under the effect of stress, “positive” and “negative” structures are formed. In particular, when the faults are relatively close, the fault combination presents a diamond shape on the planar and the horsts are developed inside of the diamond shape faults. The diamond horst almost locates on a high position, and it is potential for the hydrocarbon accumulation (Figure 5f).

4.3 Profile assemblage pattern of transtensional faults

Profile assemblage pattern of transtensional fault directly reflects the tectonic stress deformation character. According to the dissecting result of the assemblage pattern on the plane, seven kinds of typical profile assemblage patterns are identified and summarized. These faults formed various kinds of trap types as the major exploration objects (Figure 6).

(1) Horst-graben faulted type: It is a typical tensional tectonic pattern, composed of synthetic faults or antithetic faults. The edge of the horst is located on the high position

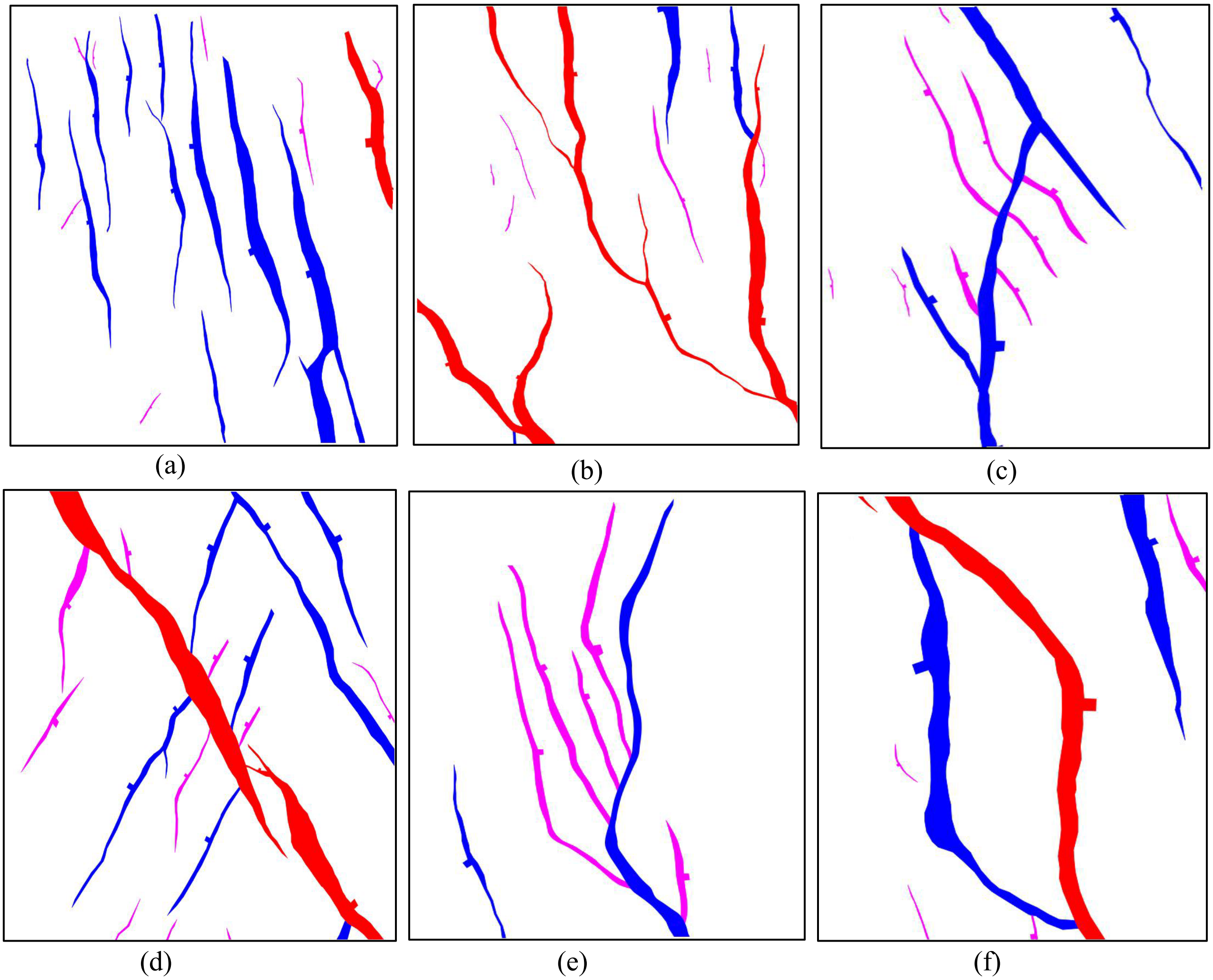

Figure 5. Typical plane assemblage patterns of transtensional faults. The fault location is shown in Figure 3). (a) En echelon pattern; (b) broom pattern; (c) pinniform pattern; (d) comb pattern; (e) horsetail pattern; (f) diamond pattern.

of the structure, once the fault blocks or fault noses are formed; it is apt to capture the hydrocarbon. Exploration practice indicates that this fault type is the main reservoir type (Figure 6a).

(2) Consequent faulted type: It is consisted by a series of normal faults with the same dip. The upthrown of the faults are declined along the same direction, and the dip of the strata and fault is the same. This kind of structure pattern is well developed in the gentle slope belt of the study area (Figure 6b).

(3) Antithetic faulted type: Contrary to the Consequent fault terrace pattern, the fault block is rotated along the fault section, so it shows a tilted feature. The dip of the fault is opposite to that of the strata. This kind of structure pattern is well developed in the middle part of the study area. Most oil and gas structures, such as fault blocks, fault noses and rolling structures, are well developed in consequent and antithetic fault terrace pattern (Figure 6c).

(4) "Y" and reverse "Y" type: They are the reflection of tension stress action, composed of the main fault and intersecting secondary faults. Through the seismic section perpendicular to the structure trend, there are a series of secondary faults on the lateral side of the main fault. The faults are converged in the deep layer, and are dispersed to the shallow layer, which can be called "Y" pattern. The reverse "Y" pattern is the mirror image of the "Y" pattern. These kinds of assemblage patterns are easy to form a series of fault blocks and fault noses for accumulation of hydrocarbon (Figures 6d and 6e).

(5) "X" type: It is also known as conjugate faults, formed by the diagonal extension deformation action. It consists of two groups of torsion fractures, showing as an "X" on the seismic section. Because of intense diagonal

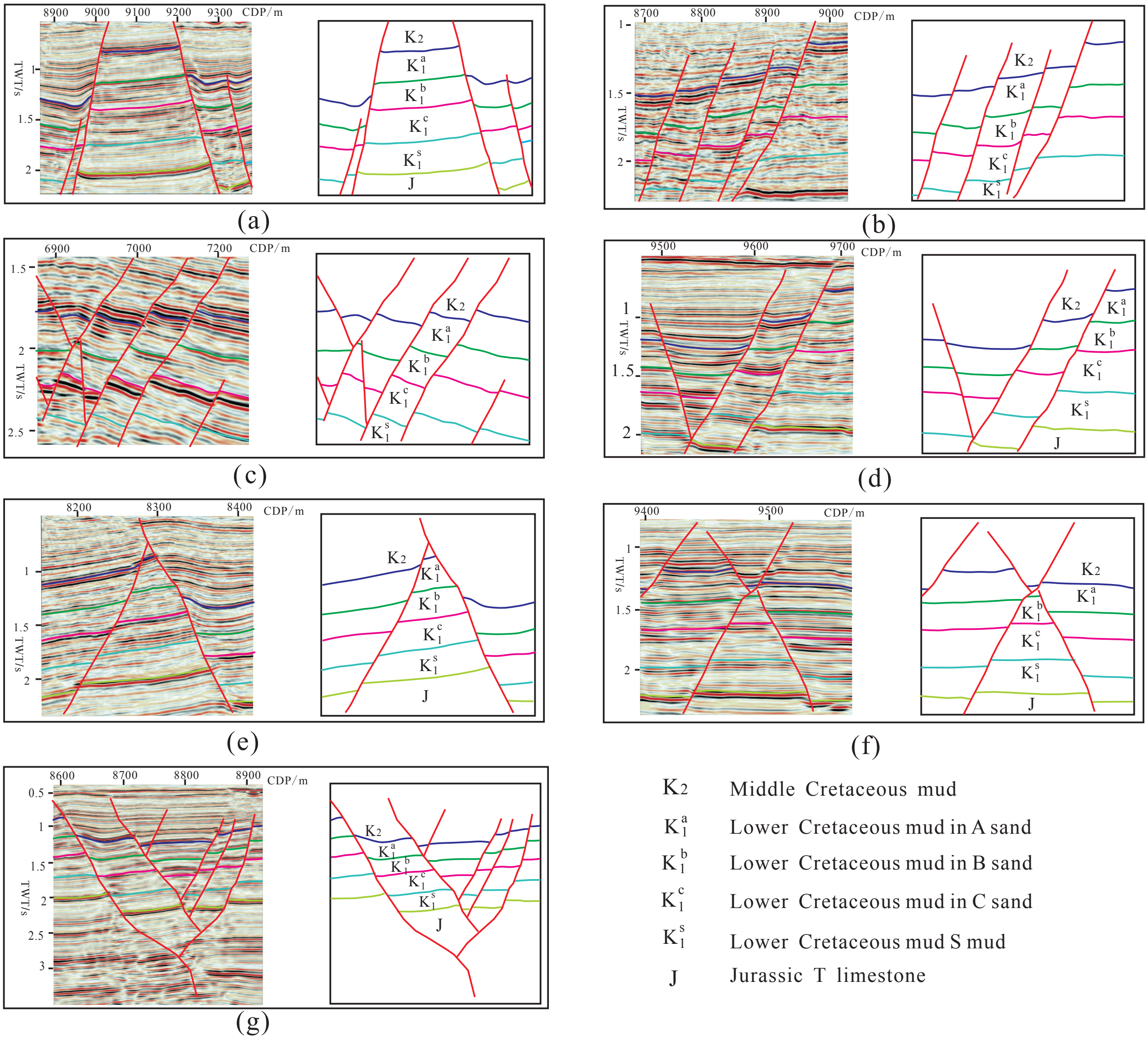

Figure 6. Typical profile assemblage pattern of transtensional fault (seismic section location is shown in Figure 3. (a) Horst-graben fault block pattern in L1 seismic section; (b) consequent fault assemblage pattern in L2 seismic section; (c) reverse fault block assemblage pattern in L3 seismic section; (d) type "Y" assemblage pattern in L4 seismic section; (e) reverse type "Y" assemblage pattern in L5 seismic section; (f) X assemblage pattern in L6 seismic section; (g) negative flower-shaped assemblage pattern in L7 seismic section.

extension in the Cretaceous, the "X" assemblage pattern is well developed in the study area (Figure 6f).

(6) Negative flower type: It is often located on the saddle of the structure. Under the transtensional stress setting, the faults are converged from the shallow layer to the deep layer on both sides, forming a synclinal structure and a series of normal faults. The small faults are evolved to one main deep large fault as the depth increased, and straightly cut the basement. It is the typical strike-slip structure pattern, well developed in the study area (Figure 6g). In addition, the strike-slip shear effect can cut or change other faults that cause sudden change in both the upthrown and downthrown formations. Besides, the assemblage patterns on the plane are diverse, such as linear extension, zonal distribution, and horsetail or en echelon distribution (Figure 5).

5. Discussion

Tectonism in the petroliferous basin not only controls the forming of the basin, but also has close connection with the oil and gas accumulation process (Teng et al., 2017; Acharyyaa and Saha, 2018; Feng and Ye, 2018; Robson et al., 2018; Shabeer et al., 2018, Nabavi et al. 2019). Throughout the oil and gas generation, migration, accumulation and later transformation, the fault activity is the key point for the study of oil and gas geologic conditions.

5.1. Fault structure evolution

Based on the detailed 2D and 3D seismic interpretation result and balanced cross-section technique analysis, it is found that the fault evolution is closely related to the Indo-Pakistan plate tectonics and the Indus Basin tectonic evolution, which can be roughly divided into five periods as follows (Figures 7 and 8).

5.1.1. Rifting in Jurassic

In Jurassic (about 196 Ma ~ 116 Ma), as a consequence of disintegration of Gondwana, the Indian Plate began to move towards the northeast**,** which was opposed to the African plate. The rudiment of the Indus Basin was constituted by the regional Gondwana breakup (Chen et al., 2016). Regional extensional tectonics occurred in the basin, and only a few normal faults with extensional properties developed in the study area. These normal faults have small fault throw and short extension length (Figures 7a and 8a).

5.1.2. Passive continental margin stage in early Cretaceous

In the early Cretaceous (117 Ma ~ 94 Ma), the Indian Plate was at the initial stage of drift. The basin experienced flexure subsidence and continental margin sedimentation during this stage. S Block was in the wide and gentle slope area, and the tectonic activity was relatively gentle, some small scale normal faults were developed locally. The corresponding sedimentary environment was open marine. Thick shelf mud and delta sandstone in the onshore-offshore transitional zone were deposited, which constituted the most important source rock (K_{1S}mud) and reservoirs ($K_{1a\text{-}d}$sand) in the study area (Nazir et al., 2012; Anwar et al., 2016) (Figures 7b and 8b).

5.1.3. Diagonal extension stage in Late Cretaceous

In the Late Cretaceous (94 Ma ~ 63 Ma), the rotation and drift of the Indian Plate is intensified towards the northeast, and the plate was rotated by nearly 60 degrees in counter clockwise direction. The basin was subjected to strong diagonal tension, and the large-scale fault systems in rows and belts were formed. The fault systems can be extended up to hundreds of kilometers, and the penetration depth of fault was big, mostly cutting across the Jurassic and Cretaceous. Under the regional torsional stress, a series of fault structure patterns, including canyons, grabens and horsts, as well as the local faulted blocks were formed, and they were shaped in the latest Cretaceous (Figures 7c and 8c).

5.1.4. Thermal subsidence stage in Paleocene

In Paleocene (64 Ma ~ 25 Ma), the drift and rotation of the Indian Plate became slow, the tectonics activity in the basin became weak, the basin entered into the thermal subsidence stage and the intensity of fault activity is also gradually weakened. The continuously tectonic uplift happened in the southeastern part of the basin, which resulted in the local erosion, and formed a wide regional unconformity (Figures 7d and 8d).

5.1.5. Plate collision and tectonic reverse since Eocene

Since the Eocene (25 Ma ~ present), the rotation and drift of the Indian Plate is intensified towards the northeast again. The strong and continuous collision occurred between the Indian Plate and the Eurasian plate (Huang et al., 2000; Lin et al., 2008). Located in the northwest of the Indian plate, the Indus Basin gradually evolved into the foreland basin under the regional north-westward extrusion stress, which was concentrated in the foreland basin. S Block is far away from the orogenic belt, and the structure was slightly adjusted owing to the regional tectonic inversion. The subsidence center was rapidly migrated from northwestern to the southeastern area. Besides, there was a relatively small influence on Cretaceous tectonic features in this stage (Figures 7e and 8e).

5.2 Faulting activity promoted hydrocarbon generation

In the early Cretaceous, thick limestone and shelf or prodelta shale was formed in the expansive continental shelf environment. The total thickness is 1000–3000 m with abundant organic matter, which is the material basis of source rock. In the Cretaceous, faulting and folding was caused by the intense diagonal tension; especially large deep fault activity could cut the strata, which could cause changes in the surrounding temperature-pressure field. It is worth mentioning that changes of geothermal heat flow in the northwest area played an important role in the geothermal gradient and source rock evolution. It accelerated the maturity of the source rock and also provided the driving force for the discharge and migration of oil and gas (Xia et al., 2007; Arif et al., 2014).

Vitrinite reflectance (Ro) is the most important indicator of organic matter maturity and is used to determine the thermal evolution of organic matter from early diagenesis to deep metamorphism. The Ro value was obtained mainly from well sample testing. According to the wells thermal evolution simulation analysis result (Figure 9), source rock entered the oil threshold in the early stage of Late Cretaceous (about 90 Ma), Ro value is greater than 0.63%, and the buried depth is about 2800 m. During the Late Cretaceous period (about 65 Ma), it was in the peak of oil generation Ro value ranged from 1.0% to 1.3%. It is easy to find that the source rocks began to the threshold of oil generation and entered the geological period of the peak of oil generation (from 90 Ma ~ 65 Ma), which formed a good coupling relationship with the transtensional faults activity stage of the Late Cretaceous (90 Ma ~ 65 Ma). In Paleogene (about 25 Ma), with the tectonic reverse and regional subsidence compaction, the source rock was overmatured, Ro value was between

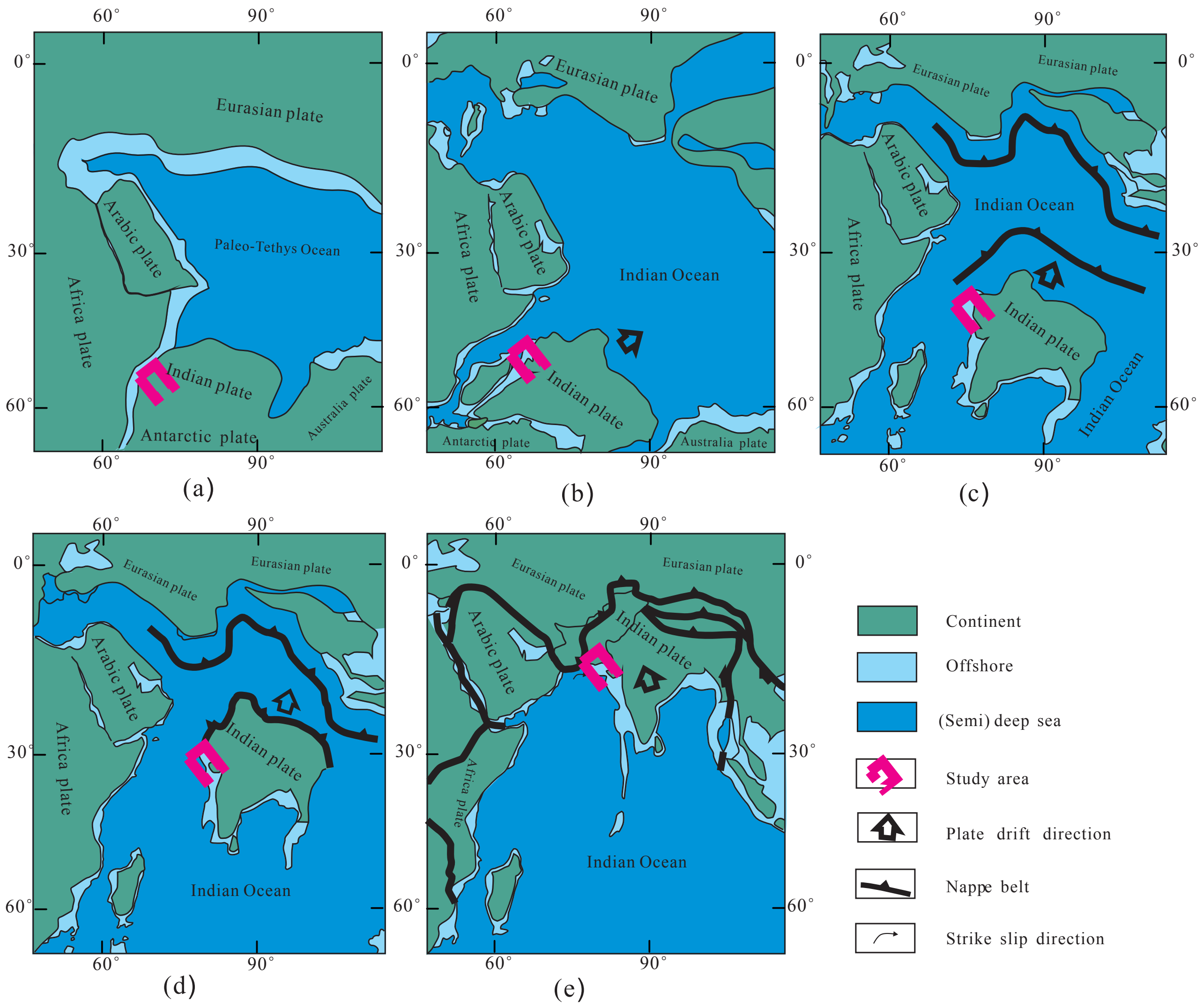

Figure 7. India-Pakistan plate tectonic background from Jurassic to present. (a) Rifting in Jurassic (about 196 Ma–116 Ma); (b) passive continental margin stage in the Early Cretaceous (about 117 Ma–94 Ma); (c) diagonal extension stage in the Late Cretaceous (about 94 Ma–63 Ma); (d) thermal subsidence stage in the Paleocene (about 63 Ma–25 Ma); (e) plate collision and tectonic reverse since Eocene (about 25 Ma to present) (modified form Huang et al., 2005).

1.3% and 2.0%, and entered the gas generation period. At present, it is still in the wet-dry gas window and provides an abundant oil-gas source.

5.3. Faulting activity controlled the formation of hydrocarbon traps

As mentioned previously, during the passive continental margin stage of the Early Cretaceous, the quick subsidence occurred in the S Block, which formed of the source rock and clastic reservoir. Since the Late Cretaceous, the transtensional fault activity was frequent, and the strong oblique tensile action caused the early strata to be faulted, and the delta sand body was effectively coordinated with the fault structure to form the favorable traps (Ken and Jerry, 2015). In the later period, the favorable petroleum geological conditions were used to capture and store oil and gas, which became the favorable exploration target. The discovered oil and gas fields are arranged and distributed along the main fault zone, which reflects that the main fault zone controls the oil-gas trap to a certain extent (Figure 3).

According to the statistics of oil and gas reservoirs (Figure 10), faulted reservoirs account for the majority, including fault blocks, fault nose and a small amount of faulted anticlines. A small number of complex reservoirs were found, such as faulted lithology and faulted stratigraphy reservoirs, while there is no industrial discovery of simple lithology or stratigraphy reservoir at present.

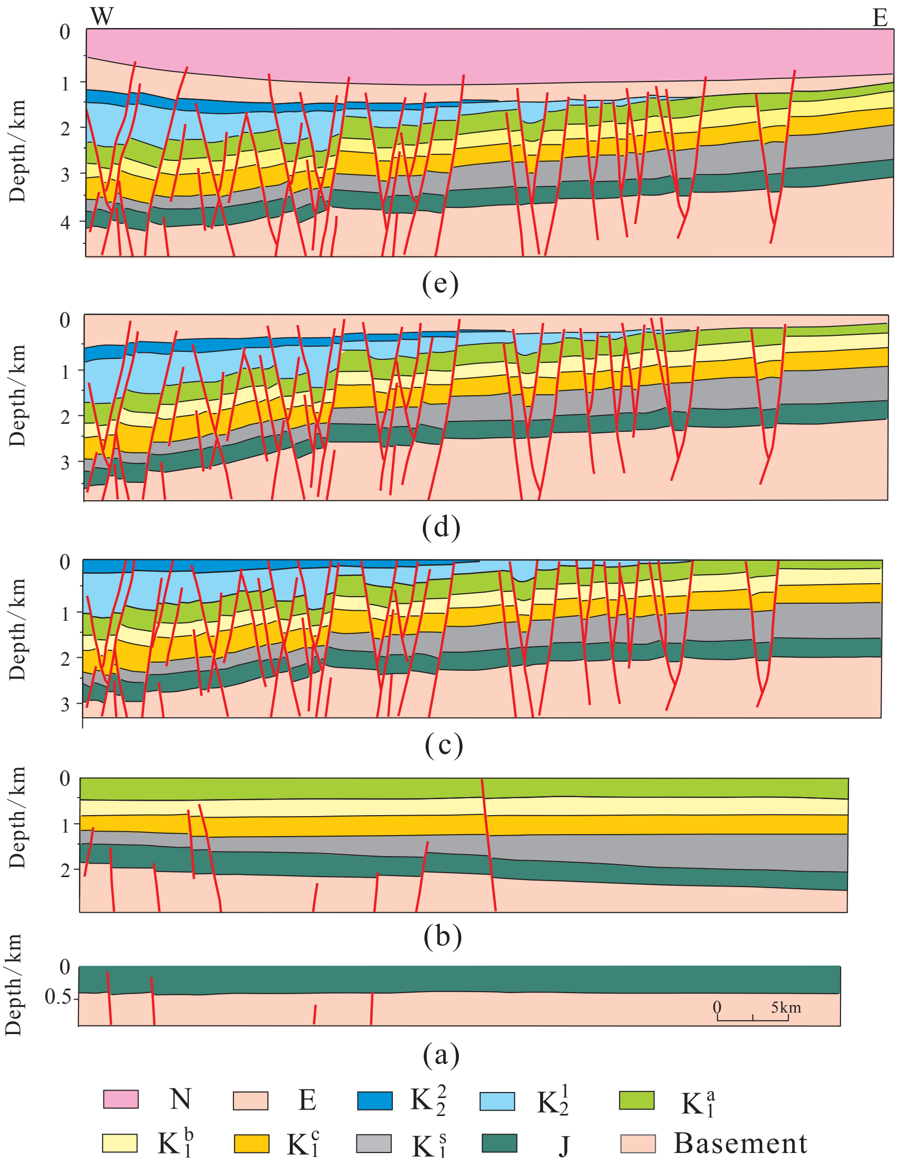

Figure 8. W-E seismic profile of fault structure evolution from Jurassic to present. (a) Rifting in Jurassic; (b) passive continental margin stage in Early Cretaceous; (c) diagonal extension stage in Late Cretaceous; (d) thermal subsidence stage in Paleocene; (e) plate collision and tectonic reverse since Eocene.

Because the fault system in the Lower Cretaceous is well developed, and the horst-graben structure pattern determines that faulting is the main factor in oil and gas exploration. Due to the huge number, wide distribution and easy discovery of faulted reservoirs, the faulted reservoirs still play a dominant role in the current rolling exploration evaluation based on high-precision 3D seismic data interpretation.

5.4. Faulting activity promoted hydrocarbon migration

Through the fault activity intensity analysis, the fault activity mainly experienced 5 stages as follows: moderate (in Jurassic), weak (in Early Cretaceous), strong (in Late Cretaceous), moderate (in Paleogene) and weak (since Neogene to present) (Figure 11). In Late Cretaceous, the fault activity was strong because of the large shearing area caused by diagonal tension, and it is conducive to the opening of the fault, which is consistent with India plate movement. At the same time, the faulting action can enlarge the vertical penetrativeness of the fault system in expanding upward. In general, the transtensional fault system activity is strong and cut deeply, the fault section is steep. It can be the oil source fault to interconnect

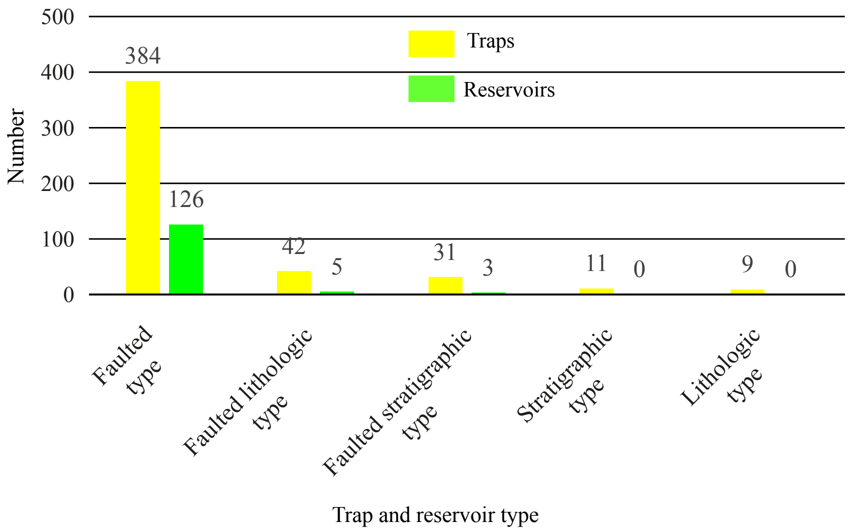

Figure 9. Thermal evolution simulation result (modified from Kai et al., 2017).

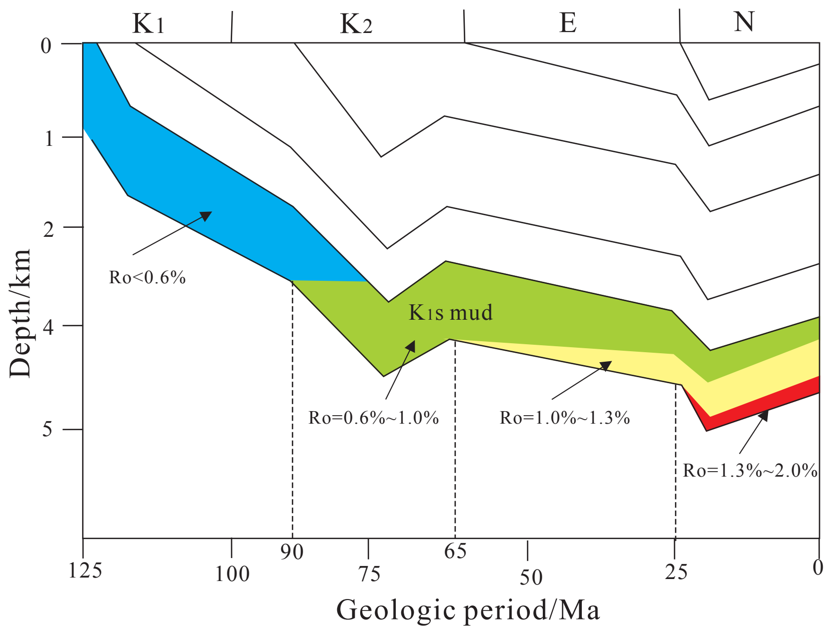

Figure 10. Traps and reservoirs statistics in the S Block.

source rock and reservoir in vertical and planar, which connects with secondary or associated faults, forming the three-dimensional channel for hydrocarbon migration and transmission. In addition, the sand bodies and unconformities developed in the Cretaceous can promote hydrocarbon migration laterally, resulting in the hydrocarbon migration and accumulation in the Cretaceous (Figure 12).

5.5. Faulting activity controlled hydrocarbon accumulation

In the early stage of Late Cretaceous, due to the regional transgression and volcanic eruption, the thick continental shelf mudstone and tight volcanic rock were deposited and formed the steadily regional cap rock. In the study area, the lower deep faults were continuously open, and the upper regional mudstone or volcanic rock tight layers were sealed, it was favorable for hydrocarbon migration and accumulation. Therefore, the fault active stage, hydrocarbon expulsion period and the trap formation time were matched well in the Cretaceous. The hydrocarbon was filled quickly and not easy to spill into the effective traps. Oil and gas reservoirs had been characterized by that the fault block is rich with oil, even though the area is small and the production of a single well is high (Wang

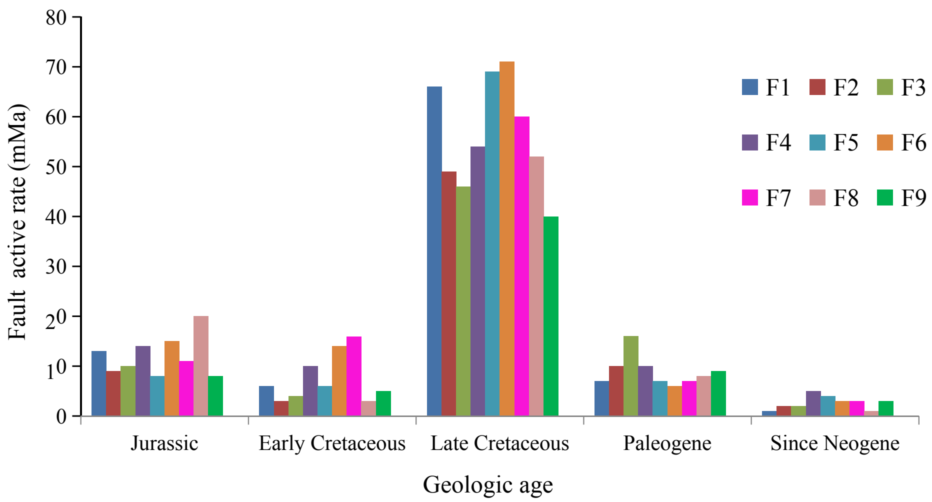

Figure 11. Activity rate of main faults since the Jurassic (see F1~F9 location in Figures 3 and 4).

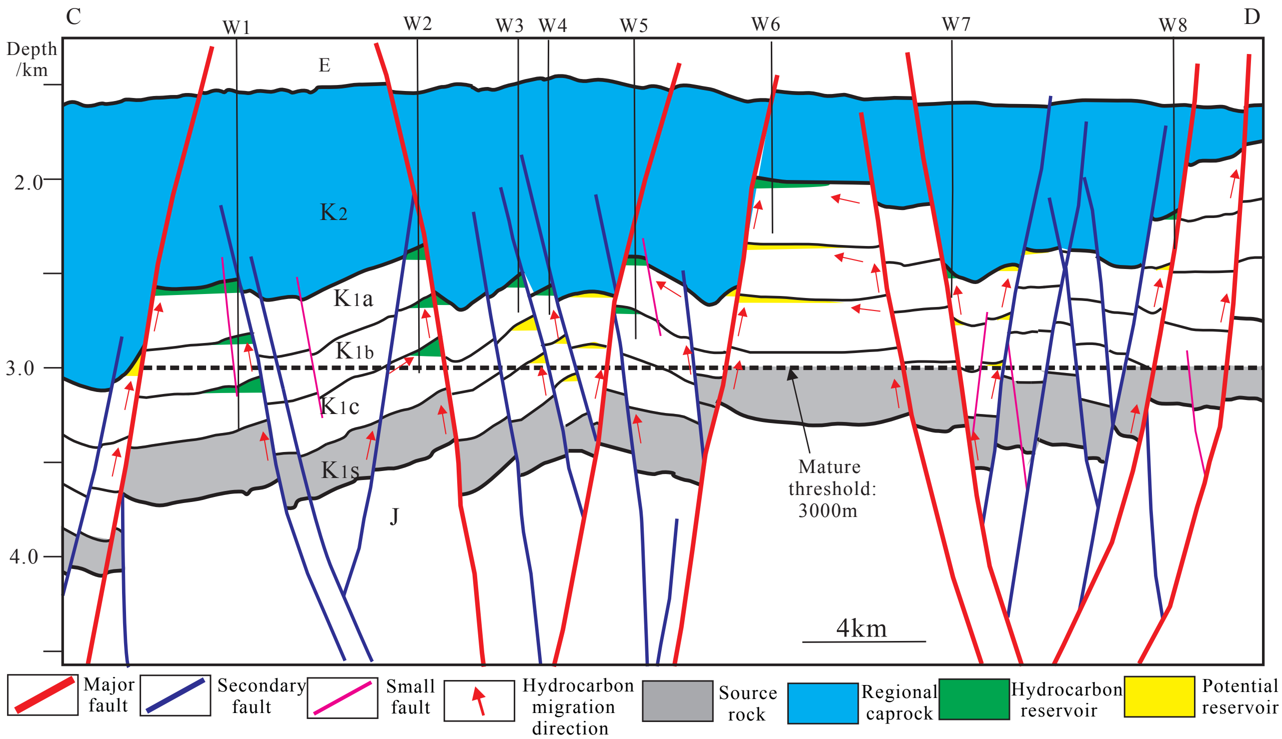

Figure 12. Hydrocarbon migration and accumulation model (The section location is shown in figure 3 "line CD").

et al., 2014). In Paleogene, the fault activity was weak, most faults were sealed and the hydrocarbons have been preserved effectively (Figure 12).

Based on the tectonic evolution analysis, this paper has analyzed the fault assemblage patterns and geological genetic type and distribution characters. The analysis suggests that the deep fault system of rows and zonal distribution from NW to SE is the result of the diagonal tensile stress, and often accompanies with secondary fault zone. The fault system is well complicated and it develops varied types of structural assemblage patterns, forming the favorable area of oil and gas accumulation and the favorable zone for tapping potential. Except for the discovered oil and gas field, there are plenty of oil-bearing structures needed to be proven and are the main targets for oil exploration (Figure 12).

6. Conclusion

This study investigates the transtensional fault structure characteristics and hydrocarbon accumulation of Lower

Cretaceous in S Block, South Asia area. Plenty of 3D seismic data and drilling data is analyzed in order to characterize transtensional fault assemblage patterns, favorable trap types and basic hydrocarbon accumulation conditions. Comprehensive geological analysis result shows that there is a close relationship between transtensional fault activity and hydrocarbon accumulation. It is concluded that:

1. The diagonal extension stage of the Late Cretaceous has a significant effect on the transtensional fault formation and evolution of the S Block. Under the strong diagonal tensile stress, the whole horst-graben structures and locally complex fault blocks are formed.
2. The transtensional faults are well developed in the study area, forming a series of large scale and nearly NNW-SSE fault systems, which was shaped in the Late Cretaceous. A variety of positive tectonic zones is formed due to different fault types, which are the preferential fields for hydrocarbon exploration.
3. Transtensional fault assemblage patterns are regular and diverse, which form various types of hydrocarbon traps, including faulted block, faulted nose, faulted anticline and composite traps.
4. The transtensional fault activities promote the hydrocarbon maturity and its expulsion from the source rock, control the type and development of hydrocarbon traps, including faulted block, faulted nose, faulted anticline and composite traps. Meanwhile, the source faults provide the favorable channels for hydrocarbon vertical migration and transportation.
5. In addition, it shows that there is good temporal and spatial relationship among fault activities, hydrocarbon expulsion and traps forming period. Therefore, it is a favorable zone to find large and medium-sized oil and gas fields near the deep transtensional faults.

Data availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of interest

The authors declare that they have no conflicts of interest.

Funding

This research was funded by "Natural Science Foundation of Hubei Province, grant number 2020CFB372, and Open Foundation of Cooperative Innovation Center of Unconventional Oil and Gas (Ministry of Education & Hubei Province), grant number UOG2020-14".

Acknowledgments

The authors are thankful to the Natural Science Foundation of Hubei Province, and the Open Foundation of Cooperative Innovation Center of Unconventional Oil and Gas (Ministry of Education & Hubei Province) for providing funding to carry out this research work.

References

Abukova LA, Volozh YA, Dmitrievsky AN, Antipov MP (2019). Geofluid dynamic concept of prospecting for hydrocarbon accumulations in the Earth Crust. Geotectonics 53 (3): 372-382.

Acharyyaa SK, Subhrangsu K, Saha P (2018). Himalayan Paleogene foreland basin and its collision induced early volcanic history and failed rift initiation. Journal of Asian Earth Sciences (162): 3-12.

Adeel N, Shabeer A, Sarfraz HS, Solangi SH (2016). Sedimentary facies interpretation of Gamma Ray (GR) log as basic well logs in central and lower Indus Basin of Pakistan. Geodesy and Geodynamics 7 (6): 432-443.

Ahmad Z, Akhter G, Bashir F, Khan MA, Ahmad M (2015). Structural interpretation of seismic profiles integrated with reservoir characteristics of Bitrism block (Sind Province), Pakistan. Energy Sources 32 (4): 303-314.

Anwar A, Peter DC, John S (2016). Indus Basin sediment provenance constrained using garnet geochemistry. Journal of Asian Earth Sciences 126: 29-57.

Arif N, Tahira F (2014). Petroleum geochemistry of lower Indus Basin, Pakistan: geochemical interpretation and origin of crude oils. Journal of Petroleum Science and Engineering 122: 173-179.

Asif MA, Nazir TA (2011). Applications of polycyclic aromatic hydrocarbons to assess the source and thermal maturity of the crude oils from the lower Indus Basin, Pakistan. Petroleum Science and Technology 29 (1): 2234-2246.

Audrey T, Roger S, Laurent GF (2017). Fault-Related Controls on Upward Hydrothermal Flow: An Integrated Geological Study of the Têt Fault System, Eastern Pyrénées (France). Geofluids 2017: 1-19.

Carmichael SM, Akhter S, Bennett JK (2009). Geology and hydrocarbon potential of the offshore Indus Basin, Pakistan. Petroleum Geoscience 15 (3): 107-116.

De CDL, Bezerra FHR (2015). Fault evolution in the Potiguar rift termination, Equatorial margin of Brazil. Solid Earth 6 (1): 185-196.

Feng DX, Ye F (2018). Structure Kinematics of a Transtensional Basin: An Example from the Linnan Subsag, Bohai Bay Basin, Eastern China. Geoscience Frontiers 9 (03): 305-317.

Harding TP, Lowell JD (1979). Structural styles their plate tectonic habitats and hydrocarbon traps in petroleum provinces. AAPG Bulletin 63 (7): 1016-1058

Henderson AL, Najman Y, Parrish R, Mark DF, Foster GL (2011). Constraints to the timing of India Eurasia collision; a re-evaluation of evidence from the Indus Basin sedimentary rocks of the Indus-Tsangpo suture zone, Ladakh, India. Earth Science Reviews 106 (3-4): 265-292.

Johnson SY, Watt JT, Hartwell SR, Kluesner, JW (2018). Neotectonics of the Big Sur Bend, San Gregorio-Hosgri Fault System, Central California. Tectonics 37 (7-8): 1930-1954.

Kai Q, Sun XH, Xu XQ, Han RH, Fan Y et al. (2017). The characteristics petroleum geology, hydrocarbon distribution and gas rich areas in the lower Indus Basin. Natural Gas Geoscience 28 (12): 1797-1809.

Ken LF, Jerry XM (2015). Sea-level responses to erosion and deposition of sediment in the Indus River basin and the Arabian Sea. Earth and Planetary Science Letters (416): 12-20.

Lafosse M, Acremont E, Rabaute A, Lépinay BMD, Gorini C (2017). Evidence of quaternary transtensional tectonics in the Nekor basin (NE Morocco) . Basin Research 29 (4): 470-489.

Li JY, Chen X, Dong YW, Wang HM, Yang JF et al. (2016). Structure characteristics and hydrocarbon trap types in Papuan Eastern foreland Basin. Oil Geophysical Prospecting 1 (1): 190-196, 203.

Li LT, Li YZ, Zhao HX, Wang DL, Zhu YT et al. (2015). Hydrocarbon accumulation rules and main control factors in Indus foreland basin. Journal of Petroleum and Natural Gas 37 (9): 7-14.

Li R, Dong S, Dan L, Duan L (2013). Tectonically driven organic fluid migration in the Dabashan Foreland Belt: Evidenced by geochemistry and geothermometry of vein-filling fibrous calcite with organic inclusions. Journal of Asian Earth Sciences 75: 202-212.

Li R, Liu HQ, Zhu RJ, Deng XQ, Li YH et al. (2013). Anomalous pressure driving oil migration: Evidence from multiphase boiling hydrocarbon fluid inclusions in Yuan Chang Reservoir, Ordos Basin. Chinese Journal of Geology 48 (4): 1219-1233.

Li YJ, Zhang Q, Zhang GY, Yang HJ, Yang XZ et al. (2015). Late Cenozoic transtensional fault belt discovered on the boundary of the Awati Sag in the northwestern Tarim Basin. International Journal of Earth Sciences 104 (5): 1-13.

Nabavi ST, Alavi SA, Jabarabadi HJ (2019). The Dinevar transtensional pull-apart basin, NW Zagros Mountains, Iran: a geological study and comparison to 2D finite element elastic models. International Journal of Earth Sciences 108 (1): 329-346.

Nazir A, Javed M, Shehzad CH, Mehmood K, Nasar et al. (2012). Shale gas potential of Lower Cretaceous Sembar formation in middle and lower Indus Basin, Pakistan. Pakistan Journal of Hydrocarbon Research 2 (1): 1-62.

Nosheen S, Pham HG (2017). Evaluation of shale gas potential in the Lower Cretaceous Sembar formation, the southern Indus Basin, Pakistan. Journal of Natural Gas Science and Engineering 44: 162-176.

Odluma ML, Stockli DF, Capaldi TN, Thomson KD, Fildani A (2019). Tectonic and sediment provenance evolution of the south eastern Pyrenean foreland basins during rift margin inversion and orogenic uplift. Tectonophysics (76): 226-248.

Qin XL, Li RX, Yang L, Dong SW, He W et al. (2017). High pressure paleofluid in the Dabashan intercontinental orogenic belt and its migration dynamics. Earth Science Frontiers 24 (2): 123-129.

Ravi KM, Mishra DC, Singh B (2013). Lithosphere, crust and basement ridges across Ganga and Indus Basins and seismicity along the Himalayan front, India and western fold belt, Pakistan. Journal of Asian Earth Sciences 75: 126-140.

Robson AG, Holford SP, King RC (2018). Structural evolution of horst and half-graben structures proximal to a transtensional fault system determined using 3D seismic data from the Shipwreck Trough, offshore Otway Basin, Australia. Marine and Petroleum Geology 89: 615-634.

Saffer DM (2015). The permeability of active subduction plate boundary faults. Geofluids 15 (1-2): 193-215.

Shabeer A, Sarfraz HS, Saeed M (2018). Tectonic evolution of structures in southern Sindh monocline, Indus Basin, Pakistan formed in multi-extensional tectonic episodes of Indian plate. Geodesy and geodynamics (3): 1-9.

Shaun LL, Stephen FC, Stephen M, Eggins M, Gagan MK (2006). Microchemical evidence for episodic growth of antitaxial veins during fracture-controlled fluid flow. Earth and Planetary Science Letters 250 (1):331-344.

Teng CY, Hao F, Zou HY (2017). Development and evolution of the structure JX1-1 in Liaodong Bay Depression and its significance in petroleum exploration: Oil Geophysical Prospecting 52 (3): 599-611.

Tieshu L, Mai C, Huaicun J, Li XJ, Wang L et al. (2013). Comprehensive study and regional optimization of oil and gas geology in South Asia. China Petroleum Exploration 18 (4): 58-67.

Underschultz J, Strand J (2016). Capillary seal capacity of faults under hydrodynamic conditions. Geofluids 16 (3): 464-475.

Weidong L (2008). Characteristics of petroliferous system and accumulation model in Indus river basin. Natural Gas Industry 28 (8): 19-21.

Wu XL, Li RX, Hu JM, Liu FT, Zhao BS et al. (2020). Discovery of Cenozoic hydrocarbon inclusions in Liupanshan Basin, North China and its petroleum geological significance. Earth Sciences 45 (1): 303-316.

Xu C, Caiqin L, Hongmei W, Xie RJ, Yang JF et al. (2017). Tectonic characteristics and hydrocarbon accumulation in T block of Indus Basin. Petroleum geophysical exploration 52 (6): 1305-1314.

Yiping X, Wanhui L, Ligui X (2007). The identification of strike-slip fault and its significance in petroleum geology. China Petroleum Exploration 21 (1): 17-23.

Yu FS, Dong YX, Tong HG Xiong LQ, Long X (2017). Characteristics and origins of structural deformation in the Paleogene in the Western Sagof Liaohe Depression Bohai Bay Basin. Oil & Gas Geology 36 (1): 52-60.

Yuhang C, Genshun Y, Pengcheng T, Fuliang LV, Yintao Lu (2016). Multi-stage tectonic deformation and its control on hydrocarbon accumulation in the Kerimbas Basin, East Africa. Geotectonics and Metallogenesis 28 (8): 491-502.

Zuxi H, Yuman W, Yucheng W (2005). Sequence stratigraphy and tectonics in Middle Indus Basin. Petroleum Exploration and Development 32 (1): 134-140.