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The research on fault and structural trap of the Weixinan Sag, Beibuwan Basin, South China Sea

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The Weixinan Sag in Beibuwan Basin is a pilot area of the offshore exploration and development integrated technology. The main oil bearing layers, first member of Liushagang formation and third member of Weizhou formation, develop many fault systems and structural traps. The key factors of the offshore exploration and development integrated technology are"the fault research"and "the effectiveness of structural trap". Fault research includes the study of the geometry, dynamics, kinematics characteristics of fault, and the division of fault system. The effectiveness of structural trap include analogical studies on the structural characteristics of traps, quantitative studies on fault lateral sealability, fault vertical sealability, and prediction technology of oil column height. Synthesizing the relationship of the law of oil and gas distribution,the differential fault system in the internal of the No. 2 fault zone, and the effectiveness research of traps, the fault-controlled reservoir laws and the dominant fault-controlled reservoir mode are obtained. The research on fault and trap of offshore integrated exploration and development has been successfully applied in the Weixinan Sag. The 37 of 45 development evaluation wells have been drilled successfully and the drilling success rate is 82%. It has promoted the ODP(original drilling project) implementation of 5 oilfields, the adjustment implementation of 8 oilfields and made important contribution to the increase of reserves and production in the Weixinan Sag.

Keywords Fault system, Trap effectiveness, Fault sealability, Oil column height, The Weixinan Sag

The Weixinan Sag in Beibuwan Basin has gradually become a highly mature exploration and development zone of oil and gas in the Western part of the South China Sea after years of exploration and development[1–4]. The oil reservoirs are distributed in a continuous way on the plane. However, the newly founded potential targets have the problems of "broken fault blocks and small resource scale". At present, most oil fields have been in the middle and late stages of development with the risk of unsustainable development. The traditional evaluation model has a long production period, the lack of overall development between oilfields, the low conversion rate of storage and production within oilfields, and the conventional relay mode of exploration and development cannot meet the demand of reserves and production.

The problems faced by Wexinan Sag also exist in the middle and late stage of exploration and development of many onshore oil fields. The exploration and development integrated technology is an effective way to solve this problem. In order to ensure the sustainable exploitation of developed oilfields in Weixinan Sag, the successful experience of the exploration and development integration technical means of onshore oilfields are investigated[5–9], it is supplemented that the exploration target and development deployment are closely combined in the rolling exploration and development of Jiangsu Oilfield. According to the working procedures of rolling exploration, rolling evaluation and rolling development, the research and production of oil and gas exploration and development are arranged and deployed. Huabei Oilfield has formed an integrated and effective well location research and organization management mode from target research to organization management at different levels, which has improved the overall exploration effect. Tarim Oilfield organizational structure integration, investment and deployment integration, scientific research and production integration, production organization integration, engineering geological integration, ground and underground integration, to achieve a carbonate

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reservoir production increase. And the offshore exploration and development integrated technology is presented. The offshore exploration and development integrated technology is a rapid evaluation mode , which is based on offshore oil and gas field facilities in production or construction, and aims at the discovery and development of potential reserves within and around oil and gas fields[10–15]. The advantage of the exploration and development integrated mode is that it can closely integrate the exploration, evaluation, development and production stages of the oilfield, and finely evaluate the resource potential inside and around the oilfield. Basing on the above investigation, in order to achieve sustainable oilfield exploitation, the offshore exploration and development integrated technology has been carried out around the Weixinan Sag. Through the basic research of structural traps, such as "fault zone research" and "trap effectiveness research", the potential targets are searched and evaluated, and the drilling is carried out by developing evaluation well mode. The overall deployment of development plan promotes use of resources, sustainable development of the oilfield and maximizes economic benefits.

Geological setting

The Beibuwan Basin, where Weixinan Sag is located, is a rift-subsidence basin formed in Cenozoic and has experienced Paleogene rifting stage and Neogene depression stage successively [2,16]. Under the effect of regional stress, the Weixinan Sag develop multiple fault zones and branch faults, such as Weixinan fault zone, No. 1 fault zone, No. 2 fault zone, and No. 3 fault zone from North to South during the Paleogene rifting period, and the branch faults play an important role in oil and gas migration and accumulation[17]. Slope belts, such as the Xieyang slope belt and the Southern slope belt, are also favorable directions for hydrocarbon migration and accumulation[18]. In general, the Weixinan Sag has the structural characteristics of fault growing in the north and superposition growing in the south, and it is adjacent to the Haizhong Sag through the Weixinan Low Uplift(Fig. 1).

In the early Cenozoic era, under the influence of the northward movement of the South China Block, the northern margin of the South China Sea was in the background of the extensional stress and formed many rift-subsidence basins, such as the Beibuwan Basin[19,20]. The terrigenous lacustrine sedimentary facies were well developed in Weixi'nan Sag during this period, and the clastic rocks such as sandstone and mudstone interlayer were developed. Changliu formation of Paleocene, Liushagang formation of Eocene, and Weizhou formation of Oligocene deposited from lower to upper sedimentary strata (Fig. 2). It is revealed by drilling that the second member of Liushagang formation mainly develops thick dark gray shale or oil shale and mudstone with thin light gray fine sandstone and siltstone, which is the most important source rock formation in Weixi'nan Sag[21,22] (Fig. 2). The first member of Liushagang formation and the third member of Weizhou formation are the most important oil-bearing strata, among which, the water body of the first member of Liushagang formation gradually became shallower during the sedimentary period, from the shore-shallow lacustrine facies to the delta facies, the lithology were unequal thickness interbeds of dark gray shale, gray mudstone, gray fine sandstone and siltstone[17,23]. The reservoir-seal assemblage in the first member of Liushagang formation was good, and structural traps or structural-lithological traps were mainly developed. In the third member of Weizhou formation, the water body was deepening but the water depth was shallow, the Delta facies was mainly developed, the lithology was coarser, and it was thick gray gravel sandstone, medium sandstone and fine sandstone[24,25]. The water body was

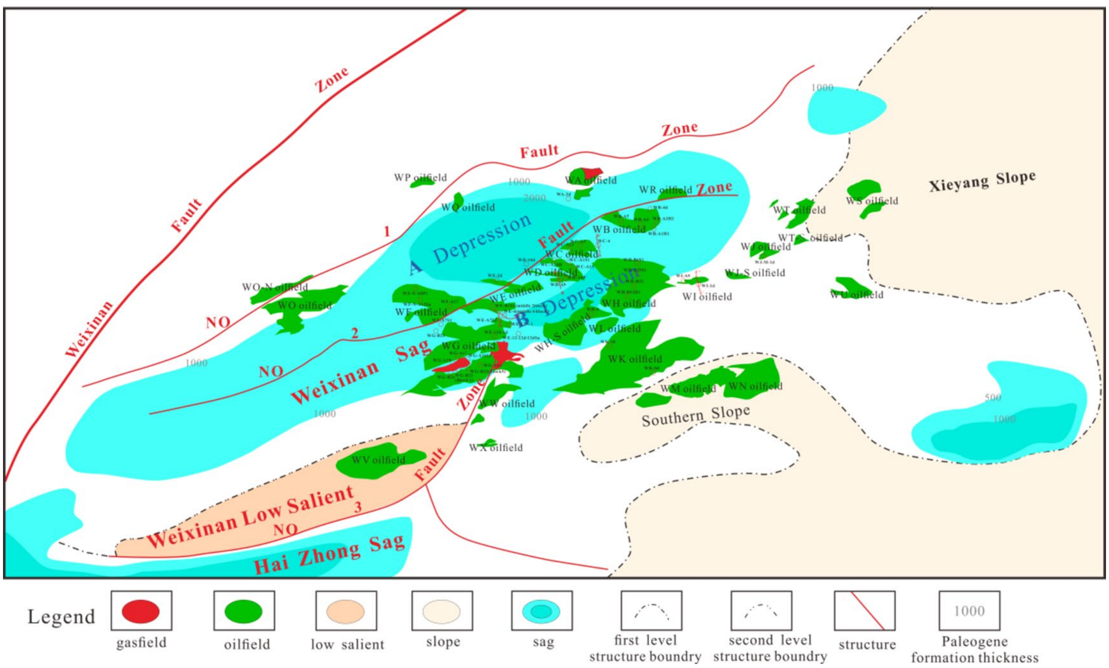


Figure 1. Regional structure and distribution of oilfields in the Weixinan Sag. Weixinan fault zone, No.1 fault zone, No.2 fault zone and No.3 fault zone are developed from north to south in Weixinan sag. Among them, No.2 fault zone is rich in oil and gas, and many large and medium-sized oil fields have been found. Most of these oil fields are tectonic origin. The study of faults and structural traps is very important.

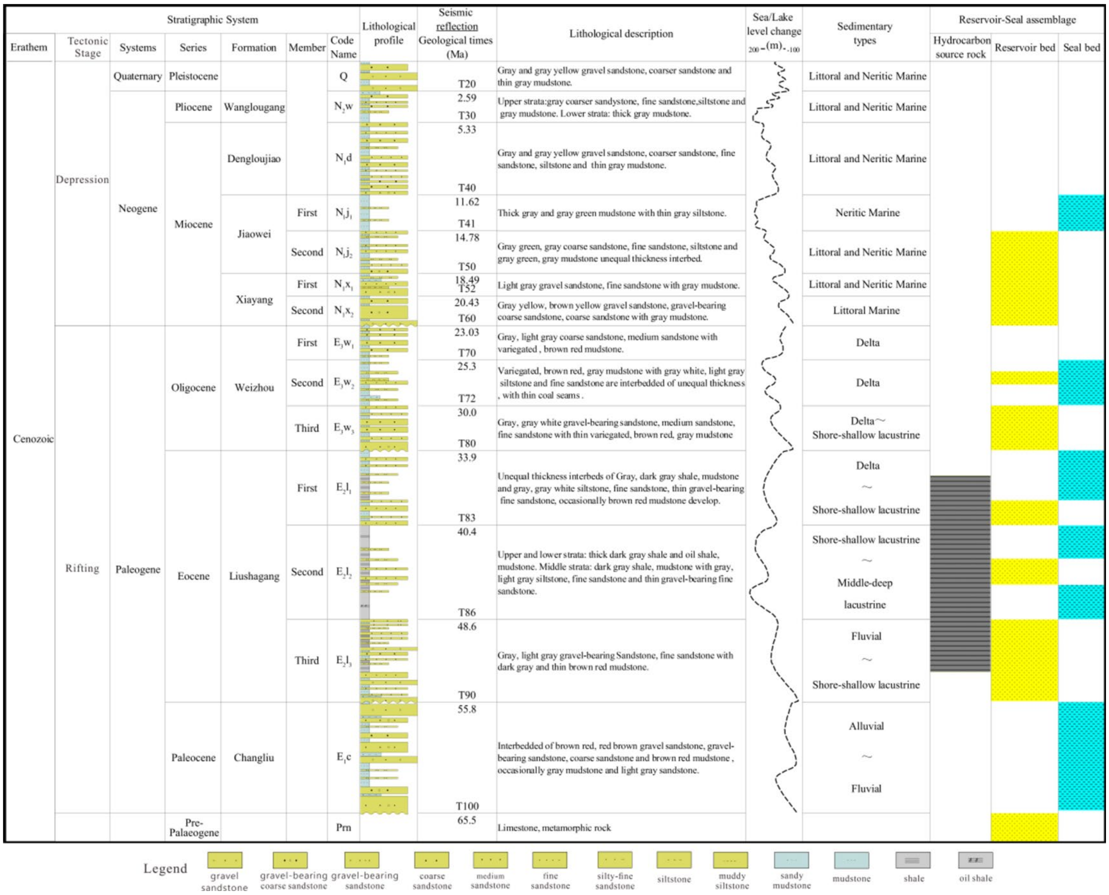


Figure 2. Comprehensive stratigraphic characteristics of Weixi'nan sag in Beibuwan Basin.

deep and the lacustrine facies was semi-deep in the second member of Weizhou formation. The lithology was thick layer variegated mudstone with thin layer fine sandstone and siltstone, which formed good reservoir-seal assemblage with the thick sandstone of the third member of Weizhou formation. And the structural traps were mainly developed in the third member of Weizhou formation[17](Fig. 2).

The Weixinan sag has the characteristics of multiple oil-bearing strata, including the Paleogene formation of the first, second and third members of the Liushagang formation, the third and second members of the Weizhou formation, the Neogene formation of Jiaowei formation and the Xiayang formation. At the same time, oil and gas are widely distributed on the plane. B depression, A depression, No.2 fault zone, No.3 fault zone, No.1 fault zone, Xieyang slope zone and southern slope zone are all oil and gas enrichment zones.

At present, 29 oilfields or oil and gas bearing structures have been discovered and a crude oil production area with an annual output of 3.5 million cubic meters has been built in Weixinan Sag, and the production has been stable for more than 10 years. However, multiple oilfields have entered the middle and late stages of exploration and development.

Research method

The Paleogene is the active period of fault depression in Weixinan Sag, which led to the extremely developed stratum faults in the first member of Liushagang formation and the third member of Weizhou formation, forming a large number of fault and structural genetic traps[1,17,20].

This study utilizes technical means such as fault research, effectiveness research of traps and the relationship with the oil and gas distribution law. Fault research includes the study of the geometry, dynamics, kinematics characteristics of fault, and the division of fault system. The research on the effectiveness of traps include analogical studies on the structural characteristics of traps, quantitative studies on fault lateral sealability, fault vertical sealability, and prediction technology of oil column height. Synthesizing the relationship of the law of oil and gas distribution,the differential fault system in the internal of the No. 2 fault zone, and the effectiveness research of traps, the fault-controlled reservoir laws and the dominant fault-controlled reservoir mode are obtained.

Basing on the investigation of fault zones and the laws of faults controlling reservoirs[26–32], the No. 2 fault zone in the dominant oil and gas enrichment area is taken as the research object. This study focuses on the echelon faults and structural traps in the No. 2 fault zone, and the research data includes relevant data of faults and traps on different survey lines(Table 1

Stratum	Survey line 1				Survey line 2				Survey line 3				Survey line 4				Survey line 5				Survey line 6				Survey line 7				Survey line 8				Survey line 9			
	Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m		Time ms		Depth m	
	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth	Top depth	Down depth
T90	2598	2935	3793	4543	2032	2794	2669	4222	2378	2658	3336	3922	2938	3666	4550	6377	2458	2914	3499	4494																
T86	2298	2578	3176	3750	2718	3450	4053	5806	2354	3150	3288	5053	2282	2530	3145	3649	2074	2802	2747	4240																
T83	1526	1914	1809	2456	1626	1978	1968	2571	1602	2190	1929	2966	2022	2522	2651	3632	1982	2334	2578	3248	1762	1974	2193	2564	1670	1906	2040	2442	1622	1938	1962	2499	1514	1682	1790	2060
T80	1430	1718	1661	2119	1566	1846	1872	2337	1470	2014	1722	2636	1814	2374	2282	3328	1710	2046	2106	2695	1570	1866	1878	2372	1398	1558	1613	1859	1366	1704	1565	2096	1346	1654	1536	2014
T72	1298	1702	1466	2093	1318	1642	1495	1994	1286	1902	1448	2435	1550	2194	1847	2973	1518	1890	1796	2414	1394	1658	1607	2020	1238	1322	1380	1500	1190	1462	1313	1710	1242	1418	1386	1643
T70	1230	1445	1369	1701	1286	1454	1448	1707	1304	1625	1474	1986	1509	1834	1782	2350	1574	1769	1885	2208	1540	1693	1836	2077	1514	1562	1809	1880	1523	1665	1833	2042				
T60	1161	1187	1273	1309	1253	1266	1401	1420	1322	1347	1500	1537	1467	1473	1717	1727	1629	1647	1973	2002	1686	1727	2066	2134	1789	1801	2239	2260	1855	1867	2353	2374				

Table 1. The relevant data of faults in the No. 2 fault zone.

Result

The internal fault system division of the no. 2 fault zone

Fault system is a combination of various faults formed in a certain area of the tectonic stress field[19], which is related to the migration and preservation of oil and gas, and is an important controlling factor for oil and gas accumulation. The study of fault system division is a comprehensive study of main and branch faults dynamics, kinematics and geometry on the basis of the recovery of stratum compaction and denudation. The No.2 fault zone is adjacent to the A and B depression, which is a favorable oil and gas accumulation zone. The No.2 fault zone has a unique en echelon distribution characteristics, and a unique structural trap is formed between the main faults and the branch faults. The study of the No.2 fault zone is helpful to better carry out oil and gas exploration and development research in this zone.

The characteristics of fault dynamics

The target area of the Weixinan Sag is located on the Northern shelf of the South China Sea, which is mainly affected by the interaction of the Eurasian plate, the Pacific plate and the Indian Ocean plate[33].

At the end of late Cretaceous, the Indian plate rapidly subducted under the Eurasian Plate along the NNE direction, resulting in forming the Himalayan Mountain with the uplift of the Eurasian plate. The geologic period turns into the Himalayan period. Due to the fact that the subduction rate of the Pacific Plate to the Eurasian plate is much less than that of the Indian Plate, the dextral Shear tensile stress field is generated in eastern China and its adjacent areas, the crust is stretched thin, the mantle is upwelling, and the South China Sea begins to form.

In the middle and late Oligocene, the subduction of the Indian Plate weakens, the subduction of the Pacific Plate intensified, and the subduction rate of the two plates is similar. At this time, the dextral Shear tensile stress weakenes, and the subduction of the Pacific Plate results in the tectonic uplift and partial denudation of eastern China. This is consistent with the regional tectonic uplift at the end of Oligocene and partial denudation of the first member & second member of Weizhou formation.

Since Miocene, the cooling of mantle flow results in the continuous structure subsidence, forms a marine sedimentary environment and entered the depression period. The Pacific Plate is subducted faster than the Indian Plate. At this time, the Weixi'nan sag is far from the Pacific Plate subduction zone, so the impact of wall subduction is relatively small and the fault is not developed. The analysis of regional dynamic characteristics shows that the South China Sea region in which the target area is located has been affected by SE-S dextral tensile stress as a whole since the Himalayan movement[33].

The kinematic characteristics of fault

In Paleogene, the No. 2 fault Zone is formed and active under the regional tectonic stress of SE ~ S direction. The kinematic characteristics of fault formation and active period are studied by using "fault growth rate".

The "fault growth rate" takes into account the thickness of the hanging wall and foot wall of the fault and the corresponding deposition time. The "fault growth rate" is the ratio of the strata drop caused by fault activity to the sedimentary time of a certain strata in a certain period of geological history[34,35].

$$V_f = H/T = (H_2 - H_1)/T \tag{1}$$

In the formula, V_f represents the fault growth rate, m / Ma; T represents the sedimentary time, Ma; H_2 represents the strata thickness of the hanging wall of the fault, m; H_1 represents the strata thickness of the foot wall of the fault, m.

Nine main echelon faults of the No. 2 fault zone in Weixinan Sag are selected to calculate and make statistics of the fault growth rates in the first member of Changliu formation to Weizhou formation in the Paleogene period[34,35]. The fault growth rates of the Changliu formation, the third member of the Liushagang formation, the second member of the Liushagang formation, the second member of the Weizhou formation, and the first member of the Weizhou formation are all greater than 0, with average growth rates ranging from 10 m/Ma to 60 m/Ma, which indicate strong fault activity. The growth rates of the first member of Liushagang formation and the third member of Weizhou formation are close to 0, and faults are not active (Fig. 3).

Fault geometry characteristics

The static relationship between main faults and branch faults is determined by analyzing the profile geometry characteristics and plane geometry characteristics of the echelon main faults and branch faults in No. 2 fault zone[36]. The fault system is divided into two different fault combination styles. one style is theramp-flatfault system with the plane style of "broom-shaped combination"and the profile style of "negative flower-shaped combination", which is mainly distributed in the middle section of the No. 2 fault zone. The other style is a listric fault system consisting of the plane style of "geese and row combination" and the profile style of "fault step combination", which is mainly distributed on both sides of the No. 2 fault zone (Fig. 4).

Under the action of regional tectonic stress, the two different fault system models have some similar geometric features. Most of the en echelon main faults break through the seismic reflection surface of T60 ~ T100 (the Paleogene strata) , the dip angle of faults in Paleogene rifting period are 10 ~ 58, the average dip angle is about 40, the dip direction is southward, and the strike direction of faults change from NEE to EW gradually. The plane extension length is about 6.4 km. The branch faults can be divided into early faults and late faults, which converge to the bottom surface (T86) and the top surface (T83) of the plastic shale in the second member of Liushagang formation (Fig. 4). The strike of each branch fault is similar to the main fault, which is NEE ~ EW direction.

The two different fault system models have different geometric characteristics. The average vertical fault distance of the en echelon main fault of ramp-flat fault system is 930 m, and the average horizontal fault distance

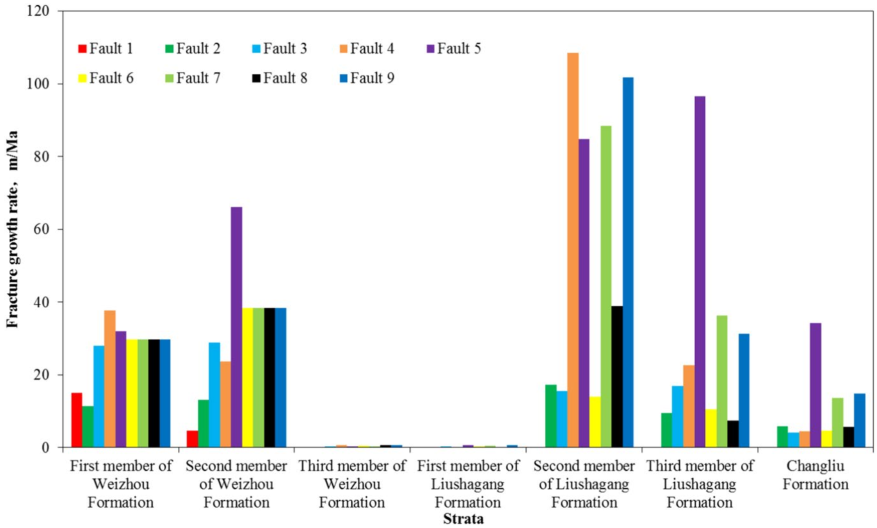


Figure 3. The fault growth rate of No.2 fault zone. Nine echelon main faults are selected from west to east for No.2 fault zone, and the growth index of different strata in Paleogene is analyzed.

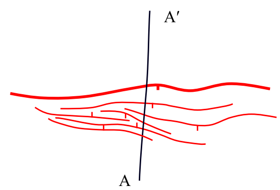
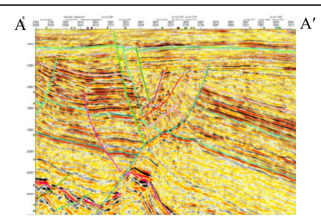
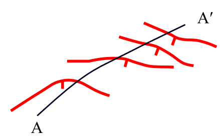
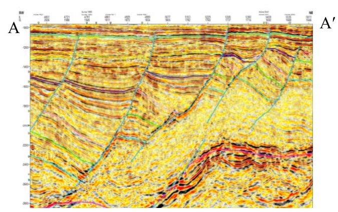
Structural Layers	Association Patterns	Examples	
		planar association	profile association
Fracture System	"ramp-flat fracture" profile association: "negative flower-like type" planar association: "broom-type"		
	"listric fracture" profile association: "fracture terrace type" planar association: "en echelon type"		

Figure 4. The fault system models of No.2 fault zone. The plane and profile characteristics of ramp-flat fault and shovel fault are summarized.

is 960 m, which are larger than that of the listric fault system. The average vertical fault distance of the listric fault system is 720 m, and the average plane fault distance is 700 m. This shows that ramp-flat fault system is subjected to stronger in-situ stress and more intense fault activity in geological history. On the whole, the en echelon main faults in the No. 2 fault zone are intense activity with the vertical and plane fault distance concentrating at 0 ~ 1 km and 0 ~ 1.5 km respectively. The main fault density of the ramp-flat fault system is 0.34 ~ 0.69 / km^2, which is obviously higher than that of the listric fault system(0.09 ~ 0.29 / km^2). This also proves that the ramp-flat fault system has higher in-situ stress intensity and more intense fault activity.

The main fault of the ramp-flat fault system are tilted under the strong regional crustal stress, and the dip direction of the branch faults develop in the later Weizhou formation are both to the South and to the North. however, The branch faults dip direction of the listric fault system developed in Weizhou formation is the same as the main fault, which are southward.

On the whole, the dip angle of the branch faults are 34 ~ 78, the average dip angle is 53. The average vertical and plane fault distances of ramp-flat fault system are 78 m and 100 m respectively, which are larger than those of the listricfault system. These average vertical and plane fault distances are 39 m and 63 m, it is further shown that the ramp-flat fault system is subjected to stronger in-situ stress, resulting in more developed branch faults. In general, the vertical and plane fault distances of the en-echelon main faults in the No. 2 fault zone are concentrated in the range of 0 ~ 100 m.

The fault system division

According to the fault dynamic, kinematic and geometry research, the ramp-flat fault system and the listric fault system of the No. 2 fault zone are divided. Regionally, the Weixinan fault growing as a basin-controlling fault is the first-level fault, the No. 1 fault zone evolving as a sag-controlling fault is the second-level fault, and the No. 2 fault zone's echelon main fault developing as the regional trap-controlling fault is the third-level fault. Aiming at the internal of No. 2 fault zone and integrating the fault characteristics of dynamics, kinematics, and geometry, the fault system of the No. 2 fault zone is divided into 3 levels. Among them, the main echelon fault is classified as third-level fault. The first-level branch faults of the main echelon fault are classified as fourth-level faults, and the next-level branch faults of the fourth-level faults are classified as fifth-level faults (Fig. 5).

According to the above analysis, the ramp-flat fault system is subjected to higher in-situ stress intensity and stronger fault activity. The third-level echelon main fault, the fourth and fifth-level branch faults are more developed. Comparing with the listricfault system, theramp-flat fault system is more conducive to the development of structural traps, the migration and preservation of oil and gas along the vertical direction of the fault.

The research scale is impenetrated fine to the inside of fault zone through "the division of the internal fault system". A set of fault evaluation techniques for regional fault zones has been formed, which has achieved good application results and provided technical support for the study of other regional fault zones.

The trap effectiveness

This chapter mainly conducts quantitative research on the fault sealability of structural traps with superior trap structure morphology. Quantitative analysis technology of fault sealability of Weizhou formation in Weixinan Sag combines the analysis of lateral sealability of fault with vertical sealability analysis[36–41], through SGR(Shale

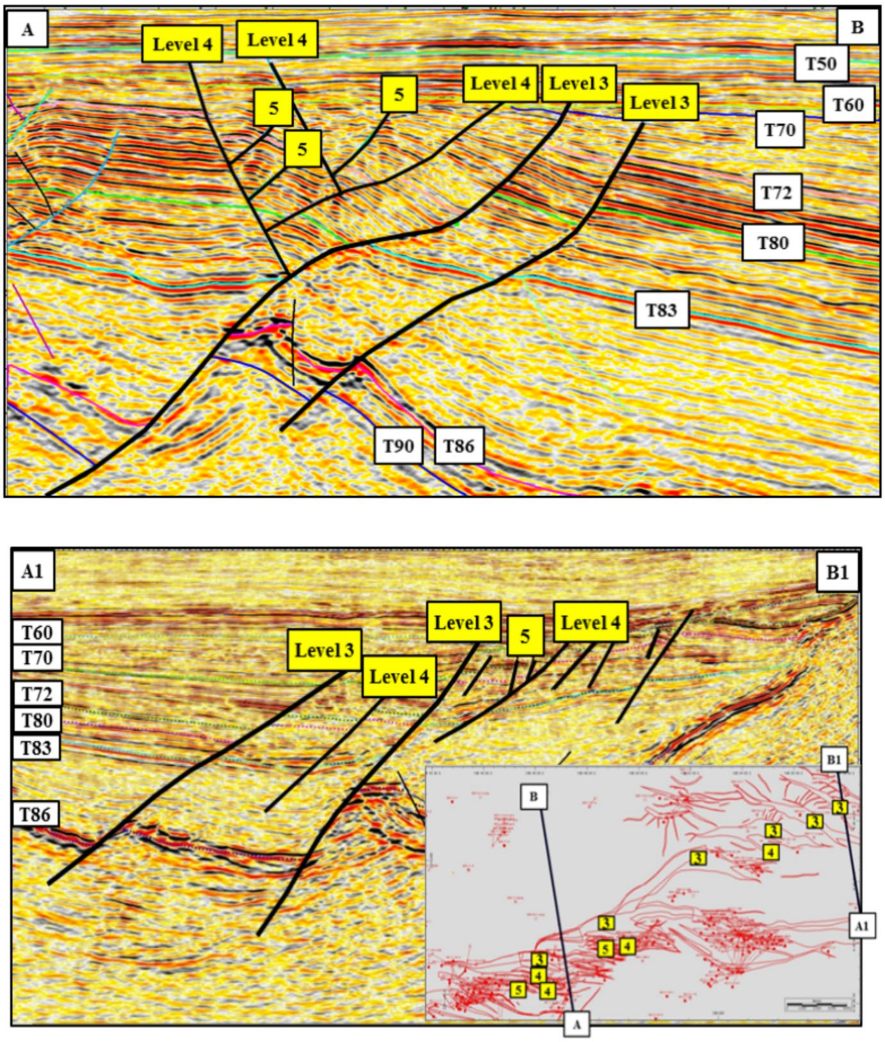


Figure 5. The fault system classification of Weizhou formation, No.2 fault zone. The tendency of the main fault and the branch fault of the ramp-flat fault is both the same and different, reflecting that the in-situ stress in this area is strong during the geological history. The tendency of the main fault of the shovel fault is the same as that of the branch fault, which is mainly formed by the tensile stress.

Gouge Ratio)-SSF(Shale Smear Factor) fault lateral sealing qualitative chart and the vertical sealing qualitative chart which provide a comprehensive qualitative analysis of the fault sealing performance. Based on the principle of molecular mechanics equilibrium of crude oil, the maximum oil column height blocked by faults can be predicted quantitatively, which can provide a basis for the calculation of filling degree in the follow-up prediction of potential resources.

Quantitative analysis technology of fault lateral sealability

Whether a structural trap accumulates is mainly determined by the fault sealability, and is fundamentally determined by the relationship between the fault displacement pressure Pf and the target disk displacement pressure Pt[36]. When Pf > Pt, oil and gas cannot break through the fault, and the fault is sealed laterally to accumulate; when Pf < Pt, the oil and gas can break through the fault constraint, and the lateral sealing of the fault is poor, and no reservoir is formed. The size of Pf depends on the nature of the filling in the fault. The higher the shale content, the greater the Pf. Therefore, according to the argillaceous content in the fault zone, the ratio of fault gouge and mudstone smear coefficient are introduced.

The Shale Gouge Ratio is the ratio of the total argillaceous content thickness of mudstone and sandstone to the fault distance within the range of fault displacement[42]:

$$S_{GR} = \left(\sum_{i=1}^{n} h_{li} + \sum_{i=1}^{n} c_{li} \right) \Big/ L \tag{2}$$

The Shale Smear Factor is the ratio of the fault distance to the total thickness of the mudstone within the fault displacement[36]:

$$S_{\mathrm{SF}} = L/(\sum_{i=1}^{n} h_{\mathrm{l}i}) \tag{3}$$

In the formula, h_{1i} represents the thickness of the ith set of mudstone in the range of fault distance, m; C_{li} represents the shale thickness in the ith set of sandstone in the fault distance range, m; L represents the fault displacement, m.

Based on the functions of SGR and SSF parameters in fault lateral sealing ability analysis, the SGR-SSF chart is established and applied to quantitative analysis of fault lateral sealing ability, and the potential blocks of several oilfields in the depression are evaluated. First, the lateral sealability of the main fault of the drilled trap in the study area is analyzed, and the SGR and SSF values of multiple faults and survey lines are obtained, and the SGR-SSF discriminant chart of fault lateral sealing property and oil–gas bearing property is established. Then, combined with the actual oil–water relationship at each survey line, the SGR-SSF discriminant chart is divided into oil zone, transition zone, and water zone (Fig. 6). Among them, the boundary between the oil zone and the transition zone is the minimum SGR value and the maximum SSF value of the actual drilled oil layer point, and the boundary between the transition zone and the water zone is the minimum SGR value and the maximum SSF value of the actual drilled oil and water layer, oil-bearing water layer, etc.

The analysis of the lateral sealability of the faults in the drilled blocks of different oil fields shows that the critical values of the SGR-SSF discriminant chart are different. For example, when SGR > 0.64 and SSF < 2.15 in Weizhou formation of Oilfield A, it is oil zone. When SGR > 0.67 and SSF < 1.55 in Weizhou formation of Oilfield B, it is oil zone. When SGR > 0.41 and SSF < 2.2 ,Oilfield C is oil area(Fig. 6). Compared with the previous research methods, due to different oil fields, structural traps and fault types may be inconsistent, the critical SSF value of the research block is much less than 3. Therefore, in the analysis of the lateral sealability of the fault in the potential block, different regions cannot be directly compared.

Quantitative analysis technology for faults vertical sealability

The vertical sealability of fault refers to the ability to vertical migration of oil and gas[36,41]. When the fault is active, the fault opens vertically and does not have sealability. When the fault is inactive, the fault vertically seals oil and gas by the displacement pressure difference generated by the fault fillings between the two walls of the fault. The higher the mud content of the fault zone, the greater the displacement pressure difference between the two walls of the fault, and the better the fault sealability. Similarly, The stronger the late compaction diagenesis is, the greater the displacement pressure difference between the two walls of the fault is, and the better the fault sealability is. The degree of compaction diagenesis mainly depends on the magnitude of compaction diagenesis pressure and the duration of compaction diagenesis. Both can be reflected by the depth of compaction diagenesis. The deeper the burial depth is, the stronger the compaction diagenesis is[36].

Considering the influence of mud content in the fault zone and compaction diagenesis, a discriminant chart of the fault vertical sealing ability is established, which take the thickness of the cap layer of the contact wall as the abscissa and the product of the mud content and depth as the ordinate. It is applied to the well-drilled block of Weizhou formation in the No. 2 fault zone of Weixinan Sag (Fig. 7), and it is found that when the product of mud content and depth is greater than 0.66, the accumulation probability is large.

Quantitative prediction technology of oil column height

The fault sealability is fundamentally determined by the relationship between the fault displacement pressure Pf and the target wall displacement pressure Pt. When Pf > Pt, the fault sealability is good. When Pf < Pt, the fault sealability is poor. So when Pf = Pt, the maximum oil column height that the fault trap can be reached[43] .

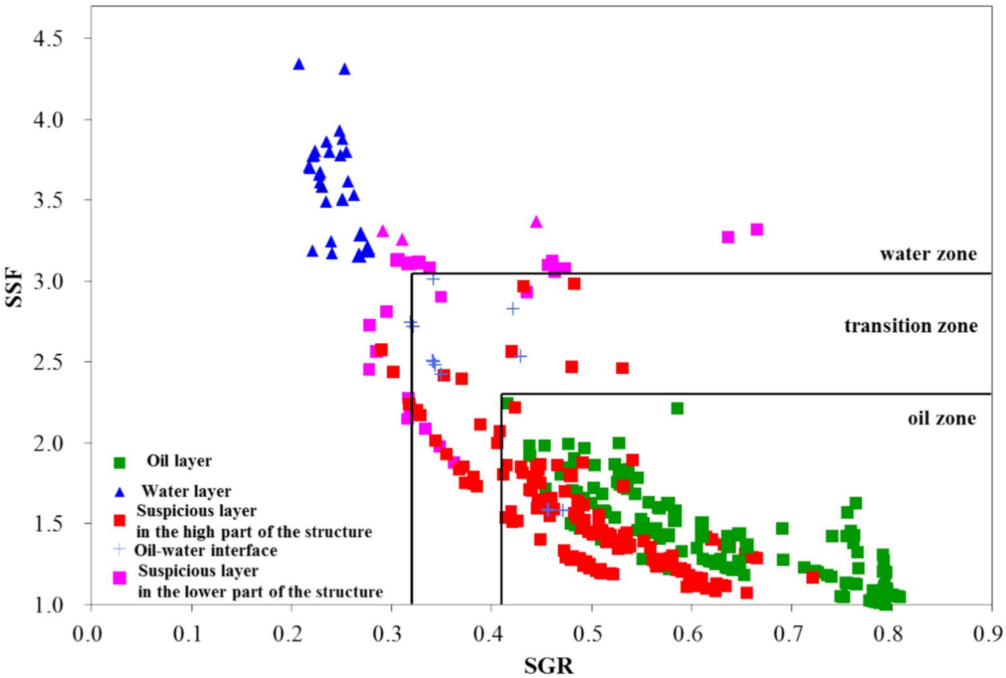


Figure 6. The lateral fault sealing quantitative analysis chart of SGR—SSF for No.2 fault zone, Weixinan Sag. Green represents the drilled oil layer, blue represents the drilled water layer, red represents the suspicious oil layer in the high part of the structure, cross represents the oil–water interface, and light purple represents the suspicious oil layer in the bottom part of the structure in the No.2 fault zone.

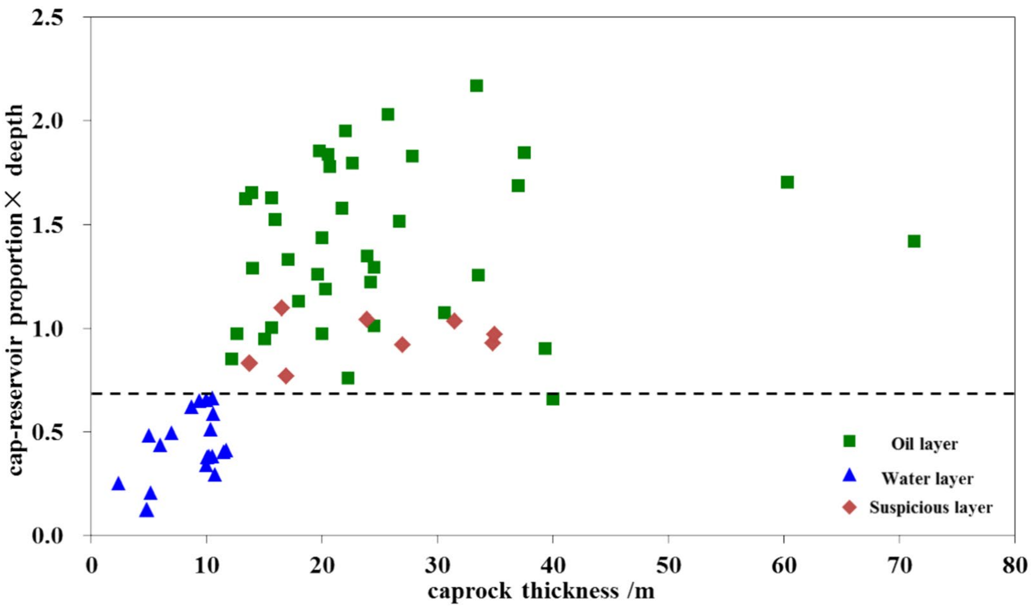


Figure 7. The vertical fault sealing quantitative analysis chart of No.2 fault zone, Weixinan Sag. Green represents the drilled oil layer, blue represents the drilled water layer, brown represents the suspicious oil layer in the No.2 fault zone.

The target wall displacement pressure Pt depends on the relationship between oil and water, the formation dip and the height of the oil column:

$$p_t = \left[(\rho_w - \rho_o)gH - p_c\right]\sin\theta \tag{4}$$

Since the reservoir of Weizhou formation has high-porosity and high-permeability, the influence of capillary pressure(Pc) can be ignored. Displacement pressure is related to argillaceous content in fault rocks[42]:

$$p_f = 10^{(S_{GR}/d - c)} \tag{5}$$

When the maximum depth of the target stratum is less than 3 km in geological history, c=0.5. According to formula (4) and formula (5), when Pf = Pt, the regional oil column height prediction model is established:

$$H = 10^{(S_{GR}/d - c)} / \left[(\rho_w - \rho_o) g \sin\theta\right] \tag{6}$$

In the formula, ρ_w represents the density of water, g/cm^3; ρ_o represents the density of oil, g/cm^3; ɵ represents Stratigraphic dip, H represents prediction of oil column, m; d is the constant to be calibrated.

According to the data of drilled oil–water interface, the value of d is obtained, and then the regional oil column height prediction model is applied to the drilled blocks in the study area. If the predicted oil column height is greater than the actual drilling value, and the predicted water top oil column height is less than the actual drilling value. It is proved that the prediction results are consistent with the geological reservoir law and can be applied to the prediction of oil column height in potential blocks. For example, this method is applied to drilled blocks in E oilfield. The predicted height of the oil column in the E oilfield is greater than the actual drilled value, and the predicted height of the water-top oil column is less than the actual drilled value(Fig. 8), the prediction results are consistent with the geological reservoir law. On the basis, the d value of the oilfield is 0.142.

The prediction model of oil column height is applied to potential block of E oilfield, and the height of oil column is predicted to be 10.9 ~ 33.2 m, and the oil filling degree is 36-95% (Table.2), which provides technical support for accurate prediction of potential resources.

Discussion

The research of fault-controlling traps law

By dividing the internal fault system of the No. 2 fault zone of Weixinan Sag, the control effect of the fault zone on the formation of structural traps has been implemented. The morphological characteristics of traps are mainly characterized by the properties of the main control fault. Statistics show that the accumulation probability of broken nose traps with fewer main control faults is higher than that of fault-block traps with more main control faults in the drilled traps in Weixinan Sag. The accumulation probability of the traps with the reverse main control faults are higher than the traps with the consequent main control faults, and 89.6% of the main control faults in the reservoir structural traps are reverse faults.

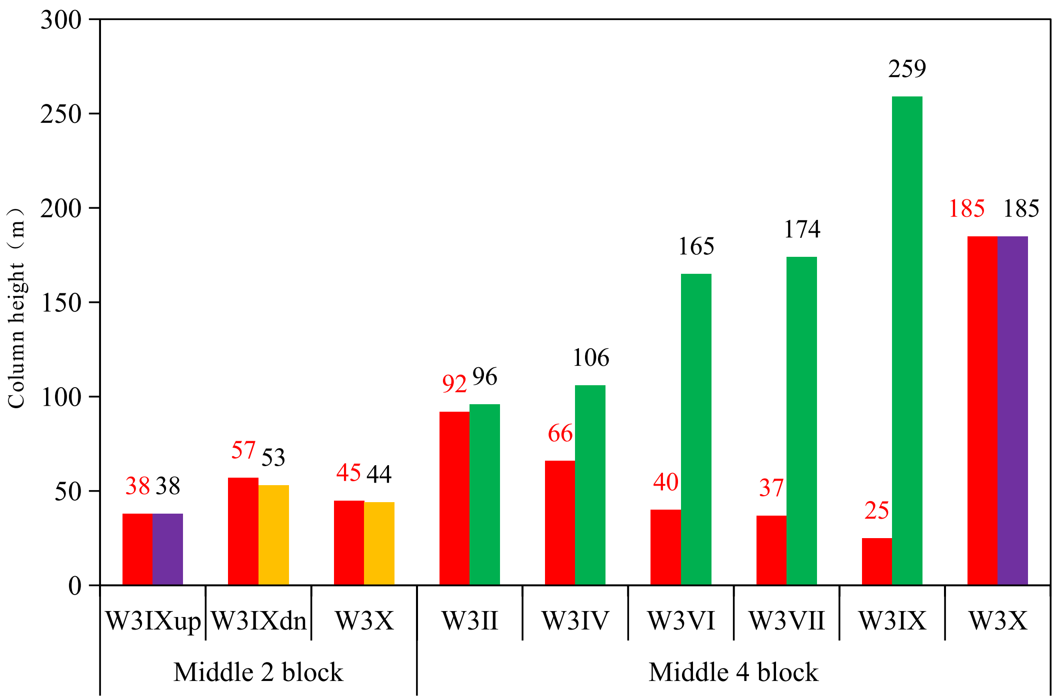


Figure 8. Application results of the oil column height prediction in the drilled blocks of E oilfield. Block 2 and Block 4 are selected. The red represents the predicting oil column height using the quantitative prediction technology of oil column height to the drilled block, and compares it with the oil column height of the oil layer, the water column height of the water layer and the oil column height of oil–water interface. The oil column height of the oil layer is represented by green, the water column height of the water layer is represented by yellow, and the oil column height of the oil–water interface is represented by purple.

oil series	SGR	subsurface oil density g·cm^{-3}	water density g·cm^{-3}	*d*	formation inclination°	prediction of oil column height m	prediction of oil–water interface column depth m	prediction of filling degree %	top depth of trap m	low depth of trap m	tectonic range m
W_3IV	0.55	0.889	1	0.142	12	17.2	1547.2	68.89	1530	1555	25
W_3V	0.51				10	10.9	1590.9	36.22	1580	1610	30
W_3VI	0.60				13	33.2	1663.2	94.78	1630	1665	35
W_3VII	0.56				14	18.6	1708.6	61.96	1690	1720	30
W_3IX	0.59				14	28.9	1903.9	57.72	1875	1925	50

Table 2. The oil column heights, filling degrees prediction chart of potential blocks in E oilfield.

The internal structure of the fault mainly includes the induced fault zone and the sliding fault zone[40]. The induced fault zone is mainly distributed near the hanging wall, the stress environment is tensile, and a large number of small faults develop, which are more conducive to oil and gas migration and not conducive to oil and gas preservation[44]. The forward fault target wall is mainly concentrated on the hanging wall of the fault, adjacent to the induced fault zone, and oil and gas are easily lost (Fig. 9). The sliding fault zone is adjacent to the footwall of the fault, and the stress environment is compressive[44]. The dislocation and squeezing effect of the two faultd walls has a good blocking and sealing effect on oil and gas. The target wall of reverse fault is mainly concentrated in the footwall of the fault, adjacent to the sliding fault zone, which is conducive to the accumulation of oil and gas[45] (Fig. 9).

The trap attribute characteristics such as the dip angle of the trap formation and the seismic amplitude response characteristics have a certain degree of indicating significance for the hydrocarbon accumulation of the Weizhou formation. The dip angle plays an important role in hydrocarbon charging[46]. If the formation dip angle is too small, the component force of oil and gas buoyancy along the formation direction is small, which makes it more difficult for oil and gas to enter the trap. If the formation dip angle is too large, the component force of oil and gas buoyancy along the formation direction is too large, which leads to the loss of the oil and gas by breaking the displacement pressure of the fault sealing. Statistics show that the dip angles of the reservoir traps of Weizhou formation in Weixinan Sag are mainly distributed in 5-15°(Fig. 10).

The seismic amplitude response is used as an auxiliary method in the analysis of trap morphological characteristics, which has a certain correlation with the hydrocarbon-bearing properties of Weizhou formation in Weixinan Sag. Regional statistics show that reservoirs with strong amplitude response in Weizhou formation have higher oil-bearing probability than those with weak amplitude response.

The research of fault-controlling reservoirs law

The first member of Liushagang formation and the third member of Weizhou formation are the most important oil-bearing strata in Weixinan Sag[33,47,48]. Structural traps of the first member of Liushagang formation and the third member of Weizhou formation are important strata and trap types for the search and evaluation of exploration and development integrated targets[49].

Oil and gas distribution law of the No. 2 fault zone

The No. 2 fault zone is an important oil and gas enrichment area in Weixinan Sag. According to the longitudinal and planar distribution characteristics of the reservoir, the statistics are made respectively. In the plane, a number of oilfields are distributed along the No.2 fault zone. Longitudinally, the oil reservoirs are distributed in multiple layers from the Jiaowei formation to the Carboniferous, among which the deep-seated oil reservoirs are concentrated in the oilfields on both sides of the No. 2 fault zone. It is found that the key model of hydrocarbon

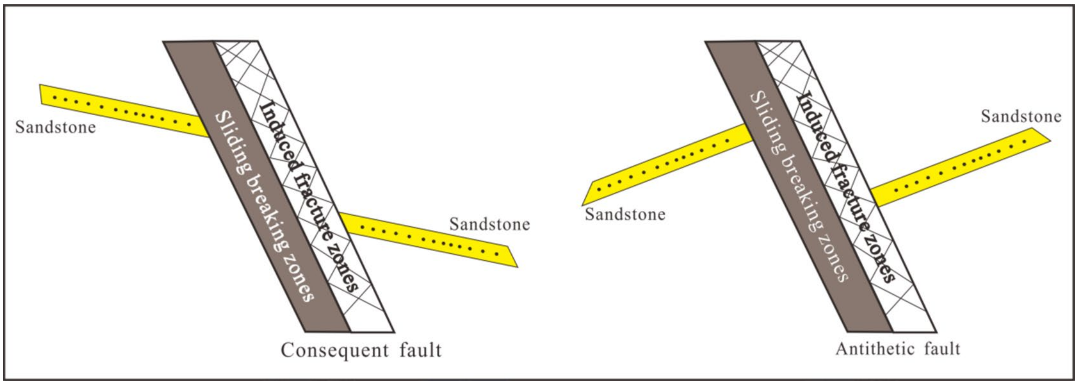


Figure 9. The internal formation pattern of fault.

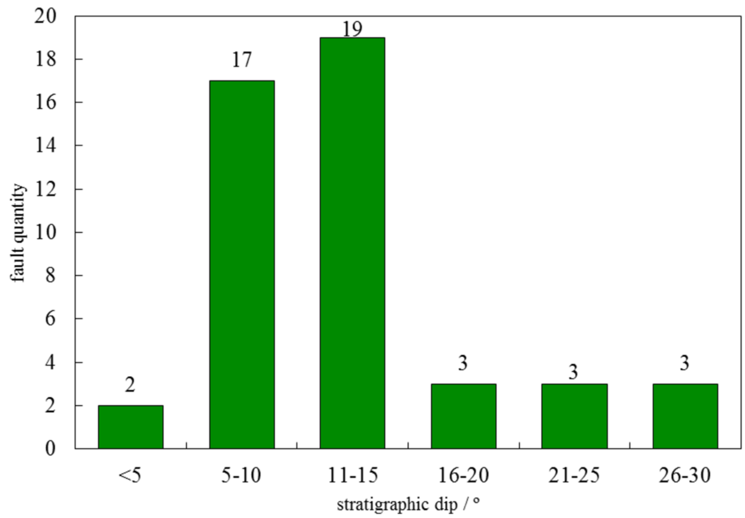


Figure 10. Stratigraphic dip of oil bearing traps in the Weixinan Sag.

accumulation is ' source ~ fault ~ ridge ~ sand ~ ring ' model. After the maturity of hydrocarbon source rocks, oil and gas are driven by displacement pressure difference, and vertically migrate through migration channels such as trench source faults, and then migrate through structural ridges, unconformity surfaces and sandstone laterally to the target layer of traps to accumulate(Fig. 11). For example, the number of oil reservoirs in the third member of Weizhou formation in the F oilfield accounted for 52%. Weizhou formation reservoirs are concentrated in the middle section of the No. 2 fault zone. Weizhou formation reservoirs in E oilfield account for 55%.

The distribution of hydrocarbon in No. 2 fault zone is not accidental and random, but closely related to the fault system. During the Paleogene period, the No. 2 fault zone had strong activity of fault, and the faults were very well developed. The faults were not only different, but also related to each other, which formed a fault system

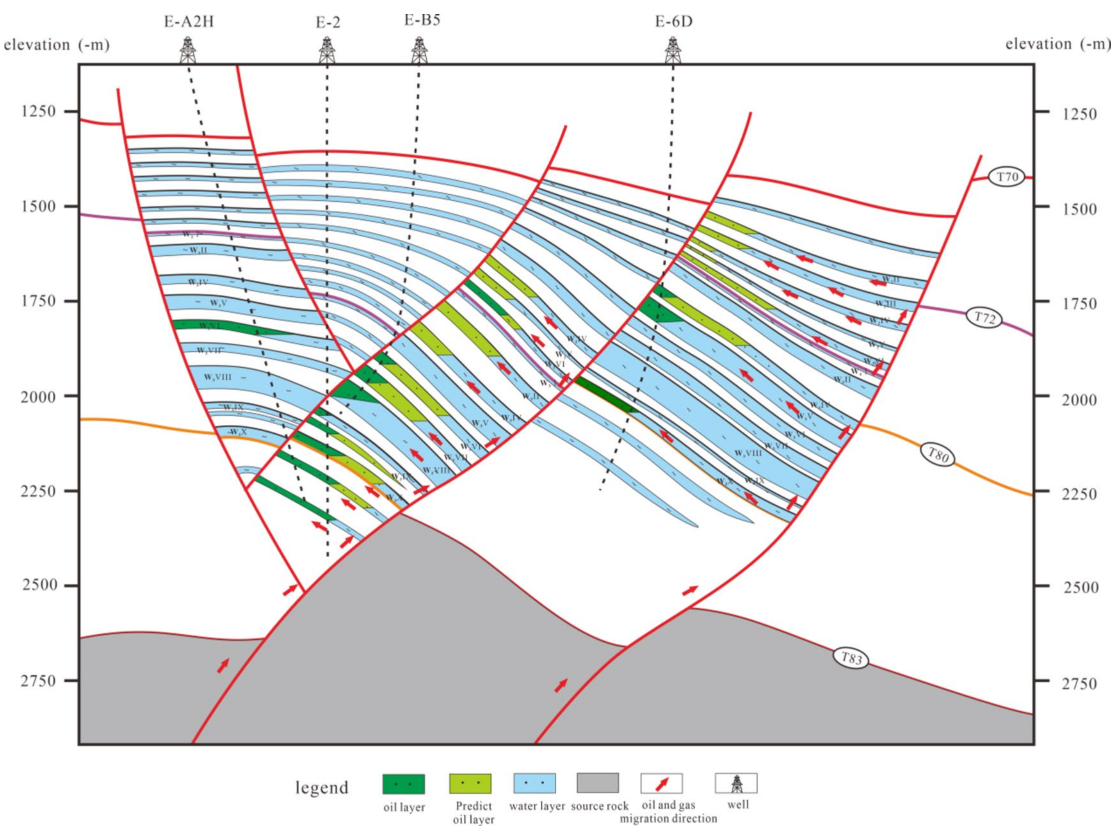


Figure 11. The accumulation pattern map of E oilfield.

and controlled the migration, accumulation and preservation of hydrocarbon. The relationship between the characteristics of fault development and the hydrocarbon distribution response of the No. 2 fault zone in different rifting periods is studied. It is found that the oil-bearing layers of the third member of Liushagang formation, the first member of Liushagang, the third member of Weizhou and the secondary member of Weizhou in No.2 fault zone are mostly distributed in ramp-flat fault system (Fig. 12).

The relationship between oil and gas distribution and the fault systems

The key to the study of hydrocarbon accumulation is the study of fault's effect on hydrocarbon transport and occlusion[50,51]. In the middle section of the No. 2 fault zone, the ramp-flat fault system is more developed under the action of higher strength in-situ stress. The main fault is active from the early Changliu formation to the second member of Liushagang formation, and from the late of second member of Weizhou formation to the first member of Weizhou formation. Oil and gas mainly come from the B depression, and the peak of its hydrocarbon expulsion is from the second section of Weizhou formation to the present. The trap formation period of the main oil-bearing strata matches the period of fault activity and the peak period of hydrocarbon generation and expulsion. The key mode of accumulation is the "source-fault-ridge-sandstone-trap"mode. Driven by displacement pressure difference after source rocks mature, hydrocarbon migrates vertically through gully source faults and other migration channels, and then migrates laterally through structural ridges, unconformity surfaces and sandstone to the target member of the trap.

The fault lateral sealability analysis of the "ramp-flat type" fault system in the middle section of the No. 2 fault zone, including the 4th level blocking fault, 3rd level blocking fault, and 3rd level branch blocking fault, shows that the SGR chart values are all greater than 0.4. In the quantitative chart of fault lateral sealability analysis of the SGR-SSF, the vast majority of breakpoints are located in the "oil and gas area", confirming good fault lateral sealability. The migration faults corresponding to level 5 blocking faults are either level 4 or level 5 faults. In most cases, the oil and gas filling intensity cannot migrate to the traps controlled by level 5 blocking faults. At the same time, the fault throw of level 5 blocking faults is small, and the shale smear effect is poor, resulting in poor fault lateral sealability. The SGR values are all small, so the traps controlled by level 5 blocking faults are mostly distributed in the "water zone" in the lateral fault sealing quantitative analysis chart of SGR—SSF.

Law of fault-controlling reservoirs

Comprehensive analysis of the relationship between the differential fault system in the internal of the No. 2 fault zone and the law of oil and gas distribution, three aspects of fault-controlled reservoir laws and the dominant fault-controlled reservoir mode are obtained.

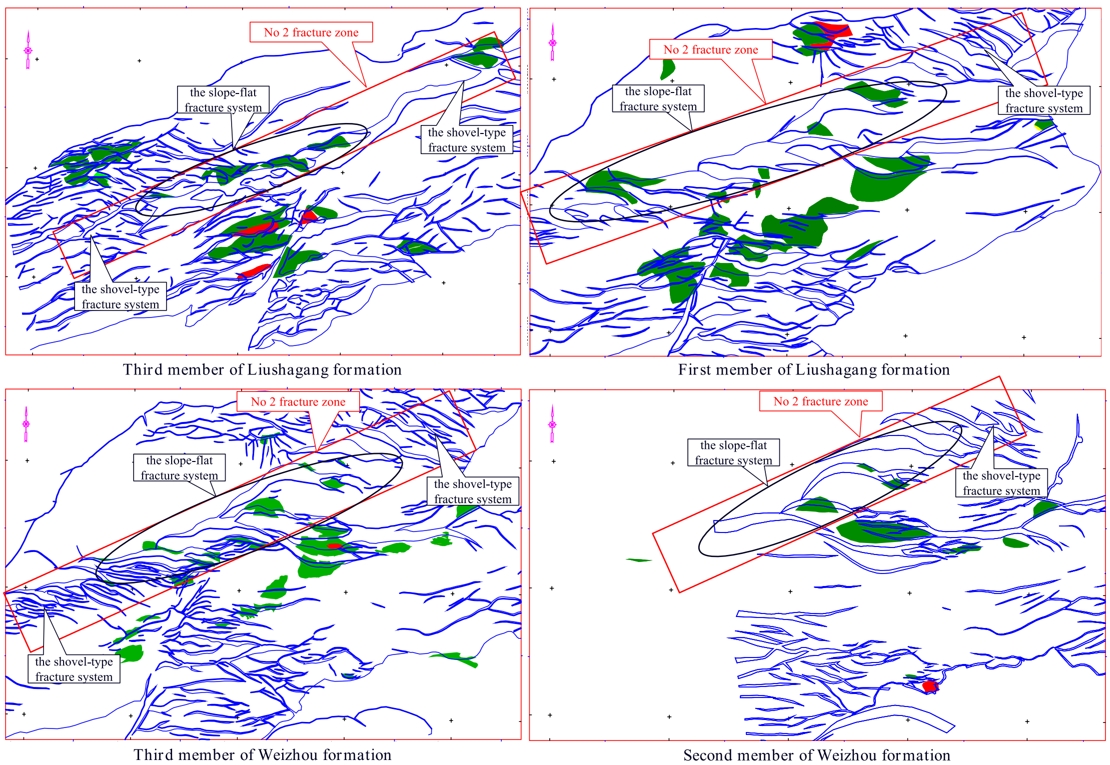


Figure 12. The fault developmental characteristics and oil reservoirs distribution of the No.2 fault zone. The green represents the oil field, the blue line represents the fault, the red frame represents the listric fault zone, and the black ellipse represents the ramp-flat fault zone of the No.2 fault zone.

- The migration fault mode is that the migration capacity of the third-level fault is better than the migration capacity of the third-level branch fault, and is better than the combined migration mode of the third and fourth-level faults. For the ramp-flat fault system, oil and gas migrate vertically along the third-level source faults, preferentially charge in the structural traps that migrate through the third-level faults, and then move to the "flower center" along the fourth-level faults. The intensity of oil and gas charging determines whether it can reach the "flower center" position. For the listric fault system, the third-level fault is the main way of oil and gas migration, and the migration of fourth-level fault mainly depends on the sealing ability of the fault itself. Due to poor fault sealing performance, oil and gas migrated vertically into fourth-level fault, and the fault sealing performance was good, oil and gas accumulated at the high point of trap sheltered by fourth-level fault.
- The most important sealability faults are the fourth-level faults, followed by the third-level sealability faults and the third-level branch sealability faults, but the fifth-level sealability faults are less likely to accumulate. The reason for the highest proportion of the fourth-level sealability faults is that the fourth-level sealability faults are the second level branch faults of the third-level faults, which are adjacent to the third-level faults and can form broken nose and block trap with the corresponding the third-level faults. The third-level sealability faults and the third-level branch sealability faults can respectively form the broken nose and block traps with the adjacent third-level faults and the third-level branch faults. This fault combination mode has a high probability of reservoir formation.
- The oil and gas in the No. 2 fault zone are concentrated in the two main echelon faults (between the third-level faults), the branch faults of the main fault (between the third-level branch faults), the secondary faults of the main fault and the main echelon fault (between the fourth-level and the third-level fault). The middle section of the No. 2 fault zone has stronger in-situ stress and greater density of faults. The main faults are mostly slope-type. The tectonic stress causes the fault to tilt[52] (Xu et al.2015), resulting in a "sloping-type" fault system. Compared with the two sides, there are more fourth-level faults, forming the trap dominated by the fourth-level occlusion faults, and forming the dominant trap conditions with the third-level migration faults.

On the basis of the mechanism research of faults controlling reservoirs, through statistics on the characteristics of migration faults and blocking faults of the Weizhou formation in the No. 2 fault zone, the four dominant faults controlling reservoirs are summarized. The mode of fourth-level blocking faults and third-level migration branching faults, the mode of third-level blocking branch faults and third-level migration fault, the mode of fourth-level blocking fault and the third-level migration fault, the mode of third-level blocking fault and third-level migration fault. These modes guide significantly in the process of potential target search (Fig. 13).

Research application effect

Overall application effect

Based on the "fault zone research" and "quantitative research on the effectiveness of structural traps" in Weixinan Sag, 45 development evaluation wells were searched, evaluated and drilled in and around the oilfields, among which 37 wells were successfully drilled and 8 wells were drilled failed. The drilling success rate is 82%, which

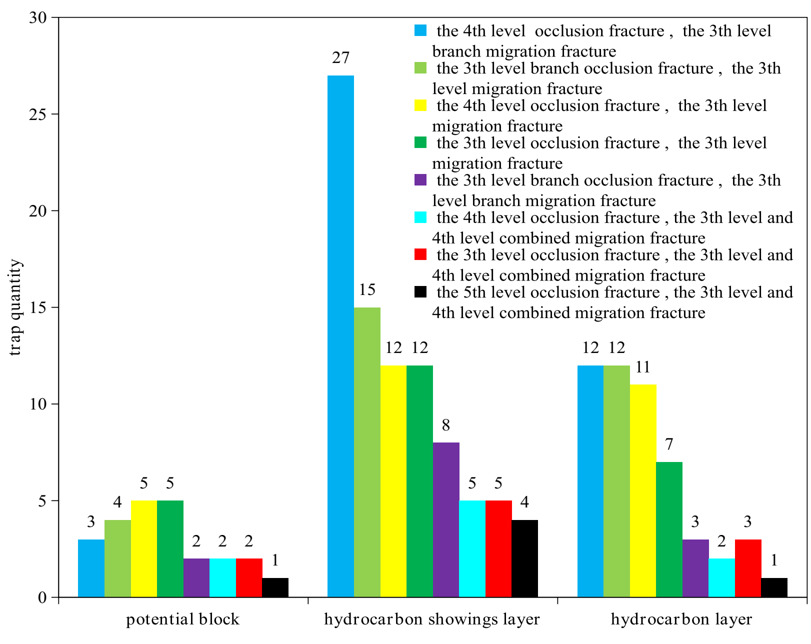


Figure 13. The faults controlling reservoirs modes of No.2 fault zone.

proves that the offshore exploration and development integrated mode has a good application effect in the middle and late stages of oil and gas field' exploration and development.

Development evaluation wells are wells with appraisal properties aimed at upgrading oil and gas field reserves, evaluating new layers (adjacent blocks) within the oil and gas fields and potential areas around the oil and gas fields[10]. The drilling modes of development evaluation wells are flexible and diverse. Compared with exploration wells, development evaluation wells can be drilled on the production platform, and can be directly put into production after the potential target oil and gas content and the scale of reserves are implemented, realizing the rapid conversion of reserves and production. Compared with production wells, development evaluation wells can drill potential targets beyond the control scope of the production platform through the exploration mode of rapid evaluation. If the evaluation is successful, the target oil and gas content and reserve scale will be implemented, and subsequent development and adjustments will be promoted. If no oil and gas layers are encountered, risks can be avoided for subsequent development.

Development evaluation well drilling mode includes “development mode” and “exploration mode”. The “development mode” is summarized into two modes: “production platform drilling mode” and “development well project drilling or concurrent drilling mode”. The "exploration mode” can be summarized as “rapid evaluation mode” and “concurrent exploration mode of rolling exploration well”.

A total of 2 development evaluation wells were implemented in the “production platform drilling mode”, and 2 wells were successfully drilled. The drilling success rate was 100%, and the number of wells accounted for 4%. A total of 29 development evaluation wells were implemented in the “development well project drilling or concurrent drilling mode”, of which 24 wells were successfully drilled. The drilling success rate was 83%, accounting for 64% of the total number of wells. Among them, 9 wells were developed and evaluated in the “ODP(Original Drilling Project) project drilling mode”, 7 wells were successfully drilled, with the drilling success rate of 83%. 3 wells were developed and evaluated in the “ODP concurrent exploration mode”, and 2 wells were successfully drilled, with the drilling success rate of 67%. There were 16 development evaluation wells drilled under the “adjustment well project drilling mode”, of which 15 wells were successfully drilled, with the drilling success rate of 94%. A total of 12 development evaluation wells were implemented in the “Quick evaluation mode”, and 10 wells were successfully drilled. The drilling success rate was 83%, accounting for 27% of the total number of wells. There were 2 development evaluation wells in the “concurrent exploration mode of rolling exploration well”, and 1 was successfully drilled. The drilling success rate was 50%, accounting for 4% of the total number of wells.

A comparative study is carried out on four development evaluation well modes. The development evaluation well under the “production platform drilling mode” is aimed at the potential targets within the coverage of the production platform. Risk evaluation is carried out without the implementation of ODP and adjustment well projects. Therefore, this mode has the risk of no pre-planned wells taking over after the evaluation failure. The implementation of this mode requires high reservoir reliability of potential targets. If there are development layers in adjacent blocks or adjacent layers, the mode can be adjusted and implemented as a pre-plan to reduce the implementation risk of development evaluation wells. Due to the strict requirements of this mode, only two wells have been drilled so far, but all of them have been successful. The proven geological reserves are nearly 2 million cubic meters, accounting for 5% and realizing rapid production.

“The development well project drilling or concurrent drilling mode” is the most important mode of drilling. Because this mode accounted for the biggest from drilling, successful well number or total proven reserves. The proven geological reserves of 29 development evaluation wells under this mode are nearly 23 million cubic meters, accounting for 63%, which drive the process of oil and gas field development effectively. There will be comprehensive adjustments to old oilfields and ODP implementation in new oilfields in mature exploration and development areas, and there will always be difficult to produce proven or controlled reserves within oilfields. How to search for potential targets within oil and gas fields to drive the production of the reserves difficult to produce and promote ODP in the early stage of oil and gas field development Implementation and comprehensive adjustments in the middle and late stages of oil and gas fields are an important part of the exploration and development integrated research work.

“The development evaluation well drilling mode” of development evaluation well is the concrete practice of this important research content and has achieved remarkable results. The implementation of WE-B5, WC-A1S1, WG-B21 and WG-B22 Wells promoted effectively the implementation process of ODP in Weizhou E, Weizhou C and Weizhou G oilfields. The implementation of WE-B1S1, WF-A17, WF-N-A8P1, WB-A4, A5, WD-A9, WH-B29S1 and WH-B6S1 promoted effectively the adjustment process of Weizhou E oilfield, Weizhou F oilfield, Weizhou B oilfield, Weizhou D oilfield and Weizhou H oilfield.

Although the “Rapid evaluation mode” development evaluation wells are used for rapid evaluation of potential targets beyond the scope of production platform coverage, they can also promote the implementation of ODP in the early stage of oil and gas field development and comprehensive adjustments in the middle and late stages of oil and gas field development. The proved geological reserves of 12 “rapid evaluation mode” development evaluation wells are over 10 million cubic meters, accounting for 30%, which plays an important role in promoting the development and adjustment of oil and gas fields. The successful drilling of WH-8 and WI-1D Wells have realized the continuous oil-bearing situation from Weizhou H oilfield to Weizhou J oilfield. The successful drilling of Well WH-8 promoted strongly the erection of the WH-W platform and the implementation of ODP in the Weizhou H–S oilfield.The successful drilling of Well WI-1d promoted the implementation of ODP in Weizhou I oilfield and WH-4 well area. The implementation of wells WB-4d, WD-10d, WE-12-12d, and WE-12N-1 successfully promoted the follow-up internal adjustments in the Weizhou B, Weizhou D and Weizhou E oil fields. The development evaluation wells of “Concurrent exploration mode of rolling exploration well” are mainly aimed at potential targets that are far away from the production platform or with high accumulation risk. By means of concurrent exploration mode of rolling exploration well, the oil and gas content is determined to reduce drilling costs and avoid investment risks. The proven geological reserves of two wells are nearly 1 million cubic meters, accounting for 2%. Although compared with the former three drilling modes, this mode has the disadvantages of fewer drilled wells, low drilling success rate and small scale of discovered reserves. However, this pattern is indispensable during development evaluation well pattern, because it can imply the accumulation risk relatively large blocks through the smallest drilling cost. Once the evaluation is successful, it will effectively promote the development of surrounding areas.

Typical application case analysis

The G oilfield in Weixinan Sag is a producing oilfield. Many wells encountered oil layers in the third member of Weizhou formation and the first member of Liushagang formation, which proved that the oil and gas migration and accumulation conditions are good and the conditions for accumulation are superior. Block 1 and block 5 are searched and selected for research.

The fault zone research of Blocks 1 and 5 is carried out. Blocks 1 and 5 have the same migration fault, which extends downward to the second member of Liushagang formation and is a third-grade dominant migration fault. The main control faults of the structural traps are both grade 3 faults in the late stage of rifting. The result is a fourth-level shielding fault, which forms a fourth-level fault shielding and a third-level fault migration dominant fault controlling reservoir mode, which is a listric fault system of planar "echelon combination" and section "fault step combination". The main control fault of block 1 has a dip angle of 35.5–45.0º, inclined to SE, with a fault distance of 30-40 m. The upper $W_3$0 and second upper oil group of $W_3$0 have an excellent combination of faults, which are mode of reverse fault shielding and forward fault migration. Towards the deep strata, the combination mode of shielding faults in the lower $W_3$0 and W_3Iupper oil groups is both reverse fault and forward fault, and the risk of accumulation is high (Table.3). Block 5's main control fault has a fault dip angle of 30.8–39.8º, a tendency of SE, and a fault distance of 20-60 m. The third member of Weizhou formation has an excellent combination of faults, all of which are reverse fault shielding and forward fault migration, which is good reservoir forming conditions (Table.3). Block 1 is fault-controlled trap, and its object formation upper $W_3$0 and second upper oil group of $W_3$0 traps are superior. The trap type is broken nose trap, with gently stratigraphic dip of around 10º, and characterized by high amplitude response. The trap type of the lower $W_3$0 and upper W_3I oil group in the deep formation are fault block trap dominated by three faults, with steepening stratigraphic dip, weaker amplitude attribute, so the trap morphological become deviation(Table.3).The trap type of the third member of Weizhou formation in Block 5 is broken nose trap with gentle strata and its dip angle is less than 15º. Except for the lower W_3II oil formation, the trap generally shows strong amplitude response and has good trap shape(Table.3).

The analysis of fault lateral and vertical sealability shows that $W_3$0 and the second upper oil groups of $W_3$0 of block 1are both located in the oil and gas area, and the lateral and vertical sealability of the fault is predicted good(Figs. 14 and 15). The possibility of accumulation is great. The lower $W_3$0 and upper W_3Ioil groups are

Potential block	Oil series	Trap type	Fault type	Formation dip angle º	Seismic amplitude	Fault dip angle º	Fault dip direction	Fault distance m	Fault combination
Block 1	$W_3 0_u$	Fault-nose	Reverse	11.3	Strong	45.0	SE	30	Reverse sealing fault and consequent migration fault
	$W_3 0_u^2$	Fault-nose	Reverse	10.3	Strong	35.5		40	Reverse sealing fault and consequent migration fault
	$W_3 0_d$	Fault-block	Consequent plus reverse	14.5	Strong				Bad sealing fault combination
	$W_3 I_u$	Fault-block	Consequent plus reverse	15.5	Less weak				Bad sealing fault combination
Block 5	$W_3 0_u$	Fault-nose	Reverse	13.0	Less strong	34.9	SE	60	Reverse sealing fault and consequent migration fault
	$W_3 0_d$	Fault-nose	Reverse	14.6	Less strong	31.7		50	Reverse sealing fault and consequent migration fault
	$W_3 I_u$	Fault-nose	Reverse	14.0	Less strong	39.8		50	Reverse sealing fault and consequent migration fault
	$W_3 I_d$	Fault-nose	Reverse	14.0	Less strong	30.8		40	Reverse sealing fault and consequent migration fault
	$W_3 II_d$	Fault-nose	Reverse	11.8	Less weak	33.7		20	Reverse sealing fault and consequent migration fault

Table 3. The statistics of target trap type of the Weizhou formation in Block 1 and Block 5 of the G oilfield.

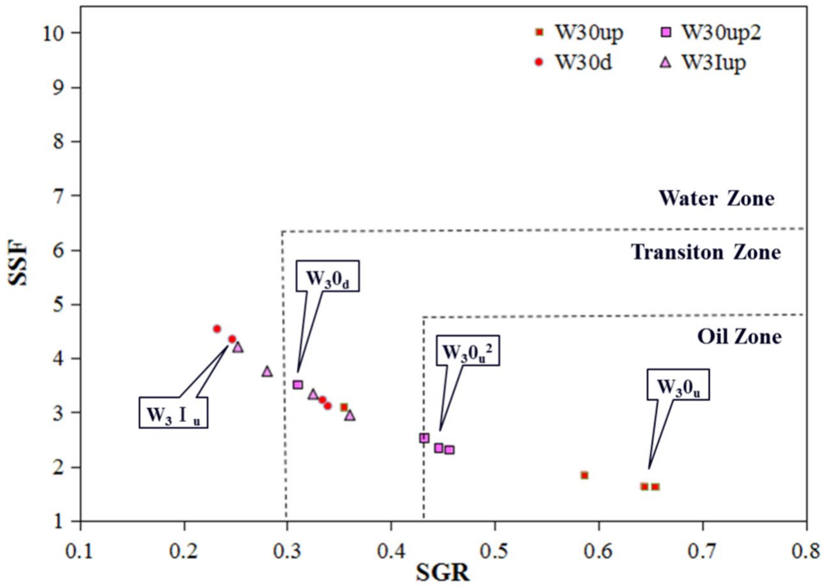


Figure 14. The SGR-SSF chart of the lateral fault sealing in potential block 1 of the G oilfield.

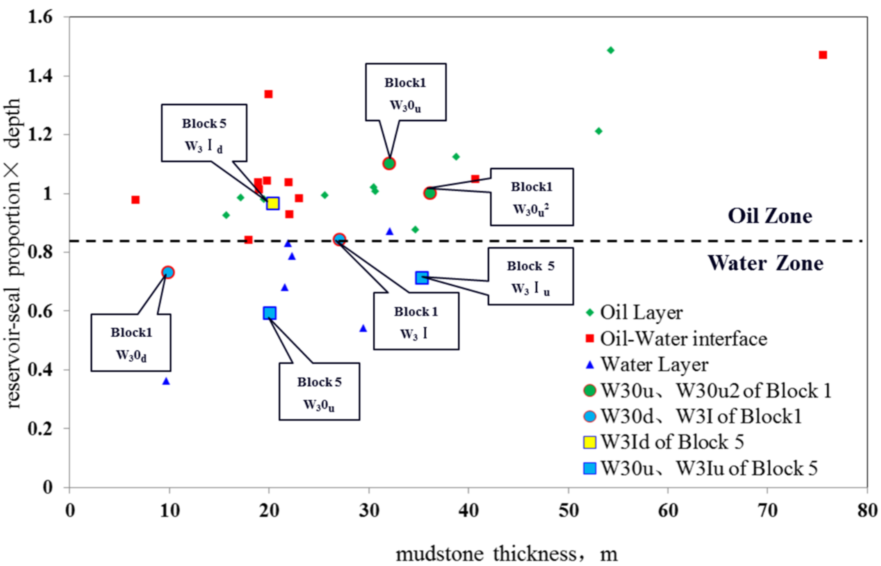


Figure 15. The vertical fault sealing and oil-bearing in potential block 1 and block 5 of the G oilfield.

located in the transition zone and water zone of the lateral fault sealing chart (Fig. 14), and in the water zone of the fault vertical sealing chart (Fig. 15). The fault sealing ability is poor and there is a certain risk of reservoir.

The upper W_3I and lower W_3Ioil groups of block 5 are located in the oil and gas area, with good fault lateral sealing ability (Fig. 16), the lower W_3I oil group is located in the oil and gas area with good vertical sealing ability. The upper W_3Ioil group is located in the water area with poor vertical sealing ability and a certain risk of reservoir(Fig. 16). The upper $W_3$0, lower $W_3$0, and upper W_3II oil groups are located in the transition zone and the water zone, and the fault lateral sealing ability and vertical sealing ability are poor, so there is a certain risk of accumulation. Comprehensive analysis suggests that the oil accumulation possibility of W_3I is high.

The quantitative analysis technology of fault sealing is used to predict the oil column height of each oil group in the third member of Weizhou section of the drilled block in the G oilfield. The relationship between the predicted oil column height and the actual drilled oil column height is consistent with the regularity of geological reservoirs. On this basis, quantitative prediction of the oil column heights carried out for the target layer with high accumulation probability of fault sealing analysis in block 1 and block 5, and the predicted oil column height is 15 ~ 33 m, and the corresponding oil and gas fill degree is 37.5% ~ 73.3% (Table.4). The results are applied to the prediction of potential resources. The potential resources of $W_3$0 and second oil groups of $W_3$0 in block 1

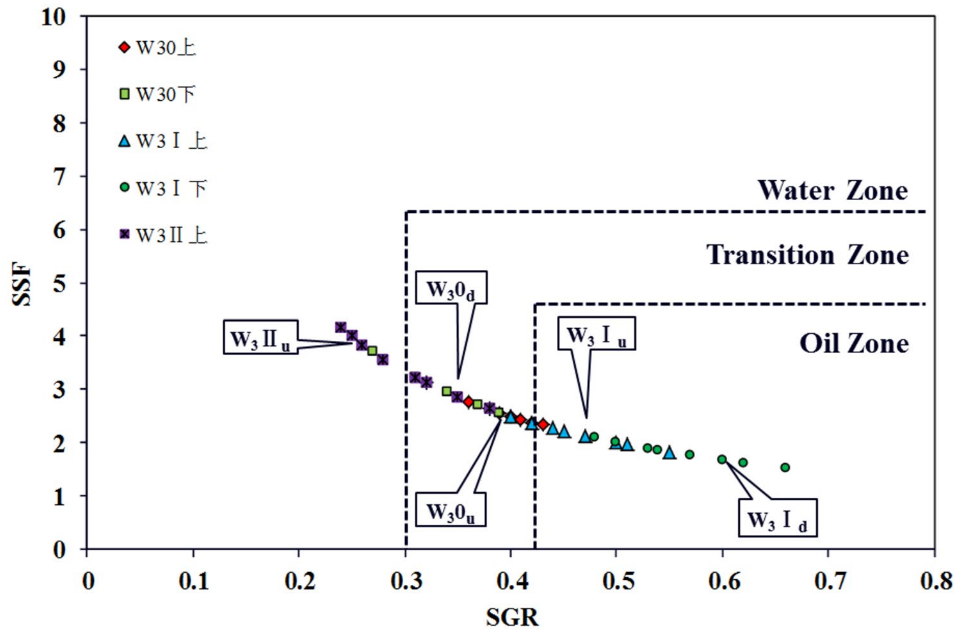


Figure 16. The SGR-SSF chart of the lateral fault sealing in potential block 5 of the G oilfield.

Potential block	Oil series	Trap type	Top depth of trap m	Low depth of trap m	Tectonic range m	Prediction of oil–water interface m	Prediction of oil column height m	Filling degree %
Block 1	W_30_u	Fault nose	1370	1410	40	1391	21	52.5
	$W_30_u^2$	Fault nose	1410	1450	40	1425	15	37.5
Block 5	W_3I_d	Fault nose	1655	1700	45	1688	33	73.5

Table 4. The oil column height and filling degree data of the potential Block 1 and Block 5 in the G oilfield.

are 13.3 million cubic meters and 7.3 million cubic meters, respectively, and the potential resources of W_3Ioil group in block 5 are 36.123 million cubic meters.

The development evaluation well WG-B21 well was deployed in block 1 and the development evaluation well WG-B22 was deployed in block 5. Among them, the second oil groups of upper $W_3$0 and upper $W_3$0 in WG-B21 well encountered oil layers of 9.5 m and 13.7 m respectively, Which is consistent with the results of the pre-drilling trap effectiveness analysis. The post-drilling calculation proved geological reserves of 12 million cubic meters and 6 million cubic meters, which are not much different from the pre-drilling potential resource prediction results. 17 m oil layer was drilled in lower W_3I oil group of WG-B22 Well , which is consistent with the effectiveness analysis result of the trap before drilling. The post-drilling calculation proved geological reserves of 32.39 million cubic meters, which is not much different from the prediction result of potential resources before drilling. The quantitative analysis technology of trap effectiveness has a better application effect in the third member of Weizhou formation in block 1 and block 5 of G oilfield, which can more accurately predict the reservoir-forming strata and predict the potential resource amount more accurately.

Conclusion

- The problems of "fragmented fault blocks and small resource scale" exist in the exploration and development of Weixinan Sag has the risk of "low reserve-production ratio and rapid production decline". The traditional evaluation mode has a long production cycle, lack of regional overall development between oilfields, and low storage-production conversion rate within the oilfield. Conventional exploration and development relay modes cannot meet the needs of reserves and production. Therefore, an offshore exploration and development integrated mode is proposed. The offshore exploration and development integrated technology conducts basic research on structural traps, such as "Fault zone research" and "Quantitative Research on the effectiveness of structural traps", carries out potential target search and evaluation, and conducts drilling through the development evaluation well mode.
- "The fault research" includes the study of fault research and the effectiveness of structural trap. fault research includes the study of the geometry, dynamics, kinematics characteristics of fault, and the division of fault system. The inner division of fault system is divided into the level 3 fault, the level 4 fault and the level 5 fault

by researching the dynamic, kinematic and geometric characteristics of the main and branch faults. The effectiveness of structural trap include analogical studies on the structural characteristics of traps, quantitative studies on fault lateral sealability, fault vertical sealability, and prediction technology of oil column height. The SGR-SSF discriminant chart of fault lateral quantitative analysis chart and the vertical fault sealing quantitative analysis chart of No.2 fault zone, Weixinan Sag is established. Oil and gas content and the quantitative prediction technology of oil column height were established, which improves the prediction accuracy of the fault sealing performance and potential resources.

- Comprehensive the relationship of the law of oil and gas distribution,the differential fault system in the internal of the No. 2 fault zone, and the effectiveness research of traps, three aspects of fault-controlled reservoir laws and the dominant fault-controlled reservoir mode are obtained. The three aspects of fault-controlled reservoir laws: The best migration fault is the third-level fault, the most important sealability fault is the fourth-level faults, and the oil and gas in the No. 2 fault zone are concentrated in the two main echelon faults, the branch faults of the main fault, the secondary faults of the main fault and the main echelon fault. The four dominant faults controlling reservoirs: The mode of fourth-level blocking faults and third-level migration branching faults, the mode of third-level blocking branch faults and third-level migration fault, the mode of fourth-level blocking fault and the third-level migration fault, the mode of third-level blocking fault and third-level migration fault. These modes guide significantly in the process of potential target search.
- The application of the offshore exploration and development integrated mode in Weixinan Sag has achieved good results. 45 development evaluation wells have been implemented, 37 wells have been successfully drilled, and the drilling success rate has reached 82%, which has promoted the implementation of 5 oil and gas ODP and adjustments process of 8 oilfields.

Data availability

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

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Chen Kui, Zhu Yushuang and He Shenglin are responsible for the design of article ideas. Chen Kui, Zhu Shaopeng and Yuan Chao are responsible for the design and implementation of article experiments. All authors are responsible for the writing and revision of articles.

Competing interests
The authors declare no competing interests.

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