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Control of facies/potential on hydrocarbon accumulation: a geological model for lacustrine rift basins

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Abstract: The formation and distribution of hydrocarbon accumulations are jointly controlled by "stratigraphic facies" and "fluid potential", which can be abbreviated in "control of facies/potential on hydrocarbon accumulation". Facies and potential control the time-space distribution of hydrocarbon accumulation macroscopically and the petroliferous characteristics of hydrocarbon accumulation microscopically. Tectonic facies and sedimentary facies control the time-space distribution. Lithofacies and petrophysical facies control the petroliferous characteristics. Favorable facies and high porosity and permeability control hydrocarbon accumulation in the lacustrine rift basins in China. Fluid potential is represented by the work required, which comprises the work against gravity, pressure, interfacial energy and kinetic energy. Hydrocarbon migration and accumulation are controlled by the joint action of multiple driving forces, and are characterized by accumulation in the area of low potential. At the structural high, low geopotential energy caused by buoyancy control anticlinal reservoir. The formation of lithological oil pool is controlled by low interfacial energy caused by capillary force. Low compressive energy caused by overpressure and faulting activity control the formation of the faulted-block reservoir. Low geopotential energy of the basin margin caused by buoyancy control stratigraphic reservoir. The statistics of a large number of oil reservoirs show that favorable facies and low potential control hydrocarbon accumulation in the rift basin, where over 85% of the discovered hydrocarbon accumulations are distributed in the trap with favorable facies and low potentials. The case study showed that the prediction of favorable areas by application of the near source-favorable facies-low potential accumulation model correlated well with over 90% of the discovered oil pools' distribution of the middle section of the third member of the Shahejie Formation in the Dongying Depression, Bohai Bay Basin.

Key words: Jiyang Depression, subtle trap, facies controlling hydrocarbon accumulation, fluid potential, coupling of facies and potential

1 Introduction

The "petroleum system" concept proposed by Magoon and Dow (1994) provides an excellent means for the evaluation of petroleum potential in a sedimentary basin. A petroleum system is a natural system, in which the key elements are source and its related critical processes. Some Chinese geologists proposed similar concepts, such as composite oil-gas accumulation zone (Hu et al, 1986) and hydrocarbon accumulation system (Jin et al, 2003). All the essential geological elements encompassing source, reservoir and seal rocks and critical processes including hydrocarbon generation and expulsion, carrier and trap formation, and hydrocarbon migration and accumulation are considered in these concepts. Sedimentary rock is without doubt a key element for hydrocarbon generation, migration and accumulation with physical and chemical characteristics, which could be a good clue to demonstrate its environment at the time of formation (Teichert, 1958). Sedimentary rocks are porous with the pore space forming an intricately branching three-dimensional network for fluid flow. As oil and gas possess energy with respect to their position and environment, the potential at any given point of the fluid should be considered in hydrocarbon migration and accumulation (Hubbert, 1953). Whether hydrocarbon is accumulated or not in a trap is decided by its stratigraphic facies and fluid potential to a large degree, when the hydrocarbon source is sufficient.

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2 Concept and research significance

The formation and distribution of hydrocarbon accumulation is jointly controlled by "stratigraphic facies" and "fluid potential", which can be abbreviated as "control of facies and potential on hydrocarbon accumulation". Facies and fluid potential control the time-space distribution of hydrocarbon accumulation on the macroscopic scale and the petroliferous characteristics of hydrocarbon accumulation on the microscopic scale.

Exploration focus has shifted from structural plays to subtle plays in east China due to increasing exploration maturity (Jia and Chi, 2004; Yuan and Qiao, 2002). The traditional anticlinal or so-called "gravitational" theory is not sufficient to explain the hydrocarbon accumulation mechanism in subtle traps, like sand lenses in turbidity. Rift basins are well known as prolific hydrocarbon-bearing provinces worldwide (Morley, 1999). The Jiyang Depression is a typical group of Paleogene half-grabens in the Bohai Bay Basin, east China. New geological theories are urgently needed to find more reserves in subtle traps in rift basins of east China. In recent years, the subtle trap formation mechanism, distribution, dynamics and its related exploration techniques have been the focus of research. A series of geological theories and models have been proposed, such as the model of fault slopes controlling sand bodies, multiple transportation system, fault-fracture mesh petroleum plays, and control of facies/potential on hydrocarbon accumulation (Lin et al, 2000; Zhang et al, 2004; Li et al, 2003). The progress of understanding of subtle traps provides important guidance for worldwide research into rift basins (Li et al, 2002). The application of these advanced theories resulted in extraordinary achievements of petroleum exploration and development in the Shengli Oilfield Company, SINOPEC. More than 60% of reserves were found in subtle traps in recent years (Li, 2004). 882 exploration wells in searching for subtle traps were drilled from 1996 to 2003, and the success rate exceeded 75%. 107.2 billion barrels of oil and reserves were discovered from subtle reservoirs, accounting for one third of total reserves in the Jiyang Depression until the end of 2006.

3 Characteristics and models of control of facies on hydrocarbon accumulation

3.1 Concepts of facies

Facies is a Latin word meaning face, figure, appearance, aspect, look, condition (Teichert, 1958). Since Gressly (1838) proposed the concept of stratigraphic facies, probably no geological term has been used in a wider range of concepts than facies. Facies could be classified into four categories while considering the control of facies on hydrocarbon accumulation. Tectonic facies was first proposed by Stille (1924) and modified by Robertson (1994) and Hsu (1991). The principal uses of tectonic facies are in aiding systematic and objective analysis of orogenic belts, recognizing discrete tectonic settings and expressing a group of combinations of formation and structure with the similar deformation and displacement characteristics. Sedimentary facies is widely used in geological analysis to demonstrate the total sedimentation changes and the sedimentation formed in a specific condition and reflect a specific environment or process (Gressly, 1838). Lithofacies is used to describe the rock or rock combination formed in a specific sedimentary environment. Petrophysical facies is introduced for the infiltrating fluid characteristics of rock formed in a specific sedimentation environment, mainly including porosity and permeability (Xiong et al, 1994).

3.2 Tectonic facies and sedimentary facies controlling the time-space distribution of hydrocarbon accumulation

Jiyang Depression is a typical lacustrine rift basin. Rift architecture is controlled by fault geometry, which is affected by pre-existing fabrics (Morley, 1995). Each sag in the Jiyang Depression is characteristic of a half-graben as presented by Morley (1995). A half-graben is controlled by differential subsidence of basement and different activity of boundary faults. These boundary faults affected rift geometry and stepwise evolution of rift stratigraphy as well as sedimentary patterns (Lambiase and Bosworth, 1995), so that each sag can be divided into a northern steep slope zone (relatively close to the large boundary fault margin), sag zone (central part of the rift), central uplift zone and southern gentle slope zone (relatively close to the flexural margin) (Li, 2004). The differences of tectonic settings and tectonic situations between the four structural zones contributed to the difference of sedimentary environment and the development of sand bodies and controlled the distribution of oil and gas.

In the Paleogene rifting period of the Jiyang Depression, the northern boundary of the four sags was characterized by steep paleo-topography slope with high altitude, affected by paleo-basement fault planes. Paroxysmal and seasonal fluvial and alluvial fans, fan deltas, subaqueous fans were thus developed in the rifting stage close to sedimentary source. Gentle slopes were well developed in the south of four main sags in the Jiyang rift. They are characterized by persistent and low magnitude structural activity with numerous basinwards sub-faults developing from the early to the late Shahejie Formation depositional period. In the flexural margin towards the sag center, due to gentle and low magnitude paleo-topography, sediments in rifting periods on the southern gentle slope are characterized by lower energy, small grain-size and a distal sedimentary source. Braided deltas, fan deltas and beach-bars were well developed and laterally changed to abyssal and bathyal mudstone sediments or distal-basin turbidite in the sag center. In the syn-rifting period (especially the Es_3 and Es_4), the central part of sags were characterized by maximal burial depth, low and smooth paleo-topography, high bathymetric level and a euxinic sedimentary environment. These positions are basin depocenters and source rock centers where mainly abyssal lacustrine mudstone and shale were deposited. Turbidites were often deposited in deepwater settings.

The statistics of 797 oil and gas reservoirs of the four sags in the Jiyang Depression show that the number of reservoirs and reserves developed in different structural zones are different. Most reservoirs and reserves were found in the central uplift region, then fewer in the steep slope and sag belts and least in the gentle slope belt. Fig. 1 probably suggests that the central uplift and the northern steep slope zone are the most advantageous areas for the formation and distribution of oil reservoirs. Statistics of 797 oil and gas reservoirs of the major sedimentary facies in the Jiyang Depression show that the number of reservoirs and reserves developed in different sedimentary facies are also different. Fig. 2 indicates that most reservoirs are discovered in lacustrine turbidite fan facies, then fan delta, delta, beach bar and least in alluvial fan sedimentary facies.

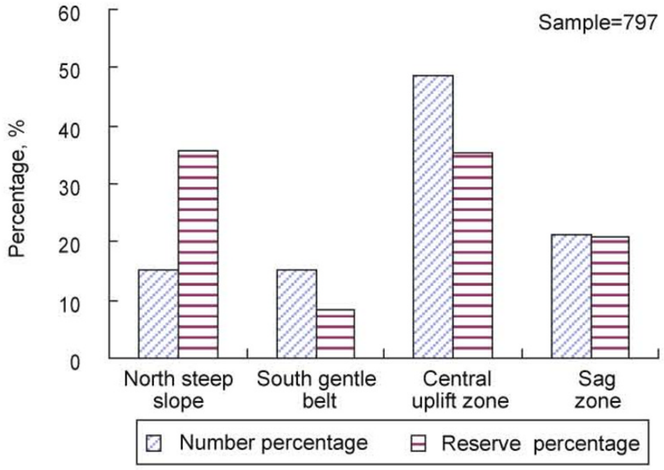

Fig. 1 Histogram shows the number percentage and reserve percentage of oil reservoirs in the four structural zones in the Jiyang Depression

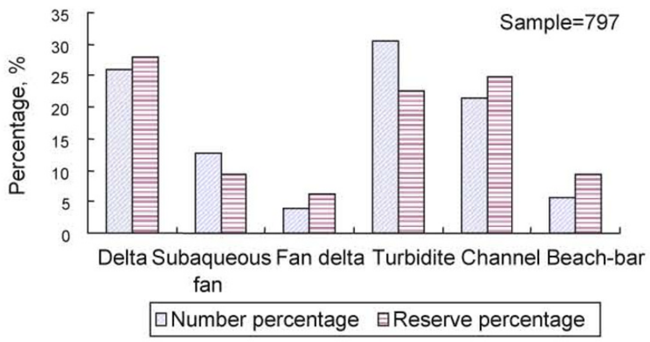

Fig. 2 Histogram shows the number percentage and reserve percentage of oil reservoirs in the sedimentary facies in the Jiyang Depression

3.3 Lithofacies and petrophysical facies controlling the petroliferous characteristics of hydrocarbon accumulation

The lithofacies of clastic reservoirs controlled the oil and gas accumulation and occurrence, with the original sedimentation affecting the physical properties of the reservoir. In ideal geological conditions, the rock with the highest granularity, best sorting, high structural and compositional maturity is the most favorable for hydrocarbon accumulation. But for poorly sorted rock, such as sandy gravel stone and muddy siltstone, the physical properties of reservoir are degraded because the pores between coarse grains are filled with fine grains. It could explain the phenomenon of development of low porosity and permeability reservoirs in gravel stone while high porosity and permeability reservoirs occur in fine sandstone or siltstone. In the Jiyang lacustrine sedimentary system, the ordinary rock types include gravel stone, pebbled sandstone, coarse sandstone, medium sandstone, fine sandstone, siltstone and argillaceous rock. The statistics of 533 oil and gas reservoirs of the four sags in the Jiyang Depression show that the number of reservoirs and reserves developed in different rocks vary. Fig. 3a probably suggests that the siltstone and fine sandstone are the most advantageous rocks for the formation and distribution of oil reservoirs. Fig. 3b shows that the average granularity of oil reservoir ordinarily varies from 0.03 to 0.5mm, which is the range between siltstone and medium sandstone.

Porosity and permeability are the most important physical properties controlling hydrocarbon accumulation in the rock pores. The statistics of 341 oil and gas reservoirs show that when porosity is below 10% or permeability is below 1md, it is difficult to discover hydrocarbon accumulation (Fig. 4(a) and (b)). The discovered hydrocarbon accumulations are

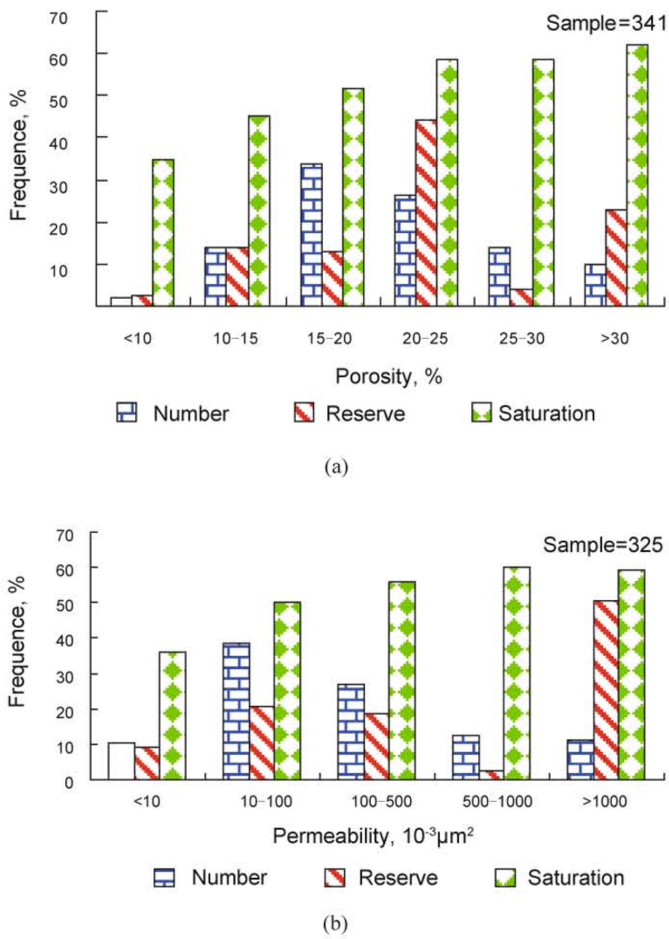

Fig. 3 Histogram shows the number percentage, reserve percentage and degree of saturation of oil reservoirs in rock with different porosities and permeabilities in the Jiyang Depression

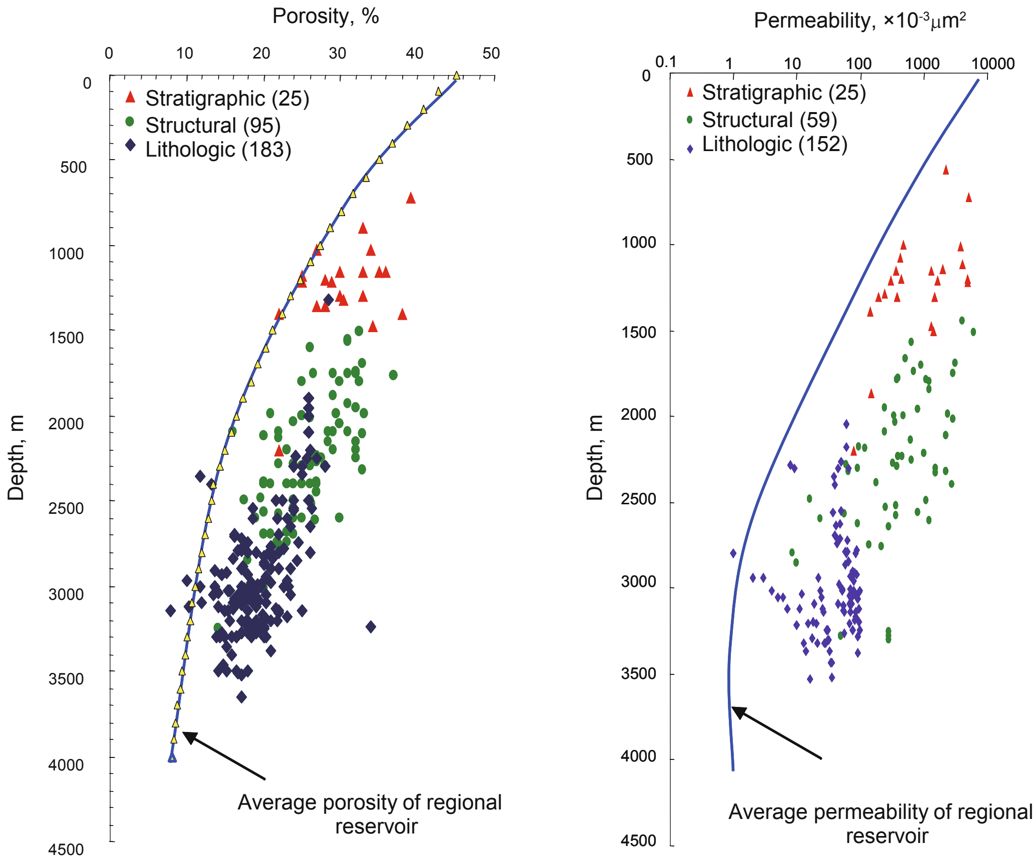

Fig. 4 Correlation of depth and porosity and permeability of oil reservoirs

mostly distributed in the reservoirs with porosity between 15% and 25%, and the permeability between 10md and 500md. The discovered hydrocarbon reserves are mostly distributed in the reservoirs with porosity more than 20% and the permeability more than 100md. The saturation of hydrocarbon accumulation increases with increasing porosity or permeability in the range between 45% and 65%. The statistics of hydrocarbon accumulation of the Dongying, Zhanhua and Huimin Depressions show that porosity and permeability vary with burial depth. Compared with the average porosity and permeability of ordinary regional reservoir beds, the porosity and permeability of oil reservoirs are higher, which suggests probably a threshold value of porosity and permeability (Fig. 4). The threshold porosity and permeability vary with burial depth. In the shallow strata, the value of threshold porosity may be 28% in the 1300m depth, but it would be 16% in the 2400m depth, 14% in the 2800m depth and 12% in the 3300m depth, even decreased to 10% in the 4000m depth in the Dongying Depression.

3.4 Models of control of facies on hydrocarbon accumulation

Favorable facies and high porosity and permeability control hydrocarbon accumulation in the lacustrine basins in China. Favorable facies means the most favorable rock for hydrocarbon accumulation, in which the ordinary granularity of rock ranges from 0.1 to 0.5mm and principal rocks are siltstone and fine sandstone. High porosity and permeability mean relatively high porosity and permeability, of which the threshold values decrease with burial depth. The statistics of all the oil reservoirs in the Jiyang Depression show that the oil reservoirs are controlled by the combination of favorable facies and high porosity and permeability. The model of favorable facies and high porosity and permeability controlling hydrocarbon accumulation is proposed and shown in Fig. 5. There are four regions in Fig. 5. The rock in region A is favorable facies and high porosity and permeability. The rock in region B is favorable facies and low porosity and permeability. The rock in region C is coarse-grain stone and low porosity and permeability. The rock in region D is fine sandstone and low porosity and permeability. 96 percentages of the rock of oil reservoirs in the Jiyang Depression are distributed in region A (Fig. 6).

4 Characteristics and models of control of potential on hydrocarbon accumulation

4.1 Concept of fluid potential and basic principle

Since the hydraulic theory of oil and gas accumulation was proposed from 1909 to 1930s, geologists have been aware of the importance of dynamics in the petroleum exploration. Hubbert (1953) and England et al (1987) defined the fluid potential by making use of the fundamental principles of a mechanical system. But the definitions of the two geologists have a small difference. In the definition of Hubbert, the fluid potential is referred to unit mass of oil and gas possessing energy at any point. England defined the fluid potential as the work necessary to transfer unit volume of fluid from reference conditions to the relevant conditions of interest. Despite the difference of the two definitions, the potential is a substitute term of energy or work and the oil and gas in subsurface conditions possess potential. When the potential of oil or gas in a specified point is not a local minimum, an unbalanced force will drive the fluid to move in the direction in which its potential decreases. The fundamental principles of potential controlling fluid movement is that oil and gas migrate from regions of higher energy levels to those of lower energy levels, and ultimately rest in positions where their potentials assume local minimum values.

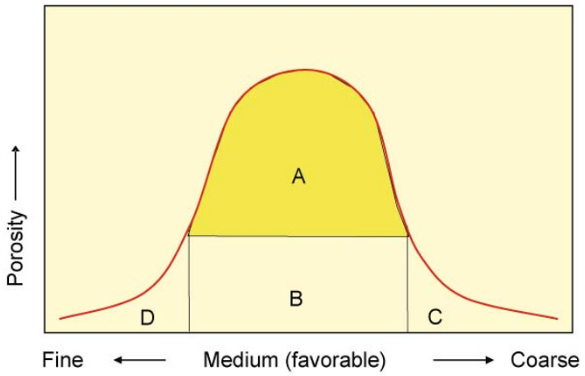

Fig. 5 Model of facies controlling hydrocarbon accumulation

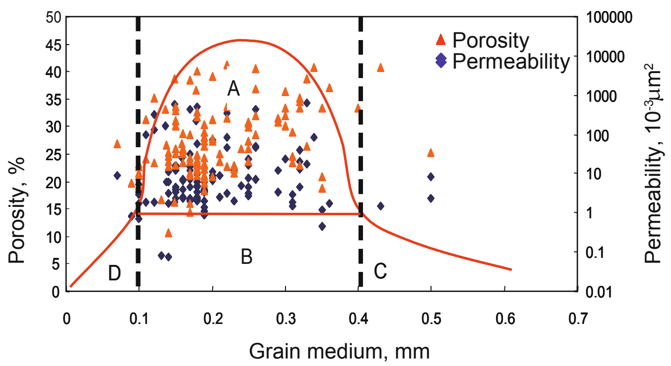

Fig. 6 Correlation of grain size, porosity and permeability of oil reservoirs in the Jiyang Rift

4.2 Type and category of potential

Fluid potential is generally composed of four parts in both of the formulas of Hubbert and England. The potential of a given fluid is represented by the work required, which comprise the work against gravity, pressure, interfacial energy and kinetic energy. For slow-velocity flow, kinetic energy can be neglected and the flow of oil and gas in the surface is a slow creeping motion. So, as for oil and gas, it usually includes only geopotential energy, interfacial energy and compressive energy and is shown in Equation 1.

$$\phi_o = \phi_Z + \phi_r + \phi_p + \phi_q \qquad (1)$$

The geopotential energy of subsurface fluid is related to a given point. It is related to structural contour (Z). If taking ground surface as the given point, the shallower the burial depth, the smaller the potential energy. The statement is shown in Equation 2.

$$\phi_z = -mg(Z - Z_0) \qquad (2)$$

Interfacial energy is the work required for subsurface multi-phase fluid with respect to rock. It is related to multi-phase fluid contact angle (θ), pore throat diameter of rock media (r_1 and r_2) and fluid boundary tension (σ).The statement is shown in Equation 3.

$$\phi_r = 2\sigma \cos\theta\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \qquad (3)$$

Compressive energy is the potential of subsurface fluid taken from the pressure imposed on itself. It is positively correlated with pressure (P). The statement is shown in Equation 4.

$$\phi_P = \int_1^P \frac{\mathrm{d}P}{\rho(P)} \qquad (4)$$

Kinetic energy is the potential of fluid taken from subsurface water flowing. It is related to the square of the water flow velocity (q). The statement is shown in Equation 5.

$$\phi_q = m\frac{q^2}{2} \qquad (5)$$

4.3 Characteristics of fluid potential controlling hydrocarbon accumulation

When the potential of a specific fluid in a region of underground is not a local minimum, an unbalanced force will act upon the fluid, driving it in the direction in which its potential decreases. Hence, oil and gas will accumulate in positions where their potentials assume local minimum values. Since the potential of oil and gas principally comprises of geopotential energy, interfacial energy and compressive energy, any change of these energies would lead to the change of the potential values. Since ϕ depends on the variables Z, P and r, ϕ will change when any of these parameters varies. Each change of these parameters is actually caused by force or variation of force. The variation of Z is fundamentally caused by gravity or buoyancy, and the variation of P is caused by fluid pressure (water-saturated pressure on the surface). Variation of r will consequently lead to the change of interfacial energy.

The application of fluid potential is generally to analyze the direction of hydrocarbon migration. Gravity, without doubt, plays an especially important role in hydrocarbon migration and accumulation. Oil and gas can move upwards from basin center to the edge of basin and from the deeper strata to shallower strata under the buoyancy caused by the difference of density between oil or gas and water. This movement trend would be destroyed when the migration pathway encountered an anticline where the potential of its structural high is lower than the value in the wing or edge of the anticline. In this condition, the difference in potential would keep the hydrocarbon stationary and accumulated in the anticline, forming an anticline oil reservoir. It may indicate that low geopotential energy controls hydrocarbon accumulation and mainly forms anticlinal hydrocarbon accumulations. The accumulation mechanism is hydrocarbon migrating along the dominating channel from bottom to top due to buoyancy and accumulating in the structural high with low geopotential energy (Fig. 7(a)).

Fluid pressure is one of the most important parts in fluid movement. Hubbert's (1953) general concepts about fluid pressure are still applicable to the shallow normal pressure rocks in most basins. Deep abnormal pressure occurs, however, as a worldwide phenomenon (Hunt, 1990). The abnormal pressure apparently occurs due to the formation of seals to produce large differences in fluid pressure across short intervals. The pressure differences at the boundaries of the compartment generally cannot be maintained when the surrounding seal is destroyed or hydrocarbon migrates accompanying surface water along conduits (Hao et al, 2005). Faults connecting source rock to reservoir rock are the major conduits for fluid migration. The pressure difference without doubt leads to the difference in potential. All the reservoirs related to the decompression of overpressure and oil seepage by faults are genetically related to low compressive energy. Some faulting reservoirs belong to the principal type of such reservoirs. The accumulation mechanism is hydrocarbon migrating and accumulating from the high pressure area along the decompression pathway to a low pressure area (Fig. 7(c)).

In the viewpoint of Hubbert (1953) and England et al (1987), the interfacial potential should be handled separately. The contribution of capillary pressure to fluid potential can be safely ignored in rocks with large pores such as sandstones, but it will be significant in clays or mudstone. Capillary effects will be negligible for most secondary migration because of the large pores found in the carrier beds. In contrast, since many source rocks are organic-rich clay or mudstone, primary migration will be influenced by capillary effects. Capillary effects are important in lithologic reservoirs surrounded by source rocks. Hydrocarbon accumulated in lithological traps with sand lens configurations in the Shahejie Formation turbidite in the Jiyang Depression, when it was surrounded by source rocks especially central sag turbidites involved in primary hydrocarbon migration (Pang et al, 2007; Chen et al, 2008). This primary migration model can be found in the permeable parts in Stainforth's (1990) conceptual model of primary migration systems. In his conceptual model, permeable material can comprise silty and sandy, or coarse carbonate, lenses with moderately good porosity and permeability. This system is isolated from the secondary migration system by the "impermeable" material. The capillary pressure of water against oil preferentially water-wet environment facilitates passage of oil globules from fine to coarse-textured rocks because of the difference between the radius of sandstone and that of mudstone. The difference in capillary pressure consequently leads to the local difference in potential. The accumulation mechanism is hydrocarbon migrating from a mudstone area with higher capillary potential and accumulating in a high porosity and permeability sandstone area with lower capillary potential under capillary pressure (Fig. 7(b)).

Since oil or gas migration occurs in a ground-water environment, the determination of the energy field for oil or

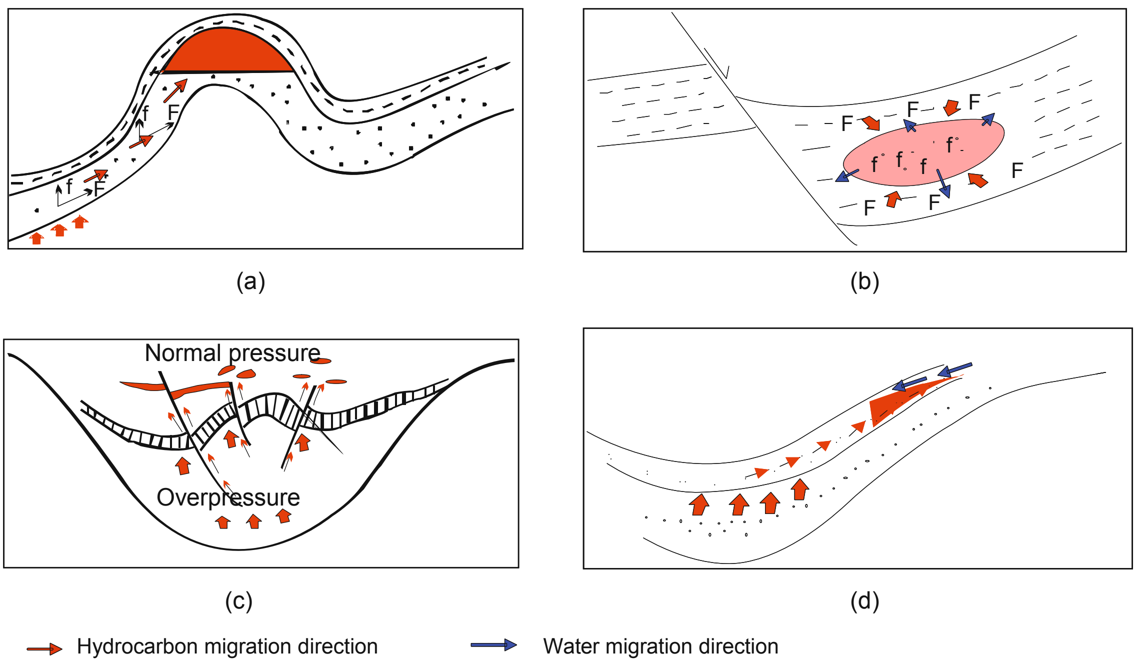

Fig. 7 Model of four potentials controlling hydrocarbon accumulation
(a) gravity (b) interfacial (capillary) energy (c) pressure (d) kinetic energy

gas can most effectively be done in terms of the energy of the ambient ground water. For the slow, creeping motion of underground flow, kinetic energy is so small in comparison with the geopotential energy and compressive energy that it may be neglected. For high-velocity flow, however, kinetic energy would also be an important factor controlling hydrocarbon accumulation although this case is rarely found. The formation of fluid trap is the case. When a fluid potential gradient exists in an aquifer, hydrodynamic force may bar the up-dip movement of any oil or gas in the aquifer, in which oil or gas will accumulate into a pool (Levorson, 1954). The accumulation mechanism is hydrocarbon migrating to the margins and shallows of the basin with lower kinetic energy from flowing water (Fig. 7(d)).

4.4 Geological model of fluid potential controlling hydrocarbon accumulation

Hydrocarbon migration and accumulation are controlled by the joint action of multiple driving forces, and are characterized by accumulation in areas of low potential. Different types of potential control different types of reservoirs. But there is a general trend of hydrocarbon distribution in the area of low potential. The comprehensive model of control of potential on hydrocarbon accumulation is composed of four parts (shown in Fig. 8), considering the construction and properties of rift basins in east China. Generally speaking, east China experienced complex tectonic movements represented by intense fault-block rifting and active magma movement during the Mesozoic and Cenozoic. Significant petroleum reserves in anticlinal, faulted, stratigraphic and lithological oil pools are distributed in the Jiyang Depression.

The anticlinal oil pools are generally distributed related to the central high of the Jiyang Depression under the uplifting of a plastic vaulted structure. In the structural high of the anticline, low geopotential energy caused by buoyancy controls anticlinal reservoirs and hydrocarbon accumulates on the top of the traps (reservoir type 1 in Fig. 9). The reservoirs in lithologic traps occur in three major depositional settings of the sag centers in the Jiyang Depression: proximal turbidite fan, pro-deltaic slumping turbidite and fluvial sandstone. These deposition centers have more than 10 sags, including the Niuzhuang, Lijin, Bonan and Boxin Sags. In the lithologic reservoir rocks, the formation of the lithological oil pools controlled by low interfacial energy is caused by capillary forces (reservoir type 2 in Fig. 9). The faulted oil pool is the most important type in the Jiyang rift basin, which is related to the syn-rift intensive rifting in the late Eocene and Oligocene. It is estimated that more than 1600 multiple faults developed in the depression and among them 14 base faults were formed in pre-rift dividing uplifts and depressions, 46 sub-faults were formed in the early Eocene of syn-rift dividing major structural elements. Seepages of oil and gas are often associated with faulting, which is commonly thought to be vertical channels, allowing overpressure to decrease greatly from the source rock and become normal pressure in the rocks of the faulted oil pool. Low compressive energy caused by overpressure and faulting activity controls the formation of the faulted block reservoir (reservoir type 3 in Fig. 9). Sedimentary discontinuity or stratigraphic discordance is the basic and key geological factor forming stratigraphic traps, although almost all of the stratigraphic traps are related to structural factors. Considering the relation between reservoirs and unconformity planes, there are three types of stratigraphic traps in the Jiyang Depression, including overlap traps above an unconformity plane,

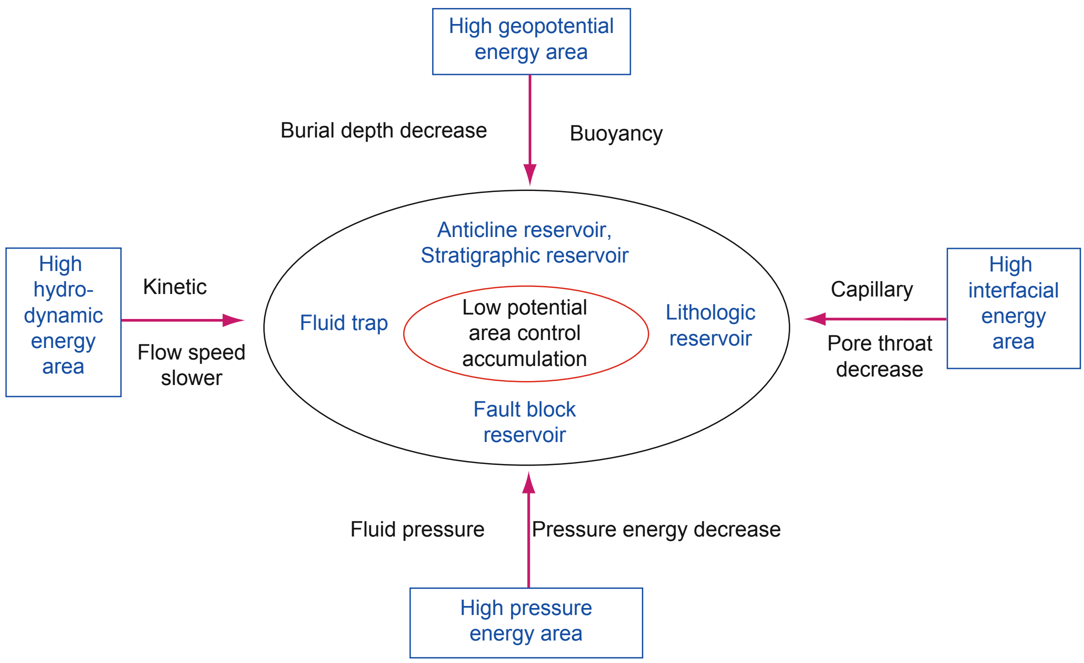

Fig. 8 Schematic model of control of potential on hydrocarbon accumulation

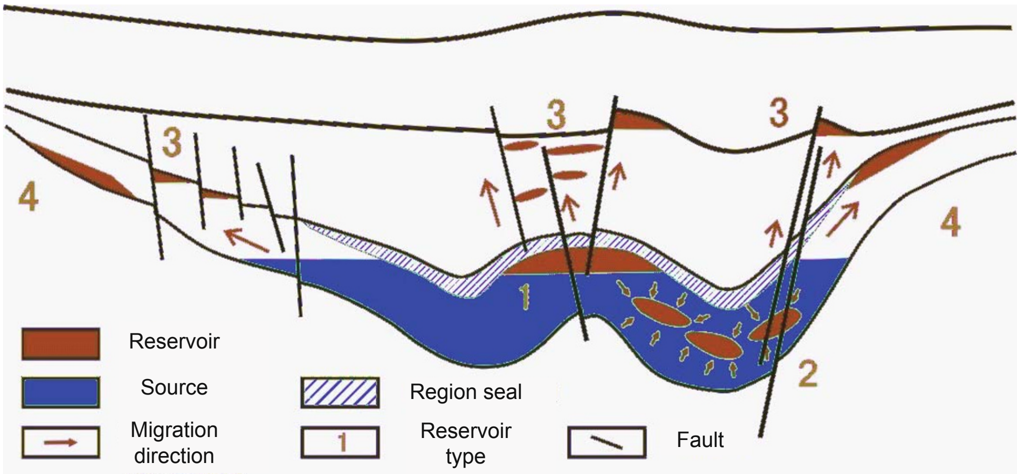

Fig. 9 Geological model of control of potential on hydrocarbon accumulation in the rift basin
Note that: 1. Low geopotential energy controls anticline reservoirs; 2. Low interfacial energy controls lithologic reservoirs; 3. Low compressive energy controls faulted block reservoirs; 4. Low geopotential energy and kinetic energy control stratigraphic reservoirs

truncated traps below unconformity planes and buried hill traps related to paleogeomorphology. Generally speaking, the distribution of the stratigraphic reservoirs is close to the edge of rift basin. In this case, low geopotential energy of the edge of rift basin caused by buoyancy controls the formation of stratigraphic reservoirs, and hydrocarbons accumulate on the top of the traps (reservoir type 4 in Fig. 9).

The complexity of structural and sedimentary evolution in the actual geological condition, however, will cause the complex distribution of different oil pools in the basin and complicated combination of different oil pools even in the same structural zone in the rift basin. The basic properties and models of low potential controlling hydrocarbon formation and accumulation will be a permanent rule.

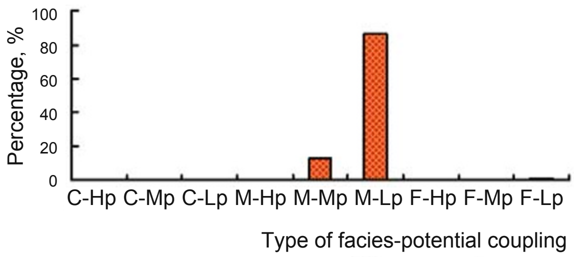

Fig. 10 Type of facies-potential coupling and oil pools distribution in the Jiyang Depression
Notes: C means rocks with coarse grain, M is medium grain, F is fine grain, Hp means trap with high potential, Mp is medium potential, Lp is low potential

5 Prediction method and application

5.1 Model of control

As mentioned above, favorable facies and low fluid potential control hydrocarbon accumulation. The distribution of hydrocarbon in the lacustrine basin is jointly controlled by facies and potential, and the coupling of favorable facies and low potential is most favorable to hydrocarbon accumulation. The statistics of over 300 oil pools in the Jiyang Depression show that more than 85% of discovered hydrocarbon accumulations are distributed in the traps with favorable facies and low potential (shown in Fig. 10). It may suggest that favorable facies and low potential controlling hydrocarbon accumulation is universal in the rift basin.

The coupling of facies and potential is the key factor for the formation of oil reservoirs. The traps with favorable facies and low potential, however, are not necessarily oil pools. Other conditions such as effective source rock kitchen, multiple transporting system, effective matching of hydrocarbon accumulation period and trap formation period are also important factors of hydrocarbon accumulation. Source rock, facies and potential are the most important factors, and the conditions of near source, favorable facies and low potential are most advantageous for the formation of hydrocarbon accumulation. Fig. 11 is the map for the near source-favorable facies-low potential accumulation model.

$$K_L = \frac{R_L}{R_L + R_f + R_p}, \quad K_f = \frac{R_f}{R_L + R_f + R_p}, \quad K_p = \frac{R_p}{R_L + R_f + R_p}$$

are the three axes in the map. R_L is the relative distance from source rock kitchen to reservoir, which is equal to the ratio of the distance from source to reservoir to the farthest distance from source to reservoir. R_f is the relative facies value. R_p is the relative potential value.

5.2 Prediction method

Searching for favorable areas is the major application of the model of control of facies and potential on hydrocarbon accumulation. The most important aspect is searching for the area with relative favorable facies and the area with relative low potential respectively, and consequently superimposing both favorable areas. The specific steps are as follows: The first step is collecting the geological data corresponding to structural facies, sedimentary facies, lithofacies and petrophysical facies and drawing the contour maps of favorable facies index to choose the most favorable areas. The

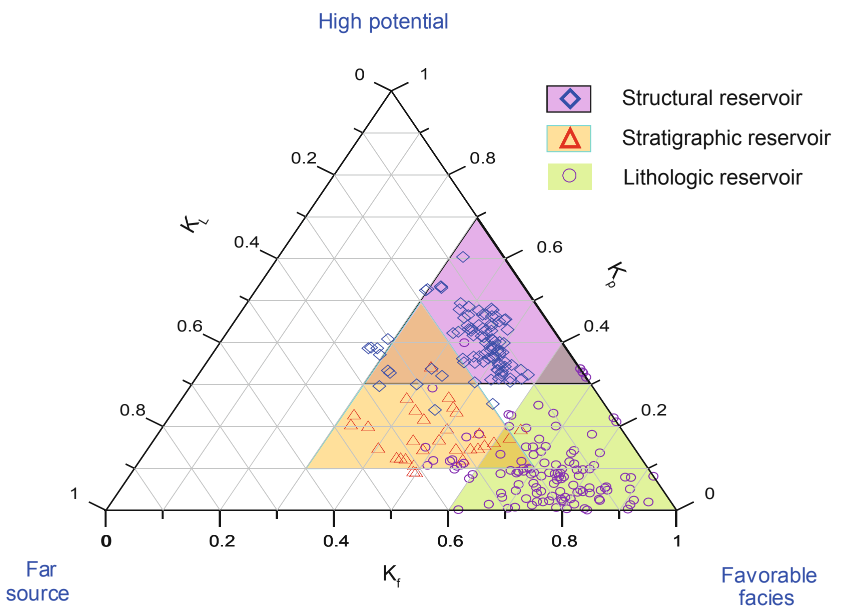

Fig. 11 Map for the near source-favorable facies-low potential accumulation model and hydrocarbon accumulation distribution in the Jiyang Depression

second step is collecting the geological data corresponding to present and paleo-potential, including low geopotential potential, low pressure potential and low interfacial potential and drawing the contour maps of low fluid potential index to choose the most favorable areas. The third step is superimposing both favorable areas and choosing and evaluating the favorable areas by the near source-favorable facies-low geopotential energy model to predict the favorable distribution areas for anticline reservoirs, by the near source-favorable facies-low compressive energy model to predict the favorable distribution areas for faulted reservoirs, by the near source-favorable facies-low interfacial energy model to predict the favorable distribution areas for lithological reservoirs.

5.3 Case study

The near source-favorable facies-low potential accumulation model is applied to predicting favorable areas by taking the middle section of the third member of the Shahejie Formation (Es_3^m) of the Paleogene in the Dongying Depression in the Bohai Bay Basin for example (shown in Fig. 12). On the basis of detailed reservoir evaluation, the favorable facies index (*Fi*) is outlined in the plane view. The favorable facies index (*Fi*) is expressed by the ratio of average value of porosity and permeability of the reservoir to the maximum value of porosity and permeability of the regional rocks. In Fig. 12, it is apparently shown that the favorable facies index (*Fi*) in most discovered oil pools is generally over 0.5, and with the increase of the value of the favorable facies index (*Fi*), the oil-bearing properties will probably be improved. Low geopotential areas, low compressive pressure areas and low interfacial energy areas are also predicted on the basis of a detailed analysis of the value of *z* (structural map), *P*, *r*, porosity and permeability. The contour maps of low potentials and the contour maps of the favorable facies index (*Fi*) are superimposed to predict the probable distribution areas of structural oil pools, lithological oil pools and stratigraphic oil pools. The analysis shows that

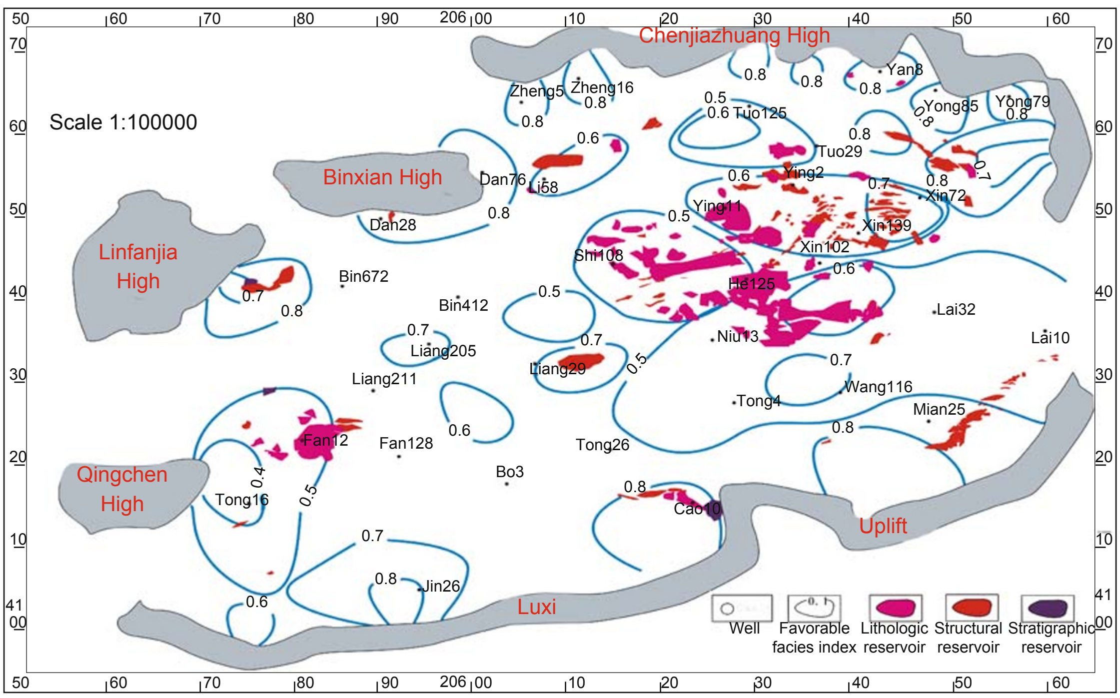

Fig. 12 Favorable facies index (*Fi*) and oil pools in the Es_3^m of the Paleogene in the Dongying Depression, Bohai Bay Basin

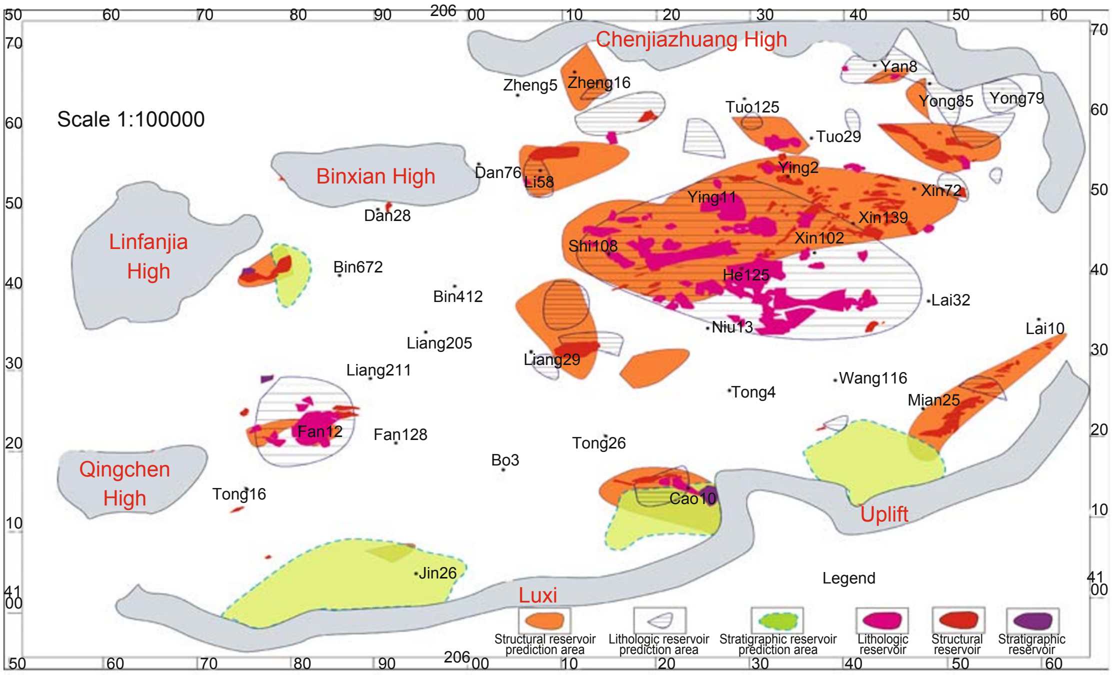

Fig. 13 Distribution of the predicted favorable areas of the middle section of the third member of the Shahejie Formation in the Dongying Depression, Bohai Bay Basin

the lithological oil pool probably is the dominant type in the Es_3^m and the structural oil pool is in the next place, which agrees with the actual distribution. The case study also shows that the correlation of the predicted favorable areas by application of the near source-favorable facies-low potential accumulation model and the discovered oil pools distribution is over 90% (Fig. 13).

6 Conclusions

(1) Facies can be classified into four categories while considering the control of facies on hydrocarbon accumulation. Tectonic facies and sedimentary facies control the time-space distribution of hydrocarbon accumulation. Lithofacies and petrophysical facies control the petroliferous characteristics of hydrocarbon accumulation. It is a basic model of favorable facies and high porosity and permeability that control hydrocarbon accumulation in lacustrine rift basins in China.

(2) The potential of a given fluid is represented by the work required, which comprises the work against gravity, pressure, interfacial energy and kinetic energy. Hydrocarbon migration and accumulation are controlled by the joint action of multiple driving forces, and are characterized by accumulation in the area of low potential. Different types of potentials control different types of reservoirs. But there is a general trend of hydrocarbon distribution in area of low potential.

(3) Favorable facies and low fluid potential controlling hydrocarbon accumulation appears universal in the rift basin, where more than 85% of the discovered hydrocarbon accumulations are distributed in the trap with favorable facies and low potentials.

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