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Lithologic Hydrocarbon Deposits in Rift Lake Basins in Eastern China

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Abstract The rift lake basins in the eastern China have abundant hydrocarbon resources of lithologic deposits, which resulted from excellent source rocks and multi-type sandbodies developed during strong rifting. Vertically, the lithologic deposits are mainly distributed in the lowstand, lacustrine invasion and early highstand systems of third-order sequence corresponding to a secondary tectonic episode of strong rifting, and laterally they are closely related to various fans and turbidite sandbodies controlled by syn-sedimentary faults. A variety of lithologic traps have been developed in the rift lake basins, and they generally have favorable conditions of source-reservoir-seal assemblage and hydrocarbon accumulation dynamics, indicating that there is a great exploration potential of lithologic deposits in the rift lake basins. In order to obtain satisfactory effects of lithologic deposit exploration, it is required to combine new theories with advanced technical methods.

Key words: Rift lake basin, dustpan-shaped rift, lithologic deposit, sequence stratigraphy, sedimentation model

1 Geologic Background

In the Paleogene, accompanied by the subduction of the Pacific plate towards the Eurasian plate, the earth's mantle in the eastern China upwelled and resulted in the rifting of the earth's crust and formation of numerous continental rift basins. During the strong subsiding of these rift basins, lacustrine argillaceous source rocks of relatively larger thickness and good quality generally deposited; therefore, most of the rift basins in eastern China are rich in oil and gas (Fig. 1). Through several decades of exploration, the rift lake basins in eastern China have become the most important bases of oil production in China, in which the Bohai Bay Basin is the highest in proven oil reserves and annual oil production among all rift lake basin in the country.

With continuous advance of petroleum exploration , it is more and more difficult to search for large-scale structural reservoirs in these oil-rich rift basins, and the percent of proven oil reserves that the lithologic deposit account for is higher and higher (Qiao and Wang. 2002). In the Jiyang depression in the Bohai Bay Basin, for example, the proven oil reserves from lithologic deposits as of the year 2002 is up to 13.54×10^8 t, accounting for 34.92% of the total proven reserves in the depression (Table 1). It is predicted that with further progress of exploration and advancing towards deep zones and sags, the percent of lithologic deposit proven reserves will increase continuously, and this type of reservoir will finally become the most important in the oil reserves composition.

Most rift basins in eastern China are asymmetrical, and their formation and evolution are controlled by the syn-sedimentary fault activities. On the two sides of a rift, the rifting rate along the main basin-controlling faults is obviously different. A steep slope belt can form on the side with a higher rifting rate, and a gentle slope on the other side, resulting in the geometry of "dustpan-shaped rift".

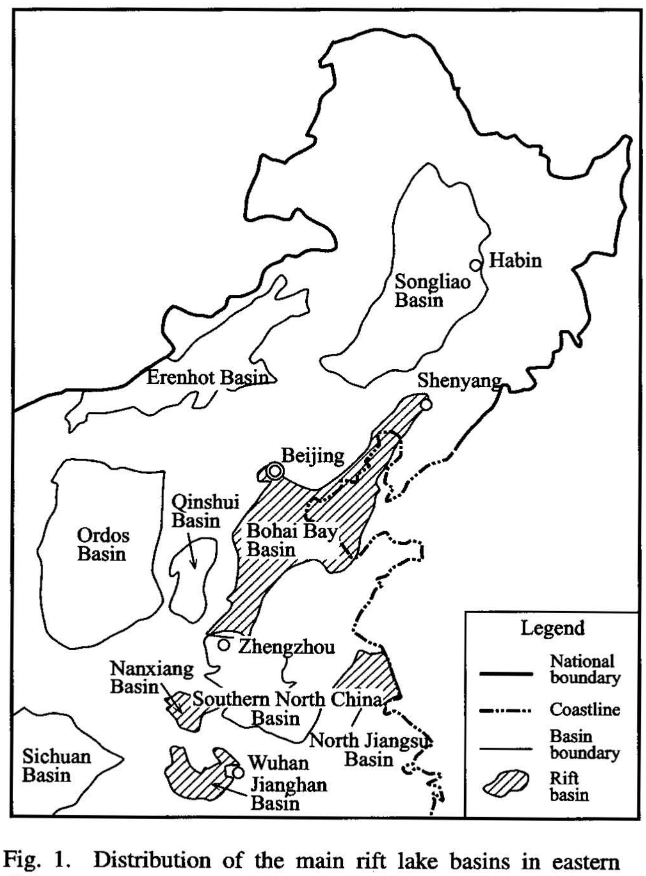


Fig. 1. Distribution of the main rift lake basins in eastern China.

Table 1 Proven oil reserves from lithologic deposit in four sags of the Jiyang depression and their total proven oil reserves as of the end of 2002

Sag	Proven reserves from lithologic deposit ($\times10^8$ t)	Total proven reserves ($\times10^8$ t)	Percentage of proven reserves from lithologic deposit (%)
Dongying	8.04	20.87	38.54
Zhanhua	5.12	13.52	37.88
Chezhen	0.17	1.37	12.73
Huimin	0.20	3.01	6.64
Total	13.54	38.77	34.92

During the evolution of the structure and sedimentation in a dustpan-shaped rift, a rifting episode can result in a complete rifting sequence, corresponding to a first-order sequence. The rifting rate of a rifting episode was generally lower in the early stage, higher in the middle stage and lower again in the late stage, based on which the rifting episode can be further divided into multiple sub-episode that have resulted in the second-order sedimentary sequences. In the early slower rifting stage, the best developed sedimentary systems were diluvial because the basin was small in area and abundant in provenance supply and could be in a state of over-compensation. In the middle stage, a lacustrine sedimentary system could be the best developed in a dustpan-shaped rift due to rifting acceleration of rifting, continuous basin enlargement, water deepening and an under-compensation state. In the late stage, the lake basin could be filled up and shrunk and then an alluvial system could be the best developed, because the rifting was slowing down, the sedimentation rate was gradually exceeding the growth rate of accommodation space and the basin was again in a state of over-compensation (Fig. 2).

In the severely subsiding second-order sequences, the excellent lacustrine source rocks and numerous types of reservoir sandbody are well developed and very favorable for the formation of lithologic deposits. The variation of factors such as climate has resulted in fluctuating of lake level, which, together with tectonic subsidence, has a control on the change of deposition base level. As the sedimentation response, there is an alternation of multiple sandstone and mudstone vertically, and multiple reciprocation sedimentary facies migration towards the basin and land respectively, forming a series of third-order sequences.

The sedimentary facies association of a dustpan-shaped rift is not only controlled by the rifting episode, but also related to the overall structural framework in the basin. In the different structure-sedimentation zones, the patterns of facies association and evolution are obviously different. On the steep slope, with a high gradient and rapid facies changes, a sedimentary system composed of alluvial fan (land), fan delta (transition zone), subaqueous fan (shallow and half-deep lake) and turbidite fan (deep lake) may be developed, and on the gentle slope, a sedimentary system composed of river (land), delta (transition zone) and shallow lake is the best developed. For the depression, the best developed sedimentary system may be turbidite fan (half-deep lake and deep lake) (Table 2).

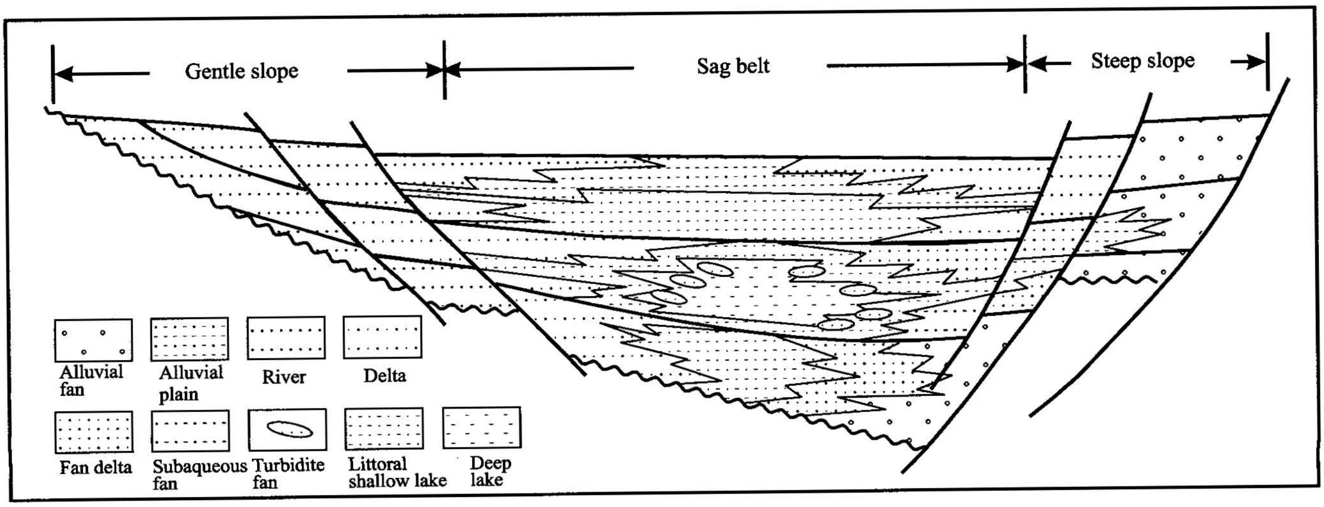


Fig. 2. Structural sequences and sedimentary characteristics of a dustpan-shaped rift.

Table 2 Sedimentary facies associations of different types of sequences in dustpan-shaped rifts

Sequence type	System domain	Sedimentary system		
		Steep slope	Depression	Gentle slope
Alluvial	Highstand	Denudation, river	River, alluvial plain	Denudation, river, alluvial plain
	Lacustrine invasion	River, alluvial plain	Shallow lake, delta	River, alluvial plain
	Lowstand	Alluvial fan, river	River	River
Lacustrine	Highstand	Alluvial fan, fan delta	Delta, shallow lake	River, delta
	Lacustrine invasion	Alluvial fan, fan delta, subaqueous fan	Turbidite fan, deep lake	Delta, shallow lake
	Lowstand	Alluvial fan, fan delta	Turbidite fan, half deep lake	River, delta
Diluvial	Highstand	Denudation, alluvial fan	Fan delta, coastal lake	River
	Lacustrine invasion	Alluvial fan	Fan delta, shallow lake	River
	Lowstand	Denudation, alluvial fan	Fan delta, coastal shallow lake	River

2 Main Types of Lithologic Reservoir in the Rift Lake Basins

The common lithologic deposits in the rift lake basins in eastern China can be divided into two types and ten sub-types (Fig. 3). Firstly, they are divided into two types in terms of their lithologic categories, i.e. the normal lithologic reservoir (sandstone or conglomerate) and the special lithologic with the normal sandstone and conglomerate reservoirs predominant. For the normal reservoir, six sub-types can be divided according to the factors such as trap shape, lithologic variation and structural relation. For the special lithologic reservoir, four sub-types are divided according to their lithologic types.

3 Distribution of Lithologic Deposits in the Rift Lake Basins

3.1 Vertical distribution of lithologic deposits controlled by sedimentary sequence evolution

During the lowstand stage of lacustrine third-order sequences, coarse grained sediments with a strong progradation were the best developed. In the sags of large and deep rift basins and in the downthrow blocks of sag-controlling faults, subaqueous fans or turbidite fans could be developed. They are easy to form lithologic reservoirs for being covered by the fine-grained sediments during lacustrine invasion. During the lacustrine invasion, the water was increasingly deepened, generally resulting in the deposition of shallow lake beaches and deep-water turbidite fans, together with the development of source rocks and seals, which was extremely favorable for the occurrence of lenticular lithologic deposits. During the early highstand stage, the delta front turbidite sandbodies with a progradation were also easy to form lenticular lithologic traps. During the late highstand stage, there occurred a strong progradation of fan deltas or normal deltas toward the basins, and sand bodies were unusually developed. These factors, together with the poor development of source rocks, have resulted in more difficulties of forming traps and lithologic reservoirs.

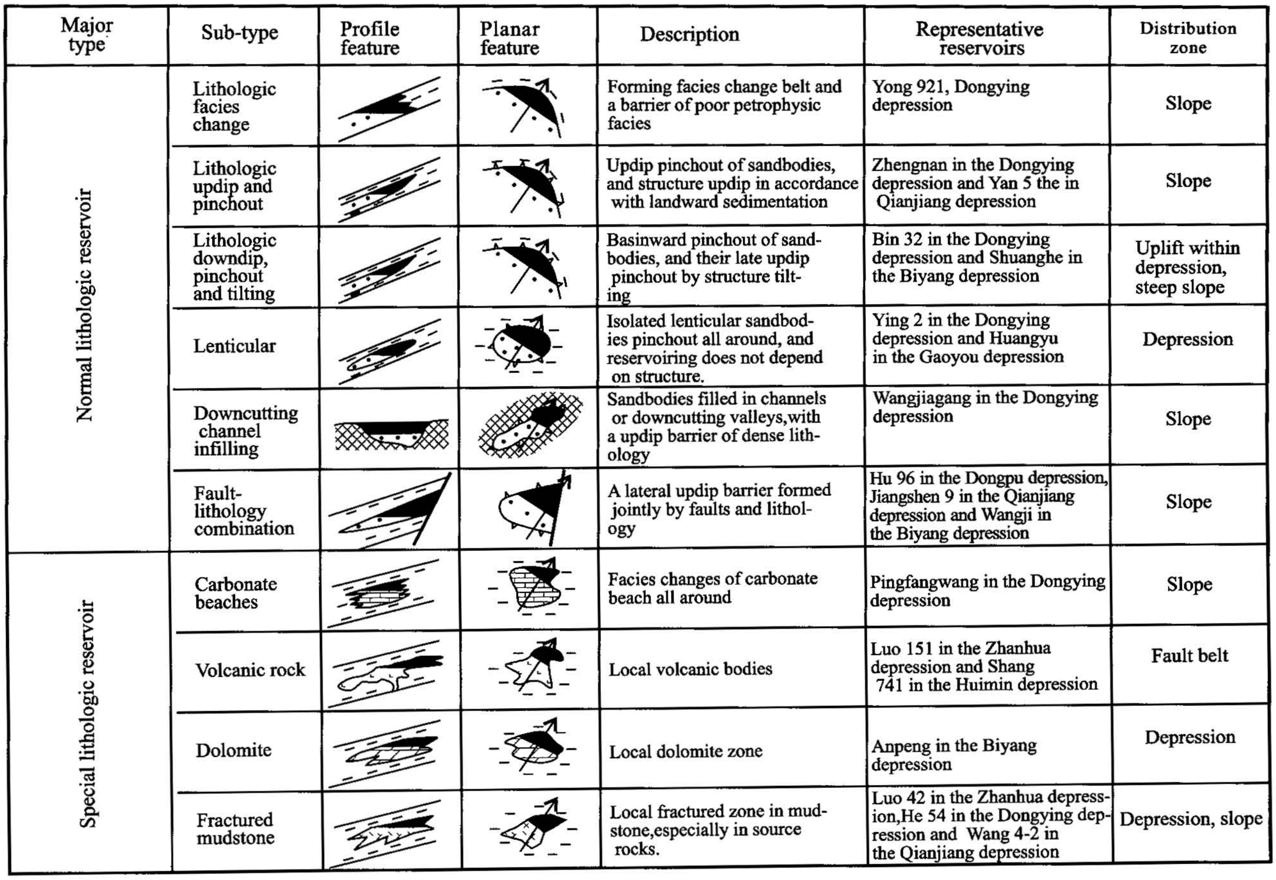
In the lacustrine third-order sequences, the lithologic deposits can mainly form in the fan bodies, turbidite sandbodies and beach sandstone deposited during the lowstand stage, lacustrine invasion and early highstand stage. These sediments were covered by or alternated with fine-grained source rocks, resulting in an excellent source-reservoir-caprock assemblage.

3.2 Lateral distribution of lithologic deposits controed by tectono-sedimentary features

Generally, fans are developed on the step slope of a dustpan-shaped rift lake basin, and near-coast subaqueous fans and turbidite fans usually deposit in the downthrow block of second-bench faults. They are all mainly controlled by paleo-provenence and paleo-topography. On the paleo-topography, the basinward position of scour channels usually correspond to the fan development area. On the downthrow blocks of various-order syn-sedimentary faults, the occurrence of topographic slope break can result in the unloading of coarse-grained sediments during their transportation to lakes, and local sandbodies may deposit in deeper water. This is very favorable for the formation of lithologic deposits.

On the gentle slope, there are generally channel-filled sandbodies, river deltas and off-coast turbidite fans, and the basinward position of channels usually correspond to the sandbody development area. For the syn-sedimentary faults, the landward side of downthrown block is favorable for the formation of lithologic reservoirs.

In a depression, syn-sedimentary faults can result in a slope break, and turbidite sandbodies are generally developed on the depressionward side of the slope break. In



Major type	Sub-type	Profile feature	Planar feature	Description	Representative reservoirs	Distribution zone
Normal lithologic reservoir	Lithologic facies change			Forming facies change belt and a barrier of poor petrophysic facies	Yong 921, Dongying depression	Slope
	Lithologic updip and pinchout			Updip pinchout of sandbodies, and structure updip in accordance with landward sedimentation	Zhengnan in the Dongying depression and Yan 5 the in Qianjiang depression	Slope
	Lithologic downdip, pinchout and tilting			Basinward pinchout of sandbodies, and their late updip pinchout by structure tilting	Bin 32 in the Dongying depression and Shuanghe in the Biyang depression	Uplift within depression, steep slope
	Lenticular			Isolated lenticular sandbodies pinchout all around, and reservoiring does not depend on structure.	Ying 2 in the Dongying depression and Huangyu in the Gaoyou depression	Depression
	Downcutting channel infilling			Sandbodies filled in channels or downcutting valleys,with a updip barrier of dense lithology	Wangjiagang in the Dongying depression	Slope
	Fault-lithology combination			A lateral updip barrier formed jointly by faults and lithology	Hu 96 in the Dongpu depression, Jiangshen 9 in the Qianjiang depression and Wangji in the Biyang depression	Slope
Special lithologic reservoir	Carbonate beaches			Facies changes of carbonate beach all around	Pingfangwang in the Dongying depression	Slope
	Volcanic rock			Local volcanic bodies	Luo 151 in the Zhanhua depression and Shang 741 in the Huimin depression	Fault belt
	Dolomite			Local dolomite zone	Anpeng in the Biyang depression	Depression
	Fractured mudstone			Local fractured zone in mudstone,especially in source rocks.	Luo 42 in the Zhanhua depression,He 54 in the Dongying depression and Wang 4-2 in the Qianjiang depression	Depression, slope

Fig. 3. Main lithologic deposit types in the rift lake basins in eastern China.

a large rift lake basin (such as the Dongying Depression), the depression zone is controlled by axial water flow, and a large system of delta-slumping turbidite fan may deposit. For the actively area of fixed water systems, lithologic deposits are well developed.

4 Hydrocarbon Accumulation Condition Analysis of Lithologic Deposits

4.1 Source-reservoir-seal assemblage

For lithologic deposits in rift lake basins, the reservoir is porous rocks in various facies, the source rock is mudstone in deep lake and half-deep lake facies, and the seal is generally fine-grained sediment associated with the lithologic reservoir.

Vertically, sandbodies developed during the lowstand stage, lacustrine invasion and early highstand stage are easy to be covered by deep-water mudstone facies, and have a better condition of source-reservoir-caprock assemblage. Laterally, it is more difficult for the onshore alluvial fans and river facies sandbodies to form lithologic deposits, and the structural condition is generally needed. For the turbidite fan and subaqueous fan near the depression, lithologic deposits are easily developed due to an excellent combination with source rocks. The sandbodies of transition-facies delta and fan delta are between the two cases mentioned above in the formation of lithologic deposit. In the downthrow block of a syn-sedimentary fault, water may deepen greatly, and fans are often developed, resulting in an excellent condition of forming lithologic deposits because these fans are good in petrophysical property and are surrounded by deep-water facies mudstone (Table 3).

4.2 Driving Force for Hydrocarbon accumulation

Lithologic deposit bodies are usually surrounded by source rocks. After hydrocarbon generation in the source rock, an abnormal high pressure can occur under the action of overlying sediment compaction and hydrothermal pressurization, resulting in a residual pressure difference between the source and the reservoir. This is the driving force for hydrocarbon accumulation in lithologic deposit (Wang et al., 2000; Xie et al., 2003). The main resistance against oil and gas during their migration to lithologic deposit bodies comes mainly from the pore capillary pressure. A superpressure helps to pore preservation in reservoir sandbodies, and this may reduce the resistance against oil and gas during migration and be favorable for

Table 3 Hydrocarbon accumulation conditions of various sandbody lithologic deposits in rift lake basins in eastern China

Sandbody type	Environment	Reservoir	Source rock	Seal	Lithologic trap type	Accumulation condition
Alluvial fan	Onshore	Better	Poor	Poor	Facies change, combination	Poorer
River	Onshore	Good	Poor	Poor	Combination	Poor
Fan delta	Transition	Better	Poorer	Poorer	Facies change, combination	Better
Delta	Transition	Good	Poorer	Better	Updip pinchout, down dip pinchout tilting, Facies change, combination	Better
Near-coast subaqueous fan	Half-deep lake	Poorer	Better	Good	Lenticular, downdip pinchout tilting, combination	Good
Sand bank	Shallow lake	Good	Better	Better	Lenticular	Good
Turbidite	Half deep lake and deep lake	Better	Good	Good	Lenticular trap, updip pinchout, downdip pinchout tilting	Good

hydrocarbon accumulation of lithologic deposits. In rift basins, the greater the abnormal pressure, the stronger the driving force for hydrocarbon accumulation, and the better the accumulation condition of lithologic deposit. For multiple isolated sandbodies simultaneously surrounded by source rock, the better the reservoir properties, the easier the hydrocarbon accumulation in lithologic deposit.

5 Theories and Techniques of Lithologic Deposit Exploration

It is much more difficult to evaluate lithologic deposits than structural deposits, and lithologic deposits are called "subtle traps". The exploration of these deposits can be successful only on a basis of higher exploration level and abundant geological data and by applying new geological theories and technical systems. A set of systematic geology theories and exploration technique systems has been established for lithologic deposits in rift basins in eastern China in several decades of exploration.

There are three research levels of lithologic deposits exploration. The first is to study sequence stratigraphy and sedimentary system, and its purposes are to fully understand sedimentary facies distribution of isochronous stratigraphic units and to determine favorable intervals and zones of lithologic deposit development. The second level is to predict sandbodies, with its purpose to seek spatial distribution of lithologic traps. The third level is a prediction of hydrocarbon potential, and its purpose is to determine whether oil and gas exist in the traps. The corresponding geologic theories and exploration technique systems have been established for each research level (Table 4).

In the sedimentary system prediction, researcers have successfully applied sequence stratigraphy derived from passive continental margin to the rift lake basins. They have made a deep discussion about sequence mode, sequence control, and process mode in the rift lake basins, resulting in a basic understanding of the sedimentary models in these basins (Zhang and Ji, 1996; Liu and Wang, 1996; Feng et al., 2000; Cao et al., 2002; Lin et al., 2002; Zheng, 2002). In addition, a study of high-resolution sequence stratigraphy has been made, isochronous stratigraphic units have been divided in detail, and the refined sedimentary facies have been mapped, in order to meet the requirement of exploration accuracy. To a certain extent, these works have enriched the theories of sequence stratigraphy and sedimentology.

The geological theories of sandbody distribution are based on an analysis of sandbody origin. The sandbody distribution in rift lake basins is controlled mainly by provenance, paleo-topography and syn-sedimentary faults. The sandbody development near provenance depends on the basement paleo-topography, which has resulted in a concept of paleo-topography-controlled sandbody for the Jiyang depression. From this concept, a sandbody prediction model that a scour channel is matched with a fan has been established, by which the sandbody can be indirectly predicted from determining the channel position on paleo-topography. According to the theory of slope break-lowstand fan (Jiang et al., 2002), syn-sedimentary faults have a control on the distribution of sandbodies. There may occur significant topographic slope breaks and abrupt changes of water depth on the both sides of different-order synsedimentary faults, and fans composed of sandstone and conglomerate are generally developed near the slope breaks. According to the theory of fault adjustment belt, the adjustment belt is an area between two parallel syn-sedimentary faults, and may become a passageway to transport coarse-grained sediments to the basin. The theory has further broadened the exploration field of lithologic deposit. In the northern slope of the Nanyang depression, however, the slope break is controlled by a topographic buckling towards the basins instead of a syn-sedimentary fault, and the sediments can be unloaded to form lithologic sandbodies below the buckling belt. Therefore, sandbodies can be predicted by analyzing the buckling position in different sequences and combining

Table 4 Main theories and technique systems for lithologic deposit exploration in rift lake basins in eastern China

Research level	Sedimentary system prediction	Sandbody description and prediction	Hydrocarbon potential prediction
Geologic theory	High resolution sequence stratigraphy, sedimentation model of rift lake basin	Structural paleogeomorphology (Jiyang Depression), Slope break-lowstand fan (Jiyang Depression), Fault adjustment belt (Jiyang Depression), Topographic buckling belt (Nanyang Depression)	Petroleum system, Source-reservoir-seal assemblage, Hydrocarbon accumulation dynamics
Exploration technique	Sedimentary microfacies prediction, seismic attribute analysis	Fine study of structure, Seismic attribute analysis, Seismic lithologic inversion, Reservoir modeling, 3-D visualization,	Pressure-sealed compartment, Fluid potential, Bright spot technique, Multi-parameter detection of hydrocarbon potential

with the paleocurrent distribution. For the exploration techniques, the 3-D seismic topography analysis is mostly used to predict sandbodies (Ding and Lei, 1999; Gao et al., 2001; Cui et al.,2002), and reservoir modeling is used to predict the communication between two sandbodies.

The theory of hydrocarbon potential prediction can be used to analyze hydrocarbon accumulation conditions of sandbodies. In the petroleum system study, source rock is always emphasized, and as an origin, it can be used to assess the space-time assemblege of accumulation elements and to predict favorable plays. The theory of source-reservoir-seal assemblege has focused on the study of hydrocarbon accumulation mechanism, and tried to describe the features and assemblage relations of a "deposit", so as to predict the play with various source-reservoir-seal assemblages by using the carrier system as an origin connection for multi-source and multi-type oil deposit. The study of hydrocarbon accumulation dynamics is to analyze the dynamic system for hydrocarbon deposits, and to select favorable lithologic exploration targets (Zeng et al., 1998) by analyzing the dynamic differences of different sandbodies in the same play. With regard to the prediction techniques of lithologic trap hydrocarbon potential, pressure-sealed compartment and fluid potential can be used to indirectly predict the hydrocarbon potential by predicting the accumulation conditions of sandbodies. The direct prediction methods mainly depend upon seismic data. Except the conventional bright spot technique, the multi-parameter and nonlinear mathematical prediction model can be established by using multiple parameters of geology and seismic topography analysis, and by taking the oil and gas occurrences drilled as a control, by which the hydrocarbon potential of a sandbody can be comprehensively predicted, resulting in a great improvement of prediction accuracy.

6 Exploration Potential

Generally speaking, rift lake basins in eastern China have a higher exploration level, but the exploration level is lower when approaching the interior of a depression. In addition, the study and exploration of lithologic deposit are quite difficult. All these may mean a great exploration potential of lithologic deposit. According to a current analysis, it is likely to discover 40%–50% reserves of lithologic deposits finally in these rift lake basins. Based on the statistics of the Jiyang depression, Dongpu sag, Nanxiang basin, Jianghan basin and North Jiangsu basin operated by SINOPEC, the total oil resource is 109.1×10^8 t. If the final ratio of proven reserves is 75%, and 50% of the proven reserves comes from lithologic deposits, the proven reserves can be finallydiscovered from the lithologic deposits are 40.9×10^8 t. The new proven reserves that remain to be discovered is 27.4×10^8 t after deducting 13.5×10^8 t reserves that were already discovered, indicating an extensive exploration potential of lithologic deposit in rift lake basins in eastern China. If there is an integrated and refined exploration with the support of new geologic theories and advanced exploration techniques, the lithologic deposit will definitely play a more and more important role in stabilizing petroleum development in eastern China.

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