Orderliness of Hydrocarbon Accumulation Distribution in Rift Basins of Eastern China

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Abstract: The Cenozoic rift basins in eastern China show a clear temporal and spatial zonation and episodic tectonic evolution, which control their episodic hydrocarbon generation and zonal accumulation. In this paper, based on the study of depositional architecture, hydrocarbon migration system and dynamic evolution in the rift basins, combinations of hydrocarbon accumulation elements were analyzed using sequence stratigraphy. Hydrocarbon distribution in system tracts with different sequence orders was further studied. And we summarized stacking patterns and horizontal combination relationships for different types of reservoirs, such as lithological, tectonic-lithological, tectonic and stratigraphical reservoirs which can be observed from depression center to basin margin. The result reveals that various scales of pools exhibit significant distribution and evolution orderliness in different pool-forming units, i.e., depositional systems, plays and depressions. The regular distribution of various scales of pools is closely related to tectonic evolution and depositional filling in the rift basins. The result can be applied to the fine petroleum exploration in rift basins in eastern China. It will promote the scientific prediction and evaluation of reservoir types and their spatial distribution, lead to the active shifts of exploration targets in different zones, and thus support the stable progress of fine exploration in mature exploration areas.

Key words: rift basin, pathway system, reservoir-forming element, distribution regularity of hydrocarbon accumulation, Cenozoic

1 Introduction

Hydrocarbon accumulation distribution is an ultimate objective in petroleum geology studies, and is a direct expression of geological understanding. Taken the Dongying depression as an example, understanding of hydrocarbon accumulation distribution starts from the original source-controlling theory (Hu, 1982), to the secondary tectonic belt-controlling process (Li et al., 2004), complex petroleum accumulation zone theory (Hu et al., 1986), field-zoning distribution (Liu et al., 1996; Li, 2001) and the current facies-potential controlling model (Wang, 2007). This understanding process represents the geological knowledge evolution of geometry-kinematics-dynamics. With the development of the current exploration work, geological theory and sequence stratigraphical framework, exploration geologists began to research hydrocarbon accumulation distribution in rift basins from the aspects of system tracts, source rock, reservoir rocks, pathway system and traps (Cai et al., 2003).

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In the eastern China, there develop a series of continental rift basins. These rift basins isolate with each other, and have differences in paleogeography, paleotectonics and paleoclimate. This makes basin correlation difficult. However, tectonic control exerts essentially the same role on the rift basins developed in the Yangtz block, Qinling orogenic belt and the North China block. This allows close similarity in tectonic evolution and depositional filling among these rift basins (Feng, 1999; Cai et al., 2003; Feng and Qiu, 2003; Feng et al., 2003; Li et al., 2003; Zhang et al., 2003; Zong, 2003). Integrated sequence stratigraphy with orderliness of hydrocarbon accumulation in the rift basins, this paper analyzed hydrocarbon accumulation elements for different system tracts and presented their orderliness in an effort to provide evidence for petroleum evaluation and prediction.

2 Orderliness of Hydrocarbon Accumulation

The tectonic evolution and depositional filling characteristics of the Cenozoic rift basins in Eastern China exert a key control on their hydrocarbon accumulation elements. And they are the basis for orderliness of hydrocarbon accumulation in different types of reservoirs.

2.1 Orderliness of basin filling architecture

Depositional filling of the continental rift basins in Eastern China exhibits episodic features. The evolution can be divided into three stages: (1) the early rifting and filling stage. In the Yangtze area, it occurred in the late Cretaceous to Paleocene, and in the North China block and Qinling orogenic belt, it occurred in the Paleocene-Eocene; (2) the middle faulting and filling stage. In the Yangtze area, it occurred in the Paleocene-Oligocene, and in the North China block and Qinling orogenic belt, it occurred in the Eocene-Oligocene; and (3) the late post-rift stage (Neogene). Although obvious differences of filling sequences exist during the evolution stages, basin depositional filling in the same stage displays similarity.

In the basin filling stage, due to the limit of lake water volume, one time of rifting and tilting may produce structural slope break and lake water redistribution. During deposition of the lowstand system tracts (LST), onshore exposure occurred in the gentle slope zone to form incised channel deposition, and under this slope break, abandoned delta and fan delta developed. In the sag region, deep lake and semi-deep lake deposition can be observed. When deep lake and semi-deep lake facies occurred in the steep slope zone, nearshore subaqueous fan formed. When the steep slope belt developed two or more fault terraces, water level is shallow under the fault terraces, forming fan delta. And water level becomes deep on the fault terraces, flooding turbidite fans or slump turbidite fans in fan delta front form. During the extensional system tract, nearshore submarine fan formed in the steep slope; turbidite fan formed in the front fan; or nearshore turbidite fan formed in the deep water area of steep slope; due to the limit of terrigenous clastic, shore-deep lake facies beach-bar formed in the gentle slope, and near the source shore, small-scale fan delta-slumping turbidite fan formed. In the HST depositional stage, rifting made this area steep, and a large amount of detritial material flew to the lake, forming delta or fan delta foreset sandbody. Varied sequences in the rift basins exhibit similar sequence structure, and this similarity originates from the special structural-depositional filling texture of the rift basins (Feng et al., 2010). That is, a complete sequence from lake center to lacustrine basin margin or from LST to HST, all display depositional sequence of deep lake turbidite-incised channel-beach-bar-slumping trubidite fan-fan delta-fluvial facies (Fig. 1), forming regular depositional pattern.

2.2 Orderliness of pathway system

Symmetrical characteristics of the profile texture in rift basins of Eastern China exert a critical control on symmetrical distribution of pathway systems in the profile. This allowed regular planar zonation of pathway systems in different horizons of depression belts. From uplift zone in gentle slope uplift belt, gentle slope belt, steep slope belt to uplift belt in steep zone, the pathway systems display as unconformity pathway (sand body+unconformity) -step pathway (fault+sand body)-sand body type (fissure type)-step pathway (fault+sand body)-unconformity pathway (sand body+unconformity) pattern (Fig. 2).

Along the hydrocarbon migration way, reservoir types in different tectonic belts are mainly controlled by the major pathway systems (Hao, 2006). When the pathway systems vary in the sequence of fissure-sand body-fault-unconformity in the plane, reservoir types show a sequential lithological-tectonic-stratigraphical pattern. As we all know, variance of geological bodies in the basin is not completely abrupt, and there are intermediate states between two states. When there are combined effects of two or more pathway elements, complex change patterns of reservoir types are formed. There are lithological-fault pathway systems between skeleton sand body-dominated pathway system and fault-dominated systems, and

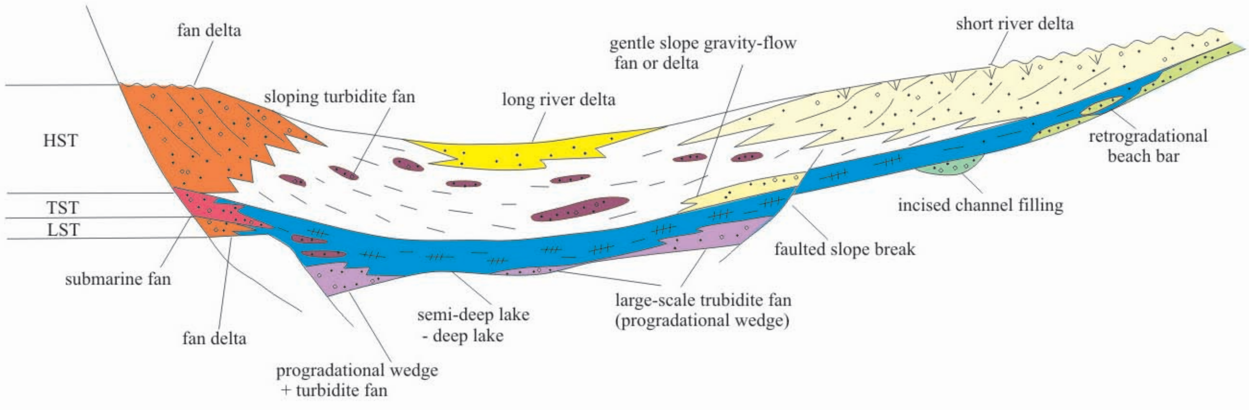

Fig. 1. Depositional model of a single sequence unit in the rift basin.

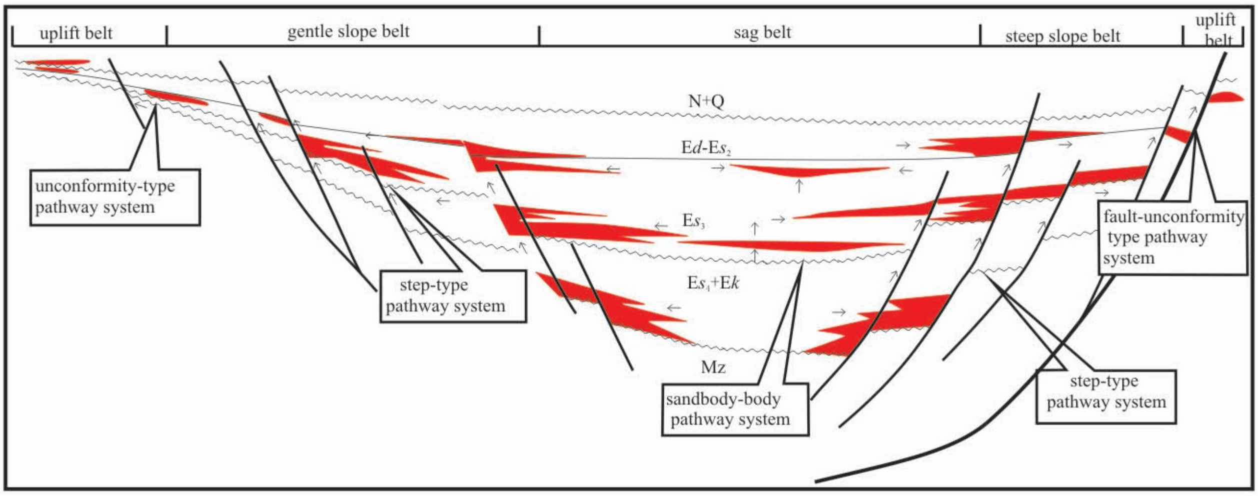

Fig. 2. Stratigraphic cross section showing distribution of hydrocarbon conduits in the Bonan depression.

tectonic-stratigraphical pathway systems exist between fault pathway system and unconformity pathway system. It is thus concluded that besides the zonal distribution features in the plane of reservoir types, they are also characterized by planar orderliness (Fig. 2) (Hao, 2006).

2.3 Orderliness of reservoir-forming dynamics

Sequence stratigraphical studies reveal several sedimentary cycles and several maximum flooding surfaces (MFS) in the basin. We define it as a long-term cycle between two MFS. From sedimentary aspect, the MFS is lacustrine or deep-lake facies, and develops widespread dark shale. From reservoir-forming dynamics, it is favorable for development of source rocks. The MFS tends to develop undercompacted zone or abnormal high pressure zone, forming self-original power in the basin and stopping vertical hydrocarbon migration. If the MFS enters hydrocarbon generation threshold, it is the beginning horizon from source rock to trap. It isolates the basin into several isolated fluid dynamic systems, and fluid can thus only migrate and accumulate laterally along sand bodies and unconformities in the developed-between LST, TST and HST (Cross and Lessenger, 1996).

In the Jiyang depression, different pressure systems control the reservoir types, and the reservoir-forming dynamic systems assume regular distribution. From hydrocarbon generation center to basin margin, reservoir-forming dynamics evolve in the sequence of overpressured-transitional-normal pressured systems. Correspondingly, overpressured systems are dominated by abnormal high pressure; transitional systems are mainly combined effects of pressure and buoyancy; abnormal systems are mainly affected by buoyancy. Take the Dongying depression as an example, from the middle section of the 3rd member in the Shahejie Formation (Es_3), ultrahigh pressure developed in the shale, and slightly high pressure developed in the deep burial depth. Pressure in the lower section of Es_3 increased to middle-to ultra-high pressure, and in the 4th member of the Shahejie Formation (Es_4), ultra-high pressure developed. In the plane, ultrahigh pressure reaches the highest in the depositional center, and becomes low from the depositional center to basin margin. The pressure exhibits a ring-shape distribution, and hydrocarbon forms a hydrocarbon generation center-centered ring-shape distribution pattern in the Dongying depression (Fig. 3).

3 Orderliness of Hydrocarbon Pools Under Control of Sequence

Application of sequence stratigraphy to hydrocarbon pool prediction and evaluation is based on: (1) combined effects of tectonics and climate lead to rise or fall of the water level, resulting in increase or reduce of accommodation; and (2) accommodation in the changing cycle of water level changes with the shift of different locations, making the sediments accumulate in different sedimentary environments at varied rates. This leads to variance of sedimentary facies, geometry, inner texture and temporal and spatial distribution (Cross and Lessenger, 1996), and ultimately controls the source rock-reservoir rock-seal features and their dispositional relationships (Table 1).

3.1 Orderliness of vertical hydrocarbon distribution

Sequence stratigraphical framework controls depositional systems and their spatial distribution, and controls trap type and reservoir scale from the source rock-reservoir rock-seal association. From the source rock and seal developed in the sequence, we can infer the

Table 1 Characteristics of source rocks, reservoir rocks, seals, migration and traps for different types of system tracts in the continental rift basins (modified from Sangree)

System tract		Reservoir rock	Source rock	Seal	Migration	Trap
Low stand	Basin floor fan	Typically high porosity and permeability, but with poor continuity	From the deep source rocks, and the upper shale maybe source rock	The surrounded shale as seal	Vertical migration from deep source rocks, or migrate downward or laterally	Typically lithological trap
	Slope fan	With super good porosity and permeability, good continuity	Undetermined, maybe from the deep	The upper transgressive shale as seal rock	Migrate along faults or LST fans	Typically lithological traps, with some lithological–structural traps
	Incised channel filling	Typical braided river sandstone, with good continuity	Deep source rock dominates, upper transgressive source rock maybe exist	Transgressive shale as seal, with good or undetermined sealing	Migrate upward mainly along fault	Typically lithological or faulted traps
Transgressive	Turbidite beach bar	Beach bar – turbidite sandstone, with fairly good porosity and permeability, extends well	Upper and lateral transgressive source rock	Upper transgressive shale with good sealing, and lateral and bottom shale with changeable sealing	Typical downward and lateral migration in the transgressive system tract	Isolated sand bodies are lithological traps, and the bottom continual TST sand bodies are lithological–structural traps
High stand	(fan) delta	Fan delta front or pro-delta sandstone	Deep source rocks, and HST shale developed poorly	Up dipping to LST, lateral leakage, and the flooding surface is always the upper seal	Mainly migrate along sand bodies and faults	Mainly structural traps, and commonly stratigraphical traps in the basin margin
	Alluvial fan	Alluvial conglomerate and sandstone, with poor to medium continuity and permeability	Difficult to form oil source, and the basin source rocks tends to generate oil	Without seal, with great danger. Shales related to TST are the best, but incised by channels	Vertical migration along faults, or lateral migration along HST sand bodies and unconformities	Structural traps are the best, maybe stratigraphical traps

source rock-reservoir rock-seal association relationships. In the TST of the Jiyang Depression, there are mainly shale, dark grey mudstone and calcareous mudstone; they are abundant of organic matter and have high maturity. They are the major source rock section. According to systemic analysis of the Well Niu 38 from the Dongying depression, shale in the TST of Es_3 is abundant of organic carbon and chloroform bitumen A, has high total hydrocarbon / total carbon ratio; and its kerogen is of I type. This makes the source rock high-quality, abundant in organic matter, and has strong hydrocarbon-generation capacity. The Paleogene strata in the rift basin of Eastern China are characterized by self-original power. However, based on dispositional relationship of source rock-reservoir rock-seal association, it can be classified into: (1) source rock in the upper and reservoir rock at the bottom, (2) source rock at the bottom and reservoir in the upper and (3) Self-generation and self-accumulation. In one sequence, the association (1) is developed in the sublacustrine fan, low-stand fan delta and incised channel sand body of LST at the bottom of the sequence. Its upper part is covered by shale developed in the TST, forming lithological or lithological-tectonic reservoir dispositional with faults. The association (2) can be observed in the slumping turbidite fan and flooding turbidite fan developed in the HST or TST, mainly forming lithological reservoirs. The association (3) is observed in the delta sand body developed in the HST in the upper of the sequence or sand body of coastal shallow lake facies in the TST. In the upper of the high-stand fan delta sand body, there always developed unconformities, lack of good shale seal. Therefore, reservoirs here should couple with tectonic traps to form tectonic reservoirs, or couple with unconformities to form stratigraphical reservoir. The sandstone developed in the TST always extends sheet-like and widely, and it superposed with shale vertically, forming faulted-lithological reservoirs.

In a complete sequence, the MFS in the upper of TST is an important boundary in the sequence stratigraphical framework, and is also a boundary for division of reservoir-forming dynamic system. It always forms abnormal pressure boundary in the reservoir-forming dynamic system. It is commonly recognized that sequence stratigraphical framework and reservoir-forming dynamic system have an obvious coupling relationship in the system tract scale. The cyclic strata comprised the reservoir-forming dynamic branch system. Shale deposited in the MFS stage isolates fluid activity, and is the source bed for compacted force. Sandstone deposited between the two MFS and unconformity comprises the side pathway system in the branch dynamic system (Fig. 4). The fault slope belt forms the vertical pathway system for this

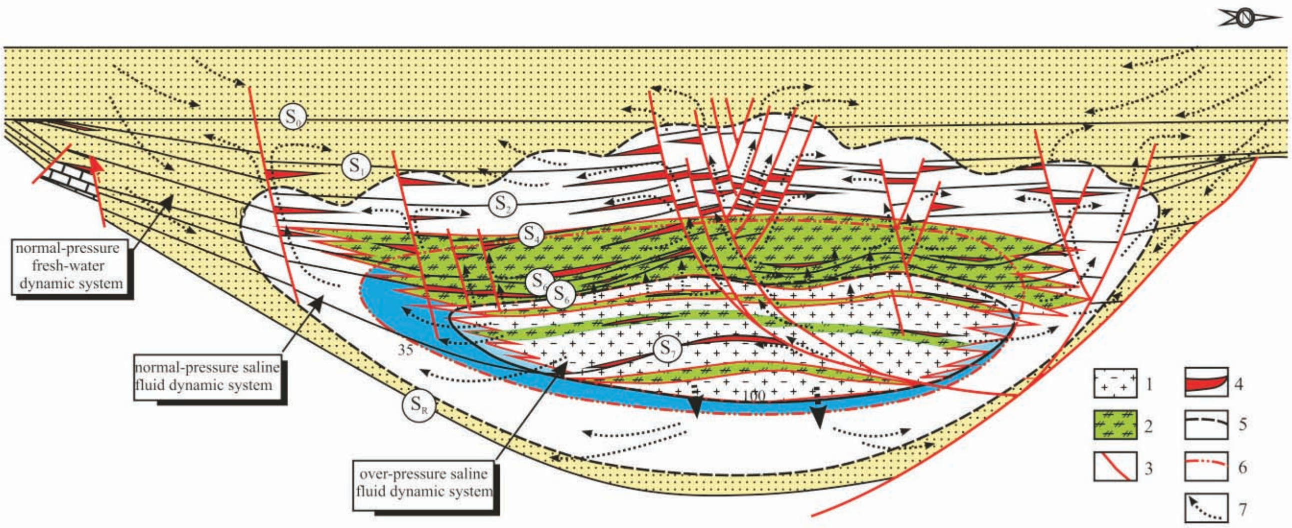

Fig. 3. Schematic model of fluid pressure system in the Dongying depression.

1, salt bed or mud bed; 2, source rock; 3, growth fault; 4, trap/reservoir; 5, salinity contour (g/L); 6, boundary between hydrostatic pressure and over pressure; 7, migration direction; S1—Sr, stratumborser.

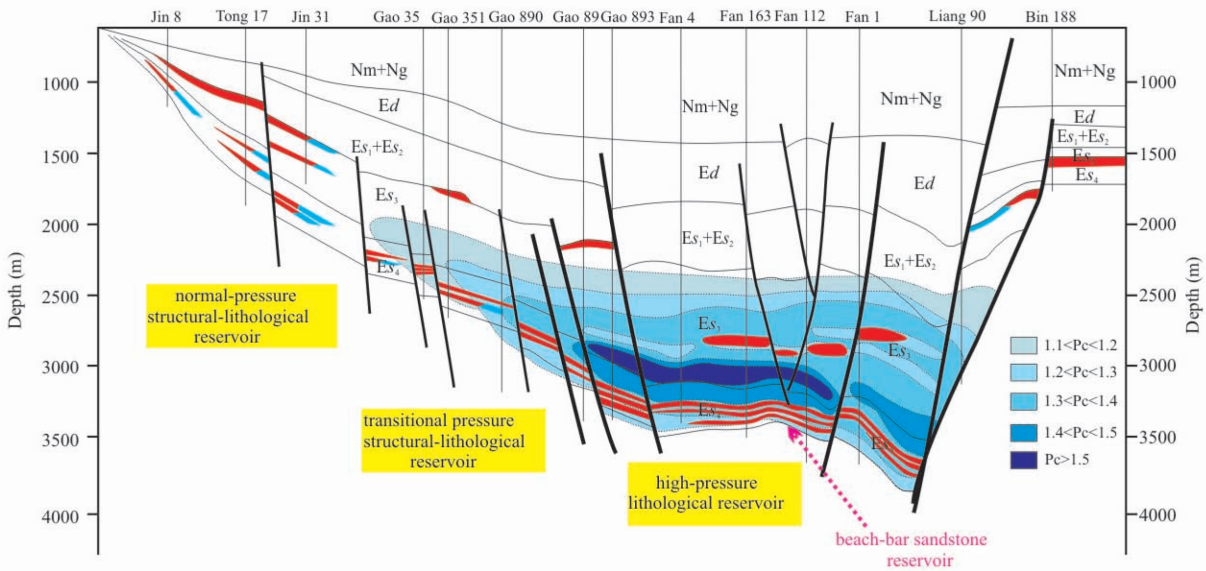

Fig. 4. Schematic model showing the relationship between abnormal pressured system and hydrocarbon pool type in the Dongying depression.

dynamic system (Li, 1991). It can be inferred that this pressure system has a trend from abnormal high pressure to normal pressure from depositional center to basin margin. Integrated source rock-reservoir rock-seal association with pathway system, it is suggested that in a complete sequence, the reservoir type has a sequence of abnormal high pressured lithological reservoir-transitional pressured tectonic-lithological or lithological-tectonic reservoir to normal pressured stratigraphical reservoir from sequence center to basin margin.

3.2 Orderliness of hydrocarbon distribution

Controlled by the effective source rock and tectonic zonation, hydrocarbon distribution assumes a ring shape. Tectonic deformation in different parts of the basin exhibits significant differences, resulting in tectonic zonation. Half-graben depression can be classified into uplift belt in steep slope zone-steep slope belt-deep sag zone-slope zone-uplift belt in slope zone. Tectonic zonation controls sedimentary zonation in the basin, and further controls zonation of the reservoir rock, source rock, pathway system, trap and energy filed. This leads to the zonation of hydrocarbon accumulation in different structures (Fig. 5).

(1) The steep slope belt is adjacent to the deep sag hydrocarbon-generation area and the area with the maximum source rock thickness. It has abundant oil source. The coarse-grained reservoir rocks are well

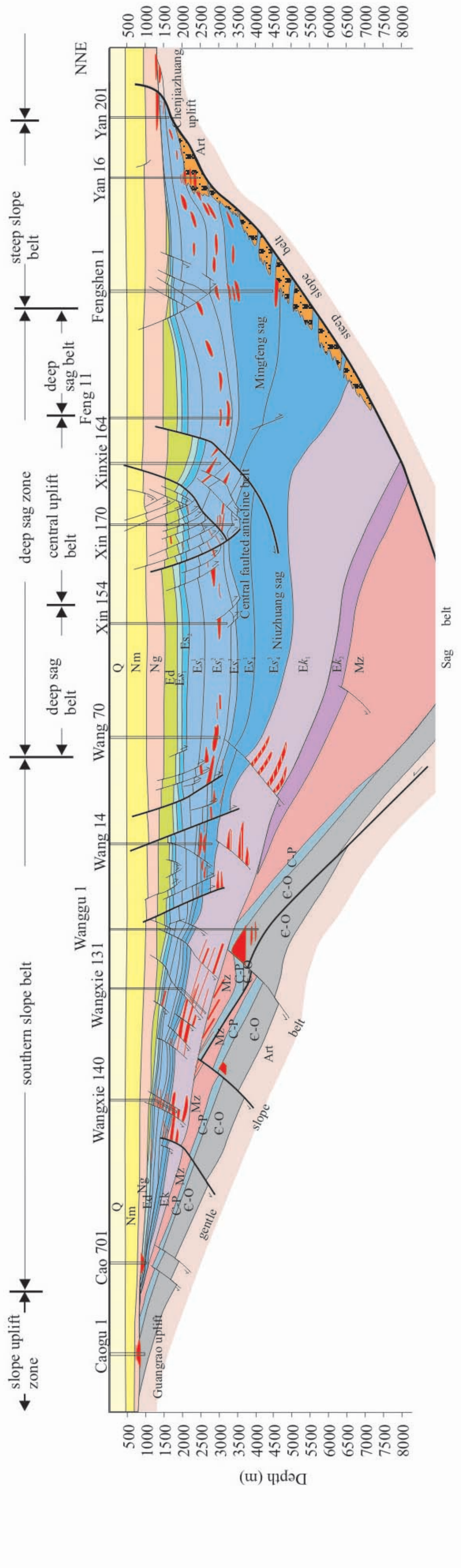

Fig. 5. Schematic model showing the relationship between structure zoning and hydrocarbon pool type in the Dongying depression.

developed. The boundary faults are large scale and active, providing good migration conditions for hydrocarbon. The boundary faults were accompanied by rollover anticline, with well-developed anticline traps. With the evolution of the basin, the boundary faults gradually branched, forming multi-level fault terraces and faulted traps. Glutenite reservoirs, tectonic-lithological reservoirs and rollover anticline reservoirs can be commonly observed here.

(2) The deep sag zone in the central of the basin is in the hydrocarbon-generation center, with abundant oil conditions. Overpressure is well developed, with strong migration force. Compared with the basin margin, sandstone was not well developed, but turbidite sand bodies dominated. Faults were not developed, and concealed pathways were dominated, forming lenticular lithological reservoirs.

(3) The central tectonic belt or abnormal deep sag zone. With the evolution of basin structure, the center of the depression underwent tectonic deformation, forming central uplift belt (such as the Dongying depression central uplift belt) or central fault belt (such as the Yingzijie fault belt in the Southern Huimin depression). The oil source, pressure and reservoir rock conditions in the central tectonic belt are similar to these of deep sag zone. The uplift belt always develops large-scale anticline structures, and it is an important hydrocarbon accumulation belt. The fault belt is an important belt for releasing pressure, with abundant migration force, and always develops compacted comb-like reservoirs.

(4) In the slope belt of the basin, it is near the hydrocarbon-generation area in the depression, with abundant oil source. However, the marginal basin is the hydrocarbon migration direction. Several types of sand bodies developed, e.g., delta, fan delta in the gentle slope and beach-bar system. Faulted-lithological reservoirs, faulted reservoirs and updip pinch-out reservoirs were well developed in this area.

(5) The marginal uplift belt can be divided into 2 types: steep slope belt and slope uplift belt. Hydrocarbon in the steep uplift belt migrates vertically along boundary faults in the steep slope. It accumulates in the upper tectonic bed, forming stratigraphical reservoirs in the bedrock. However, the slope uplift belt is far away from the hydrocarbon-generation depression, and hydrocarbon here depends on long-distance migration. Reservoir rocks developed here. Sand bodies are widespread and have several beds to form large-or medium-sized reservoirs. Compared with steep uplift belt, hydrocarbon accumulation scale and amount in the slope uplift belt are greater.

In the continental rift basins, structure, sedimentary facies and over pressure are all controlling factors for

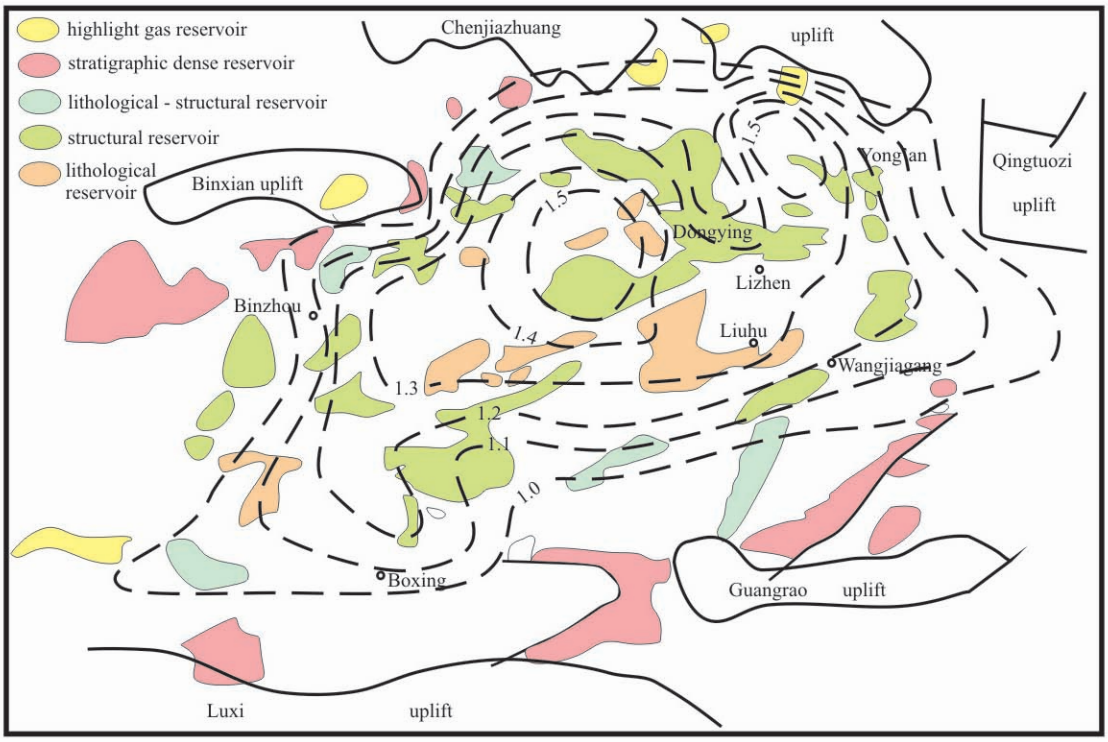

Fig. 6. Map showing abnormal pressure and hydrocarbon distribution in the Dongying depression (modified from Li, 1991).

hydrocarbon differential accumulation. And over pressure system has a critical controlling effect on hydrocarbon reservoirs. Over pressure section always develops source rocks, and the upper boundary of over pressure section tends to accumulate hydrocarbon (Huffman and Bowers, 2002). Leach (1993) observed the relationship of oil, water and gas yield with over pressure for 25, 204 wells in the Gulf Coast of the USA, and reached a conclusion that hydrocarbon in the over-pressured basin was mainly near the upper over pressure boundary (Leach, 1993). Fig. 6 indicates that most of the hydrocarbon in the Dongying depression was distributed with a ring shape along the ultrahigh pressure system, and the hydrocarbon is centered by the Lijin and Niuzhuang depressions with a ring or semi-ring shape (Wu and Qian, 1997). It is obvious that orderliness of hydrocarbon pools distribution is controlled by structure, sedimentary facies and overpressure. And overpressure system exerts a critical control on hydrocarbon reservoir type and distribution.

4 Application in Petroleum Resource Evaluation and Prediction

The tectonic evolution and depositional filling features in the rift basin of Eastern China determines the regularity of reservoir-forming elements, forming orderliness of reservoir distribution in a basin.

The above studies suggest that orderly evolution of depositional filling, pathway system, reservoir-forming dynamics and reservoir-forming association together exert key controls on orderliness of reservoir types in the rift basins. This orderliness can be summarized as that reservoir types are shown as over pressured lithological or tectonic-lithological to transitional pressured tectonic-normal stratigraphical reservoirs, and they exhibit features of vertical superstition, traversal adjacent and overlapped highly. It is concluded that the delta front in the Dongying depression developed many lithological and tectonic-lithological reservoirs (Fig. 7). Based on this, we emphasize on turbidite distribution regularity of Es_3 in the Dongying depression, study delta sequence framework, and describe turbidite distribution which is favorable for hydrocarbon accumulation. And many turbidite reservoirs were found in the delta front of the Dongying depression, which are the main exploration targets for enhancing reserve and production in the Dongxin, Niuzhuang, Xianhezhuang, Haojia, Shinan and Shengtuo oilfields. The annual increased geological reserve is greater than 10×10^6 t, indicating their great potential.

The knowledge of hydrocarbon accumulation orderliness promotes the scientific prediction and evaluation of reservoir types and spatial distribution in the Dongying depression. It allows the active shift of exploration objects from delta plain to prodelta turbidite lithological reservoir. And the exploration of lithological and tectonic-lithological reservoirs in the Dongying

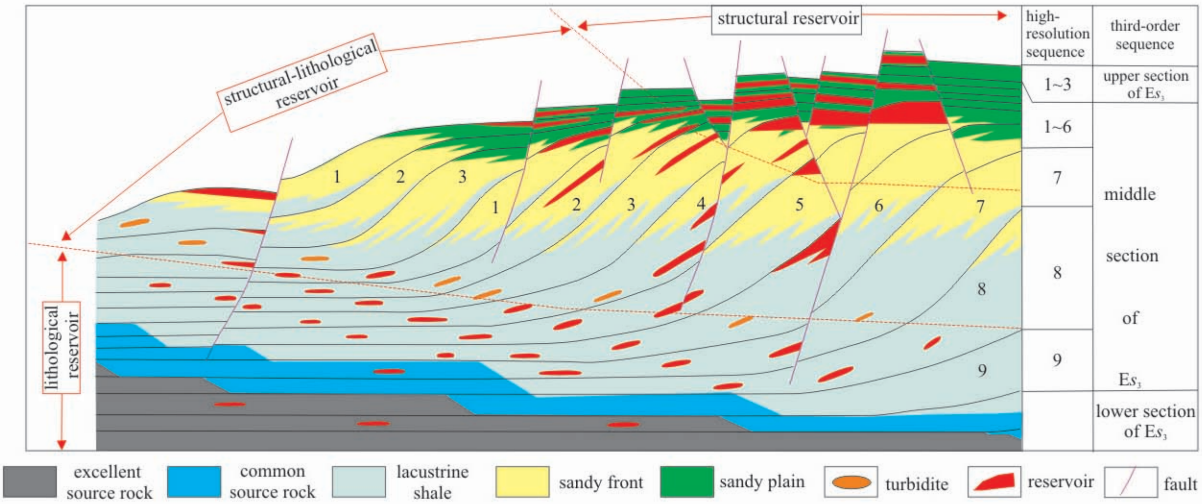

Fig. 7. Schematic model showing regular distribution of hydrocarbon reservoirs in delta system in the middle part of the Dongying depression.

depression (increased proven reserve as 94.26 million ton) is a successful transfer after exploration of tectonic reservoirs. Furthermore, precise exploration of turbidite in the other depressions also achieved significant breakthrough.

5 Conclusions

Previous studies of hydrocarbon pool distribution commonly start from analysis of play, horizon and type to reach conclusions. This characterizes their geometrical features from different aspects, but essentially it is a refined summary of phenomenon. At a basin scale, analysis of hydrocarbon accumulation should start from hydrocarbon-controlling factors and their relationship, and it is of importance to research the evolution of hydrocarbon-controlling factors temporally and spatially and their coupling process. This is just the analysis idea of reservoir type pattern in the rift basin, and is the basis for orderliness conclusion. As it should be that summary of any regularity have stage features. Practical scientific knowledge can be obtained only through transcending phenomenon and creative scientific abstraction.

Similarity of tectonic evolution to depositional filling in the rift basins of Eastern China is the basis for orderliness of hydrocarbon pools. The overall knowledge of reservoir distribution can be summarized as similarity between basins, orderliness of reservoir distribution in the basin and differences of hydrocarbon accumulation types in different plays. The similarity of reservoir-forming regularity in the rift basins of Eastern China and the orderliness of reservoir distribution provide guidance for hydrocarbon exploration. This knowledge is effective for deployment of petroleum basin group, petroleum basin and hydrocarbon plays, and is favorable for the stable development of mature exploration areas.

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