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Petroleum systems in the Damintun Depression, Liaohe Oilfield

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Abstract: There are two different types of oils—high-wax oil and normal oil—found in the Damintun Depression of Liaohe Oilfield after several years of exploration and development, but their distributions and origins had confused the explorers in the oilfield. The introduction of petroleum-system concept shifts the view of geoscientists from geology and geophysics to oil, gas and their related source rocks. After detailed study, two petroleum systems have been identified in the Damintun Depression: (1) the ES_4^2-Ar buried hill petroleum system (called the high-wax oil petroleum system) and (2) the ES_4^1+ES_3^4-ES_4 and ES_3 petroleum system (called the normal oil petroleum system). Based on the detailed analysis of the basic components, and all the geological processes required to create these elements of the two petroleum systems, it is put forward that targets for future exploration should include the area near Dongshenpu-Xinglongpu and the area near the Anfutun Sag. This provides scientific basis and has theoretical and practical meaning for the exploration and development.

Key words: Petroleum system, Source rock, Geochemical characteristics, Hydrocarbon migration
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INTRODUCTION

More than three decades ago, Dow (1972) presented the concept of the oil system at the AAPG Annual Meeting in Denver, Colorado. Since then, the "oil system" has evolved into the "petroleum system" and gained recognition by the petroleum industry as a useful exploration tool (Dow, 1974; Perrodon, 1983; 1992; Demaison, 1984; Ulmishek and Harrison, 1984; Ulmishek, 1986; Magoon, 1987; 1988; 1989; 1992; Demaison and Huizinga, 1991; Magoon and Dow, 1994; Ulmishek and Magoon, 1994).

The concept of the petroleum system (Magoon, 1988) provides geologists with a unified model to explain the distribution of hydrocarbons in the subsurface. In simplest terms, the concept is based on the genetic relationship between a generative petroleum source rock and the resulting entrapped accumulations. A "petroleum system" is a dynamic, petroleum generating and concentrating physico-chemical system, functioning in a geological space and time scale. The petroleum system is the naturally occuring hydrocarbon-fluid system in the geosphere. It encompasses a pod of active source rock (provenance) and all related oil and gas, and includes all the essential elements needed for oil and gas accumulations to exist (Magoon and Dow, 1994). Basic elements of a petroleum system include source rock, reservoir rock, seal rock and migration path. In addition to these four basic components, a petroleum system also includes all the geological processes required to create these elements. Crucial factors of proven petroleum systems include: organic matter richness, type and volume of generative source rock, adequate burial history to ensure the proper time-temperature conditions for source rock maturation, timing of maturation and expulsion in relation to timing of trap formation, presence of migration pathway linking source with reservoir rocks, preservation of trapping conditions from the time of entrapment to present day and relative efficiency of sealing layers.

After more than thirty years exploration, two different types of oils (high-wax oil and normal oil) and five oil-bearing reservoir rocks (Ar, Pt, ES_4^1, ES_3, ES_1) have been identified in the Damintun Depression, Liaohe Oilfield. These two types of oils are of great disparity, so their origin and occurrence had confused the explorers in Liaohe Oilfield for a long time. The petroleum system concept shifts the focus of petroleum exploration from geology and geophysics to oil and gas. After years' study, two petroleum systems were identified according to Magoon and Demaison's classification method (Magoon and Dow, 1994; Demaison and Huizinga, 1991). Based on the analysis of the basic components, and all the geological processes required to create these elements of the two petroleum systems, including the properties of oils, the constitutes of the two petroleum systems, and the occurrence of the high-wax oil and normal oil, we draw the conclusion that the two types of oil originated from different source rocks (i.e. high-wax oil was generated from ES_4^2 shale and normal oil was generated from $E_2S_4^1$ and $E_2S_3^4$ mudstone), and further we concluded that future exploration area should include the area near Dongshenpu-Xinglongpu, the southern part of the Damintun Depression, and the area near the Anfuntun Sag, the northwest part of the Damintun Depression.

GEOLOGIC SETTING

The Liaohe Basin in northeast China developed as a result of rifting and regional subsidence. The Damintun Depression is one of the four depressions in the basin, which developed in the Paleogene. The depression is typified by two different structural units related to the tectonic events. The lower unit is characterized by the wide distribution of faults formed during the rifting stage, while the upper unit formed during the subsidence stage with less fault activity. At the beginning of Paleogene, rifting started with prevailing extension. Rifting ceased at the end of Paleogene, and regional subsidence began at the beginning of the Neogene.

The complex basement rocks in the Damintun Depression are composed of Archean (Ar) granite-gneisses and Middle-Upper Proterozoic (Pt) carbonate rocks. Cretaceous rocks (Mesozoic) are thin and of limited extent. Cenozoic rocks consists of ES_4, ES_3, ES_1, Ed formation in the Lower Tertiary, as well as Upper Tertiary (N) and Quaternary (Q) clastic rocks (Fig.1). Among them, ES_4 and ES_3 were subdevided into ES_4^2, ES_4^1 and ES_3^4, ES_3^3, ES_3^2 and ES_3^1 subgroups respectively from the bottom up. The Lower Tertiary rocks are about 800 km^2 and the maximum thickness exceeds 6000 m. The main petroleum source rocks include ES_4^2 shale and ES_4^1-ES_3 mudstone. Ar (or Pt) buried hill granite-gneisses and carbonate rocks, ES_4 and ES_3 sandstones are the main reservior rocks, while the ES_4^2, ES_4^1 and ES_1 provide good seal rocks.

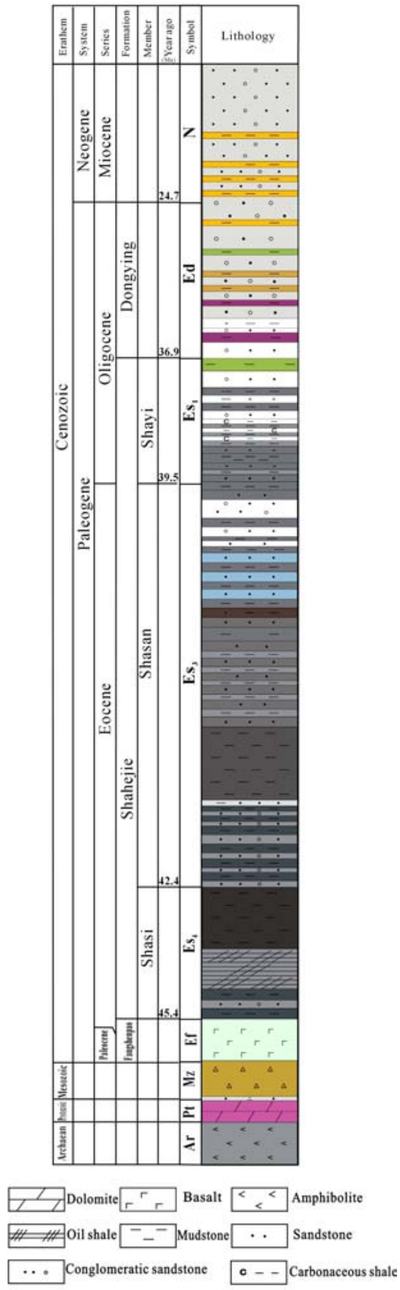

Fig.1 Stratigraphic column in the Damintun Depression

The Damintun Depression has been a significant source of oil and gas in Liaohe Oilfield since production began in 1971. In 1971, two exploratory wells S1 and S2 were drilled in western part of the Damintun Depression. Well S1 showed hydrocarbon and Well S2 produced high-wax oil whose wax content was as high as 47.94%. Wells S5 and S6 were drilled also in western part of the Damintun Depression and proved to be commercial wells in 1972. After that time, wells S8, Q5, S12 and S14 also produced commercial petroleum. Up to the end of 1979, there were 82 exploratory wells and two oilfields—Damintun and Fahaniu—were found. Well Sh3 was drilled in 1982, which proved the Archeozoic (Ar) granite-gneisses buried-hill oil pool, and J3 was drilled in 1983, which proved the Proterozoic (Pt) carbonate rocks buried-hill oil pool. From now, exploration on buried-hills oil pool in Damintun began. Some wells were also drilled successfully to find buried-hill oil pool.

At the end of 2001, there were 347 exploratory wells and a proved oil-bearing area of 192.58 km^2. The oil-bearing area includes normal oil (83.48 km^2, in-place reserves of 0.9494×10^8 t oil) and high-wax oil (109.3 km^2, in-place reserves of 2.0443×10^8 t oil). The middle and lower parts of the Shasan Member and buried hills beneath the Tertiary in the northern part of the depression preserve large amounts of high-wax crude oil with wax contents as high as 47.79%. The central part of the depression contains mixed oil and the southern part contains normal oil with wax content lower than 20%.

MATERIALS

The samples in this study cover the whole basin. Oil samples at atmosphere pressure were collected at the wellhead or from the tool used during well testing. No chemicals were added to demulsify the oils.

METHODS

Total organic carbon of the source rock samples was determined with a CS-244 carbon and sulfur determinator. Following TOC (total organic carbon) analysis, the rock samples were pyrolyzed using a Rock-Eval II instrument to determine the parameters such as S_1, S_2 and T_{max}, and hydrocarbon index (HI) values. The asphaltene of fractions of the source rock and crude oils were precipitated with n-pentane and the deasphaltened samples were separated into saturate, aromatic, and polar (NSO) fractions using thin layer chromatography (TLC). The saturate and aromatic fractions of source rock extracts and crude oils were analyzed using a HP-5890 series II gas chromatography with an FID (flame ionization detector). The branched and cyclic saturate fractions obtained were used for gas chromatography-mass spectrometry (GC-MS) and gas chromatography-tandem mass spectrometry (GC-MS-MS) analysis in a QUATTRO II GC-MS-MS instrument.

PETROLEUM SYSTEM

Source rock

Determining genetic petroleum families and their correlation with source rocks are critical to define petroleum systems and interpret the processes that control the generation, migration and accumulation of petroleum within sedimentary basins. Geochemical parameters based predominantly on biomarkers have been established to genetically correlate crude oils with their source rocks and define petroleum systems (Peters *et al.*, 2005).

There has been much discussion about the source rock for petroleum in the Damintun Depression (e.g. Li *et al.*, 1985; Huang *et al.*, 1992). Two types of source rocks have been found: the lower part of Shasi Member (ES_4^2), the upper part of Shasi Member (ES_4^1) to the Shasan Member in Shahejie Formation (ES_3). The results of oil and source rock samples analyses indicate that the ES_4^2 shale shows excellent correlation with the high-wax oils. The ES_4^2-ES_3 mudstones show good correlation with the normal oils of the Damintun Depression (Huang *et al.*, 2003). The ES_4^2 strata in the lower part of the Shasi Member contain total organic carbon contents (TOC) as high as 9.61 wt% with hydrocarbon index (HI) as high as 800 mg hydrocarbon (HC)/g TOC and are considered to be the source rocks of the high-wax oil in the depression, with good organic matter type—mainly I and II_A (Table 1; Tissot and Welte, 1978). This type of source rock occurs mainly in Anfutun Sag (Fig.2). The ES_4^1-ES_3 strata have TOC

Table 1 Properties of source rock samples from the Damintun Depression

Well	Depth (m)	Formation	TOC (wt%)	HI (mg HC/g TOC)	Kerogen type	*Ro* (%)
S119	3111	ES_4^2	2.73	556	II_A	
A17	2472	ES_4^2	9.61	656	I	
S136	3214	ES_4^2	3.76	264	II_B	
S166	3006	ES_4^2	6.89	808	I	
S119	3150~3162	ES_4^2	1.92	146	III	0.62
C3	2140	ES_4^1	1.99	89	III	0.55
C11	2245	ES_4^1	1.21	85	III	0.67
C12	1674	ES_4^1	1.85	94	III	0.66
A92	2758	ES_4^1	1.79	97	III	0.76
S203	1636.7	ES_4^1	1.07	63	III	0.75
S130	2646	ES_3^4	1.35	62	III	
XS60	3207	ES_3^4	1.05	39	III	0.80
S111	2030	ES_3^4	1.67	135	III	0.55
S142	3348	ES_3^4	2.54	333	II_B	
S80	1860	ES_3^3	0.84	142	III	
S101	2126~2143	ES_3^3	1.36	117	III	0.42
S143	2312	ES_3^3	2.18	296	II_B	
S80	1852~1854	ES_3^3	0.81		III	

Ro: vitrinite reflectance

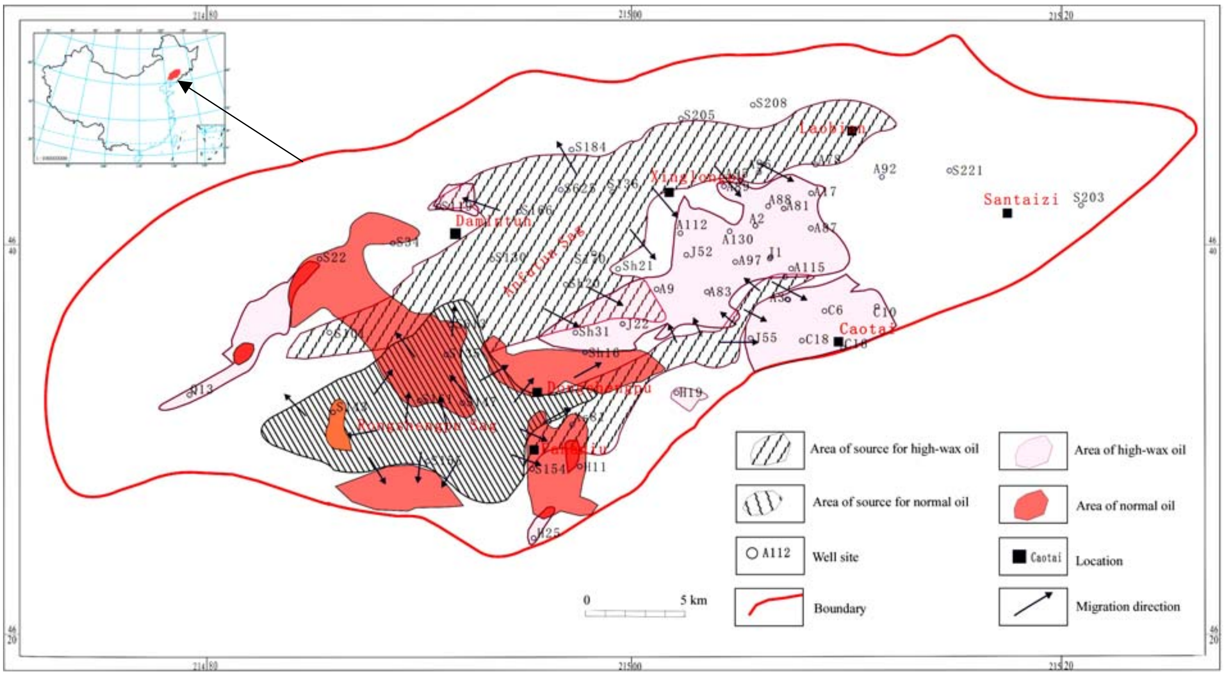

Fig.2 Distribution of petroleum systems in the Damintun Depression

values of 0.81 wt%~2.54 wt% (Table 1). The average TOC of the ES_4^1-ES_3 mudstone is 0.98 wt%~1.77 wt%, whose organic matter type is main type III. This type of mudstone occurs in Rongshengpu Sag (Fig.2). ES_3 and ES_4 Members are fine source rocks with 2.16% average organic carbon contents. Abundant organic matter, including higher plant and plankton in the source rocks, increased the wax contents. Th edibenzothiophene/phenanthrene ratio assesses the availability of reduced sulfur for incorporation into organic matter and the pristane/phytane ratio assesses the redox conditions within the depositional environment (Hughes *et al.*, 1995). In the Damintun Depression, the ratio between dibenzothiophene and phenanthrene in the source rock extracts (e.g. ES_4^2 samples from well S166, A17, and ES_3^4 samples from well S135, J41) is lower than 1.0 and the pristane/phytane ratio (e.g. ES_4^2 samples from well S166, S119, ES_4^1 samples from well S221, C3, ES_3^4 samples from well Sh17, J22, and ES_3^3 samples from well S127, S80) is lower than 3.0, suggesting that the whole Shahejie Formation formed in a reductive freshwater environment with terrestrial high plant input.

Reservoir rock

The reservoir beds in the Damintun Depression include the Archaean to the present, and consist of Archaean granite-gneisses, Proterozoic carbonates and Tertiary clastics. The clastic rocks (sandstones) occur mainly in ES_4^1 and ES_3^4.

Reservoir rocks for the normal oil petroleum system are mainly fan-delta sandstone in ES_4, delta and fan-delta sandstones in ES_3. The thickness of meandering stream and delta sandstone in ES_3^4 is between 100 and 300 m, average porosity is 21.1%, and average permeability is 360 mD. The thickness of alluvial fan-delta sandstone in ES_4^1 is between 200 and 500 m, porosity is 19%~23%, and permeability is in the range of 50~96 mD. In addition, ES_3^3, ES_3^2 and ES_3^1 sandstones can also become oil-bearing reservoirs in the area adjacent to faults.

Reservoir rocks for the high-wax oil petroleum system are mainly basal buried hills, the fan-delta sandstone in ES_4, the delta and alluvial sandstone in ES_3, among which the basal buried hills and delta sandstone in ES_3 are dominant. The Ar metamorphic rocks have no original porosity, but have secondary porosity, such as weathering fractures, structural fractures, brecciated pores, secondary corrosion pores, and secondary replacement pores. Fractures, especially structural fractures, form the only migration passages and main reservoir porosity for hydrocarbons in the buried hills. The porosity of fractures is 0.23%~1.68%, while permeability is 1~600 mD (Xue *et al.*, 2002).

Seal rock

Regionally extensive lacustrine shale in ES_4^1 and flooding plain mud in ES_3^3 provide excellent seals for most of the fields in the area. Shale within ES_4^2 provides seals for basal buried hill accumulations in basement rock.

Trap types

Most of the large accumulations occur immediately below the Ar or Pt erosional unconformity and are sealed by the overlying regional Shahejie Formation. Ar granite-gneisses and Pt carbonate rocks became effective basal buried-hill reservoir rocks as a result of extensive weathering and erosion, which enhanced fractures and porosity. High-wax oil generated from Shasi shale migrated vertically into the basement rocks through the unconformity. Compression from Eocene through Early Miocene time resulted in anticlines and fault traps (Li *et al.*, 2006) sealed by the fault gauge or juxtaposed shale. However, favorable juxtaposition is difficult in this fluvial, alluvial, and shoreline sandstone dominated group. The traps were in place in the Damintun area during the stage of Shasi and Shasan Member deposition. Anticline, fault and stratigraphical traps reservoirs formed when oil migrated into overlying Tertiary sandstone and accumulated there through faults and sand carrier beds.

Properties of oils

The physical and chemical properties of the oil in the Damintun Depression are highly variable, even at the reservoir level. The oil within the Depression has a density range of 0.8025~0.9363 (Table 2). Ninety-five percent of Damintun Depression oils have gravity between 0.8 and 0.9 g/cm^3. Most oils fall within one of two groups (Fig.3). The first group is high-wax oils from buried hills, ES_4, and ES_3 reservoirs (wax content up to 41.43%, but commonly around 30%) having high viscosity (Table 2). They occur at Jinganpu, Caotai, Fahaniu and in buried hills (Ar or Pt), ES_4, and ES_3 sandstone reservoirs. The second group of oils is normal oils from ES_4 and ES_3 sandstone reservoirs. They have lower wax content (less than 10%), lower viscosity (Table 2) and occur at Qiandangpu, Fahaniu, and Dongshengpu. Biodeg-

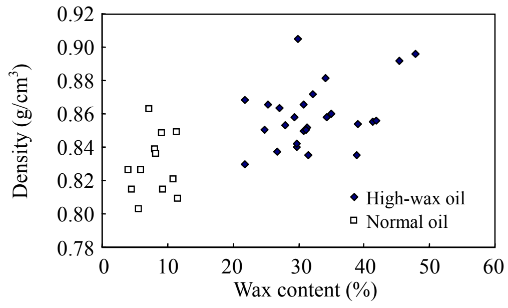

Fig.3 Wax content vs density in the Damintun Depression

Table 2 Physical properties of oil samples from the Damintun Depression

Well	Formation	Oil type	Density (g/cm^3)	Viscosity (mPa·s)	Wax content (%)
A110	Ar	High-wax oil	0.8562	86.79	41.95
A100	Ar	High-wax oil	0.8652	17.39	25.27
SH21	Ar	High-wax oil	0.8420	19.73	29.73
H19	Ar	High-wax oil	0.8578	6.03	29.38
H25	Ar	High-wax oil	0.8295	8.61	21.76
C18	Ar	High-wax oil	0.8577	40.81	34.31
J55	Ar	High-wax oil	0.8635	48.66	27.17
C10	Pt	High-wax oil	0.8370	54.12	26.67
A92	Pt	High-wax oil	0.8553	6.14	41.43
S119	ES_4	High-wax oil	0.8516	9.27	47.79
A9	ES_3	High-wax oil	0.8401	5.80	29.67
S78	ES_3	High-wax oil	0.8598	7.52	34.93
SH20	ES_3	High-wax oil	0.8717	14.64	32.20
A3	ES_3	High-wax oil	0.8533	32.47	28.03
S150	ES_3	Normal oil	0.8142	2.23	9.40
J4	ES_3	Normal oil	0.8209	2.45	10.95
J29	ES_3	Normal oil	0.8146	2.09	4.60
F1	ES_3	Normal oil	0.8356	3.87	8.32
F25	ES_3	Normal oil	0.8087	2.42	11.63
Q11	ES_3	Normal oil	0.8025	2.20	5.70
J22	ES_3	Biodegraded	0.9363	48.62	8.57
SH15	ES_3	Biodegraded	0.9173	15.80	29.37

radation occurs in shallow reservoirs (some ES_3 sandstone), forming heavy oils (density from 0.9173~0.9363 g/cm^3). The concentration of sulfur in most nonbiodegraded oils is low, between 0.05 % and 0.15 % (Xie *et al.*, 2004).

High-wax oils derived from ES_4^2 shale, such as those in Jinganpu (Fig.2) have relatively high pristane:phytane ratios (as high as 2.84), while the pristane:phytane ratios of normal oils in the south of Damintun Depression are lower than 2.0.

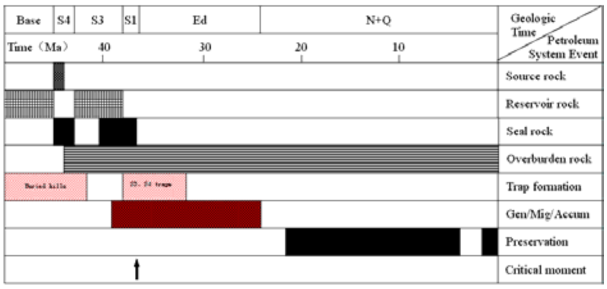

Fig.4 High-wax oil petroleum system event chart for the Damintun Depression

Maturation, migration and accumulation

The maximum depth of the ES_4^2 strata exceeds 3400 m. The hydrocarbon-generation intensity is about 1008×10^4 t/km^2 and hydrocarbon-expulsion intensity is about 424×10^4 t/km^2 by basin modeling software BASIMS4.5. Peak generation and primary migration occurs at 36.7 Ma (Fig.4). Experimental maturation and sampling from Well S166 indicate that the beginning maturation and hydrocarbon generation of the source rocks occur at *Ro* of 0.6% to 0.9%. Calculated maturity from source-rock extracts was compared to vitrinite reflectance measurements and indicates that discovered oils were generated at maturity levels of *Ro* 0.7%~0.8%. In addition, the north part of the depression has long been in the low maturation stage. This weak oxidation-low maturation environment is the key factor for high-wax oil to be preserved.

The cumulative thickness of the ES_4^1 and ES_3 mudstone exceeds 1500 m. Hydrocarbon generation intensity is about 1178×10^4 t/km^2 and hydrocarbon expulsion intensity is 685×10^4 t/km^2 with basin modeling software BASIMS4.5. Peak generation and primary migration occurs at 34.3 Ma (Fig.5). Experimental maturation and sampling from Well S101 indicate that the beginning maturation and hydrocarbon generation of the source rocks occur at *Ro* 0.65%~1.8%.

Oil and gas generation and expulsion from ES_4^2 to ES_3 source rocks in the Damintun Depression oc-

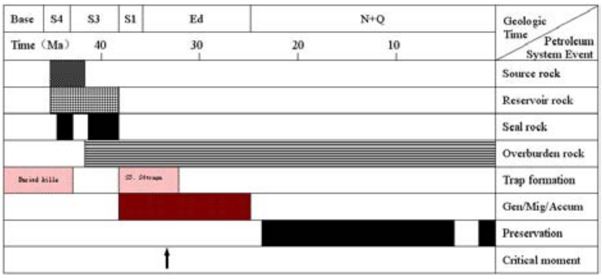

Fig.5 Normal oil petroleum system event chart for the Damintun Depression

curred during the earliest deposition of the Dingying Formation due to higher heatflow and subsidence of this area prior to formation of trapping structures before deposition of Dongying Formation. After Dongying Formation trap formation, oil was generated from the ES_4^2 to ES_3 source rocks, due to the predominance of oil fields in this region.

Vertical migration occurred in the eastern portions of the Damintun Depression, and significant lateral migration is cited for accumulation in the southern Damintun Depression. The ES_4^2 shale–the Ar buried hill–the ES_4^2 shale is the perfect source-reservior-seal rock assemblage. There are two important carrier patterns for the high-wax oil system—from source to buried hill and from source through faults to sandstone (Fig.6). For the normal oil system, alternating beds between sandstones and mudstones are obvious, so oil generated from source rocks can either migrate directly into sandstones or from fractures and faults for a short distance. Discovery trends that locate most oil in the depression are explained by the migration paths and the state of maturity of the immediately adjacent synclinal 'kitchen'. Oil pools in the depression are thought to tap only oil-mature source rocks within the migration area.

Fluid potential is the principal factor controlling hydrocarbon migration in a reservoir (Hunt, 1990). The development of overpressure in the Damintun Depression has a crucial influence on the distribution of fluid potentials, which agrees with that of overpressure in general. By recovering the paleo-formation pressure and imitating distribution model of the paleo-fluid potential field, the knowledge of the law of hydrocarbon movement can be raised to predict the beneficial hydrocarbon accumulation area, and prosperous drilling events increased (Guo, 2007). The results of fluid potential analysis in the Damintun Depression indicate that the areas of Dongshenpu-Xinglongpu and the southwestern part of the depression are the most favorable sites for hydrocarbon migration and accumulation.

CONCLUSION

Two petroleum systems have been identified in the Damintun Depression: the ES_4^2-Ar buried hill petroleum system and the ES_4^1+ES_3^4-ES_4 and ES_3 petroleum system. The two petroleum systems intersect laterally and overlap vertically.

The distribution of the two petroleum systems is directly connected with that of the source rock. The high-wax oils in ES_4^2-Ar buried hill petroleum system were generated from ES_4^2 shale which occurs mainly in Aufutun Sag, while the normal oils in the ES_4^1+

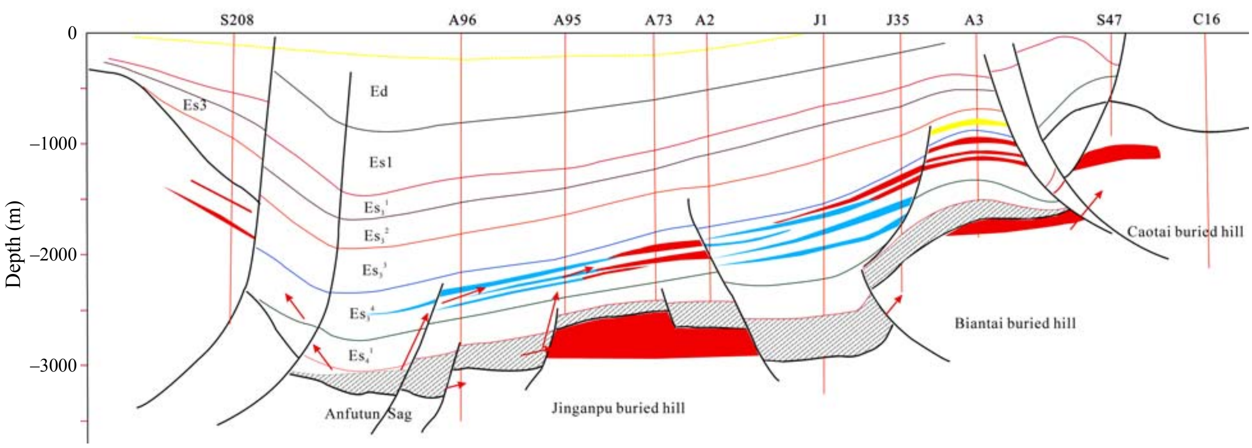

Fig.6 Regional geological section in the Damintun Depression

ES_3^4-ES_4 and ES_3 petroleum system were generated from $E_2S_4^1$ and $E_2S_3^4$ mudstones which occur mainly in Rongshengpu Sag.

Reservoir rocks for the high-wax oil petroleum system are primarily basal buried hill, the ES_4 and ES_3 sandstones are secondary, which determined Ar or Pt buried hills become the main trap type. Reservoir rocks for the normal oil petroleum system are sandstones in ES_4 and ES_3, so anticline, fault and stratigraphical traps are dominant trap types.

The generation, migration and accumulation of the high-wax oil petroleum system occurred earlier than that of the normal oil petroleum system. Traps formed during deposition of Shasi Member to Dongying Formation, which is slightly earlier than migration; these traps can accumulate oils effectively.

Target for further exploration is the area of Dongshenpu-Xinglongpu and the southwestern part of the depression. In the future, exploration for high-wax oil should progress around the ES_4^2 shale, especially near the Anfutun Sag, while the normal oil should be explored near the Rongshengpu Sag.

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