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CHARACTERISTICS AND DISTRIBUTIONS OF MARINE PALEO-RESERVOIRS IN THE NORTHERN MARGIN OF THE JIANGNAN-XUEFENG UPLIFT, SOUTHERN CHINA

DAFEI DENG[(a)], LIANFU MEI[(a)*], CHUANBO SHEN[(a)], ZHAOQIAN LIU[(a)], JIGUANG TANG[(b)], YUANFANG FAN[(c)]

[(a)] Key Laboratory of Tectonics and Petroleum Resources, Ministry of Education, China University of Geoscience, Wuhan 430074, China
[(b)] Yangtze University, Jinzhou 434023, China
[(c)] Xi'an Shiyou University, Xian 710065, China

Abstract. *More than 156 marine paleo-reservoirs (or residual oil reservoirs) and hydrocarbon shows are found in the Neoproterozoic, Paleozoic and Mesozoic marine strata of the northern margin of the Jiangnan-Xuefeng uplift, southern China. In this paper, the characteristics and distributions of marine paleo-reservoirs are statistically analyzed. It is suggested that paleo-reservoirs and hydrocarbon shows were controlled by the ancient uplift and its tectonic evolution. These paleo-reservoirs and hydrocarbon shows in different marine strata have different characteristics and distributions. Paleo-reservoirs and bituminous shows appear mainly in the Ediacaran system of the Neoproterozoic and Lower Paleozoic, and oil and gas shows occur predominantly in the Permian and Triassic, which is obviously related to the development of source rocks and thermal evolution of hydrocarbon. The paleo-reservoir bitumen and hydrocarbons fill predominantly in the fractures and pores of carbonate and clastic reservoirs, which are controlled by the characteristics of original reservoirs and their succeeding transformation with the tectonic evolution, respectively. As estimated by the reservoir scale sequential method, the marine strata hold approximately 368 × 10^8 tonnes of total geological reserves in place of an initial crude oil in the northern margin of the Jiangnan-Xuefeng uplift.*

Keywords: *marine paleo-reservoir, hydrocarbon accumulation, Jiangnan-Xuefeng uplift, southern China.*

* Corresponding author**:** e-mail *lfmei@cug.edu.cn*

1. Introduction

Located between the Yangtze and Cathaysian blocks, the Jiangnan-Xuefeng uplift is a NNE-trending uplift tectonic belt (Fig. 1). It is mainly composed of Neoproterozoic greenschist-facies metamorphic rocks, initiated during the Jinning epoch (about 850 Ma), developed during the Caledonian epoch, and underwent especially the intra-continental tectonic evolution since the Indosinian epoch [1–3].

A large number of paleo-reservoirs and hydrocarbon shows occur in the marine strata of the Ediacaran system of the Neoproterozoic, Paleozoic and Mesozoic around the uplift [4–6]. Especially in the northern margin of the uplift there is a huge hydrocarbon accumulation zone, which is nearly 1400 km long and 40–80 km wide (Fig. 1). The marine hydrocarbon accumulations took place since the Caledonian epoch, but suffered transformation and destruction later. These marine hydrocarbons were mostly transformed to the deposits of paleo-reservoir bitumen. The total geological reserves in place of an initial crude oil of six giant paleo-reservoirs are about 50×10^8 tonnes, including the reserves of Majiang (16×10^8 tonnes) [7, 8], Dachang (8×10^8 tonnes), Weng'an (5.12×10^8 tonnes), Wangcun (about 100 km^2 area and 60 m thick for asphalt enrichment) [9], Bankeng (more than 4×10^8 tonnes), and Taishan (4×10^8 tonnes) [10] paleo-reservoirs.

The transformation and destruction of the hydrocarbon enrichment zone are common phenomena around the world, e.g. in the margin of the Tarim basin, northwestern China, and the fold-thrust belt of the North American Rocky Mountain, especially the uplift belt or structural belt having undergone a strong tectonic process in later periods. The Silurian paleo-reservoirs in the Tazhong, Tabei and Keping paleo-uplifts and their slopes have residual oil sand geological reserves of about 126×10^8 bbl [11], the amount of destroyed hydrocarbon reaches 86.3×10^8 tonnes in the Tarim basin [12]. The fold-thrust belt developed in the Rocky Mountains belongs to the North American petroliferous domain [13]. Its front contains one-fifth of the world's giant oil-gas fields, and develops huge oil sand and asphaltite deposits. The reserves of oil sand and asphaltite only in Alberta are approximately equal to the recoverable petroleum reserves of Saudi Arabia [14]. Alberta's massive marine hydrocarbons accumulation [15, 16] and destruction [17, 18] in geological history are very impressive events.

The objective nature laws and relationships between the characteristics and distributions of paleo-reservoirs and hydrocarbon shows are revealed in the northern margin of the Jiangnan-Xuefeng uplift. This research contributes to the analysis of hydrocarbon enrichment controlling factors and destruction mechanisms of hydrocarbon accumulation. It also provides guidance for marine hydrocarbons exploration and evaluation around the Jiangnan-Xuefeng uplift.

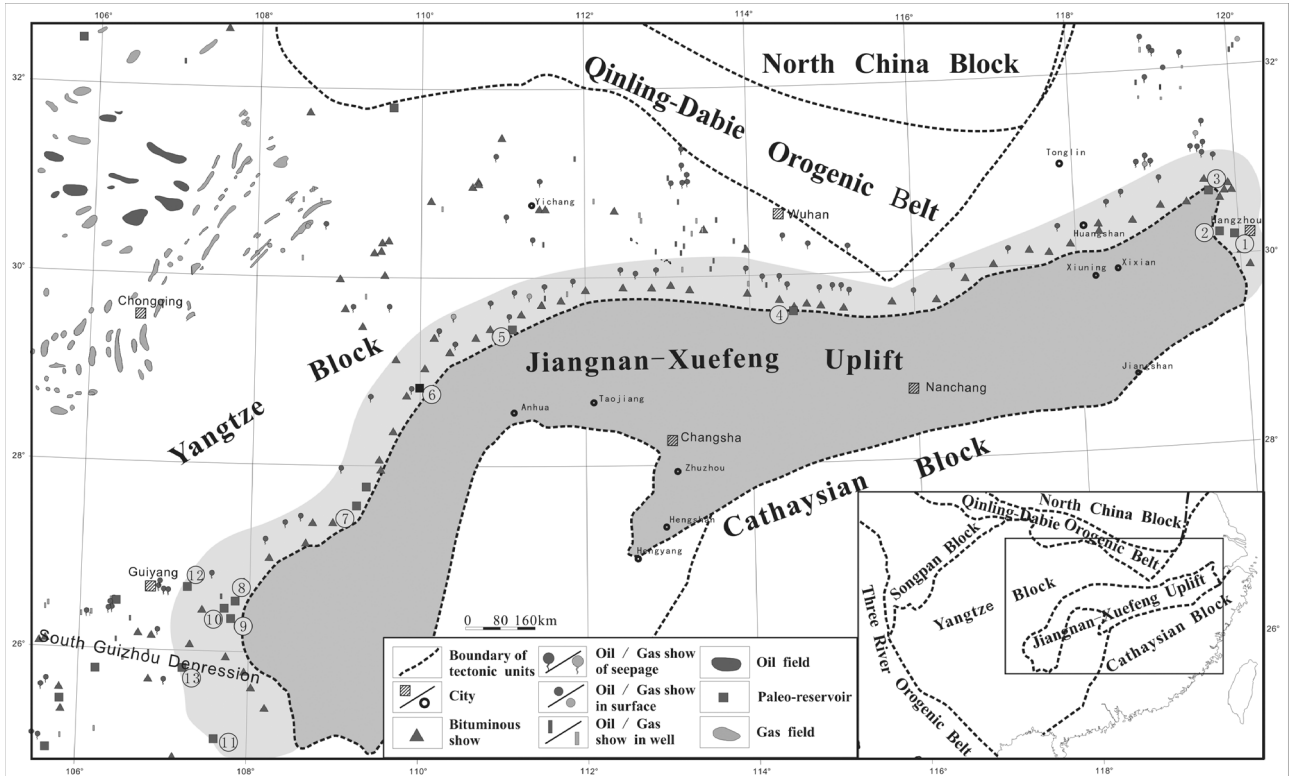


Fig.1. Tectonic units and paleo-reservoir (hydrocarbon show) distributions in the Jiangnan-Xuefeng uplift and the neighboring area: ① – Taishan paleo-reservoir; ② – Xintangwu paleo-reservoir; ③ – Kangshan paleo-reservoir; ④ – Bankeng paleo-reservoir; ⑤ – Nanshanping paleo-reservoir; ⑥ – Wangcun paleo-reservoir; ⑦ – Tongren-Wanshan paleo-reservoir; ⑧ – Kaili residual reservoir; ⑨ – Danzhai paleo-reservoir; ⑩ – Majiang paleo-reservoir; ⑪ – Dachang paleo-reservoir; ⑫ – Weng'an paleo-reservoir; ⑬ – Pingtang paleo-reservoir.

2. Characteristics and distributions of paleo-reservoirs and hydrocarbon shows

In the northern margin of the Jiangnan-Xuefeng uplift, there are up to 156 paleo-reservoirs (or residual oil reservoirs) and hydrocarbon shows in the hydrocarbon accumulation zone (Fig. 1, Table 1).

2.1. Distributions of paleo-reservoirs and hydrocarbon shows

Paleo-reservoirs and hydrocarbon shows are mainly developed in ancient anticline and fault zones, and controlled by the paleo-uplift. Because of the tectonic uplift and denudation, the paleo-reservoirs and bituminous shows occur mainly in the Ediacaran system of the Neoproterozoic and Lower Paleozoic of the structural belts near the paleo-uplift margin having a strong deconstruction and erosional edge. However, oil and gas shows are mainly developed in the Upper Paleozoic and Mesozoic, far away from the paleo-uplift and the coverage area (Fig. 1, Table 1).

From Figure 2 and Table 2 it can be seen that the paleo-reservoirs and bituminous shows appear mainly in the Ediacaran system of the Neoproterozoic and Lower Paleozoic, constituting respectively 37.5% and 50% of show types in the Ediacaran system of the Neoproterozoic. Oil and gas shows occur mainly in the Upper Paleozoic and Mesozoic, especially the Permian and Triassic, accounting for respectively 29.17% and 54.17% of show types in the Triassic, for instance.

The distributions of paleo-reservoirs and hydrocarbon shows on the stratohorizon are obviously closely related to the development of source rocks and hydrocarbon thermal evolution. The original reservoirs were developed in the Ediacaran system of the Neoproterozoic and Lower Paleozoic. Their source rocks are mainly Cambrian and Silurian. The original reservoirs underwent both thermal cracking during a long time and uplift and denudation at later times, and were mostly destroyed and transformed into paleo-reservoirs. For these reasons, the paleo-reservoirs and bituminous shows are mainly seen in the Ediacaran system of the Neoproterozoic and Lower Paleozoic. The hydrocarbon thermal evolution in the Upper Paleozoic and Mesozoic was modest, which suggests that oil and gas shows originate mainly from these eras, especially the Permian and Triassic (Fig. 2, Table 2). In all, paleo-reservoirs and hydrocarbon shows of 141 typical locations were statistically analyzed. The same show location has different show types and strata.

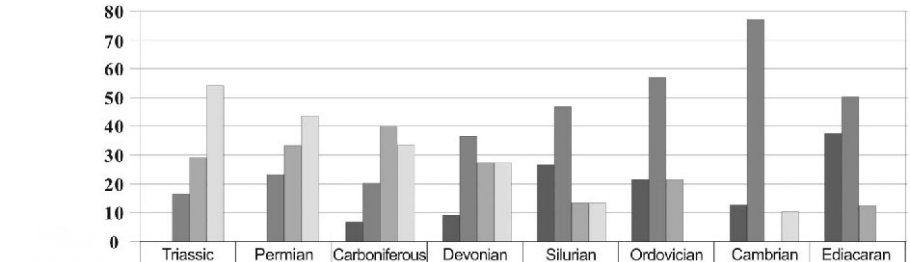
2.2. Occurrences of paleo-reservoirs and hydrocarbon shows

The occurrences of 141 typical paleo-reservoirs and hydrocarbon show locations were statistically analyzed. The same show location has different occurrences and types. As seen from Figure 3 and Table 3, the occurrences of paleo-reservoirs and bituminous shows are mainly fractures and pores.

Table 1. Features of typical paleo-reservoirs and hydrocarbon shows in the northern margin of the Jiangnan-Xuefeng uplift

Number	Well location or name	Stratum	Type of show	Occurrence
1	Fengshan town	P_2, T_2	Oil seepage	Fracture, geode
2	Hu 47 well	S	Oil and bituminous show	Fracture
3	Zhuang 1 well	S	Oil and bituminous show	Fracture
4	Qianshan 1 well	∈	Oil and bituminous show	Fracture
5	Pingtang paleo-reservoir	C_1	Bituminous show	Fracture, pore
6	Dachang paleo-reservoir	D_2	Bituminous show	Fracture, pore, dissolution pore
7	Danzhai paleo-reservoir	$∈_3$	Oil and bituminous show	Fracture, pore, dissolution pore
8	Kaili residual reservoir	S_{1-2}, O_1	Oil and bituminous show	Pore, dissolution pore
9	Majiang paleo-reservoir	S_{1-2}, O_1	Bituminous show	Pore
10	Qianya 2 well	D_1	Bituminous show	Fracture
11	Ya ultra-deep well	D_2	Oil show	Fracture, geode
12	Weng'an paleo-reservoir	$∈_1$	Bituminous show	Pore
13	Tongren-Wanshan paleo-reservoir	$∈_2$	Bituminous show	Fracture, dissolution pore
14	West A'laying	$∈_3$	Bituminous show	Fracture, cave
15	Shuidatian	$∈_3$	Bituminous show	Fracture, cave
16	Shimen county	P_1	Gas seepage	Fracture
17	Matoupu, Li county	T_1	Oil and bituminous show	Fracture, cave
18	Li 5 well	T_1, P_1	Oil show	Fracture, cave
19	Dayong city	T, P	Oil and bituminous show	Fracture
20	Sangzhi county	T, P	Oil and bituminous show	Fracture
21	Nanshanping paleo-reservoir	NP_3	Bituminous show	Pore, fracture
22	Wangcun paleo-reservoir	$∈_3$, O_1	Bituminous show	Fracture, dissolution pore
23	Lican 1 well	T_1	Gas show	Fracture
24	Jiangcan 4 well	S	Bituminous and gas show	Fracture
25	Chacan 1 well	P_1	Oil show	Fracture
26	Baiyunshan village, Jiayu county	P_1	Oil seepage	Fracture, geode
27	Beimencha, Puqi city	P_1	Oil seepage	Fracture, cave
28	Banking paleo-reservoir	S_1	Bituminous show	Fracture
29	Dongchuanling village, Guangde county	P_1, P_2	Oil seepage	Fracture, geode
30	Gangkou town, Ningguo city	T_1, P_2	Oil seepage	Fracture, pore
31	Taiping county	S1	Bituminous dyke	Fracture
32	Xintian town, Xuancheng city	P_1, P_2	Oil seepage	Fracture, pore
33	Taishan paleo-reservoir	NP_3, ∈	Bituminous show	Pore
34	Xintangwu paleo-reservoir	NP_3	Bituminous show	Fracture, dissolution pore
35	An'ji county	$∈_1$	Bituminous show	Fracture
36	Shijiatou village, Banqiao county	O_2	Bituminous show	Fracture
37	Kangshan paleo-reservoir	S_2, S_1	Bituminous show	Fracture
38	Dongchuanling village, Guangde county	P_2, P_1	Oil seepage	Fracture, geode
39	Qingshan reservoir, Lin'an city	NP_3	Bituminous show	Fracture

Note: NP3, ∈ , O, S, D, C, P and T represent the Ediacaran, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian and Triassic, respectively.



	Triassic	Permian	Carboniferous	Devonian	Silurian	Ordovician	Cambrian	Ediacaran
Paleo-reservoir	0%	0%	6.67%	9.09%	26.67%	21.43%	12.82%	37.5%
Bituminous show	16.67%	23.33%	20%	36.36%	46.67%	57.14%	76.92%	50%
Oil show	29.17%	33.33%	40%	27.27%	13.33%	21.43%	0%	12.5%
Gas show	54.17%	43.33%	33.33%	27.27%	13.33%	0%	10.26%	0%

Fig. 2. Histogram of the strata of marine paleo-reservoirs and hydrocarbon shows in the northern margin of the Jiangnan-Xuefeng uplift.

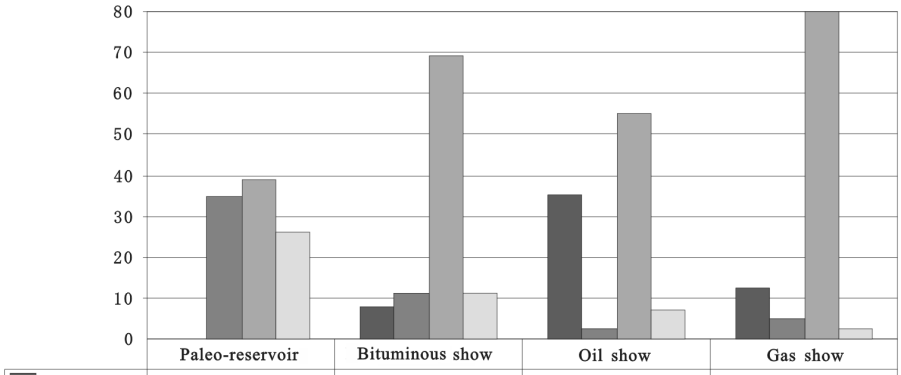
Table 2. Marine paleo-reservoirs and hydrocarbon shows and their strata in the northern margin of the Jiangnan-Xuefeng uplift

Type and quantity / Stratum		Paleo-reservoir	Proportion of show, %	Type of show					
				Bituminous	Proportion of show, %	Oil	Proportion of show, %	Gas	Proportion of show, %
Mesozoic	T	0	0	8	16.67	14	29.17	26	54.17
Paleozoic	P	0	0	7	23.33	10	33.33	13	43.33
	C	1	6.67	3	20	6	40	5	33.33
	D	1	9.09	4	36.36	3	27.27	3	27.27
	S	4	26.67	7	46.67	2	13.33	2	13.33
	O	3	21.43	8	57.14	3	21.43	0	0
	∈	5	12.82	30	76.92	0	0	4	10.26
Proterozoic	NP_3	3	37.50	4	50	1	12.50	0	0

Note: NP3, ∈, O, S, D, C, P and T represent the Ediacaran, Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian and Triassic, respectively.

For instance, the occurrences of bituminous shows are geodes, pores, fractures, and dissolution pores and caves, accounting for 7.95%, 11.36%, 69.32% and 11.36%, respectively. The occurrences of oil and gas shows are mostly fractures and geodes, more specifically, those of oil shows are geodes, pores, fractures, and dissolution pores and caves, accounting for 35.29%, 2.35%, 55.29% and 7.06%, respectively.

The occurrences of paleo-reservoirs and hydrocarbon shows are controlled by the characteristics and later transformation and destruction of original reservoirs. Paleo-reservoirs are the embodiment of original reservoirs, and also the record of later transformation and destruction. Their occurrences are mainly pores and fractures. Pores and dissolution pores are mostly the response of original reservoir space. Fractures and cracks are



	Paleo-reservoir	Bituminous show	Oil show	Gas show
Geode	0%	7.95%	35.29%	12.50%
Pore	34.78%	11.36%	2.35%	5%
Fracture	39.13%	69.32%	55.29%	80%
Dissolution pore and cave	26.09%	11.36%	7.06%	2.50%

Fig. 3. Histogram of the occurrences of marine paleo-reservoirs and hydrocarbon shows in the northern margin of the Jiangnan-Xuefeng uplift.

Table 3. Occurrences of marine paleo-reservoirs and hydrocarbon shows in the northern margin of the Jiangnan-Xuefeng uplift

Occurrence / Type	Geode		Pore		Fracture		Dissolution pore and cave	
	Quantity	Proportion of show, %	Quantity	Proportion of show,%	Quantity	Proportion of show,%	Quantity	Proportion of show,%
Paleo-reservoir	0	0	8	34.78	9	39.13	6	26.09
Bituminous show	7	7.95	10	11.36	61	69.32	10	11.36
Oil show	30	35.29	2	2.35	47	55.29	6	7.06
Gas show	5	12.5	2	5	32	80	1	2.5

probably the evidence of more recent transformation and destruction. Bituminous shows mainly stem from the original reservoir or its destruction. One of the major factors influencing destruction is faulting, and crude oil may migrate to another place along the cracks (fractures). The occurrences of oil shows are mainly fractures and geodes. Fractures and geodes filled with calcite probably partly conserve the crude oil after the destruction. It is common that clean oil and bituminous show coexist, which is the result of pyrolysis of early hydrocarbons [4].

3. Scale of hydrocarbon enrichment

The scale of the marine hydrocarbon accumulation along the northern margin of the Jiangnan-Xuefeng uplift is mainly determined using the

reservoir scale sequential method. This method is an extrapolation and forecast technique. It uses the Pareto law to extrapolate and forecast the hydrocarbon reserves of undiscovered fields and the whole hydrocarbon zone, according to the number and hydrocarbon reserves of known fields [19]. The Pareto law is applied to a complete and independent hydrocarbon system, such as basin and zone. The generation, migration, accumulation and geological evolution of hydrocarbon occurred in the same geological conditions of the system, and at least three reservoirs have been found in the estimated unit [20, 21]. The northern margin of the Jiangnan-Xuefeng uplift is a complete and independent tectonic zone. Its marine strata have nearly the same tectonic environment, evolutionary history and petroleum geology conditions. The reservoir scale sequential method can be used to extrapolate its original reservoirs with reason.

The distributions of ultimate oil field reserves arranged in a descending order obey the Pareto law. The Pareto law is expressed as:

$$Q_m/Q_n = (n/m)^k, \tag{1}$$

where Q_m is the reservoir of number m; Q_n is the reservoir of number n; K is the real number; m, n are 1, 2,..., i.e. any number of the sequence of integers, $m \neq n$.

Taking both ends of Equation (1) to the base 10 logarithm will give Equation (2):

$$(\lg Q_m - \lg Q_n)/(\lg m - \lg n) = -k \tag{2}$$

In double logarithmic coordinates, the vertical axis represents the reservoir scale and the horizontal axis represents the sizing number of reservoirs, and Equation (2) fits a straight line with the slope of –k. The value of k can be determined by the scale of the found reservoirs. The reservoirs distributions are determined using Equation (2) to fit. Then, the undiscovered fields and hydrocarbon reserves can be forecasted.

The scale of reservoir I is:

$$Q_I = Q_{max}/I^k, \tag{3}$$

where I = 1, 2, 3,..., n.

The total reservoirs of resource

$$Q = Q_1 + Q_2 + Q_3 + \cdots + Q_t, \tag{4}$$

where t is the number of reservoirs of minimum size (Q_{min}).

Among the paleo-reservoirs found so far, the Majiang paleo-reservoir has the largest original hydrocarbon reservoirs with about 16×10^8 tonnes (Table 4). The second largest is the Dachang paleo-reservoir and its original hydrocarbon reservoirs hold 8×10^8 tonnes. The difference value of the above two reservoirs is too big. If the value of original hydrocarbon reservoirs of the Majiang paleo-reservoir is included in the fitting directly, the sequential deviation is larger. In practice, the value of original hydro-

carbon reservoirs of the Majiang paleo-reservoir could be taken as a special value and cannot be included in the fitting. A similar approach can be used in the reservoir scale sequential method [19].

Table 4. The original marine oil reservoirs of paleo-reservoirs in the northern margin of the Jiangnan-Xuefeng uplift

Number	Paleo-reservoir	Original oil reservoirs, 10^8 t	Data source
1	Majiang	16	[7]
2	Dachang	8	Tian et al., 2002, internal report
3	Weng'an	5.12	Tian et al., 2002, internal report
4	Banking	4	Mei et al., 2002, internal report
5	Taishan	2	[10]
6	Danzhai	1	[8]
7	Nanshanping	0.8	Tian et al., 2002, internal report
8	Shitouzhai	0.5473	[22]

Equation (1) can yield:

$$Q_1/Q_2 = 8/5.12 = 2\ k, \tag{5}$$

where k = 0.64.

One can obtain from Equation (2):

$$\lg Q_m = 4.9–0.64\ \lg m. \tag{6}$$

It can be fitted in the double logarithmic coordinates, and the seven known paleo-reservoirs are projected (Fig. 4). According to the fitting, these paleo-reservoirs have high anastomosis with the forecast fitting points. The total original marine hydrocarbon reservoirs of the northern margin of the Jiangnan-Xuefeng uplift comprise 368×10^8 tonnes ($Q_{min} = 5.0 \times 10^6$ tonnes), as established by the reservoir scale sequential method. There are 26 paleo-reservoirs whose original hydrocarbon reservoirs include more than 1.0×10^8 tonnes (Table 5).

The total original marine hydrocarbon reservoirs of the northern margin of the Jiangnan-Xuefeng uplift (368×10^8 tonnes) accounted for more than one-tenth of the proven oil reserves (3645×10^8 tonnes[1]) in the Middle East Persian Gulf Basin by the end of 2010. The area (7×10^4 km^2) of the corridor is less than one-fortieth of the hydrocarbon accumulation area (305×10^4 km^2) in the Persian Gulf Basin. The scale of hydrocarbon accumulation per km^2 is far more than in the Persian Gulf Basin.

Table 5. Fitting of the original marine oil reservoirs of paleo-reservoirs in the northern margin of the Jiangnan-Xuefeng uplift

Original oil reservoirs	$> 10 \times 10^8$ tonnes	$1–10 \times 10^8$ tonnes	$0.5–1 \times 10^8$ tonnes
Number of reservoirs	1	25	51

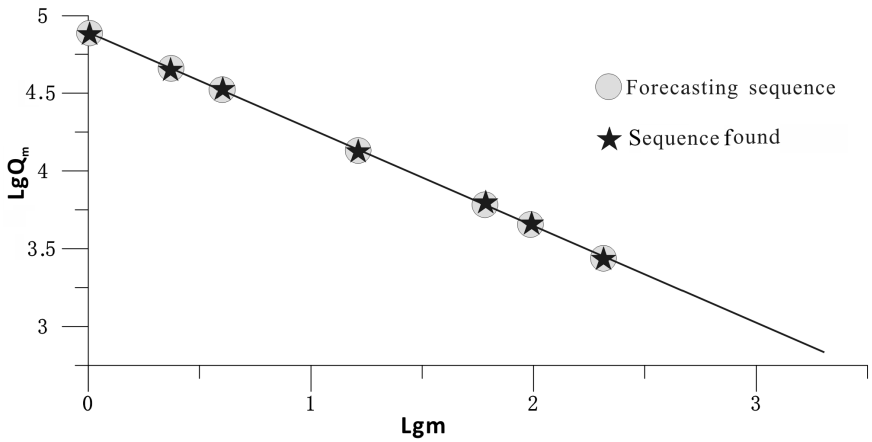


Fig. 4. Fitting diagram of the original marine oil reservoirs of paleo-reservoirs in the northern margin of the Jiangnan-Xuefeng uplift.

4. Discussion

The enrichment zones (areas) of abundant hydrocarbon are mainly developed in the passive continental margin, active continental margin and continental rift system in the global [23]. The proved reserves of the zones (areas) account for 67% or more of the world's total proven reserves [24]. Favorable tectonic setting, abundant and effective source rocks, favorable reservoir-cap combination and trap types are the major factors influencing the development of the enrichment zones (areas), the tectonic setting being the key factor in the process of hydrocarbon enrichment.

Compared to the huge hydrocarbon enrichment zones (areas) around the world, the northern margin of the Jiangnan-Xuefeng uplift does not have similar tectonic settings of passive continental margin, active continental margin and continental rift system. Recent studies [25, 26] indicate that the Yangtze block (including the Jiangnan-Xuefeng uplift) and the Cathaysian block have relatively similar features of the intra-continental tectonics inherent to the Caledonian tectonic cycle.

The paleo-uplift is favorable to the development of reservoir bed, the migration and accumulation of hydrocarbon, and the formation of large-medium sized oil-gas fields. The uplift axis and the upper slope are the best positions for hydrocarbon accumulation [27]. However, several strong structural transformations at later times have substantially influenced the preservation of hydrocarbon. With the most intense tectonism towards the end of the tectonic cycle, the northern margin of the Jiangnan-Xuefeng belt was the first to experience uplifting and denudation, folding, fracture and magmatism [3]. These were the main reasons for the destruction of the marine hydrocarbon accumulation.

The northern margin of the Jiangnan-Xuefeng uplift underwent the intra-continental tectonic evolution since the Caledonian. It was a typical representative of the complicated tectonic evolution of "Chinese" continent [3, 28], and located in the transition region from thick-skinned to thin-skinned structure [29]. Its tectonism was active and caused the destruction of the massive marine hydrocarbon. The northern margin of the uplift was an active region of hydrocarbon transformation and adjustment, and is worthy of further exploration.

5. Conclusions

1) Paleo-reservoirs and hydrocarbon shows in the marine strata along the northern margin of the Jiangnan-Xuefeng uplift are mainly developed in ancient anticline and fault zones, and are controlled by the paleo-uplift and tectonism. The distributions of paleo-reservoirs and hydrocarbon shows are obviously related to the development of source rocks and hydrocarbon thermal evolution on the stratohorizon.
2) The paleo-reservoir bitumen and hydrocarbons fill predominantly in the fractures and pores of carbonate and clastic reservoirs, which are controlled by the characteristics of original reservoirs and their succeeding transformation with the tectonic evolution, respectively.
3) The marine strata hold approximately 368×10^8 tonnes of total geological reserves in place of an initial crude oil in the northern margin of the Jiangnan-Xuefeng uplift, as estimated by the reservoir scale sequential method.

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